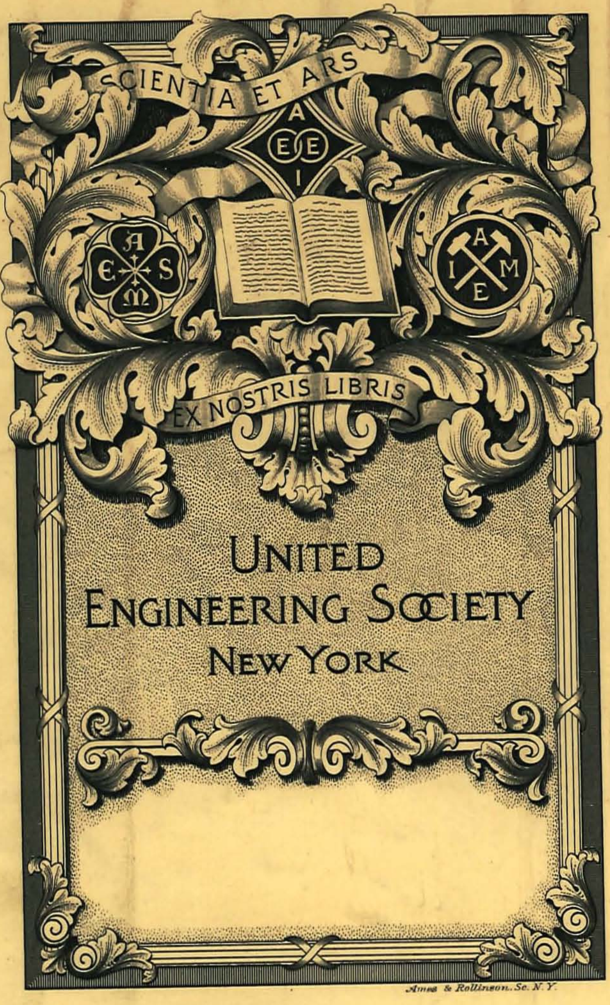
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IOWA
GEOLOGICAL SURVEY

VOLUME XXV

ANNUAL REPORT, 1914
WITH
ACCOMPANYING PAPERS

GEORGE F. KAY, H. D., State Geologist
JAMES H. LEES, Ph. D., Assistant State Geologist

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TWENTY-THIRD ANNUAL

Report of the State Geologist

IOWA GEOLOGICAL SURVEY,
DES MOINES, DECEMBER 31, 1914.

To Governor George W. Clarke and Members of the Geological Board:

GENTLEMEN:—I have the honor to report that all the investigations which were approved by you at the beginning of the field season of 1914 have been carried forward successfully, and I am sure that the Board will be gratified to learn that there has been during the year an excellent spirit of co-operation among the men who were chosen to do the special lines of work which each, by his training and experience, was prepared to undertake. When it is recalled that the remuneration of the employees of the Survey has always been small for work which requires technical knowledge, it is somewhat surprising that year after year for many years the Survey has had the services of such an efficient corps of investigators. Moreover, I am sure that many citizens of Iowa do not fully appreciate the kind and amount of service that the Survey has been rendering to the State with appropriations that are considerably less than the appropriations of several other well-equipped Surveys of the country. At a time in our history when it is necessary to know fully our resources and the uses to which they can be put, the Geological Survey is an important factor in the development of the state. In this connection I wish to impress strongly the urgent need of good roads in Iowa and to call attention once more to volume XXIV of the reports of the Survey in which the available road and concrete materials of the state are fully described. The duties of the Director of the Survey have taken him into every county of Iowa, and thus he has had unusual opportunity to study the roads of the state. It is his conviction that if Iowa, with her unparalleled agricultural resources, is to attain her true status among the progressive states of the country, proper consideration must be given at once to the lines of travel within her borders. If all the citizens of the state could but have the opportunity to see the real conditions in many parts of Iowa during certain seasons of the year, they would rise to the need and would see to it that the roads of Iowa were made to compare favorably with the best roads of the other states of the country. Fortunate indeed is our state in having in many of the counties ample supplies of gravel, sand, limestone, and other materials suitable for one or more types of road that have been found to be satisfactory in every way in other states where the conditions are similar to the conditions in Iowa.

Perhaps special attention should be called also to another feature that has impressed itself upon the Director of the Survey in recent years, more particularly during the year 1914, namely, the desire on the part of citizens of the state, and many persons outside the state, to secure reliable information regarding particular resources within the state. An unusually large correspondence has related to the probability of finding oil and gas. This question was discussed at some length in the administrative report which accompanies volume XXIII of the reports of the Survey. Many of the inquiries during the past year have had regard to oil and gas in southeastern Iowa. the recent interest having been related to the discovery of an oil field in western Illinois. With regard to southeastern Iowa, the Survey stated in volume XXIII, page xliv, that in that area there is evidence of upwarps of the nature of low domes in which the older terranes are much nearer to the surface than they would have been if the dome structure were absent, and that this dome or anticlinal structure is, as has been shown in many oil fields, one of the most favorable conditions for the accumulation of oil and gas. It was stated, however, that in none of the artesian wells that had been sunk had any oil or gas been found in the indurated rocks. Some gas has been found in sand pockets connected with the glacial deposits, but these are of little value commercially. The important artesian wells that have been sunk in southeastern Iowa, and in which no oil was found, although these wells penetrated to depths below the horizon in which the oil has been found in western Illinois, include the following:

1. Crapo Park well, Burlington, which is 2430 feet deep, and penetrates rocks of Cambrian age.

2. Keokuk wells, which enter Saint Peter sandstone of Ordovician age.

3. Fort Madison wells, several of which, apparently penetrate rocks of Ordovician age.

4. Mount Pleasant well, which is 1100 feet deep, and penetrates rocks of Ordovician age.

5. Bloomfield well, which is 1817 feet deep, and penetrates rocks of Ordovician age.

6. Letts well, which is 1135 feet deep, and penetrates rocks of Ordovician age.

Since the discovery of the oil field in western Illinois, the Iowa Survey has studied the conditions there as published in the reports of the Illinois Geological Survey, and has compared these conditions with the known conditions in southeastern Iowa.

The western Illinois oil field is in the vicinity of Colmar, Illinois, which is somewhat more than the width of one county east from Keokuk. Here there are now several producing wells. Still nearer than this to Iowa in eastern Hancock county, considerable prospecting was done in 1914. Twenty holes were put down, in only one of which was oil found. The evidence indicates that in the Colmar field the oil is in lenses of sandrock in depressions on the old eroded surface of the Maquoketa formation of the Ordovician system. These sand lenses are very irregularly distributed. They vary in thickness and in other characteristics and, even where wells have penetrated such sand lenses, oil has not always been found. The rocks in this field show dome structure; the domes are small in area and in magnitude, the crests of many of them being not more than twenty to thirty feet high. In this area the best advice that the Illinois Geological Survey has been able to give to prospective drillers is that wells should be drilled in the known domes, in the hope that sand lenses containing oil may be found.

Now, our knowledge of the geology of southeastern Iowa, gained from a study of areal geology and from the deep wells, seems to indicate that the conditions in western Illinois may prevail in Iowa. In Iowa the Maquoketa shale has been found in the wells that have been drilled, and above it is the Niagaran formation within the basal part of which the oil has been found in western Illinois. It must be kept in mind, however, that since there are numerous unconformities within the rock section, the thicknesses and other features of the different formations may vary considerably within short distances. The conditions are such that even if oil does exist in certain places in southeastern Iowa, it is extremely difficult to direct intelligently where the drilling should be done in order to reach the oil. Undoubtedly the future will see wells drilled in southeastern Iowa for the purpose of finding oil. It is the hope of the Survey that when wells are drilled oil may be found, and its officers stand ready at all times to give the best advice possible from the evidence that is available. The locations of the test wells should be selected only by those who have full knowledge of all the geological factors involved. Even when this is done no definite assurance can be given that oil will be found; on the other hand, if all the geological factors are not taken fully into consideration large sums of money may be spent where it could have been shown before operations were begun that the attempt was doomed to failure.

The work of the Survey for 1914 may be summarized as follows:

AREAL GEOLOGY.

Detailed areal work and geological mapping was done by Professor Shimek in Audubon and Shelby counties, by Dr. James H. Lees in Crawford county, and by the Director of the Survey in Lucas and Union counties. Prof. J. L. Tilton completed his report on the geology of Clarke county, and Prof. J. E. Gow submitted his manuscript on the geology of Adair county. These reports will be published in the next volume of the Survey devoted to county reports.

ARTESIAN WATERS.

A report on the Underground Waters of Iowa that has proved to be of great value to the people of the state in connection with water supplies for domestic and other purposes was published as volume XXI of the reports of the Survey. Since that report was issued Prof. W. H. Norton, the author of the volume on Underground Waters, has continued to collect and tabulate all available information regarding new wells that have been sunk in various parts of the state. By so doing the officers of the Survey, when called upon to do so, have been able to give the most up-to-date advice regarding the best sources of water in each locality where information was desired. Without such advice many thousands of dollars would have been spent in many municipalities without an adequate water supply having been secured.

CO-OPERATIVE TOPOGRAPHIC MAPPING.

The Iowa Geological Survey in 1914 continued to co-operate with the United States Geological Survey in making topographic maps of areas selected by the Director of the Iowa Geological Survey. The plan of co-operation included the following articles of agreement which were signed by the Director of the United States Geological Survey and the State Geologist of Iowa:

1. The preparation of the map shall be under the supervision of the Director of the United States Geological Survey, who shall determine the methods of survey and map construction.

2. The order in which, in point of priority, different parts of the state shall be surveyed shall be agreed upon in detail by the Director of the Iowa Geological Survey and the Director of the United States Geological Survey, or their respective representatives.

3. The survey shall be executed in a manner sufficiently elaborate to prepare a map upon a scale of 1:62,500, exhibiting the hydrography, hypsography, and public culture, and all town and county boundary lines, township and section lines, as marked upon the ground at the time of its completion, in form similar to sheets already completed in the state of Iowa. The prelim-

inary field maps shall be on such scale as the Director of the United States Geological Survey shall select to secure accuracy in the construction of the final map.

4. The hypsography shall be shown by contour lines, with vertical intervals of 5 to 100 feet, as may hereafter be mutually agreed upon.

5. The heights of important points shall be determined and furnished to the Director of the Iowa Geological Survey.

6. The outlines of wooded areas shall be represented upon proofs of the engraved maps, to be furnished to the Director of the Iowa Geological Survey.

7. Under ordinary conditions the salaries of permanent employees doing field work shall be paid by the United States Geological Survey, while the traveling, subsistence and field expenses for the same time shall be paid by the State. During the office season the salaries shall be divided between the two agreeing parties in such a way as to equalize all expenses, provided that the total cost to the state of Iowa for field and office work shall be not less than one thousand seven hundred and fifty dollars ($1,750), and provided, that the United States Geological Survey shall expend an equal amount upon the work before June 30, 1915, the Federal allotment to bear an approximate charge of 12½ per cent for the necessary expenses in connection with the proper execution of the field and office work. All accounts shall be approved by a representative of the United States Geological Survey before payment.

8. During the progress of the work free access to the field sheets and records of the topographers and draftsmen shall be afforded the Director of the Iowa Geological Survey, or his representative, for examination and criticism; and should the said Director of the Iowa Geological Survey deem that the work is not being executed in a satisfactory manner, then he may, on formal notice, terminate this agreement.

9. The resulting maps shall fully recognize the co-operation of the State of Iowa.

10. When the work is completed, the Director of the Iowa Geological Survey shall be furnished by the United States Geological Survey with photographic copies of the manuscript sheets; and when the engraving is completed, and at all times thereafter when desired, he shall be furnished by the said Survey with transfers from copper plates of the maps for use in printing editions of said maps.

The following is a summary of the field and office work accomplished during the period, January 1 to December 31, 1914, under the general direction of R. B. Marshall, Chief Geographer, and under the immediate supervision of W. H. Herron, Geographer of the Central Division:

Field work.

Quadrangles	Counties	For publication on scale of	Area mapped—square miles	Traverse		
				Primary miles	Per. marks	Secondary miles
Boone	Boone, Hamilton, Webster	1:62,500	29	....	....	80
Chariton	Lucas, Marion, Warren	1:62,500	58	15	1	241
Melrose	Appanoose, Lucas, Monroe, Wayne	....	....	7	2	......
Attica	Marion, Lucas, Monroe	....	....	36	6	......
Humeston	Wayne, Lucas	....	....	10	2	......
New Virginia	Warren, Lucas, Clarke	....	....	4	....	......
Albia	Mahaska, Marion, Monroe	....	....	10	2	......
		....	87	82	13	321

The following members of the United States Geological Survey were engaged in the field work:

Topographic Mapping:

W. L. Miller, Topographer.

Primary Traverse:

E. L. McNair, Topographic Engineer.

Office Work:

The office drafting of the Boone topographic map was begun, 80 per cent being finished on December 31, 1914.

The adjustment of the levels for the Attica and Chariton quadrangles was completed, the field notes typewritten and prepared for publication.

The topographic maps that have been issued by our Survey are proving to be, as has been stated frequently, of great value to the people of the state, and it is much to be regretted that the Iowa Geological Survey does not have an appropriation of at least ten thousand dollars a year for topographic work. This amount, with an equal amount yearly from the Federal Survey, would enable Iowa to carry forward topographic mapping as rapidly as has been done in several of the other important states of the country. The urgent need of topographic maps was stated at some length in the last administrative report of the Survey, and it is thought well to repeat the following significant paragraph:

> The development of the state in connection with a highway system, drainage projects, steam and interurban railways and in many other ways demands the preparation of topographic maps as rapidly as possible. Further delay will but add to the great financial loss that the state has already suffered through a lack of such maps. At the last meeting of the Iowa Engineering Society, and also at a recent meeting of the Iowa Academy of Science, resolutions were adopted urging that efforts be made to secure for the Iowa Geological Survey increased appropriations for this important work.

STRATIGRAPHIC GEOLOGY.

During the summer of 1914 Mr. F. M. Van Tuyl continued his studies of the Mississippian rocks, and Prof. A. O. Thomas continued his investigations of the stratigraphy and paleontology of the Devonian rocks of the state.

CO-OPERATIVE STREAM MEASUREMENTS.

During the summer of 1914 the Iowa Geological Survey continued to co-operate with the Water Resources Branch of the United States Geological Survey in the work of stream gaging and discharge measurements of the important streams of the state.

THE CLAYS OF THE STATE.

Under the direction of Dr. S. W. Beyer the investigations of the clays of the state were continued. Special attention was given to the study of ball and stoneware clays.

MINERAL STATISTICS.

As in past years the Iowa Geological Survey in 1914 co-operated with the United States Geological Survey in the preparation of statistics of mineral production in Iowa. It is gratifying to be able to state that the value of the output for the year was $26,301,865, which is higher than any previous figure of record. In 1913 the value of the output was $25,612,345 and in 1912 the value was $22,910,066. A comparison of the value of the output in 1914 with that of 1905 shows that the value in 1914 exceeded that of 1905 by $11,198,819, which is an increase of nearly seventy-five per cent in a decade. Coal continues to be the chief mineral produced. Its value at the mines in 1914 was $13,364,070, which is $132,640 less than the value for 1913. The five leading coal-producing counties in 1914 in order of tonnage were Monroe, Polk, Appanoose, Dallas and Marion. These five counties produced more than six million tons of the total tonnage, which was 7,451,022 tons, Monroe county alone producing 2,273,066 tons. The first three of the five counties mentioned have retained the same order of production for more than ten years. For many years previous to 1913, Mahaska county ranked fourth; in 1914 this county ranked sixth. In 1914 the average number of men employed in coal mining was 16,057, in 1913 the number was 15,757.

It is of interest to state that Iowa has one coal washing plant, which is located at Lakonta in Mahaska county.[1] In 1914 the quantity of coal washed at this plant was 25,706 tons, which yielded 18,000 tons of clean coal, and 7,706 tons of refuse.

The value of clay and clay products, which includes brick and tile, pottery and raw clay, was $6,405,995 in 1914; in the previous year the value was $5,575,581. In no year in the history of the state has the output of 1914 been exceeded. The values of the outputs in the three chief producing counties were as follows: Cerro Gordo county, $1,555,944; Webster county, $1,179,113; and Polk county, $856,967. Iowa continues to lead all the states in the United States in the production of drainage tile. The value of this product sold in Iowa in 1914 was $3,180,836. Wapello county leads in the production of pottery.

Since the year 1911 there have been three large modern cement plants in Iowa, two of which are located at Mason City,

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[1] Kay, George F. The First Coal-washing Plant in Iowa. Iowa Academy of Science, volume XXII, pages 225 to 227.

the third at Des Moines. In 1914 the output of these three plants had a value of $4,008,915. The highest figure previous to this year was in 1913, when the value of the output was $3,972,876. Although the output has been increasing year by year there is every reason to believe that the maximum yearly output has not yet been reached. The three plants are thoroughly equipped and there are abundant supplies of limestone and shale, which are the materials being used in Iowa for cement making.

The gypsum industry in Iowa is in a most flourishing condition. In 1914 the value of the output from Webster county, the center of the industry, was $1,321,547, the largest figure of record for the state.

The value of stone and lime in 1914 was $594,681 compared with $854,814 in the previous year. A large part of the stone was used for concrete and railroad ballast.

The value of sand and gravel produced in Iowa in 1914 was $556,868; in 1913 the value of the output was $528,066. The value of mineral waters in 1914 was $30,179, and of other products including mineral paints, sand-lime brick and natural gas was $19,700.

PLEISTOCENE GEOLOGY.

The geologists of the world who are especially interested in the Pleistocene have long recognized Iowa to be classic ground, and from time to time for more than twenty years the foremost geologists of both America and Europe have come to this state to see the interesting features that have been described by those who have made detailed studies of the glacial and interglacial deposits.

Among the many persons who, by their publications, have made known to the world the Pleistocene history of Iowa, no one has had a greater part than Doctor Calvin, who was for nearly twenty years Director of the Iowa Geological Survey. For many years, particularly from about 1895 until his death in 1911, important papers were written by him in the reports of the Iowa Geological Survey and in other channels of publication. It was he who, after he had done detailed work on the Pleistocene of the northeastern and north-central parts of Iowa, became convinced that in this part of Iowa the evidence indicated that the ice had invaded the region, not twice only, as had been held formerly, but three times. To the uppermost of these drift sheets Doctor Calvin gave the name "Iowan," and in several publications he presented his arguments in favor of recognizing the Iowan as a distinct epoch in the Pleistocene. For a number of years the interpretations of Doctor Calvin were accepted, but a few years before his death some of the leading Pleistocene geologists of America, including Mr. Frank Leverett of the United States Geological Survey, who had spent several months in a field study of the problem, raised the question as to whether or not there was sufficient evidence to establish the glacial epoch, the Iowan, distinct from the Kansan. The matter was still in controversy at the time of Doctor Calvin's death in 1911. Since that time a favorable opportunity was awaited to secure a man who had a well established reputation as a Pleistocene geologist to review in the field all the evidence with reference to the Iowan problem and, if possible, to reach a judgment regarding this important phase of Pleistocene geology, which has been the source of so much difference of opinion. The Survey was fortunate indeed in 1914 in being able to secure in connection with this work the co-operation of the United States Geological Survey. An agreement was reached whereby Dr. W. C. Alden, Chief of the Pleistocene Section of the United States Geological Survey, should undertake the investigation. As the representative of the Iowa Geological Survey Mr. M. M. Leighton was appointed to assist him. Work was begun during the past summer and will be continued in 1915. It is hoped that when this investigation is completed a valuable report may be published in which the problem of the Iowan drift will be discussed fully, and that conclusions may be reached which will be satisfactory to all students of Pleistocene geology.

During the year Mr. M. M. Leighton has submitted for publication a very thorough paper on the Pleistocene History of Iowa River Valley, North and West of Iowa City in Johnson county, Iowa.

PALEONTOLOGIC GEOLOGY.

An important paper entitled "Trilobites from the Maquoketa Beds of Fayette County, Iowa," has been furnished to our Survey for publication by Mr. Arthur W. Slocom, who was for many years connected with the paleontologic branch of the Field Museum of Natural History of Chicago. The thanks of the Survey are due the officers of the Field Museum and to Mr. Slocom for permitting our Survey to reprint, with the original illustrations, a valuable paper dealing with one of the ancient groups of life from an important stratigraphical horizon in our state.

IRON ORE INVESTIGATIONS.

For many years the iron ore deposits at Waukon, Iowa, have been of scientific interest, and it has been hoped that with proper treatment these ores might be made of commercial importance. As a result of the thorough methods of investigation of the Waukon Iron Company this hope is, apparently, soon to be realized. During the past summer Jesse V. Howell made a detailed study of these interesting deposits, including their methods of occurrence, geological relations, their origin, and the probable quantity of ore. The results of Mr. Howell's investigation have been submitted for publication. His paper is an important contribution to the literature regarding the class of iron ore deposits to which the Waukon beds belong.

THE ORIGIN OF DOLOMITE.

The origin of dolomite has been the subject of much investigation for many years, and yet the conclusions that have been reached by the several investigators have not been wholly in agreement. The Survey realized for many years that there was probably no better place in America for the study of the origin of dolomite than in Iowa, since dolomites and related limestones are well exposed in many parts of the state and at different stratigraphic horizons. It was, therefore, thought well to subject these interesting rocks to special study. Mr. F. M. Van Tuyl was chosen to carry forward the investigation. After much detailed work in the field and careful studies in the laboratory, he has prepared a paper which, it is believed, will be considered, for some years to come, an authoritative work on dolomite and will be consulted freely by those who are interested in the subject with which it deals.

NATURAL HISTORY INVESTIGATIONS.

Bulletins on Natural History are now in preparation as follows:

Mollusca, by Prof. B. Shimek.

Rodents, by Mr. Dayton Stoner.

Hawks and Owls, by Dr. B. H. Bailey and Dr. T. C. Stephens.

Orthoptera, by Prof. M. P. Somes.

GEOLOGIC HISTORY OF DES MOINES VALLEY.

As a part of the larger plan of making a broad study of the surface geology of the state it was thought well to examine in detail the physical features of Des Moines valley, this being the largest river valley within the state and offering excellent opportunity for a study of the processes of valley formation and stream work. A few years ago, Dr. James H. Lees began this work and he has now prepared a report of his investigations. This report includes a description of the valley itself, a discussion of the forces which have shaped it and an outline of the geologic history through which it has passed. It is hoped that this paper will be of value in the study of Iowa physiography and will help to make plain the history of the development of the surface features of our state.

OFFICE WORK OF THE SURVEY.

The Iowa Geological Survey continues to be for the people of Iowa and for many persons outside the state a reliable source of information regarding the mineral resources and other geological features of the state. There has never been in the history of the Survey greater demand than during the past year for the services of the Survey. There has been correspondence in connection with many phases of the geology of the state, and it has been the aim of the Survey at all times to furnish the information desired, whether it consisted only in naming a mineral that had been submitted for identification or in offering advice to those seeking investment in the state. The demand for the publications of the Survey has been so great that the editions of several of the reports and maps have been exhausted. In connection with the office work and in various other ways I wish to express my indebtedness to Dr. James H. Lees, Assistant State Geologist, and also to Miss Nellie E. Newman who has been for many years the efficient secretary of the Survey.

REPORTS FOR PUBLICATION.

I take pleasure in submitting to you the following papers, and recommend that they be published as Volume XXV, which is the Twenty-third Annual Report of the Iowa Geological Survey:

Mineral Production for 1913 and 1914, by George F. Kay.

The Iron Ore Deposits near Waukon, Iowa, by Jesse V. Howell.

Pleistocene History of Iowa River Valley, North and West of Iowa City in Johnson County, by M. M. Leighton.

Trilobites from the Maquoketa Beds of Fayette County, Iowa, by Arthur Ware Slocom.

The Origin of Dolomite, by Francis M. Van Tuyl.

Physical Features and Geologic History of Des Moines Valley, by James H. Lees.

Respectfully submitted,

GEORGE F. KAY.

MINERAL PRODUCTION IN IOWA FOR 1913 AND 1914

BY GEORGE F. KAY

MINERAL PRODUCTION IN IOWA FOR 1913 AND 1914[1]

BY GEORGE F. KAY

VALUE OF MINERAL PRODUCTION.

1912.

Coal	$13,152,088
Clay and clay products	4,524,492
Stone and lime	998,236
Gypsum	845,628
Lead and zinc	5,670
Mineral waters	11,325
Sand and gravel	563,409
Cement	2,790,396
*Other products	18,822
Total	$22,910,066

1913.

Coal	$13,496,710
Clay and clay products	5,575,581
Stone and lime	854,814
Gypsum	1,157,939
Lead and zinc	4,150
Mineral waters	7,369
Sand and gravel	528,066
Cement	3,972,876
*Other products	14,840
Total	$25,612,345

1914.

Coal	$13,364,070
Clay and clay products	6,405,995
Stone and lime	594,681
Gypsum	1,321,457
Lead and zinc	———
Mineral waters	30,179
Sand and gravel	556,868
Cement	4,008,915
*Other products	19,700
Total	$26,301,865

*Sand-lime brick, mineral paints and natural gas.

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[1] The mineral statistics were compiled by the Iowa Geological Survey in co-operation with the United States Geological Survey.

In 1913 the total value of the mineral production in Iowa was $25,612,345, and in 1914 it was $26,301,865. The value in 1913 exceeded that in 1912 by $2,702,279, and in 1914 the highest figure of record was reached. The following table shows the value of Iowa's mineral output during each of the past ten years:

VALUE OF MINERAL PRODUCTION IN IOWA FOR THE YEARS 1905 TO 1914 INCLUSIVE.

1905	$15,103,046
1906	16,414,447
1907	17,627,925
1908	18,090,447
1909	20,365,721
1910	22,744,572
1911	21,119,111
1912	22,910,066
1913	25,612,345
1914	26,301,865

A comparison of the value of the output in 1914 with that in 1905 shows that the value in 1914 exceeded that in 1905 by $11,198,819, which is an increase of nearly seventy-five per cent in the decade. With the exception of the year 1911, the value of each year of the past ten years has been higher than that of the preceding year.

Coal continues to be the chief mineral produced in Iowa, clay and clay products ranks second in value, cement ranks third, and gypsum, fourth. In 1914 these four products had a value of $25,100,437, which is 95 per cent of the total value of all the mineral products. The values for coal, and stone and lime, were less in 1914 than in 1913, but the values of clay and clay products, cement, sand and gravel, and mineral waters, were greater in 1914 than in 1913, and, moreover, the values of all these products except sand and gravel were the highest figures of record for the state.

The number of mineral producers in Iowa was 614 in 1913, and 563 in 1914.

The total production, by counties, for 1913 and 1914 is given in Table I.

TABLE I.

VALUE OF TOTAL MINERAL PRODUCTION, BY COUNTIES, FOR 1913.

Counties	No. of Producers	Coal	Clay and Clay Products	Stone and Lime	Sand and Gravel	Other Products	Total
Adair	1	----------	*	--------	--------	----------	----------
Adams	4	$ 17,536	----------	--------	--------	----------	$ 17,536
Allamakee	3	----------	*	*	--------	----------	20,310
Appanoose	58	2,436,279	*	*	*	----------	2,457,017
Audubon	4	----------	*	--------	*	----------	19,525
Benton	6	----------	$ 60,164	*		----------	60,164
Black Hawk	14	----------	*	$ 11,617	$ 30,906	*	47,543
Boone	12	522,929	91,924	--------	--------	----------	614,853
Bremer	3	----------	----------	--------	2,613	----------	2,613
Buena Vista	5	----------	27,000	--------	*	----------	27,000
Butler	3	----------	*	--------	*	----------	2,905
Calhoun	1	----------	*	--------	--------	----------	----------
Carroll	1	----------	----------	--------	*	----------	----------
Cass	1	----------	*	--------	--------	----------	----------
Cedar	1	----------	*	--------	--------	----------	----------
Cerro Gordo	10	----------	1,401,015	*	--------	*	4,505,031
Cherokee	2	----------	----------	--------	*	----------	----------
Clay	2	----------	*	--------	--------	----------	----------
Clayton	9	----------	----------	13,622	*	----------	13,622
Clinton	8	----------	13,900	*	17,236	----------	31,136
Dallas	9	1,077,293	225,311	--------	--------	----------	1,302,604
Decatur	1	----------	----------	*	--------	----------	----------
Delaware	4	----------	4,576	--------	--------	----------	4,576
Des Moines	4	----------	*	*	*	----------	20,152
Dickinson	2	----------	----------	--------	*	----------	----------
Dubuque	18	----------	50,500	86,092	30,546	$ 4,150	171,288
Emmet	3	----------	----------	--------	*	----------	1,208
Fayette	5	----------	*	*	*	----------	27,140
Floyd	6	----------	*	4,217	*	----------	60,936
Franklin	2	----------	*	--------	*	----------	----------
Fremont	1	----------	*	--------	--------	----------	----------
Greene	4	26,400	----------	--------	*	----------	26,400
Grundy	3	----------	*	--------	*	----------	26,875
Guthrie	6	11,890	*	--------	--------	----------	11,890
Hamilton	1	----------	*	--------	--------	----------	----------
Hancock	1	----------	*	--------	--------	----------	----------
Hardin	10	----------	*	*	3,171	----------	91,303
Harrison	1	----------	----------	*	--------	----------	----------
Henry	3	----------	*	*	--------	----------	24,186
Howard	3	----------	*	*	*	----------	9,048
Humboldt	1	----------	*	--------	--------	----------	----------
Ida	1	----------	----------	--------	*	----------	----------
Iowa	2	----------	*	--------	--------	----------	----------
Jackson	5	----------	*	*	*	----------	54,436
Jasper	15	567,211	27,156	--------	--------	*	596,551
Jefferson	7	*	25,774	--------	--------	*	32,709
Johnson	6	----------	22.300	--------	10,189	----------	32,489
Jones	10	----------	*	105.230	*	----------	120,006
Keokuk	14	*	120.218	*	--------	----------	132,959

TABLE I.—CONTINUED.

Counties	No. of Producers	Coal	Clay and Clay Products	Stone and Lime	Sand and Gravel	Other Products	Total
Kossuth	1	----	*	----	----	----	----
Lee	15	----	12,528	62,258	8,305	----	83,091
Linn	16	----	37,960	80,008	31,579	----	149,547
Louisa	5	----	*	*	----	120	7,670
Lucas	4	44,913	*	----	----	----	44,913
Lyon	6	----	----	----	12,890	----	12,890
Madison	4	----	*	36,925	----	----	36,925
Mahaska	20	568,314	*	----	----	----	568,314
Marion	18	487,151	53,231	----	*	----	540,382
Marshall	7	----	79,918	*	*	----	236,323
Mills	4	----	8,179	----	----	----	8,179
Mitchell	3	----	----	5,058	----	----	5,058
Monona	1	----	----	----	*	----	----
Monroe	19	4,087,032	----	----	----	----	4,087,032
Muscatine	7	----	14,705	----	*	----	14,705
O'Brien	3	----	----	----	2,277	----	2,277
Osceola	2	----	----	----	*	----	----
Page	4	*	*	----	*	----	26,528
Palo Alto	3	----	----	----	10,890	----	10,890
Plymouth	4	----	*	----	992	----	992
Pocahontas	1	----	----	*	----	----	----
Polk	45	2,984,919	692,710	----	136,649	*	4,689,545
Pottawattamie	3	----	34,207	----	----	----	34,207
Poweshiek	4	----	37,145	----	----	----	37,145
Sac	3	----	*	----	*	----	125,115
Scott	14	----	58,511	172,278	*	*	276,609
Sioux	4	----	----	----	8,387	----	8,387
Story	5	----	*	----	1,162	----	1,162
Tama	6	----	45,169	----	----	----	45,169
Taylor	3	*	*	----	----	----	15,955
Union	1	----	*	----	----	----	----
Van Buren	9	32,772	*	*	*	----	36,970
Wapello	18	259,099	67,332	*	*	----	342,973
Warren	2	*	*	----	----	----	----
Washington	5	----	30,570	----	----	----	30,570
Wayne	5	172,531	----	----	----	----	172,531
Webster	27	101,078	1,078,255	----	*	1,167,939	2,347,272
Winnebago	2	----	*	----	*	----	----
Winneshiek	5	----	*	*	971	----	7,516
Woodbury	6	----	*	----	15,985	----	15,985
Wright	4	----	*	----	3,631	----	3,631
County values represen'g less than three producers and small coal mines	----	99,363	1,255,323	277,509	199,687	3,984,965	1,019,876
Total	614	$ 13,496,710	$ 5,575,581	$854.814	$528,066	$ 5,157,174	$25.612.345

*Included in County values and totals.

TABLE I.—CONTINUED.

VALUE OF TOTAL MINERAL PRODUCTION BY COUNTIES, FOR 1914.

Counties	No. of Producers	Coal	Clay and Clay Products	Stone and Lime	Sand and Gravel	Other Products	Total
Adair	1	----------	----------	--------	--------	----------	----------
Adams	4	*	----------	--------	--------	----------	----------
Allamakee	2	----------	*	*	--------	----------	----------
Appanoose	58	$ 2,505,646	*	*	*	----------	$ 2,529,737
Audubon	5	----------	*	--------	$ 355	----------	21,900
Benton	8	----------	$ 55,914	$ 16,733	--------	----------	72,647
Black Hawk	11	----------	*	9,214	43,843	$ 7,000	60,307
Boone	12	368,175	93,873	--------	--------	----------	462,048
Bremer	6	----------	----------	*	2,811	----------	----------
Buena Vista	4	----------	25,585	--------	*	----------	----------
Butler	4	----------	*	--------	2,752	----------	3,277
Calhoun	1	----------	*	--------	--------	----------	----------
Carroll	1	----------	----------	--------	*	----------	----------
Cass	1	----------	*	--------	--------	----------	----------
Cedar	1	----------	*	--------	--------	----------	----------
Cerro Gordo	10	----------	1,555,944	*	--------	*	4,644,955
Cherokee	2	----------	----------	--------	*	----------	----------
Clay	1	----------	*	--------	--------	----------	----------
Clayton	3	----------	----------	*	*	----------	3,069
Clinton	8	----------	*	*	*	----------	29,830
Dallas	9	877,565	244,042	--------	--------	----------	1,121,607
Delaware	3	----------	*	*	--------	----------	3,748
Des Moines	5	----------	*	*	7,339	----------	13,739
Dickinson	1	----------	----------	--------	*	----------	----------
Dubuque	15	----------	42,000	59,806	*	----------	111,906
Emmett	1	----------	----------	--------	--------	----------	----------
Fayette	5	----------	*	*	7,297	----------	24,193
Floyd	2	----------	*	*	--------	----------	----------
Franklin	4	----------	*	--------	935	----------	----------
Fremont	1	----------	*	--------	--------	----------	----------
Greene	1	*	----------	--------	--------	----------	----------
Grundy	1	----------	*	--------	--------	----------	----------
Guthrie	6	10,793	*	--------	--------	----------	----------
Hamilton	2	----------	*	--------	--------	----------	----------
Hancock	1	----------	*	--------	--------	----------	----------
Hardin	8	----------	60,350	*	*	----------	82,603
Harrison	1	----------	----------	*	--------	----------	----------
Henry	4	----------	*	*	--------	----------	----------
Howard	2	----------	*	*	--------	----------	----------
Humboldt	1	----------	*	--------	--------	----------	----------
Ida	2	----------	----------	--------	*	----------	----------
Iowa	2	----------	*	--------	--------	----------	----------
Jackson	4	----------	*	*	*	----------	59,759
Jasper	14	532,396	28,203	--------	--------	25,123	585,722
Jefferson	5	*	25,440	--------	--------	----------	----------
Johnson	6	----------	16,100	--------	11,157	----------	27,257
Jones	9	----------	*	80,942	*	----------	96,905
Keokuk	11	*	269,601	*	--------	----------	279,607
Kossuth	10	----------	*	--------	*	----------	14,324

TABLE I.—Continued.

Counties	No. of Producers	Coal	Clay and Clay Products	Stone and Lime	Sand and Gravel	Other Products	Total
Lee	14	------	11,561	51,230	*	------	68,177
Linn	8	------	50,760	*	18,611	------	77,144
Louisa	5	------	*	*	------	*	6,649
Lucas	3	*	*	------	------	------	504,298
Lyon	3	------	------	------	32,811	------	32,811
Madison	3	------	*	*	------	------	33,925
Mahaska	14	400,722	*	------	------	------	439,732
Marion	17	*	*	------	11,283	------	586,682
Marshall	6	------	26,417	*	*	------	123,004
Mills	3	------	5,975	------	------	------	5,975
Mitchell	2	------	------	*	------	------	------
Monroe	18	3,646,662	*	------	------	------	3,651,512
Muscatine	9	------	17,945	*	*	------	54,086
O'Brien	5	------	------	------	3,398	------	3,398
Osceola	1	------	------	------	*	------	------
Page	3	*	*	------	------	------	17,367
Palo Alto	2	------	------	------	*	------	------
Plymouth	5	------	*	------	9,751	------	------
Pocahontas	1	------	------	*	------	------	------
Polk	43	3,219,218	856,967	------	148,313	*	5,147,887
Pottawattamie	3	------	24,029	------	------	------	24,029
Poweshiek	4	------	40,356	------	------	------	40,356
Sac	3	------	*	------	*	------	180,463
Scott	13	------	46,013	118,818	*	*	210,666
Shelby	1	------	*	------	------	------	------
Sioux	5	------	------	------	16,100	------	16,100
Story	7	------	28,875	------	4,692	------	33,567
Tama	5	------	69,208	------	------	------	69,208
Taylor	2	*	------	------	------	------	------
Union	1	------	*	------	------	------	------
Van Buren	7	17,750	*	*	*	------	24,115
Wapello	21	409,177	92,691	*	*	*	521,781
Warren	2	*	*	------	------	------	------
Washington	4	------	28,688	------	------	------	28,688
Wayne	3	151,096	------	------	------	------	151,096
Webster	25	76,614	1,182,813	------	*	1,333,957	2,596,848
Winnebago	2	------	*	------	*	------	------
Winneshiek	3	------	*	------	*	------	12,531
Woodbury	4	------	------	------	*	*	373,838
Wright	4	------	*	------	2,634	------	11,234
County values represen'g less than three producers, and small coal mines	----	1,148,256	1,531,733	262,116	235,420	4,054,280	993,578
Totals	563	$ 13,364,070	$ 6,405,995	$594,681	$556,868	$ 5,380,251	$26,301,865

*Included in County values and totals.

COAL.

For many years coal has been the chief mineral mined in Iowa, the yearly production for several years having varied up and down between 7,000,000 and 8,000,000 tons. In 1913 the production was 7,525,936 tons, with a value of $13,496,710; in 1914 there was mined 7,451,022 tons, with a value of $13,364,070 at the mines. The five leading coal producing counties in 1914, in order of tonnage, were Monroe, Polk, Appanoose, Dallas, and Marion. These five counties produced more than six million tons; Monroe county alone produced 2,273,066 tons. The first three of the five counties named have retained the same order of production for more than ten years. For many years previous to 1913 Mahaska county ranked fourth, but in 1914 this county ranked sixth. The production of coal in Lucas county in 1914 greatly exceeded the production in 1913. This increase in production was due to the activity of the Central Iowa Coal Company, which began extensive developments on properties recently acquired.

The total quantity of coal washed in Iowa in 1914 was 25,706 tons, which yielded 18,000 tons of cleaned coal and 7,706 tons of refuse. The plant is located at Lakonta and is owned by the Iowa Coal Washing Company.[2]

The average price of coal during each of the years 1913 and 1914 was $1.79.

In 1913 there were 15,757 men employed in coal mining in Iowa; in 1914 there were 16,057.

The output, disposition of product, value, average price per ton, average number of days worked and average number of men employed in 1913 and 1914 are given, tabulated by counties, in Table II.

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[2] Kay, George F., The first coal-washing plant in Iowa: Iowa Academy of Science, Vol. XXII, pp. 225-227.

TABLE II.

COAL PRODUCTION FOR IOWA IN 1913, BY COUNTIES, IN SHORT TONS.

Counties	Loaded at Mine for Shipment	Sold to Local Trade and Used by Employees	Used at Mine for Steam and Heat	Total Quantity	Total Value	Average Price Per Ton	Average Number Days Active	Average Number of Employees
Adams	------------	6,971	------------	6,971	$ 17,536	$ 2.52	182	48
Appanoose	1,130,383	64,104	12,900	1,207,387	2,436,279	2.02	170	4,186
Boone	216,189	35,243	4,780	256,212	522,929	2.04	179	754
Dallas	546,832	8,348	19,006	574,186	1,077,293	1.88	245	889
Greene	200	9,400	------------	9,600	26,400	------------	186	25
Guthrie	------------	4,492	------------	4,492	11,890	2.65	147	29
Jasper	255,200	8,867	3,500	267,567	567,211	2.12	156	800
Lucas	20,167	6,937	800	27,904	44,913	------------	44	231
Mahaska	327,655	21,748	6,334	355,737	568,314	1.60	199	698
Marion	276,064	16,249	6,239	298,552	487,151	1.63	193	581
Monroe	2,457,050	50,226	64,001	2,571,277	4,087,032	1.59	215	4,138
Polk	1,345,237	213,296	42,482	1,601,015	2,984,919	1.86	212	2,591
Van Buren	6,000	8,381	------------	14,381	32,772	2.28	224	29
Wapello	124,845	25,969	2,891	153,705	259,099	1.69	240	309
Wayne	73,215	11,760	800	85,775	172,531	2.01	193	253
Webster	42,373	1,553	1,750	45,676	101,078	2.21	215	130
Counties with less than three producers and small mines	3,523	41,626	350	45,499	99,363	------------	150	66
Total	6,824,933	535,170	165,833	7,525,936	$ 13,496,710	$ 1.79	195	15,757

TABLE II.—CONTINUED.

COAL PRODUCTION FOR IOWA IN 1914, BY COUNTIES, IN SHORT TONS.

Counties	Loaded at Mine for Shipment	Sold to Local Trade and Used by Employees	Used at Mine for Steam and Heat	Total Quantity	Total Value	Average Price Per Ton	Average Number Days Active	Average Number of Employees
Adams	------------	6,660	------------	6,660	$ 16,650	$ 2.50	232	47
Appanoose	1,195,603	64,383	12,290	1,272,276	2,505,646	1.97	168	4,084
Boone	125,462	46,970	9,520	181,952	368,175	2.02	177	556
Dallas	449,092	7,794	9,811	466,697	877,565	1.88	228	861
Guthrie	------------	3,925	------------	3,925	10,793	2.75	136	31
Jasper	214,166	22,325	5,500	241,991	532,396	2.20	190	531
Mahaska	243,885	23,975	5,008	272,868	400,722	1.47	206	522
Marion	284,791	15,805	10,587	311,183	498,894	1.60	225	573
Monroe	2,147,252	61,719	64,095	2,273,066	3,646,662	1.60	211	4,165
Polk	1,413,350	262,863	30,566	1,706,779	3,219,218	1.89	228	3,188
Van Buren	------------	6,672	------------	6,672	17,750	------------	------------	15
Wapello	206,458	26,508	4,210	237,176	409,177	1.73	231	596
Wayne	70,420	4,904	1,200	76,524	151,096	1.97	192	243
Webster	31,569	873	1,250	33,692	76,614	2.27	208	109
*Counties with less than three producers and small mines	294,344	62,392	2,825	359,561	632,712	------------	------------	536
Total	6,676,392	617,768	156,862	7,451,022	$ 13,364,070	$ 1.79	------------	16,057

*Greene, Lucas, Keokuk, Jefferson, Page, Taylor and Warren Counties.

Iowa's rank as a coal producing state in 1914 is given in the following table. From this table it is seen that Iowa ranked tenth in tonnage, and ninth in value. The same relations prevailed in 1913.

RANK OF LEADING COAL-PRODUCING STATES IN 1914, WITH QUANTITY AND VALUE OF PRODUCT AND PERCENTAGE OF EACH.[3]

Production.

Rank	State	Quantity (short tons)	Percentage of Total Production
1	Pennsylvania:		
	Anthracite	90,821,507	17.7
	Bituminous	147,983,294	28.8
2	West Virginia	71,707,626	14.0
3	Illinois	57,589,197	11.2
4	Kentucky	20,382,763	4.0
5	Ohio	18,843,115	3.7
6	Indiana	16,641,132	3.2
7	Alabama	15,593,422	3.0
8	Colorado	8,170,559	1.6
9	Virginia	7,959,535	1.5
10	Iowa	7,451,022	1.4

Value.

Rank	State	Value	Percentage of Total Value
1	Pennsylvania:		
	Anthracite	$188,181,399	27.6
	Bituminous	159,006,296	23.3
2	West Virginia	71,391,408	10.5
3	Illinois	64,693,529	9.5
4	Ohio	21,250,642	3.1
5	Kentucky	20,852,463	3.0
6	Alabama	20,849,919	3.0
7	Indiana	18,290,928	2.7
8	Colorado	13,601,718	2.0
9	Iowa	13,364,070	2.0
10	Kansas	11,238,253	1.6

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[3] From Advance Chapters of Mineral Resources of the United States for 1914.

CLAY AND CLAY PRODUCTS.

The value of clay and clay products in Iowa in 1913 was $5,575,581, and in 1914, $6,405,995. These figures have never been exceeded in the history of the clay industry of the state. The highest value recorded prior to 1913 was in 1910, when the value was $5,335,036. The following table shows the value of the clay and clay products of Iowa during each year of the past decade:

PRODUCTION OF CLAY AND CLAY PRODUCTS IN IOWA FROM 1905-1914.

Year	Value
1905	$3,408,547
1906	3,477,237
1907	3,733,476
1908	4,078,627
1909	4,916,513
1910	5,335,036
1911	4,436,839
1912	4,524,492
1913	5,575,581
1914	6,405,995

The output of clay and clay products in 1913 and 1914 was distributed as follows:

Product	1913		1914	
	Quantity in Thousands	Value	Quantity in Thousands	Value
Common brick	143,263	$1,052,036	143,534	$1,067,746
Paving brick or block	16,398	222,105	14,997	211,905
Face brick	14,078	181,911	11,183	148,394
Drain tile		2,798,816		3,180,836
Sewer pipe		503,360		558,751
Fireproofing		762,563		1,083,397
Pottery		20,698		
Other products		32,192		150,716
Clay		1,900		4,250
Total		$5,575,581		$6,405,995

In 1913 the three principal clay products in order of value were drain tile, common brick, and fireproofing; in 1914 drain tile again ranked first, but in this year the value of fireproofing exceeded that of common brick. In both 1913 and 1914 Iowa was the leading state in the production of drain tile, the chief producing counties being Cerro Gordo and Webster.

The value of drain tile and common brick sold in Iowa in the past ten years has been as follows:

PRODUCTION OF DRAIN TILE AND COMMON BRICK IN IOWA FROM 1905-1914.

Year	Drain Tile	Common Brick
1905	$1,531,376	$1,367,742
1906	1,721,614	1,125,009
1907	2,011,793	1,085,383
1908	2,522,363	896,890
1909	2,830,910	1,072,340
1910	3,457,455	1,088,266
1911	2,468,962	1,025,011
1912	2,293,084	1,017,097
1913	2,798,816	1,052,036
1914	3,180,836	1,067,746

The clay product in 1913 and in 1914 is tabulated by counties in Table III in which the distribution of the leading products is given:

TABLE III.

VALUE OF IOWA CLAY AND CLAY PRODUCTS FOR 1913, TABULATED BY COUNTIES.

Counties	No. of Producers	Common Brick	Paving Brick or Block	Face Brick	Drain Tile	Other Products†	Total Value
Adair	1	*			*		
Allamakee	1	*				*	
Appanoose	1	*					
Audubon	2	*			*	*	
Benton	5	$ 12,275			$ 32,416	*	$ 60,164
Boone	3	43,359	*	*	*	*	91,924
Buena Vista	3	*			*		27,000
Butler	1	*					
Calhoun	1	*			*	*	
Cass	1	*			*	*	
Cedar	1	*			*		
Cerro Gordo	7	48,151			1,043,440	$ 309,424	1,401,015
Clay	2	*			*		
Clinton	3	*			*		13,900
Dallas	5	9,657			194,842	20,812	225,311
Delaware	3	2,770			*	*	4,426
Des Moines	1	*					
Dubuque	3	50,500			*		50,500
Fayette	1	*				*	
Floyd	1	*			*	*	
Franklin	1	*				*	
Fremont	1	*					
Grundy	2	*		*	*	*	
Guthrie	2	*			*	*	
Hamilton	1				*	*	
Hancock	1				*		
Hardin	2	*			*	*	
Henry	2	*			*		
Howard	1	*			*	*	
Humboldt	1				*		
Iowa	2	*			*		
Jackson	2	*			*		
Jasper	6	10,010			16,825	*	27,156
Jefferson	4	5,137			15,740	4,897	25,774
Johnson	3	*			*		22,300
Jones	2	*			*		
Keokuk	10	3,941			80,451	35,826	120,218
Kossuth	1				*	*	
Lee	3	*		*			12,528
Linn	5	30,190			7,370	*	37,960
Louisa	1	*			*		
Lucas	1	*					
Madison	1	*					
Mahaska	2	*	*	*	*	*	
Marion	4	10,675			12,500	*	53,231
Marshall	4	12,174		*	39,700	*	79,918
Mills	4	8,179					8,179

TABLE III.—CONTINUED.

Counties	No. of Producers	Common Brick	Paving Brick or Block	Face Brick	Drain Tile	Other Products†	Total Value
Muscatine	4	*	----	----	*	----	10,505
Page	2	*	*	----	*	----	----
Plymouth	1	*	----	----	----	----	----
Polk	11	154,468	*	*	137,628	*	692,710
Pottawattamie	3	34,207	----	----	----	----	34,207
Poweshiek	4	1,566	----	----	33,612	*	37,145
Sac	1	*	----	----	*	----	----
Scott	4	15,108	*	----	*	*	58,511
Story	2	*	----	*	*	*	----
Tama	6	14,904	----	*	16,266	*	45,169
Taylor	1	*	----	----	----	----	----
Union	1	*	----	----	*	*	----
Van Buren	2	*	----	----	*	----	----
Wapello	3	*	----	*	*	*	50,984
Warren	1	----	----	----	*	*	----
Washington	5	9,308	----	----	15,447	5,815	30,570
Winnebago	1	----	----	----	*	----	----
Winneshiek	1	*	----	----	----	----	----
Webster	12	54,906	*	*	631,726	377,111	1,077,059
Woodbury	2	*	*	*	----	*	----
Wright	1	*	----	----	*	----	----
**Pottery	----	----	----	----	----	----	20,698
***Clay sold	----	----	----	----	----	----	1,900
Counties with less than three producers	----	520,551	222,105	181,911	520,853	544,230	1,254,619
Total	183	$ 1,052,036	$222,105	$181,911	$ 2,798,816	$ 1,298,115	$ 5,575,581

†Includes sewer pipe, fireproofing, fire brick, etc.
*Included in "Counties with less than three producers."
**Includes Delaware, Muscatine and Wapello Counties.
***Includes Black Hawk, Hardin and Webster Counties.

TABLE III.—CONTINUED.

VALUE OF IOWA CLAY AND CLAY PRODUCTS FOR 1914, TABULATED BY COUNTIES.

Counties	No. of Producers	Common Brick	Paving Brick or Block	Face Brick	Drain Tile	Other Products†	Total Value
Adair	1	*	------	------	*	------	*
Allamakee	1	*	------	------	*	*	*
Appanoose	1	*	------	------	------	------	*
Audubon	2	*	------	------	*	*	*
Benton	5	$ 8,473	------	------	$ 33,593	*	*
Boone	3	44,100	*	*	*	*	$ 93,873
Buena Vista	2	*	------	------	*	------	*
Butler	1	*	------	------	*	------	*
Calhoun	1	*	------	------	*	------	*
Cass	1	*	------	------	*	*	*
Cedar	1	*	------	------	*	------	*
Cerro Gordo	7	39,976	------	------	990,933	$ 525,035	1,555,944
Clay	1	*	------	------	*	------	*
Clinton	2	*	------	------	*	------	*
Dallas	5	3,420	------	*	224,697	*	*
Delaware	2	*	------	------	*	*	*
Des Moines	1	*	------	------	*	*	*
Dubuque	3	42,000	------	------	------	------	42,000
Fayette	1	*	------	------	------	*	*
Floyd	1	*	------	------	*	------	*
Franklin	2	*	------	------	*	*	*
Fremont	1	*	------	------	------	------	*
Grundy	2	*	------	*	------	------	*
Guthrie	2	*	------	------	*	*	*
Hamilton	2	*	------	------	*	*	*
Hancock	1	------	------	------	*	------	*
Hardin	2	*	------	------	*	*	*
Henry	2	*	------	------	*	*	*
Howard	1	*	------	------	*	*	*
Humboldt	1	------	------	------	*	------	*
Iowa	2	*	------	------	*	------	*
Jackson	2	*	------	*	------	------	*
Jasper	5	8,253	------	------	18,950	*	*
Jefferson	3	*	------	------	15,028	7,119	25,440
Johnson	3	7,100	------	------	*	------	*
Jones	2	*	------	------	*	*	*
Keokuk	8	6,299	------	------	208,187	*	*
Kossuth	1	*	------	------	*	*	*
Lee	4	7,733	------	*	*	------	*
Linn	4	43,470	------	------	6,940	*	*
Louisa	1	*	------	------	*	*	*
Lucas	1	*	------	------	------	------	*
Madison	1	------	------	------	*	------	*
Mahaska	2	*	*	------	*	*	*
Marion	4	12,400	------	------	21,021	*	*
Marshall	5	12,300	------	*	*	*	26,417
Mills	4	5,975	------	------	------	------	*

TABLE III.—CONTINUED.

Counties	No. of Producers	Common Brick	Paving Brick or Block	Face Brick	Drain Tile	Other Products†	Total Value
Monroe	1	*	--------	--------	*	*	*
Muscatine	4	11,575	--------	*	--------	*	13,195
Page	2	*	--------	--------	*	*	*
Plymouth	1	*	--------	--------	--------	--------	*
Polk	12	216,903	*	*	157,088	*	856,967
Pottawattamie	3	24,029	--------	--------	--------	--------	24,029
Poweshiek	4	*	--------	--------	30,932	*	40,356
Sac	1	*	--------	--------	*	*	*
Scott	4	9,349	*	--------	*	*	46,013
Shelby	1	*	--------	--------	--------	--------	*
Story	3	*	--------	*	*	*	*
Tama	5	22,491	--------	*	32,091	*	69,208
Union	1	*	--------	--------	*	*	*
Van Buren	2	*	--------	--------	*	*	*
Wapello	3	22,559	--------	*	*	*	64,691
Warren	1	--------	--------	--------	*	*	*
Washington	5	9,286	--------	--------	11,417	7,985	28,688
Winnebago	1	--------	--------	--------	*	--------	*
Winneshiek	1	*	--------	--------	--------	--------	*
Webster	11	79,199	*	--------	621,284	474,748	*
Woodbury	1	*	*	--------	*	*	*
Wright	1	*	--------	--------	--------	--------	*
**Pottery and clay sold	----	--------	--------	--------	--------	--------	37,000
Counties with less than three producers	----	428,856	$211,905	$148,394	808,675	745,227	2,343,057
Total	----	$ 1,067,746	$211,905	$148,394	$ 3,180,836	$ 1,760,114	$ 6,405,995

†Includes sewer pipe, fireproofing, etc.

*Included in "Counties with less than three producers."

**Black Hawk, Hardin, Webster, Muscatine and Wapello counties.

The following table shows the rank of the ten leading states in value of clay products in 1913 and 1914. It includes also the number of operating firms and the percentage of the total value produced by each of the ten states:

TEN LEADING STATES IN VALUE OF CLAY PRODUCTION IN 1913 AND 1914.[4]

1913.

State	Rank	Number of Operating Firms Report'g	Value not including Raw Clay Sold	Percentage of Total Value
Ohio	1	563	$38,388,296	21.18
Pennsylvania	2	377	24,231,482	13.37
New Jersey	3	149	19,705,378	10.87
Illinois	4	281	15,195,874	8.38
New York	5	215	11,469,476	6.33
Indiana	6	257	8,498,646	4.69
Missouri	7	105	6,602,076	3.64
Iowa	8	186	5,573,681	3.07
California	9	91	5,344,958	2.95
West Virginia	10	58	5,208,270	2.87

1914.

State	Rank	Number of Operating Firms Report'g	Value not including Raw Clay Sold	Percentage of Total Value
Ohio	1	543	$37,166,768	22.53
Pennsylvania	2	369	21,846,996	13.24
New Jersey	3	148	16,484,652	9.99
Illinois	4	263	13,318,953	8.07
New York	5	205	9,078,933	5.50
Indiana	6	240	7,655,285	4.64
Iowa	7	171	6,401,745	3.88
Missouri	8	98	6,077,284	3.68
West Virginia	9	58	5,761,411	3.49
California	10	84	4,461,661	2.70

It will be seen from this table that in 1913 Iowa ranked eighth and in 1914, seventh.

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[4] Advance chapter from Mineral Resources of the United States for 1914.

STONE AND LIME.

The value of stone and lime in Iowa produced in 1913 was $854,814, and in 1914, $594,681. The output was distributed as follows:

	1913	1914
Limestone—		
Building	$ 41,421	$ 32,332
Riprap and rubble	128,342	96,482
Crushed Stone—		
Road making	81,351	17,438
Railroad ballast	218,573	97,747
Concrete	300,767	278,071
*Other purposes	33,228	15,292
Lime	49,520	56,000
Total limestone and lime	$853,202	$593,362
Sandstone	1,612	1,319
Total stone and lime	$854,814	$594,681

*Paving, curbing, flagging, etc.

The distribution of limestone and lime in 1913 and 1914 is given by counties in Table IV.

TABLE IV.

PRODUCTION OF LIMESTONE AND LIME IN 1913.

Counties	No. of Producers	Building Stone	Riprap and Rubble	Crushed Stone			Lime	Other Uses	Total Value
				Road-making	Railroad Ballast	Concrete			
Allamakee	2	*	*	------	------	*	------	------	------
Benton	1	*	*	------	------	------	------	------	------
Black Hawk	3	*	------	*	------	*	------	------	$ 11,529
Appanoose	1	------	------	*	------	------	------	------	------
Cerro Gordo	1	*	*	*	------	*	------	*	------
Clayton	7	$ 1,262	*	------	------	*	*	------	13,382
Clinton	1	*	*	------	------	------	------	------	------
Des Moines	1	------	*	------	------	------	------	------	------
Dubuque	11	8,376	$ 40,099	$ 9,485	------	$ 13,250	*	$ 882	86,092
Fayette	2	*	------	------	------	------	------	*	------
Floyd	4	2,207	*	------	------	------	------	*	4,217
Hardin	2	*	------	------	------	*	------	------	------
Harrison	1	------	------	------	------	*	------	------	------
Henry	1	*	------	------	------	*	------	------	------
Howard	1	------	*	*	------	------	------	*	------
Jackson	2	------	------	------	------	------	*	*	------
Jones	7	13,988	28,353	*	*	42,283	------	*	105,230
Keokuk	2	*	*	------	------	*	------	------	------
Lee	8	1,661	6,839	15,181	------	31,953	------	6,584	62,218
Linn	3	------	------	*	*	*	------	------	80,008
Louisa	1	------	------	------	------	*	------	------	------
Madison	3	*	*	*	------	27,533	------	*	36,925
Marshall	2	------	*	*	*	------	------	------	------
Mitchell	3	1,145	------	------	------	------	------	3,913	5,058
Pocahontas	1	------	------	*	------	*	------	------	------
Scott	6	*	38,524	*	*	107,435	------	6,198	171,040

TABLE IV.—CONTINUED.

Counties	No. of Producers	Building Stone	Riprap and Rubble	Crushed Stone			Lime	Other Uses	Total Value
				Road-making	Railroad Ballast	Concrete			
Van Buren	1	*	----------	----------	----------	----------	----------	----------	----------
Wapello	2	*	*	----------	----------	*	----------	*	----------
Winneshiek	1	*	----------	----------	----------	----------	----------	----------	----------
Counties with less than three producers	----	12,782	14,527	56,685	$ 218,573	78,313	49,520	15,651	277,503
Total	----	$ 41,421	$ 128,342	$ 81,351	$ 218,573	$ 300,767	$ 49,520	$ 33,228	$ 853,202

*Included in "Counties with less than three producers."

TABLE IV.—CONTINUED.

PRODUCTION OF LIMESTONE AND LIME IN 1914.

Counties	No. of Producers	Building Stone	Riprap and Rubble	Crushed Stone			Lime	Other Uses	Total Value
				Road-making	Railroad Ballast	Concrete			
Allamakee	1	*	*						
Appanoose	1			*					
Benton	4	*	$ 1,061			$ 15,557			$ 16,733
Black Hawk	2	*		*		*			
Bremer	1					*			
Cerro Gordo	1	*	*					*	
Clayton	1	*							
Clinton	1	*							
Delaware	1	*							
Des Moines	1	*	*			*			
Dubuque	10	$ 7,635	11,122	$ 4,705		23,130	*	$ 2,214	59,806
Fayette	1	*							
Floyd	1							*	
Hardin	2					*			
Harrison	1	*							
Henry	2	*				*			
Howard	1	*				*		*	
Jackson	2	*	*				*		
Jones	5	*	29,879		*	41,073		*	80,908
Keokuk	1					*		*	
Lee	8	478	12,774			31,759		6,181	51,192
Linn	1			*		*			
Louisa	1		*			*			
Madison	2		*			*			
Mahaska	1	*							
Marshall	2				*				

TABLE IV.—CONTINUED.

Counties	No. of Producers	Building Stone	Riprap and Rubble	Crushed Stone			Lime	Other Uses	Total Value
				Road-making	Railroad Ballast	Concrete			
Muscatine	1	----------	*	----------	----------	----------	----------	----------	----------
Mitchell	2	*	----------	----------	----------	----------	----------	----------	----------
Pocahontas	1	----------	----------	----------	----------	*	----------	----------	----------
Scott	5	*	32,206	4,816	*	70,855	----------	6,249	117,893
Van Buren	1	*	----------	----------	----------	----------	----------	----------	----------
Wapello	2	*	*	----------	----------	*	----------	----------	----------
Counties with less than three producers	----	24,219	9,440	7,917	$ 97,747	95,697	$ 56,000	648	291,668
Total	----	$ 32,332	$ 96,482	$ 17,438	$ 97,747	$ 278,071	$ 56,000	$ 15,292	$ 593,362

*Included in "Counties with less than three producers."

SAND AND GRAVEL.

The value of sand and gravel produced in Iowa in 1913 was $528,066, and in 1914 $556,868. In both years the values were less than in 1912, when the output had a value of $563,409, the record figure for the state.

The sand and gravel sold in 1913 and 1914 may be classified as follows:

Kind—	1913	1914
	Value	Value
Sand used for—		
Molding	$ 1,560	$ 2,365
Building	231,784	272,445
Engine	3,162	3,250
Other sand	91,536	72,988
Gravel	200,024	205,820
Total sand and gravel	$528,066	$556,868

Table V shows the distribution of sand and gravel by counties in 1913 and 1914.

TABLE V.

VALUE OF SAND AND GRAVEL PRODUCED IN IOWA IN 1913.

Counties	No. of Producers	Molding Sand	Building Sand	Engine Sand	Other Sand	Gravel	Total
Appanoose	1	*	--------	--------	--------	--------	--------
Audubon	2	--------	*	--------	--------	*	--------
Black Hawk	8	*	$ 14,605	--------	$ 15,950	*	$ 30,906
Bremer	3	--------	*	--------	--------	*	2,613
Buena Vista	2	--------	--------	--------	--------	*	--------
Butler	2	--------	--------	--------	--------	*	--------
Carroll	1	--------	--------	--------	--------	*	--------
Cherokee	2	--------	*	--------	*	*	--------
Clayton	1	--------	--------	--------	*	--------	--------
Clinton	4	--------	*	*	*	$ 12,250	17,236
Des Moines	2	*	*	--------	*	*	--------
Dickinson	1	--------	*	--------	--------	--------	--------
Dubuque	3	--------	3,973	*	--------	*	30,546
Emmet	2	--------	*	--------	--------	*	--------
Fayette	2	--------	*	--------	--------	*	--------
Floyd	1	--------	--------	--------	--------	*	--------
Franklin	1	--------	*	--------	--------	--------	--------
Greene	1	--------	--------	--------	--------	*	--------
Grundy	1	--------	*	--------	--------	--------	--------
Hardin	4	--------	*	--------	--------	*	3,171
Howard	1	--------	--------	--------	--------	*	--------
Ida	1	--------	*	--------	--------	--------	--------
Jackson	1	--------	*	--------	*	*	--------
Johnson	3	--------	*	--------	--------	*	10,189
Jones	1	--------	--------	--------	--------	*	--------
Lee	3	--------	*	*	--------	--------	8,305
Linn	8	*	6,828	*	*	23,876	31,579
Lyon	6	--------	*	*	5,405	4,365	12,890
Marion	2	--------	*	--------	--------	*	--------
Marshall	1	--------	*	*	*	*	--------
Monona	1	--------	*	--------	--------	--------	--------
Muscatine	1	--------	*	--------	--------	*	--------
O'Brien	3	--------	*	--------	*	--------	2,277
Osceola	2	--------	*	--------	*	--------	--------
Page	1	--------	--------	--------	*	*	--------
Palo Alto	3	--------	--------	--------	*	*	10,890
Plymouth	3	--------	*	--------	--------	*	992
Polk	13	*	76,597	*	39,438	18,775	136,649
Sac	2	--------	*	--------	--------	*	--------
Scott	2	--------	*	--------	--------	*	--------
Sioux	4	--------	5,310	--------	*	*	8,387
Story	3	--------	*	--------	--------	*	1,162
Van Buren	1	--------	*	--------	--------	--------	--------
Wapello	2	*	*	*	*	*	--------
Webster	2	--------	*	--------	--------	--------	--------
Winnebago	1	--------	*	--------	--------	--------	--------
Winneshiek	3	--------	*	--------	*	*	971
Woodbury	4	--------	*	--------	*	4,235	15,985
Wright	3	--------	*	*	*	*	3,631

TABLE V.—CONTINUED.

Counties	No. of Producers	Molding Sand	Building Sand	Engine Sand	Other Sand	Gravel	Total
Counties with less than three producers	----	$ 1,560	124,471	$ 3,162	30,743	136,523	199,687
Total	----	$ 1,560	$ 231,784	$ 3,162	$ 91,536	$ 200,024	$ 528,066

*Included in "Counties with less than three producers."

TABLE V.—CONTINUED.

VALUE OF SAND AND GRAVEL PRODUCED IN IOWA IN 1914.

Counties	No. of Producers	Molding Sand	Building Sand	Engine Sand	Other Sand	Gravel	Total
Appanoose	1	*	-------	-------	-------	-------	-------
Audubon	3	-------	*	-------	-------	*	$ 355
Black Hawk	7	-------	$ 35,988	-------	*	*	43,843
Bremer	5	-------	*	-------	-------	$ 2,686	2,811
Buena Vista	1	-------	-------	-------	-------	*	-------
Butler	3	-------	2,752	-------	-------	-------	2,752
Carroll	1	-------	*	*	-------	-------	-------
Cherokee	2	-------	*	-------	*	*	-------
Clayton	1	-------	-------	-------	*	-------	-------
Clinton	5	-------	4,138	*	*	11,052	16,958
Des Moines	3	-------	*	-------	*	*	7,339
Dickinson	1	-------	*	-------	-------	*	-------
Dubuque	2	-------	*	*	*	*	-------
Emmet	1	-------	-------	-------	*	-------	-------
Fayette	3	-------	*	-------	-------	*	7,297
Franklin	3	-------	890	-------	*	-------	935
Hardin	3	-------	*	-------	*	*	2,025
Ida	2	-------	*	-------	-------	-------	-------
Jackson	1	-------	*	-------	-------	*	-------
Johnson	3	-------	*	-------	-------	7,117	11,157
Jones	1	-------	*	-------	-------	-------	-------
Lee	2	-------	*	*	-------	*	-------
Kossuth	1	-------	*	-------	-------	-------	-------
Linn	3	-------	-------	-------	-------	18,611	18,611
Lyon	3	-------	*	-------	*	9,512	32,811
Marion	2	-------	*	-------	*	*	-------
Marshall	1	-------	*	*	*	*	-------
Muscatine	2	-------	*	-------	*	*	-------
O'Brien	5	-------	3,248	-------	*	-------	3,398
Osceola	1	-------	-------	-------	-------	*	-------
Palo Alto	2	-------	-------	-------	-------	*	-------
Plymouth	4	-------	9,451	-------	-------	*	9,751
Polk	13	*	52,268	*	$ 48,828	44,518	148,313
Sac	2	-------	*	-------	-------	*	-------
Scott	2	-------	*	-------	-------	*	-------
Sioux	5	-------	16,030	-------	-------	*	16,100
Story	4	-------	790	-------	-------	3,902	4,692
Van Buren	1	-------	*	-------	-------	-------	-------
Wapello	2	*	*	*	*	*	-------
Webster	2	-------	*	-------	-------	*	-------
Winnebago	1	-------	*	-------	-------	-------	-------
Winneshiek	2	-------	-------	-------	*	*	-------
Woodbury	2	-------	*	-------	-------	*	-------

TABLE V.—CONTINUED.

Counties	No. of Producers	Molding Sand	Building Sand	Engine Sand	Other Sand	Gravel	Total
Wright	3	----------	----------	*	*	*	2,634
Counties with less than three producers	----	$ 160	117,850	$ 1,446	16,479	89,156	224,686
Total	----	$ 2,365	$ 272,445	$ 3,250	$ 72,988	$ 205,820	$ 556,868

*Included in "Counties with less than three producers."

GYPSUM.

In 1913 the value of gypsum produced in Iowa was $1,157,939, and in 1914 $1,321,457. These figures have never been exceeded since gypsum began to be produced in the state. In 1914 Iowa ranked first in the production of gypsum, exceeding the production of New York, which ranked second, by a value of $84,265. The value of the production in Iowa in each of the past ten years is as follows:

PRODUCTION OF GYPSUM IN IOWA FROM 1905-1914 INCLUSIVE.

Year	Value
1905	$ 589,055
1906	573,498
1907	730,383
1908	564,688
1909	655,602
1910	943,849
1911	871,752
1912	845,628
1913	1,157,939
1914	1,321,457

The principal items of production and distribution in 1913 and 1914 were as follows:

	1913		1914	
	Short Tons	Value	Short Tons	Value
Crude gypsum mined	456,031	----------	480,404	----------
Distributed as follows:				
Sold crude—				
To Portland cement mills, as land plaster, etc.	52,057	$ 45,551	65,185	$ 60,486
Sold calcined—				
As hard wall plaster	252,719	942,198	265,619	1,109,570
As stucco, plaster of Paris, etc.	80,638	170,190	69,446	151,401
Total sold calcined	333,357	$1,112,388	335,065	$1,260,971
Total sold	385,414	$1,157,939	400,250	$1,321,457

In both years 1913 and 1914 there were five mines and five mills in operation. The deposit of gypsum at Centerville has not yet been developed to the stage of production. The main reason for this fact is the difficulty in handling the large amount of water which enters the shaft a few feet above the gypsum.

LEAD AND ZINC.

In 1913 the value of lead concentrates obtained from small lots of galena mined from shallow shafts was $4,150. In 1914 there was no production.

MINERAL WATERS.

The value of mineral waters sold in Iowa was $7,369 in 1913 and $30,179 in 1914. The sale of the mineral waters was for medicinal and table uses. There were three producing springs in 1913 and five in 1914. The largest output was from the Colfax Springs in Jasper county. In 1914 two new springs began to produce, one of which is located at Colfax and the other at Sioux City.

PORTLAND CEMENT.

Since the year 1911 there have been three large modern cement plants in Iowa, two of which are located at Mason City, the third at Des Moines. In 1913 the output of these three plants had a value of $3,972,876, and in 1914, $4,008,915. Although the output in Iowa has been increasing year by year, there is every reason to believe that the maximum yearly output has not yet been reached. The three plants are thoroughly equipped and there are abundant supplies of limestone and shale which are the materials being used in Iowa for cement making.

The growth of the cement industry in the United States has been phenomenal. Year after year during the past decade the output exceeded that of the preceding year until in 1913 the maximum production of 89,541,348 barrels was reached. In 1914 the output was 87,257,552 barrels.

The figures for the quantity and value of the Portland cement shipped by the ten leading states in 1914 are as follows:

SHIPMENT OF PORTLAND CEMENT BY STATES, 1914.[5]

State	Shipping Plants	Quantity (barrels)	Value	Average Price per Barrel
Pennsylvania	20	25,985,106	$20,944,787	$ .806
Indiana	5	9,540,288	8,342,164	.874
New York	8	5,474,191	5,020,720	.917
Illinois	5	5,284,022	4,848,522	.918
California	7	5,004,633	6,698,905	1.339
Missouri	5	4,706,389	4,485,744	.953
Michigan	11	4,218,429	4,064,781	.964
Iowa	3	4,224,076	4,008,915	.949
New Jersey	3	3,530,476	3,081,205	.873
Kansas	10	3,237,906	2,643,415	.816
Total (ten states)	77	71,205,516	$64,159,158	----------
Total (other states)	34	15,232,440	15,959,317	----------

NATURAL GAS.

For many years small amounts of natural gas have been obtained from pockets of sand and gravel in the Pleistocene de-

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[5] From advance chapter of Mineral Resources for 1914.

posits of the state. The best known localities are in the neighborhood of Letts, Louisa county, and of Herndon, Guthrie county. The value of the natural gas in Iowa was $120 in 1913 and $200 in 1914. The gas was used for illuminating purposes.

IRON ORE.

During the years 1913 and 1914 the Missouri Iron Company continued to carry forward considerable work on the Waukon iron ore, but no ores were shipped for commercial purposes.

THE IRON ORE DEPOSITS NEAR WAUKON, IOWA

BY

JESSE V. HOWELL

OUTLINE.

THE IRON ORES OF IRON HILL NEAR WAUKON, IOWA

Introduction.

LOCATION.

Iron Hill lies in west-central Allamakee county, in the northeastern corner of Iowa, and is about two and one-half miles northeast of the town of Waukon. It is within the Waukon quadrangle of the United States Geological Survey.

Waukon, a town of about 2,000 population, and which is the county seat of Allamakee county, forms the terminus of a branch of the Chicago, Milwaukee & St. Paul Railway, connecting with the main line at Waukon Junction, on the Mississippi river. (See figure 1.)

RELIEF.

Iron Hill is the highest point in northeastern Iowa, and attains a height of 1,340 feet above sea level. The lowest land in the vicinity, in the southeastern corner of Makee township, is 960 feet above sea level. This indicates a maximum relief of 380 feet.

In the central and western parts of Makee township grades are low and the slopes relatively gentle, but in the eastern and northern portions the topography is markedly rugged, due to the proximity to the drainage lines. Waukon itself is located on a rolling plain whose greatest extent is to the southwest of the town. Owing to the absence of any considerable quantity of drift the topography has been controlled largely by erosion.

The district may be divided into two generally distinct topographic provinces, which differ not only in elevation but also in character and origin. These are:

(a) The upland plain.

(b) The valleys.

FIG. 1—Index map of northeastern Iowa showing location of area studied (small rectangle). Also the area covered by the Waukon sheet of the U. S. Geological Survey (larger rectangle).

The plain in general is rolling and well drained, and is covered by a thick residual soil overlain by a small amount of loess. Wherever the plain lies on the Galena formation of the Ordovician system, as it does throughout the small region to be considered, sinkholes are characteristic features. The soil is of fairly good quality and the farmers are prosperous.

The valleys are marked by outcrops of hard rock and represent an advanced stage of dissection. The larger ones have been filled with alluvium to a depth of ten to twenty-five feet, but cultivation has so increased the run-off of the hillsides that the present streams are now cutting out their old flood plains and destroying much of the arable bottom land.

The relation between the two provinces is shown by the sketch map, figure 2.

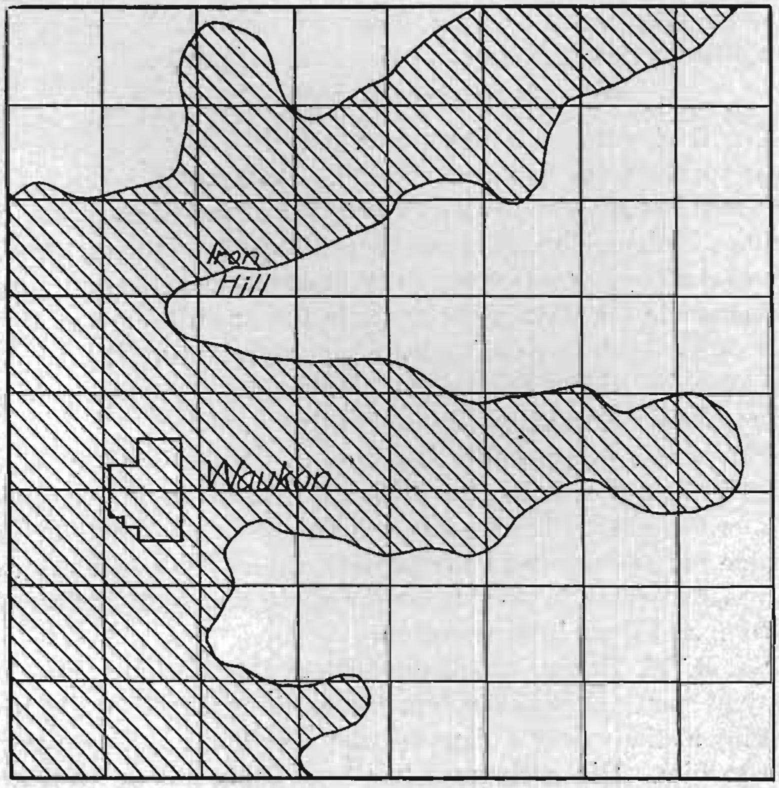

FIG. 2—Sketch map showing relation of upland and valley in vicinity of Iron Hill. Upland shaded.

DRAINAGE.

The Waukon area is drained by three chief streams, the Upper Iowa river, Village creek and Paint creek. The ridge of which Iron Hill is the highest point, forms the divide between the basins of the two former streams.

Owing to the thinness of the soil on the hillsides all except the larger watercourses are more or less intermittent, flowing as mere brooks during ordinary times, but becoming swollen to torrents during each heavy rain. The many springs which rise over the shaly members of the Platteville formation tend to equalize the flow to a marked degree, and prevent any but the minor tributaries from becoming completely dry between rains.

DEVELOPMENT.

The Iron Hill deposits are being developed by the Missouri Iron Company, of St. Louis, Missouri. Mr. R. W. Erwin is Superintendent and Manager of the local property.

FIELD WORK AND ACKNOWLEDGMENTS.

The field work on which this report is based was carried on chiefly during the summer of 1914. Four weeks were spent in the driftless area of Iowa as a member of the field course given by the Universities of Iowa and Chicago. During this trip especial attention was given to Physiographic geology. Later in the summer ten days were spent in the examination of the ore deposit and the region immediately surrounding it. In April, 1915, a third visit was made to Waukon for the purpose of verifying certain conclusions and collecting new data.

The writer is especially indebted to Professor G. F. Kay of the University of Iowa, for criticism and advice in the preparation of the work. Thanks are due also to Professor A. C. Trowbridge for assistance in the physiographic phases of the work; and to Professor A. O. Thomas for aid in the identification of the fossils, and their interpretation.

Mr. R. W. Erwin, superintendent of the Missouri Iron Company property at Waukon, has rendered invaluable assistance by placing at the writer's disposal whatever maps and data were of use to him. His assistance has been especially helpful in the preparation of those chapters dealing with the deposit itself, and with the metallurgical treatment of the ore.

GEOLOGY.

Stratigraphic Geology.

All of the indurated rocks exposed in the neighborhood of Waukon are of Ordovician age, although the Cambrian rocks lie at only a short distance beneath the surface. The generalized section below shows the relations of the various formations, which are shown also on the geological map, figure 3.

SYSTEM	SERIES	FORMATION		THICKNESS	CHARACTER OF ROCK
				FEET	
Ordovician	Mohawkian	Galena		240	Limestone and dolomite
		Platteville	Decorah	5-30	Shale & limestone
			Platteville	50-60	Limestone
			Basal shale	2-5	Arenaceous shale
	Canadian	Saint Peter		100±	Soft, incoherent sandstone
		Prairie du Chien	Shakopee	80	Dolomite
			New Richmond	20	Sandstone
			Oneota	150	Dolomite
Cambrian	Potsdamian	Saint Croix	Jordan	Not exposed	Sandstone
			St. Lawrence		Sandstone & shale
			Dresbach		Sandstone

THE PRAIRIE DU CHIEN FORMATION.

The Prairie du Chien has but a limited distribution in the district. However, it is prominent in the valley of Village creek in the eastern part of Makee township, and also in the northwest corner of Makee township along a tributary of the Upper Iowa river. An unconformity between the St. Peter and the Prairie du Chien renders these outcrops highly variable. It is a common occurrence along Village creek to find one wall of the valley composed of Prairie du Chien dolomite, while the opposite wall is of soft St. Peter sandstone. The two formations appear and disappear along the valley in a most striking manner.

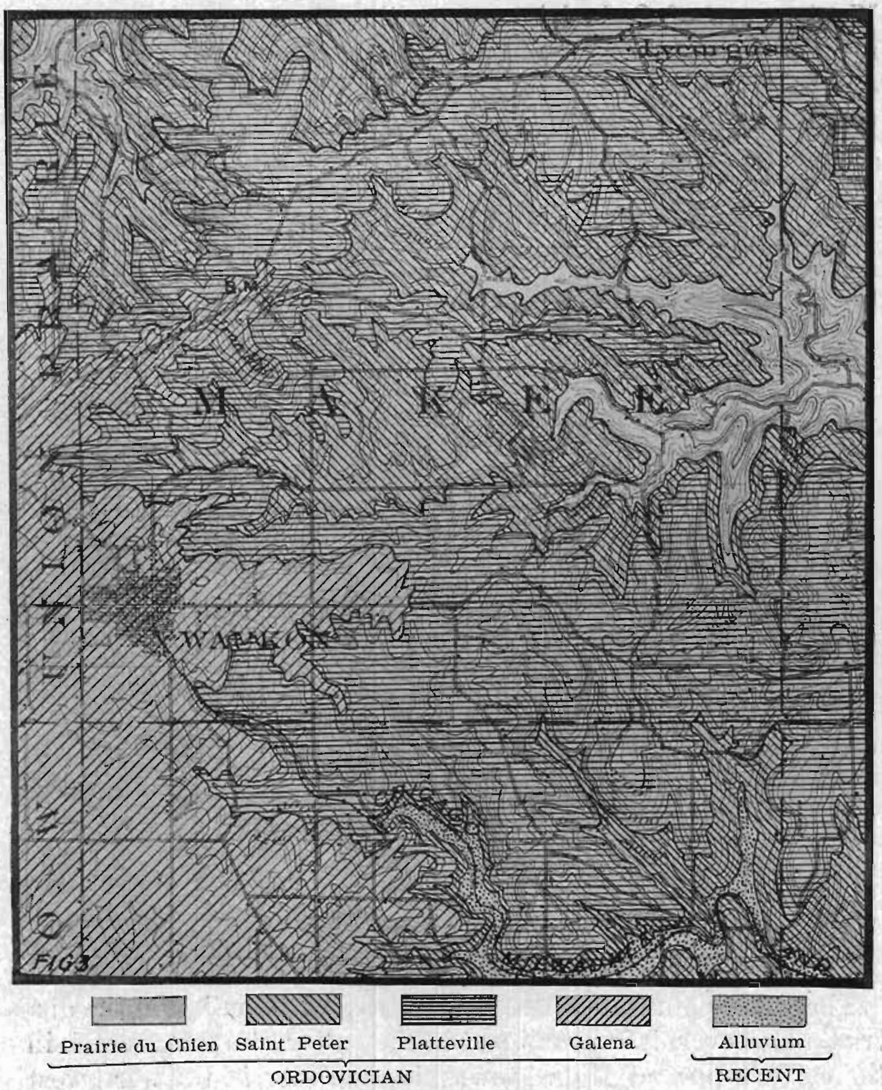

FIG. 3—Geological Map Iron Hill and Vicinity.

The Prairie du Chien formation of Iowa has been subdivided into three members, named, from the bottom up, Oneota dolomite, New Richmond sandstone, and Shakopee dolomite. The two upper members are very irregular in occurrence and in places are absent. In the limited number of outcrops found near Waukon only the Oneota and Shakopee were identified, but blocks of New Richmond float were scattered profusely in the deeper alluvium of Village creek and the Upper Iowa river.

The Oneota Dolomite.—The Oneota member is here a thick-bedded, buff-colored dolomite. It has the characteristic open texture and the sandy, crystalline appearance of a true dolomite and contains a considerable amount of chert, usually as nodules and arranged in rather definite bands. Small cavities in the rock in many cases are filled with crystals of calcite and dolomite and the faces of many exposed cliffs are thickly coated with tufa.

New Richmond Sandstone.—Good outcrops of the New Richmond sandstone are rare in northeastern Iowa and none were seen within the area. However, the presence of the above mentioned blocks in the stream alluvium indicates that outcrops of this horizon may be found. The rock commonly is a light-colored, crystalline, sparkling, almost quartzitic sandstone. Calvin has shown[1] that the hardness and crystalline character are due to a secondary enlargement of the quartz grains in such manner as to produce optical continuity between the nucleus and the envelope. The entire thickness of the member never exceeds twenty feet and is usually less where seen in adjoining regions.

The Shakopee Dolomite.—Above the New Richmond sandstone lies a considerable body of dolomite which is somewhat variable in occurrence, having been eroded, for the most part, before the deposition of the St. Peter formation. The Shakopee is similar to the Oneota and cannot be distinguished from that member on lithologic grounds alone. It is practically unfossiliferous except for the presence of a peculiar form known as *Cryptozoon minnesotense,* concerning the organic origin of which there is some question.

Fossils of the Prairie du Chien.—No recognizable fossils were found in the Prairie du Chien of Makee township or in the contiguous territory, but a few casts of cephalopods and gastropods were collected from the Oneota four miles northeast of Waukon.

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[1] American Geologist, XIII, 1894, 225-227.

Calvin has described[2] the following forms from the chert beds of the upper Oneota of southeastern Allamakee county:

Murchisonia sp.
Tryblidium sp.
Metoptoma alta.
Straparollus claytonensis
Straparollus pristiniformis
Raphistoma pepinense
Raphistoma multivolvatum
Raphistoma paucivolvatum
Holopea turgida
Orthoceras primigenium
Cyrtoceras luthei

Stratigraphic Relations of the Prairie du Chien.—The Prairie du Chien is conformable with the Jordan sandstone below, the change from the one to the other taking place through many feet of transition beds. At many places where the thickness of the Prairie du Chien and St. Peter formations may be ascertained, although the total thickness of the two formations is always the same their individual thicknesses may vary greatly. The fact that where one is thin the other is always thick, can mean but one thing, namely, that there is an erosional unconformity between the two strata. This unconformity would explain also the absence of New Richmond and Shakopee at many places, as they probably were eroded away before the deposition of the St. Peter. This unconformity has been strikingly demonstrated at many places.

THE ST. PETER FORMATION.

Lying above the Prairie du Chien, and unconformable upon it, is the St. Peter sandstone. It has a wide distribution within Makee township, forming prominent and typical outcrops in all of the stream valleys. It has its widest distribution, however, in the valley of Village creek. On account of its soft and incoherent nature it does not form towers and steep bluffs such as are characteristic of the dolomites. Weathering goes on very rapidly and it is only in fresh exposures that satisfactory study can be carried on.

The topographic expression of the St. Peter sandstone is very characteristic. The friable sandstone weathers to gentle slopes

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[2] Bull. Lab. Nat. Hist. S. U. I., Vol. II, No. 2, 189-193.

and broad, U-shaped valleys, and forms a rolling upland, easily cultivated and well drained. The soil is sandy and is of no great value for agricultural purposes.

The presence of a resistant iron band at the top of the formation results in the production of peculiar erosional forms. Flat-topped, mesalike remnants occur where the overlying formations have been entirely removed, while a more or less prominent ledge is usually noted where the Platteville-St. Peter contact appears on a hillside.

The St. Peter formation is a soft, fine-grained, incoherent, variously colored quartz sandstone. It is, in general, so loosely cemented that at many places it resembles a deposit of sand.

The rock usually is somewhat laminated, although in many places massive layers, several feet in thickness, occur. A striking illustration of this laminated phase is found 4.5 miles northeast of Waukon, where a small stream cuts through a considerable thickness of it.

The St. Peter is highly variable in color and its hues range from pure white through the shades of buff, yellow, brown, red and purplish, the colors being most pronounced in fresh and unweathered exposures. These colors are due to the iron oxide of the cement and the variation results from varying degrees of oxidation. Alternate laminae may be differently colored and impart a strikingly variegated appearance to the rock. Such an occurrence may be seen along the south side of the road some three miles east of Waukon.

The top of the formation is marked by a resistant iron band from one to four inches in thickness, below which the sandstone is more or less impregnated with ferric salts. This iron band forms a very convenient horizon marker as it lies immediately beneath the basal shales of the Platteville formation, and differential weathering at the contact usually leaves the iron band exposed.

Although in general the St. Peter sandstone is very soft and unconsolidated, there are exceptional phases where it is exceedingly hard. Just west of the main road three miles north of Waukon, in the southeast quarter of section 12, township 98 north, range 6 west, a small quarry has been opened in such a phase. The stone exposed is regularly bedded, very hard, and almost quartzitic in texture. Four miles northeast of Waukon in the northeast quarter of section 22, township 98 north, range 5 west, well-drillers were hampered by the rapid dulling of drills while passing through the St. Peter. Examination of the fragments brought up in the slush bucket showed that they came from a very hard, quartzitic sandstone.

No fossils have been found in the St. Peter of Iowa, although some have been found in Minnesota and Wisconsin. The porous and sandy character of the rock, and the conditions which must have prevailed during sandstone deposition seem sufficient to account for the absence of an extensive fauna.

THE PLATTEVILLE FORMATION.

The Platteville formation, within the present meaning of the term, embraces the lower part of the Galena-Trenton formation of the earlier reports of the Iowa Survey and follows the usage proposed by Bain.[3] That is, the Platteville is understood as including all the rocks which lie between the top of the St. Peter sandstone and the top of the Decorah shale.

The Platteville has been subdivided on lithologic grounds into the following divisions:

3.	Decorah shales	25-30 feet (Near Waukon)
2.	Platteville limestone	50 feet
1.	Basal shale	3-5 feet

The Basal Shale.—The Basal shale member of the Platteville is present very generally in northeastern Iowa and appears to be developed typically in the region under consideration. It is a rather thin band lying immediately upon the iron band which caps the St. Peter formation. The shale is arenaceous, fissile, and weathers easily to form a dark and sticky mud. Fossils are rare in this member and but two recognizable forms were collected, both of these being species of Lingula. In addition the shale is found to contain many nodules of worn and comminuted shells, apparently of linguloid character.

The following section illustrates the general character of the shale:

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[3] Bull. U. S. Geol. Survey, No. 246, 1905, p. 19.

SECTION IN "SAND CUT," SOUTH OF IRON HILL.

		FEET.	INS.
7.	Dolomite, thin-bedded, buff, arenaceous	2	
6.	Shale, gray-green, fissile	3	4
5.	Sandstone, soft, friable, ferruginous		2
4.	Shale, gray-green, arenaceous, fissile		3
3.	Sandstone, hard, brown, ferruginous		1
2.	Sandstone, broken, calcareous, some iron	2	
1.	Sandstone, massive, soft, friable	8+	

Numbers 1, 2 and 3 belong to the St. Peter sandstone; numbers 4, 5 and 6 to the basal shale; number 7 is lower Platteville limestone.

The Platteville Limestone.—Immediately above the Basal shale is a succession of limestone beds which constitute the Platteville limestone. As they occur in the Waukon district these calcareous beds reach a thickness of fifty to sixty feet, and may be divided on lithologic grounds into the following beds:

3. Upper Thin Beds.
2. Blue Beds.
1. Lower Buff Beds.

The Lower Buff Beds are made up of a relatively unfossiliferous, buff-colored dolomite. The stone is compact, hard; the beds are two to three feet in thickness and cleave readily into slabs. The stone is light buff in color when fresh, but weathers to a somewhat darker hue, though without important crumbling or scaling. The fracture is irregular and the jointing is much less perfect than in the upper beds.

Lying conformably on the Buff Beds and separated from them by a few inches of marly limestone, are the Blue Beds. The rock of which they are composed is a thin-bedded, hard, compact, somewhat broken or nodular, undolomitized limestone, of a light gray color on fresh surfaces, but weathering to a distinct light blue. Thin marly partings appear between layers. The limestone is exceedingly fossiliferous, being made up almost entirely of the shells of brachiopods.

The Upper Thin-bedded member is made up of rather heavy lower layers, sometimes a foot or more in thickness, but with the thickness gradually diminishing toward the top of the member. The general average is but a few inches. The rock is but slightly dolomitized, is gray-buff in color, much broken, and has shaly partings. The jointing is in two directions at approximately right angles and usually is noticeable in the outcrops. Fossils are very abundant, and on account of the ease with which the rock weathers it is not difficult to obtain good specimens.

The Decorah Shale.—In the Waukon district the Decorah shale maintains a thickness greater than at any point to the east, ranging from fifteen to twenty-eight feet in thickness. It is a light gray-green, calcareous, soft, fissile shale, with interbedded limestone layers and with frequent bands of calcareous nodules and lenses of shaly limestone. The limestone is usually rather impure but appears never to be dolomitic.

Immediately below the Galena the calcareous material usually predominates and often forms a massive phase, with layers six to eight inches in thickness.

The calcareous layers are highly fossiliferous, while the shaly portions are somewhat less so. The following section is characteristic of the shale as it occurs in the vicinity of Waukon:

SECTION OF DECORAH SHALE THREE AND ONE-HALF MILES NORTH OF WAUKON.

		FEET.	INS.
10.	Shale, light green, nodular, fossiliferous, calcareous		6
9.	Limestone, hard, nodular, impure	2	
8.	Shale, impure, fissile, green, soft, fossiliferous.	1	6
7.	Limestone, nodular, impure, broken; with many fossils. One 2 foot Orthoceras	1	8
6.	Shale, thin-bedded, fissile, light green	1	
5.	Concealed	4	6
4.	Limestone, compact, impure, nodular	1	
3.	Shale, thin-bedded, fossiliferous, gray-green, fissile	1	
2.	Shale, impure, nodular, calcareous; and interbedded limestone	10	
1.	Concealed	12	

Fossils of the Platteville Formation.—The Platteville undoubtedly is the most highly fossiliferous formation of the Ordovician system, and the gradual increase in the numbers and varieties seems to have culminated in the upper part. In many species there is also an increase in size in the upper part. The following species were collected[4] from the Platteville limestone, chiefly in the neighborhood of McGregor, Iowa:

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[4] Identified by Professor A. O. Thomas.

Streptelasma corniculum.
Crinoid stems.
Monticulipora (several sp.).
Orthis subaequata.
Orthis tricenaria.
Orthis testudinaria.
Rafinesquina alternata.
Strophomena minnesotensis.
Strophomena rugosa.
Strophomena sp.
Leptaena rhomboidalis.
Leptaena unicostata.
Rhynchotrema dentata.
Plectambonites sericea.
Ambonychia radiata.
Avicula sp.
Liospira vitruvia.
Trochonema umbilicatum.
Trochonema sp.
Murchisonia gracilis.
Bellerophon sp. One with indistinct keel, one with a distinct ridge, and a third with a spine.
Hyolithes sp.
Orthoceras sp.
Oncoceras pandion.
Cyrtoceras sp.
Ceraurus pleurexanthemus.
Isotelus iowensis (?).
Isotelus gigas.
Calymene sp.
Bumastus sp.
Ascidaspis sp.
Beyrichia sp.

As was noted above, the number of species and individuals shows a gradual increase toward the upper part of the Platteville formation. This tendency culminates in the uppermost member, the Decorah shales. Most of the fossils are contained in the calcareous nodules which make up a considerable part of the rock, and from these nodules they weather readily, so that excellent specimens may be secured. The following forms were collected in the Decorah shales of Makee and Ludlow townships:

Streptelasma corniculum.
Crinoid stems.
Massive bryozoa (2 sp.).
Monticulipora pulchella.
Rhinidictya sp.
Branching bryozoa (2 sp.).

Prasopora simulatrix.
Lingula iowensis.
Crania sp.
Orthis tricenaria.
Orthis (Platystrophia) lynx.
Orthis (Platystrophia) lynx var. acutilirata.
Orthis (Dalmanella) testudinaria.
Orthis (Dalmanella) subaequata.
Orthis (Dinorthis) pectinella.
Orthis (Dinorthis) subquadrata.
Orthis (Hebertella) insculpta.
Orthis (Hebertella) bellirugosa.
Orthis sp.
Rhynchotrema capax.
Rhynchotrema inequivalvis.
Rhynchotrema perlamellosa.
Rhynchotrema anticostiensis.
Plectambonites sericea.
Strophomena filitexta.
Strophomena nutans.
Strophomena sp.
Strophomena planumbona.
Rafinesquina alternata.
Rafinesquina minnesotensis.
Leptaena rhomboidalis.
Fusispira nobilis.
Fusispira intermedia.
Fusispira sp.
Liospira vitruvia.
Bellerophon sp.
Ceraurus pleurexanthemus.

Of all the above species *Prasopora simulatrix* is the most common, and within the Waukon area at least, serves as a convenient indicator of the horizon. The most abundant brachiopods are *Orthis testudinaria, Plectambonites sericea* and *Platystrophia lynx.*

THE GALENA FORMATION.

The Galena formation, as the term is used here, includes everything between the top of the Decorah shales and the bottom of the Maquoketa shale. In many of the older reports of the Iowa Geological Survey, notably the Allamakee county report, the Mid-Ordovician was considered to be represented in Iowa only by a single great formation, the Galena-Trenton. Of this the upper phase, or Galena, was dolomitized, while the lower phase was pure limestone. More recently, however, the work of Bain[5]

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[5] Geology of Dubuque County: Iowa Geol. Survey, X, pp. 402-412.

in Dubuque county and of Calvin[6] in Winneshiek county, has shown that the most satisfactory division is made at the shale horizons, as stated above.

The Galena covers the hills in the southern and western parts of the area. Waukon is located on a plain which is underlain by the Galena and a long tongue of the rock extends northeastward through Iron Hill. As there are no overlying rocks, with the exception of unconsolidated material, the formation does not reach its normal thickness, but its maximum here is less than 100 feet. Where the overlying Maquoketa formation is present, as in the Dubuque region, the Galena reaches a rather uniform thickness of 240 feet.

Good outcrops are rare near Waukon, owing chiefly to the slight thickness of rock remaining. The hillside and quarry north of the pumping station at Waukon furnish a section of the lower, non-dolomitic phase which also is highly fossiliferous. A fair exposure of the non-dolomitic lower beds is seen also in an old quarry two miles south of Waukon.

The plain underlain by the Galena is characterized by the presence of many sinkholes. Near the crossroad in the center of section 9, township 97 north, range 5 west, the sinkholes are especially well developed. By the caving in of a number of them a stream bed several hundred yards in length has been developed, with several apparent natural bridges remaining to indicate the origin.

Lithologic Character.—In general the Galena is a heavy-bedded, crystalline, vesicular, buff-colored dolomite. In the Waukon region, however, dolomitization has not taken place and the rock is a limestone. The thickness of the beds varies according to their positions within the formation, the thick beds being in the middle. On a strictly lithologic basis the Galena is divisible into five members:

	FEET.
5. Upper Thin Beds	30
4. Upper Massive Non-cherty Beds	60
3. Lower Massive Cherty Beds	90
2. Lower Massive Non-cherty Beds	50
1. Lower Thin Beds	0-10

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[6] Geology of Winneshiek County: Iowa Geol. Survey, XVI, pp. 80-82.

The two upper members, and most of the third, have been removed by erosion.

The Lower Thin Beds lie conformably on the Decorah shale and frequently grade into that member. For example, it is not possible to draw a sharp line of demarcation between the two members in the exposure just north of the Waukon pumping station as the change takes place through many feet of transition beds. Throughout most of the Waukon district this lowermost member of the Galena is undolomitized.

The Lower Massive Non-cherty member is a more or less dolomitic, crystalline, thick-bedded, buff-colored limestone. It usually contains many fossils, as is the case in the water-works section at Waukon. Here may be seen a number of fossils that have ranged upward from the Platteville.

Fossils of the Galena Formation.—Fossils are not common in the Galena of this region, except in the undolomitized lower portion. The most common form present outside of the Lower Thin Beds is *Receptaculites oweni,* which is found to lie in very definite zones, one of which is located forty feet from the base and the other seventy feet from the top of the formation. These zones are definite over wide areas and are used commonly as horizon markers in mapping. About midway between these two zones *Ischadites iowensis* is present, in places in large numbers, but it is much less persistent than Receptaculites.

The "Gastropod Zone" of the Dubuque[7] and Winneshiek[8] county reports lies about ten feet below the upper Receptaculites zone, or eighty feet below the bottom of the Maquoketa shale. In Winneshiek county[9] this zone has been found to contain *Maclurea bigsbyi, Hormotoma major,* and *Trochonema umbilicatum.* In Allamakee county, according to Calvin[10], the zone contains not only these forms but also *Maclurina cuneata, Murchisonia bellicincta, Fusispira elongata* and *Fusispira inflata.*

Near Bluffton, in Winneshiek county, according to Calvin (op. cit. [11]), there is a narrow zone about seventy feet above the base of the Galena which is particularly rich in fossils of *Plectambonites sericea.* This form, as well as *Rafinesquina*

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[7] Iowa Geol. Survey, X, 409.

[8] Iowa Geol. Survey, XVI, 90-95.

[9] Iowa Geol. Survey, XVI, p. 90.

[10] Iowa Geol. Survey, X, p. 409.

alternata and a number of other Ordovician species continues to range up into the Maquoketa, although Plectambonites is not known to be abundant in the Galena, except locally. Calvin says[11], "Of the two persistent brachiopods mentioned (*P. sericea* and *R. alternata*) the evidence at hand would indicate that they were not uniformly distributed at any particular time over the old sea bottom, but seem to have been grouped more or less in local colonies."

From the Lower Thin Beds near Waukon the following forms were collected.

Streptelasma corniculum.
Crinoid stems.
Bryozoa (2 sp.).
Orthis (Dalmanella) testudinaria.
Orthis (Platystrophia) lynx.
Lingula iowensis.
Strophomena sp.
Hormotoma gracilis.
Illaenus sp.

Structural Geology.

While the indurated rocks of northeastern Iowa are considered in general to be practically horizontal, or to slope to the southwest with a gentle monoclinal dip, there are important exceptions in many localities. McGee[12] noted the presence of a number of local disturbances and mapped them approximately. Calvin, in the reports on Allamakee and Dubuque counties, and Leonard, in the report on Clayton county, mention the presence of many abrupt pitches in the strata and note some minor folding.

Allamakee county is traversed in a northwest-southeast direction by the rather conspicuous fold that McGee has called the Sny Magill anticline. As was pointed out by Calvin, the flanks of this fold have rather variable dips and bear many minor folds.

Such a lateral fold is found to extend into Makee township from the north, occurring as a well defined anticline whose crest dips toward the southwest. The crest of this fold passes through Iron Hill (figure 4).

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[11] Iowa Geol. Survey. XVI. p. 94.

[12] Pleistocene History of Northeastern Iowa: 11th Ann. Rept. U. S. Geol. Survey, pt. 1, pp. 338-347.

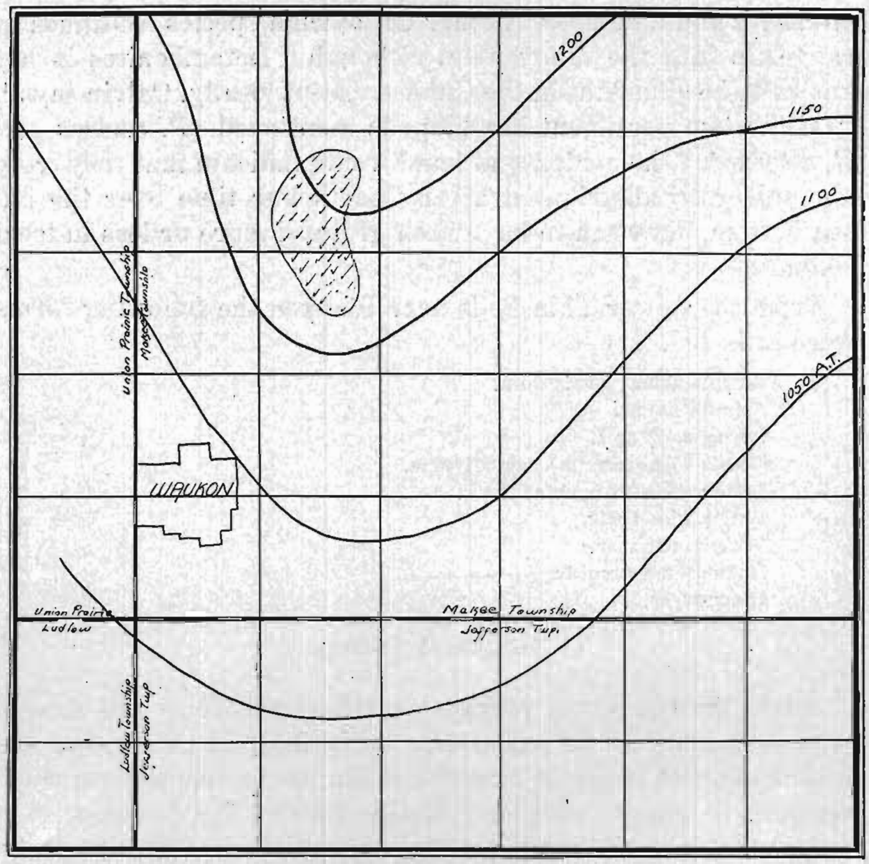

FIG. 4—Contour map of top of St. Peter sandstone, Makee Twp. Ore body shown by checks.

Physiographic Geology.

General Statement.—One of the most striking features of the topography of northeastern Iowa, as well as of the entire Driftless Area, is the singularly even skyline. This skyline maintains its symmetry throughout a wide extent of territory, being broken only by the gaps formed by deep stream valleys and by the presence of a few mounds that rise to a somewhat higher level. If the valleys which dissect the region could be filled to the level of the tops of the ridges the resulting surface would form a plain extending over much of the Driftless Area. Further filling to the level of the tops of the mounds, which include Sherrill and Sinsinawa mounds, would result in the production of a higher plain.

It would seem, therefore, that there are two very definite and well developed plains, the lower of which is the more widespread, and the more marked in the neighborhood of the streams. Farther back from the rivers the higher plain becomes well developed, and in many places, as in Allamakee and Clayton counties, both plains may be seen.

The upper of these two plains was studied by Calvin[13] in Allamakee county and by him believed to be a peneplain of Cretaceous age. Leonard[14] speaks of the presence of an old peneplain in Clayton county but ventures no opinion as to its age. Grant and Burchard[15] have described a peneplain in the Lancaster-Mineral Point area, whose lowest point is at 900 feet above sea level at Asbury, near Dubuque. They consider it to be of Tertiary age. They also note the presence of a higher plain, of which Sherrill and Sinsinawa mounds are remnants, and suggest that it may be a structural plain developed on the Niagaran. This upper plain is probably to be correlated with "Peneplain No. 1" described by Hershey[16] and by him considered to be a true peneplain of Cretaceous age. Bain[17] mentions the peneplain and agrees with Hershey regarding the explanation. Hershey[18] also recognizes a lower peneplain on which Sherrill, Sinsinawa and the other mounds form monadnocks, but to this lower plain he assigns no definite age.

Trowbridge[19] has described two plains in Jo Daviess county, Ill., the upper, or Niagara, being equivalent probably to the Allamakee Peneplain of Calvin. The lower, or Galena plain, is to be correlated with Hershey's "Peneplain No. 2" and with the Lancaster Peneplain described by Grant and Burchard. The same writer[20] correlates the higher of the Northeastern Iowa plains with the high plain at Baraboo, Wisconsin, described by Salisbury,[21] and the lower one with the Galena Peneplain in Jo Daviess county, Illinois. The latter is held to be early Pleistocene in age.

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[13] Iowa Geol. Survey, IV, 1894, p. 43.
[14] Iowa Geol. Survey, XVI, p. 229.
[15] U. S. Geol. Survey, Lancaster-Mineral Point Folio, 1907, p. 2.
[16] American Geologist, XVIII, 1896, pp. 75-78.
[17] Bull. U. S. Geol. Survey No. 294, 1907, p. 15; Bull. Wis. Geol. Survey No. XIX, 1907, p. 15.
[18] Amer. Geologist, XVIII, 1896, pp. 78-80.
[19] Jour. Geology, XXI, 1913, pp. 731-742.
[20] Bull. Geol. Soc. America, XXVI, 1915, p. 76.
[21] Jour. Geology, III, 1895, pp. 655-667.

The work of the various authors is correlated in the accompanying table:

CORRELATION OF THE PENEPLAINS.

AUTHOR	UPPER PLAIN	LOWER PLAIN	REFERENCE
Bain		Lancaster Peneplain (Tertiary)	Wis. Geol. Surv. Bull. XIX, p. 15 U. S. Geol. Surv. Bull. 294, p. 15 1907
Calvin	Allamakee Peneplain (Cretaceous)		Ia. Geol. Surv. IV, p. 43 1894
Grant and Burchard	Noted, but no name given (Cretaceous)	Lancaster Peneplain (Tertiary)	Lancaster—Mineral Point Folio, p. 2 1907
Grant		Noted, but no name given (probably Tertiary)	Wis. Geol. Surv. Bull. XIV, p. 11 1906
Hershey	Peneplain No. 1 (Cretaceous)	Peneplain No. 2 (Tertiary)	Am. Geologist XVIII, pp. 78-80 1896
Hershey	Trenton Plain Cretaceous Plain	Lower Magnesian Plain Tertiary Plain	Am. Geologist XX, pp. 246-268 1897
Kümmel		Noted, but no name given	Science, N. S., Vol. I, pp. 714-716 1895
Leonard		Noted, but no name given (Late Cretaceous or Tertiary)	Ia. Geol. Surv. XVI, p. 229 1906

CORRELATION OF THE PENEPLAINS—CONTINUED.

AUTHOR	UPPER PLAIN	LOWER PLAIN	REFERENCE
Norton	Noted, but no name given	Noted, but no name given	U. S. G. S. Water Supply Paper 293, p. 239 1912
Salisbury	No name applied (Pliocene)		Jour. Geol. III, pp. 655-667 1895
Salisbury and Atwood	The 1400 foot plain (Pliocene)		Wis. Geol. & Nat. Hist. Surv. Bull. 5 pp. 62-64. 1900
Trowbridge	Niagara Plain (Structural)	Galena Plain (Tertiary)	Jour. Geol. XXI, pp. 731-742 1913
Trowbridge	The higher plain	The lower plain (Late Tertiary or early Pleistocene)	Ia. Acad. Sci. Proc. XXI, pp. 205-209 1914
Trowbridge	Upper Plain (Late Tertiary)	Lower Plain (Early Pleistocene)	Bull. Geol Soc. Am. XXVI, p. 76 1915

The Upper Plain.—The upper of the two plains is well developed at Waukon, where it is at an altitude of about 1,300 feet above sea level. Iron Hill rises to a height of forty to fifty feet above the plain. Roads follow the plain wherever possible and the chief highways of the region are the "Ridge Roads," which lie on the divides at the level of the Upper Plain.

The Upper Plain was studied with some care by the members of the field class from the Universities of Iowa and Chicago during the summer of 1914. It was found to be well developed at the following places:

UPPER PLAIN.

Lansing	altitude 1200	lies on Platteville.
Church	altitude 1280	lies on Galena.
Waukon	altitude 1300	lies on Galena.
Eldergrove	altitude 1180	lies on Galena.
Turkey River	altitude 1200	lies on Niagaran.
Osterdock	altitude 1180	lies on Niagaran.
Sherrill	altitude 1200	lies on Niagaran.

The above table seems to indicate that the plain is not structural, for it cuts across beds in an unmistakable manner. This would indicate that it is an erosional plain. The possibility that it is a plain of marine erosion may be immediately discarded since there are no evidences of cliffs, bars or shore lines in the vicinity. It must be, therefore, a peneplain.

The presence of the high ridge near Waukon, which seems to rise above the general level of the plain may be explained in two ways. The first, and most obvious explanation, is that it is the result of warping during the uplift of the region. It may be, however, the remnant of a low divide which existed on the old peneplain, for it must not be assumed that the peneplained surface was perfectly flat. The fact that Iron Hill, which is the highest point on the ridge, lies on the crest of a local anticline, seems to favor the first view, but the fact that the anticline is beveled by the plain renders the latter explanation more probable.

At many places on the Upper Plain, and especially on Iron Hill and in the upper part of the iron ore, there are to be found many well-rounded and water worn quartz pebbles, which bear evidence of long continued rolling in stream beds. Their size is fairly uniform, from one-fourth inch to one-half inch in diameter, and there is a liberal admixture of smaller quartz pebbles and pure quartz sand. Most of the pebbles are white or yellow in color. Many are opaque, some are clear and many are translucent.

Many hundred of these pebbles were broken and examined by the writer, both in the ore pits and elsewhere, but not a single piece of igneous material was found among them. Apparently all the pebbles are quartzose and must have been deposited during a time of complete weathering. Not only are the pebbles smoothed and practically all angularity removed, but many of them are polished, a fact which bears witness to their hardness.

The Lower Plain.—The appearance and general character of the Lower Plain is very similar to that of the Upper. The divides of which it is composed are of comparatively uniform height, and the tops are gently rolling, while the stream valleys between them are steep-sided and gorgelike. Proximity to the main drainage lines has resulted in a greater degree of dissection than has occurred in the case of the more remote Upper Plain.

Study of the Lower Plain in an area considerably wider than that properly considered in this report shows that it also bevels the edges of the beds in unmistakable manner. This is illustrated in the following table:

LOWER PLAIN.

New Albin	altitude 1120	lies on Prairie du Chien.
Lansing	altitude 1100	lies on Prairie du Chien.
Waukon	altitude 1100	lies on Galena.
McGregor	altitude 1040	lies on Platteville.
Clayton	altitude 1065	lies on Galena.
Turkey River	altitude 920	lies on Maquoketa.
Osterdock	altitude 940	lies on Maquoketa.
Asbury	altitude 900	lies on Maquoketa.

Although careful search was made no igneous material was found within a considerable distance of the top of Iron Hill. Abundant glacial or fluvio-glacial material was found, however, considerably below the top, and it is common at the level of the Lower Plain. This drift is very persistent in all directions from Iron Hill, and occurs either at or below the surface of the lower plain. The deposits lie usually on the rough and weathered surface of bedrock and in most instances are found beneath an overburden of several feet of fine loesslike material.

The close association of the old glacial drift with this plain is very marked. The fact that the drift is found in the valleys below the lower plain, as well as on its surface, seems to indicate, as pointed out by Trowbridge[22], that the plain had been not only developed but also partly dissected before the first invasion of the ice. In no other way can the presence of true drift in the valleys be explained.

The drift material is very generally characterized by the advanced state of decay of the igneous pebbles, as the basalts in many cases are so far advanced in decomposition that they can be crushed between the fingers. An average of many pebble counts shows the igneous pebbles to be about 90 per cent decayed. This fact, together with the high topographic position of the material, seems to point to a very early origin for these drift deposits. The Illinoian and Wisconsin ice sheets approach the area at no point and the material is clearly too highly weathered for the Iowan. It must therefore be either Kansan or pre-Kansan. The question as to whether the deposits are of glacial or fluvio-glacial origin cannot be settled from the exposures within this small region, and in any event is not pertinent to this discussion.

Ages of the Peneplains.—It is obvious that the Upper Plain is post-Niagaran in age, since it lies partly on the eroded surface of that formation. Drift is present both upon and below the Lower Plain so it seems safe to consider that the Upper Plain had been baseleveled, uplifted, and partly dissected before the advent of the ice which gave rise to the glacial deposits on the lower plain. Had the ice sheet advanced over the region before the uplift a much greater amount of drift would have been deposited on the Upper Plain, and none would be found on the Lower Plain or beneath it.

Assuming that the Upper Plain had been partly dissected and the Lower Plain formed before the advent of the ice sheet, it must be concluded that most of the drift would be deposited in the low places; that is, on the Lower Plain.

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[22] Trowbridge, A. C., Bull. Geol. Soc. America, XXVI, 1915, p. 76.

Study of the well rounded quartz pebbles which are found so abundantly in the ore and to a lesser extent on other portions of the Upper Plain seems to shed some light on the question of its age. Gravels apparently identical with these have been found in the Baraboo region of Wisconsin, and were there studied by Salisbury,[23] who assigned to them a Tertiary age. He remarked on the similarity between the Baraboo gravels and those which had been shown to belong to the Lafayette formation and suggested that they should be correlated. He held that the high topographic position in which they occur at Baraboo (along the crest of a high bluff at an elevation of 1,560 to 1,580 feet above sea level), taken in conjunction with the lithologic character, served to fix them as a northward extension of the high-level gravels which occur at many places in the Mississippi Valley south of the limit of Pleistocene ice. Gravels apparently to be correlated with those on the crest of Crowley's Ridge, in Arkansas, were traced through Pike, Adams and Calhoun counties in Illinois, and also in Crawford county, Wisconsin. His conclusions (loc. cit.) are as follows:

(1) that the pre-Pleistocene gravel exists in the form of widely separated erosion remnants south of the drift covered country;

(2) that isolated remnants of it are known to exist at many points beneath the drift, as many as 125 miles north of the southern limit of glaciation (Adams and Hancock counties);

(3) that the glacial drift here and there at many points for 90 miles north (Rock Island County) contains gravel which might well have come from remnants of the northern extension of the same formation;

(4) that remnants of similar gravel occur in the driftless area where there has been no chance of destruction or burial by the ice; and

(5) that the gravel in all these situations has the same topographical habit, all point to the conclusion that they are parts of a once widespread and continuous gravel formation.

Chamberlin and Salisbury[24] have more recently expressed the same view and have discussed the gravels under the chapter on the Pliocene:

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[23] Jour. Geology, III, 1895, p. 662.

[24] Chamberlin and Salisbury, Geology, Vol. III, 1907, pp. 300-301.

> ......they are the older part of the complex series of river deposits, shifted repeatedly to lower levels, and nearer the sea, until the main part of the series is near the coast, while only meager remnants remain in the sites of original deposition. The farther these remnants are from the low coast-plain the smaller they are and the greater their altitude, and if the above interpretation be correct, the greater their age.

Other writers, notably Calvin[25] and Hershey[26] have considered this Upper Plain to be Cretaceous, correlating the High Level Gravels found thereon with certain supposedly Cretaceous gravels in southeastern Minnesota described by Winchell[27]. The age of the Minnesota gravels, however, seems not to have been definitely proved, hence the former view seems preferable.

The entire discussion may then be summed up as follows:

(a) The Upper Plain is certainly post-Niagaran, since it rests partly on the eroded surface of that formation.

(b) It is pre-Pleistocene, apparently, for little igneous material is found on its surface, although it is abundant on the lower plain.

(c) It may be assumed with considerable confidence to be of Pliocene age since it bears gravels similar to those which belong to the Pliocene Lafayette formation which extends from the coastal plain near the Gulf of Mexico, northward through Arkansas, Missouri, Illinois and Wisconsin, occurring always on high ridges, as in the present instance.

(d) The Lower Plain must be younger than the Upper Plain since it lies below it.

(e) This Lower Plain certainly had been formed before the earliest ice invasion, since glacial material is found on it, and below it.

(f) The Lower Plain seems to have been developed in early Pleistocene time, before the first ice invasion, since the presence of drift deposits in the valleys beneath the plain indicates that it had been partly dissected before these deposits were formed.

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[25] Iowa Geol. Survey, IV, 1894, p. 43.

[26] Amer. Geologist, XVIII, 1896, pp. 78-80. Amer. Geologist, XX, 1897, 246-268.

[27] Final Rept. Minnesota Geol. & Nat. Hist. Survey, Vol. I, pp. 305-309, 355-356.

Economic Geology.

THE IRON ORE.

GENERAL CHARACTER OF THE ORE.

The ore deposits here described form a cap on the top of the eminence known as Iron Hill. The deposit is unsymmetrical with respect to the hill, as it extends much farther down the southern than the northern slope. The greatest thickness of ore occurs on the northern side of the hillcrest, and the deposit becomes thinner in each direction from this place.

The ore body is directly in contact with the bedrock and lies unconformably on the Galena and Platteville formations and probably slumps to some extent onto the St. Peter. At the highest point of bedrock beneath the ore the deposit is underlain by forty to fifty feet of thin-bedded, undolomitized lower Galena. The fact of the presence of the Galena is shown by the fossils in the limestone fragments from those pits which were continued to bedrock. The estimate of the thickness was obtained by measurement from the Platteville-St. Peter contact on the hill just above the concentrating plant.

FIG. 5—Large limestone bowlders in the iron ore. South end of new pit.

Overlying the ore is a thickness of five feet or less of a fine, grayish, loesslike material. Probably it is not true loess, however, for it exhibits a jointed or starchy fracture on drying. The contact of the overburden with the ore is unconformable (fig. 6) and many somewhat rounded fragments of ore are found imbedded in the overburden several inches above the contact.

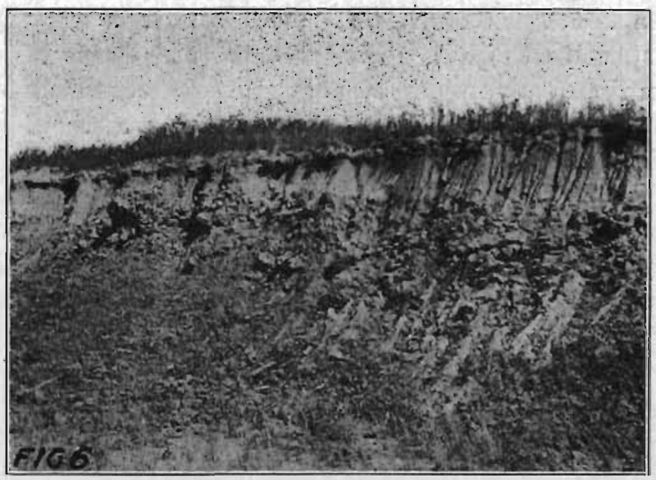

FIG. 6—Unconformable contact between ore-body and overburden. East wall of south pit.

Physical Character of the Ore.—The Waukon ore is, in the main, a brown, coarsely cellular limonite. The cavities which produce the cellular character are very irregular in size and shape, and range from a fraction of an inch to a foot or more in greatest dimension. The usual size, however, is but a few inches.

These cavities contain, in a considerable number of cases, masses of clay, usually in the form of small concretions or oölites. Mingled with the clay there are in places sand and fragments of chert and fossils of Ordovician age. These fossils will be considered more fully later.

The ore body is much jointed and fractured and this fact has resulted in the development of a bowlder character, in which the ore breaks up into large or small masses of very irregular form (figure 10). Many of these bowlders weigh hundreds of pounds or even several tons, and are so resistant to further division that it is necessary to resort to blasting to reduce the larger ones to sizes that can be handled readily. The walls of the crevices are usually somewhat weathered and the crevices are filled with clay, which varies in color from a light cream to a deep red. The different colors in many cases form alternating bands in the crevices.

Large numbers of chert nodules are found throughout the deposit, usually surrounded by a greater or less thickness of dense limonite which in some cases grades into and partly replaces the outer portion of the chert. The pieces of chert are broken and angular, but never give any indication of having been rolled or stream worn.

Many of the chert nodules are found to have been fractured and subsequently cemented by limonite. Others exhibit a core of fresh chert surrounded by roughly concentric layers of decayed chert, ferruginous chert, and limonite. (Plate I.) In the latter cases it appears that weathering must have taken place in the chert before it was imbedded in the limonite.

In the new pit of the company, as well as in many of the numerous test pits scattered over the property, there are exposed limestone bowlders, or "lime horses," some of which are of large size. The largest one seen in the pit was about ten feet in length by five feet in height, and extended for an unknown distance back from the pit wall (see figure 5). Many of these masses of rock have been removed entire and hauled outside of

FIG. 7—View of new pit near south end. Sept. 1, 1914.

the pit, where they may be examined readily. Some are well rounded (figure 8) and exhibit no angular surfaces, while others are more or less angular. In those which have not been long subject to weathering outside of the ore body the surface presents a deeply pitted appearance resembling that produced by the subaerial weathering of a dolomite, or in like measure the

FIG. 8—Large limestone bowlder from new pit, showing rounded form and pitted surface.

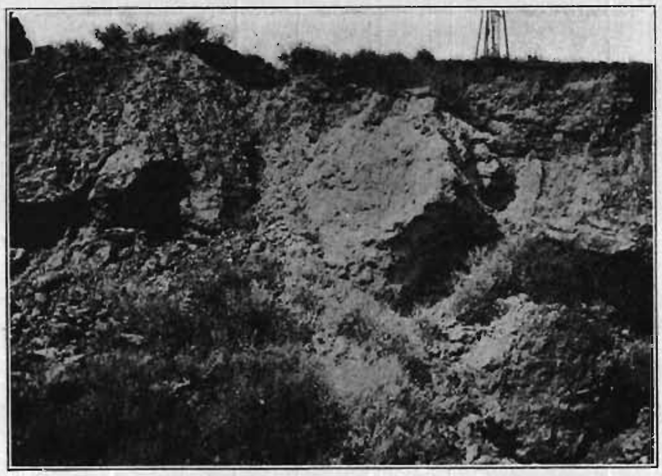

FIG. 9—View showing bowlder character of the ore.

pitting produced by the solvent action of underground water. At no place in the ore body, so far as known, is there any gradation from the ore into the limestone.

The bowlders, wherever they can be observed in position, lie with their bedding planes in close approximation to the horizontal. One bowlder in the new pit has a departure from horizontality of 8°, another of 5°, and a third of less than 1°. According to Mr. Erwin the bowlders met with in sinking the test pits in various parts of the deposit show the same approximate horizontality.

Most of the limestone bowlders are fossiliferous and many recognizable forms were obtained from them. From a large, flat bowlder in the bottom of the pit and near the south end (106 feet above top of St. Peter) the following forms were collected:

Receptaculites oweni.
Rafinesquina alternata.
Streptelasma sp.
Liospira vitruvia.
Murchisonia gracilis.
Bellerophon sp.
Ischadites sp.
Lingula iowensis.
Platystrophia lynx.
Dalmanella testudinaria.
Leptaena unicostata.
Plectambonites sericea.

This association of life, especially the presence of the index fossil *Receptaculites oweni,* indicates that the rock is of Galena age, while the brachiopods are found in the same association in the undolomitized beds of the lower Galena throughout the vicinity.

A second bowlder not far from the first one furnished the following list:

Receptaculites oweni.
Rhynchotrema capax.
Dalmanella testudinaria.
Streptelasma sp.

This one also appears to belong to the lower Galena.

From a large, horizontally bedded block of limestone in the west wall of the pit the fossils obtained were:

Plectambonites sericea.
Streptelasma sp.
Dinorthis subquadrata.
Murchisonia sp.

This bowlder appears also to belong to the lower undolomitized Galena.

On faunal grounds then, the limestone bowlders seem to have belonged to the lower part of the Galena formation, which in this vicinity is undolomitized and grades imperceptibly downward into the calcareous upper portion of the Decorah shale. In many localities it is impossible to determine the exact contact between the upper part of one and the lower part of the other.

Fossils in the Ore.—In the first published account of the Waukon iron ores Mr. Ellison Orr[28] mentions the fact that he had picked up ". . . . several pieces of ore in which were imbedded well preserved specimens of Trenton fossils." Later writers make no mention of these fossils, probably because their investigations were confined to the old pit, now abandoned, where fossils are of exceedingly rare occurrence.

If the concretions from many parts of the new pit, as well as concretions taken from various test pits, are broken open, numerous well preserved fossils can be found. Some of these occur imbedded in the sides of the cavities or in the denser ore of the walls, but most of them are only slightly attached to the interior or are found loose with the core of clayey concretions. Where the shells are yet attached to the walls they are, in many cases, found to be coated with a hard, black variety of iron oxide, or even partly replaced by that substance. The coating may be so even over the surface of the shell that identification can be made without removing it.

In the material taken from test pits in the highest part of the deposit, a very highly fossiliferous ore is found (Plate IV, figures 2, 3). In this material the body of the limonite is packed full of small, somewhat comminuted shells. Many complete shells also occur in this material, and both they and the frag-

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[28] American Geologist, I, 1888, p. 130.

ments are completely silicified and show no evidence of ferruginous replacement. In the material thrown out from the test pits there are also many loose shells, completely silicified and well preserved, but showing no replacement by iron.

The following forms have been found in the ore:

Prasopora simulatrix. Plate III, figure 13.
  Several specimens, more or less replaced.

Streptelasma corniculum. Plate III, figures 7, 9-12, 14.
  Very common and most of them well preserved. Silicified. Many with apices intact. No indication that they were ever rolled in stream.

Crinoid stems.
  Many fragments of stems, most of them with annular ribs.
  Some imbedded in limonite. Silicified.

Plectambonites sericea. Plate II, figures 1-16, 31.
  Represented by many small, perfectly preserved, siliceous specimens, both entire shells and single valves. Maximum size 16 mm. by 9 mm. Fine surface striae very distinct. No beekite rings. 40 complete specimens.

Dalmanella testudinaria. Plate II, figures 17-30.
  Many small, well preserved specimens. Many entire and several separate valves. Breadth from 4 mm. to 13 mm. Silicified. Striae perfect. No beekite. 35 complete shells.

Platystrophia lynx. Plate III, figures 1-3.
  Four well preserved specimens. Silicified and showing few beekite rings. Maximum width 18 mm. Hinge lines somewhat extended and eared.

Rafinesquina minnesotensis. Plate III, figure 5.
  A single well preserved, silicified specimen. Striae lost in silicification or by weathering. Found on dump from test pits. Width at hinge line, complete, 36 mm. Shows some beekite rings.

Hebertella bellirugosa. Plate III, figure 4.
  A single specimen, silicified, striae partly removed in silicification. Shows beekite rings.

Streptelasma profundum. Plate III, figure 8.
  A single medium sized specimen. Silicified but shows very few beekite rings. Well preserved. Part of calyx broken away.

Rhynchotrema capax (?). Plate III, figure 6.
  Posterior half only. Silicified and striae well preserved. Interior hollow and lined with quartz crystals. Bears heavy imbricating lines, even on umboes, but in other respects agrees well with R. capax. Single specimen in dump from test pit No. 291.

The fact should be emphasized, that all the fossils found in the iron ore are silicified, whereas, so far as can be determined, none of the same forms as they are found in the Platteville and Galena have been so replaced. The silicification is supposed to have taken place during weathering and as one of the processes of weathering[28a].

Composition of the Ore.—The principal ore mineral of the Waukon deposit is the hydrated sesquioxide of iron, or limonite. Associated with this mineral, however, are the lower hydrate turgite, and the anhydrous oxide hematite, although neither occurs in any considerable quantity. Mr. Erwin states that göthite also has been found, but none was seen by the writer. The relation between these minerals may be shown as follows:

NAME	COMPOSITION	PER CENT Fe_2O_3	PER CENT H_2O
Limonite..........	$2Fe_2O_3 . 3H_2O$	85.5	14.5
Göthite............	$2Fe_2O_3 . 2H_2O$	89.9	10.1
Turgite............	$2Fe_2O_3 . H_2O$	94.7	5.3
Hematite..........	Fe_2O_3	100	0

The limonite is largely of the massive variety and varies widely in both hardness and color. On fresh surfaces it is dark brown, or even black in color, with an irregular fracture, and has a hardness of about 5 in the Moh scale. On surfaces that have been exposed to weathering the color approaches a light brown and the hardness may fall as low as 1.5. The harder phase has a submetallic luster and shows no definite structure on a polished surface.

A third phase of the limonite is found to line the interiors of some of the cavities. Here the mineral has definite radial structure (Plate IV, figure 1) which results in the production of a botryoidal or renniform internal surface, which is coated with a velvety black film of the same material. This phase resembles göthite in form but may be distinguished from it by opaqueness and streak.

[28a] Bassler, R. S., Proc. U. S. Nat. Mus., Vol. XXXV, 1908, p. 135.

The limonite also forms stalactites and stalagmites in many of the cavities, and these have in many instances united and practically filled the entire space.

Hematite occurs massive in the walls of the cavities and in some cases may be determined readily by its red color and streak. In other cases its presence may be detected only by the fact that analyses of the ore show an iron content much in excess of what would be expected were it composed entirely of limonite, which contains but 59.8 per cent of iron, while hematite carries 70.0 per cent. On the whole it may be said that hematite is a rare mineral in the Waukon deposit.

Turgite is found sparingly in the interiors of some ore nodules, in which it appears as a reddish powder resembling hematite. It is rather rare and has no especial importance.

Manganese seems to be present constantly, as is shown by analyses, but the amount is not large. Mr. Erwin reports that on the east end of the property wad was found in two pits. It occurs there as a layer about eight inches thick at a depth of twenty feet.

The limonite is rather siliceous and carries a large percentage of alumina, which, in the form of clay, is disseminated through the massive ore and also is concentrated in the cavities, in most cases as concretions. Much of the silica is in the form of the chert nodules which are imbedded in the ore, while in certain portions of the deposit there is a large amount of siliceous conglomerate made up of well worn and rounded quartz pebbles cemented by limonite. In such places the ore is not of sufficient richness to repay the expense of working it.

Microscopic examinations of the clay found in the cavities in the ore and of that found in the crevices show that there are many fine, angular pieces of quartz, as well as hematite, limonite, kaolin and other unidentified minerals. The residue remaining after solution of the massive ore in concentrated acid also contains similar angular quartz fragments, as well as a few small fragments of silicified fossils.

Lining the interiors of many cavities and deposited on the surface of the fibrous limonite, there occurs a small amount of the hydrous, amorphous form of silica known as hyalite. It is found in clear, colorless, botryoidal masses, never of any great thickness or extent. See Plate IV, figure 1.

Analyses of the Ore.—The management consider the following analyses to be representative of the raw ore.

I. From test pit No. 155.
II. From test pit No. 122.
III. From test pit No. 34.
IV. From test pit No. 256.

ANALYSES OF WAUKON IRON ORE.

ANALYSIS BY MISSOURI IRON COMPANY.

	I	II	III	IV
Fe	30.99	31.49	32.32	32.30
P	.1011	.099	.17	1.87
Mn	.122	1.02	1.06	.88
SiO_2	36.08	42.40	....	35.06
Al_2O_3	11.26	3.57	7.30	9.33
Loss on ignition	5.30	7.33	11.36	6.88

ANALYSIS OF ORE FROM RICHEST TEST PIT. SAMPLE TAKEN FROM 29 TO 34 FEET FROM SURFACE. ANALYSIS FROM MISSOURI IRON COMPANY.

	PER CENT.
Fe	52.41
P	.072
Mn	.41
SiO_2	3.924
Al_2O_3	8.44
CaO	.56
Loss on ignition	7.50

ANALYSIS SHOWING LOWEST IRON CONTENT CONSIDERED AS ORE. ANALYSIS BY MISSOURI IRON COMPANY.

	PER CENT.
Fe	6.77
P	.103
Mn	.33
SiO_2	60.25
Al_2O_3	18.07

THE ORIGIN OF THE ORE.

General Features. The only effort that has been made to explain the origin of the Waukon ore is that by Calvin in his report on the geology of Allamakee County.[29] He pointed out the impossibility of the deposit having been formed by secular decay of the overlying material, and considered it to be a bog deposit.

According to this view a depression first formed somewhat above the present site of the deposit, and into this the iron oxide drained from a wide area. Here it was precipitated through organic action. After the waters of the marsh had been drained the ore hardened, and becoming more resistant than the surrounding rock, it was eroded less rapidly. As a result it now stands out in relief.

This statement of the origin of the ore has been widely copied and has been generally accepted. But certain facts which have come to light recently seem to indicate that the above explanation is inadequate. While in a general way it seems to account for the deposit, it nevertheless fails when applied to many specific features. Since a bog deposit is due to precipitation from solution it could not be expected to contain fossils of older formations, neither should it contain great bowlders of limestone. Most bog iron ore is high in phosphorus, while the Waukon ore contains but little of this element. Bog deposits also should show some evidence of bedding planes.

The theory of replacement of the limestone by iron-bearing solutions appears untenable on account of the lack of bedding planes, which should follow those of the original rock. There should be also a gradation from the fresh rock to the ore, with some evidence of siderite, which generally is an intermediate product. Such a gradation is found in no part of the deposit, but the change from ore to limestone is abrupt or through a slight thickness of residual clay.

A second feature which is antagonistic to the replacement theory is the high content of alumina in the ore. Analyses of the bedrock beneath the deposit show only small amounts of Al_2O_3.

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[29] Iowa Geol. Survey, IV, 1894, pp. 97-103.

ANALYSIS OF BEDROCK IN PIT NO. 240.

	PER CENT.
CaO	51.72
MgO	.35
Al_2O_3	.45
SiO_2	4.80
Mn	.03
P_2O_5	.056
Fe	1.09
Loss on ignition	40.95
	99.446

The amount of alumina here is small and some other means must be found to explain the marked concentration of this material in the ore. Simple replacement of limestone is not sufficient.

The apparently close relation between the ore deposit and the Upper Plain strongly suggests an origin in a bog which may have existed there. This would be much the same as the mode advanced by Calvin and the objections which were stated in connection with that theory would apply here also.

A fourth possible mode of origin is that by secular decay. Such a process might account very well for the presence of the unworn fossils, the pieces of chert, the bowlders, the absence of bedding planes and the large amount of alumina. But it seems to offer no adequate explanation for the richness of the ore nor for its physical character. True residual ores occur as concretions or nodules of limonite imbedded in a matrix of clay.

As a starting point in the discussion of the origin of the ore it seems best to consider the geologic and physiographic conditions which must have existed during the period of its formation. It has been shown (on page 61) that northeastern Iowa must have been a land area since the end of the Niagaran epoch. The process of base-leveling begun at that time continued through the Triassic, Jurassic and Cretaceous periods, and for a considerable part of the Tertiary, an enormous interval of time. Within this period the Appalachian mountains were uplifted, reduced to complete base-level (Kittatinny peneplain), uplifted a second time and again reduced to partial base-level (Shenandoah peneplain). Yet during this entire time, so far as has been determined, northeastern Iowa suffered uninterrupted subaerial erosion, and by Pliocene time had been reduced to a condition of approximate flatness, traversed by sluggish, meandering streams, which, because of low velocity, could carry only very slight loads of very fine material.

The Residuum.—It is probable that during the early part of the old age of the region the process of weathering began to forge ahead of that of transportation and the accumulated residual matter continued not only to grow somewhat deeper but to become more completely weathered.

According to Russell:[30]

> Throughout the valley of the Shenandoah and in the region drained by the James, New River, etc., in Virginia, the surface of the country is covered to a depth sometimes exceeding 50 feet with a red clay which has resulted almost entirely from the decay of limestone.

Chamberlin and Salisbury in their report on the Driftless Area[31] state that the amount of residual material varies according to the topographic position, the greatest thicknesses being on the broad ridges and in the valleys. In the Driftless Area of Wisconsin they state that the thickness of the residuum, as averaged from some 1,800 measurements, is 7.08 feet, the maximum being 70 feet.

The Shenandoah Valley, mentioned above, has been developed since the uplift of the Kittatinny Plateau, in Cretaceous time, and hence has developed its residuum in a comparatively short period. The Driftless Area has suffered erosion for a much greater length of time and might be expected to show greater thicknesses of residuum were it not for its proximity to the Mississippi and its height (400-700 feet) above the stream, which has permitted much of the rock debris to be removed.

Yet in spite of the excellent opportunities for the removal of the residuum, the ridges of Allamakee county still show considerable thicknesses of clayey material, as shown by the following well records:[32]

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[30] Bull. U. S. Geol. Survey No. 52, p. 24, 1889.

[31] Sixth Ann. Rept. U. S. Geol. Survey, p. 254.

[32] Water-Supply Paper U. S. Geol. Survey No. 293, pp. 251-252.

THICKNESS OF CLAYEY RESIDUUM ON RIDGES. NEAR WAUKON, IOWA.

LOCALITY	ELEVATION Feet	THICKNESS Feet
County Farm. NE. of Waukon	1250	30
NE. ¼, sec. 26, T. 100 N., R. 5 W	1040	40
Sec. 2, T. 99 N., R. 4 W	1040	75
SW. ¼, sec. 21, T. 96 N., R. 5 W	1100	40
SE. ¼, sec. 32, T. 96 N., R. 5 W	1120	20
Waukon pumping station	1280	40

It seems safe, then, to assume that during the later stages in the development of the upper plain considerable thicknesses of residuum had been formed, which completely mantled the surface, but no doubt reached a maximum depth on the ridges and in the valleys as at present. The amount of this residuum certainly was not less than that now present and probably was much greater.

Nature of the Residuum.—According to Merrill,[33] the subaerial decay of limestone results in the removal of $CaCO_3$ and the concentration of Al_2O_3, SiO_2 and Fe_2O_3. The analyses quoted in the following tables are typical of this process.

TRENTON LIMESTONE FROM LEXINGTON, VA., AND RESIDUE LEFT BY ITS DECAY. R. B. RIGGS. (BULL. U. S. GEOL. SURVEY NO. 52, 1889, P. 24.)

CONSTITUENT	UNALTERED LIMESTONE	RESIDUUM
SiO_2	.44	43.07
Al_2O_3	.42	25.07
Fe_2O_3	....	15.16
CaO	54.77	.63
MgO	Tr.	.03
K_2O	Und.	2.50
Na_2O	Und.	1.20
CO_2	42.72	.00
H_2O	1.08	12.98

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[33] Rocks, Rock-weathering and Soils, p. 232.

KNOX DOLOMITE AND RESIDUUM LEFT BY ITS DECAY. MORRISVILLE ALA. ANALYSIS BY W. F. HILLEBRAND. (BULL. U. S. GEOL. SURVEY NO. 52, 1889, P. 25.)

CONSTITUENT	UNALTERED LIMESTONE	RESIDUUM
SiO_2	3.24	55.42
Al_2O_3 $(+TiO_2+P_2O_5)$	.17	22.17
Fe_2O_3	.17	8.30
FeO	.06	Tr.
CaO	29.58	.15
MgO	20.84	1.45
K_2O	....	2.32
Na_2O	....	.17
CO_2	45.54	....
H_2O (2.10 at 100°C.)	.30	9.86

Such residual clays then have resulted from the leaching out of the calcium carbonate from the limestone and its removal in solution, while the less soluble silica, alumina, and iron oxide remain. Other insoluble materials are found in clay, but rarely make up over five to ten per cent of the whole. Much of the alumina and silica occurs in the colloidal condition; some of the iron also may be in the form of colloidal ferric hydroxide. Van Bemmeln[34] has shown that the hydrogels of alumina and ferric hydroxide have a strong absorptive (adsorptive) power for salts of the alkaline earths and alkalies, and this property may explain the rather high content of these usually soluble materials which is often found in the clays.

While the major portion of a residual clay is made up of fine amorphous or colloidal matter, there is to be found a considerable percentage of angular quartz fragments. This feature was discussed by Chamberlin and Salisbury[35] in their description of the residual materials of the Driftless Area. The same characteristics were noted in residual clay from the Niagaran dolomite near Dubuque.

According to Ries,[36] the process by which limestone weathers into clay consists in the dissolving out of the carbonates of lime and magnesia while the clayey impurities are left behind. The change from clay to rock is therefore abrupt, and no gradual transition is noted as in the case of granites. The surface of

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[34] Zeitschr, Anorg. Chemie, 23, 1900, pp. 321, 358, 364.

[35] Op. cit., p. 244.

[36] Clays, Occurrence, Properties and Uses, pp. 7, 8.

the rock is commonly pitted and roughened, and may be more or less spongy for a short distance from the surface, but the change from clay to unweathered rock is, nevertheless, a sharp one.

Practically all limestones are much jointed and show very distinct bedding planes. The circulating waters flow through these ready prepared channels and attack the rock from all sides of the opening (see figure 10). As a result of this process it is not uncommon to find large, rounded bowlders resting undisturbed well up in the layer of residuum. Alternating bands of thick-bedded and thin-bedded rock are especially favorable for the development of such bowlders.

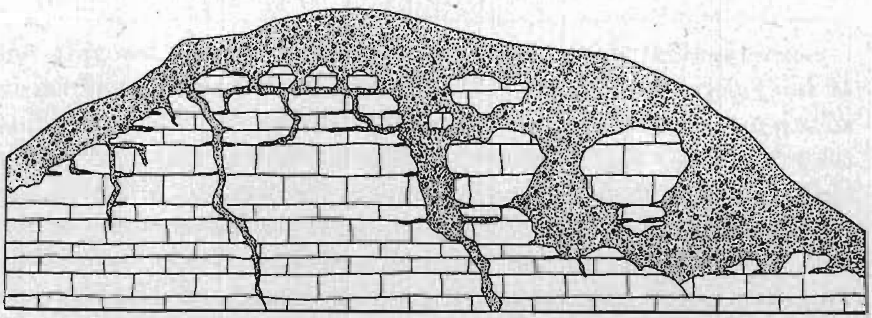

FIG. 10—Ideal section showing development of bowlders by decay of limestone. Weathering occurs most rapidly along crevices and bedding planes.

Source of the Iron.—The limestone and shale formations which once overlay northeastern Iowa were low in iron, as shown by analyses of samples from the same horizons near. Consequently the secular decay of even the somewhat excessive thickness of 800 feet assumed by Calvin cannot have produced a very highly ferruginous residuum. If, however, it be considered that a very large area was similarly covered with such a lean residuum, it must be admitted that considerable iron was available, requiring only some means of concentration.

The deposits on Iron Hill may be assumed to contain about twelve million tons of ore,[37] which averages 28 per cent metallic iron. Assume a drainage basin on the peneplain on which the ore is located, to have been of the same size as that of the Upper Iowa river; and assume also that the residuum over the entire basin had an average thickness of ten feet, a figure which is

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[37] Beyer, Iowa Geol. Survey, XII, p. 61.

only slightly greater than that which holds for the Driftless Area of today, and which certainly is far too low. Then if the residue contained the very low proportion of 5 per cent Fe_2O_3 there would be available on the plain within that drainage basin 8,712,000 tons of iron oxide. The amount of Fe_2O_3 in the twelve million tons of ore is 4,800,000 tons, so that these conditions would be adequate, provided the *means of concentration* were sufficiently perfect.

As shown above, however, the thickness of residuum present must have been nearer that found in the Shenandoah Valley of today, or about forty feet in valleys and on divides. And the average of four analyses of residual clays from southern Wisconsin[38] shows a content of Fe_2O_3 of 10.57 per cent. If we assume, then, a thickness of forty feet of residual material containing 10 per cent Fe_2O_3, 71,696,000 tons of available iron oxide are indicated.

On peneplains, however, large rather than small rivers are the rule, and the greatest change in the figures would undoubtedly arise through assumption of an increased drainage basin. Unfortunately nothing can be determined concerning the drainage of this period.

Plant growth on the plain was abundant, for climatic conditions were very favorable. The vegetation which died was not removed rapidly, and its decay produced a deep layer of humus, which in its turn tended greatly to increase plant growth. These plants too, by their products of growth and by decay, produced great quantities of the so-called humus acids,[39] which are thought to be very important agents in rock decay and weathering. These colloid organic substances have been shown to have a marked solvent action on iron compounds, probably through reduction of the ferric salts, and they must have aided greatly in the solution of the iron of the residuum.

Concentration of the Iron.—The conditions which have been described above as existing on the peneplain during the Tertiary undoubtedly were favorable for the abundant growth of vegetation. Drainage, both surficial and deep, was sluggish, and the top of the water table probably was at no great distance

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[38] Sixth Ann. Rept. U. S. Geol. Survey, p. 250.

[39] Julien, A. A., Geol. Action of Humus Acids: Proc. Am. Assn. Adv. Sci., Vol. 28, p. 311.

from the surface. Such stagnant waters are found to contain large amounts of organic matter in solution, resulting from the life processes and from the decay of plant tissues. Such organic matter, assisted by the CO_2 released from the decaying material, is highly effective in the solution of ferrous compounds.[40] This also must have added to the iron content of the sluggish waters which flowed across the northeastern Iowa peneplain.

In this region of slight relief and poor drainage swamps and bogs must have formed. The bogs occupied the depressions in the surface and probably followed the drainage lines, so that the streams had their courses through a chain of marshes. No doubt there were also ox-bow loops, which eventually would become marshes.

The residuum, especially in the plastic state induced by saturation with water, tends to slump down into depressions. Hence it seems probable that there were thick layers of clayey material beneath the marshes, and this layer was increased slightly by the action of the acids of the water which came in contact with the underlying limestone.

Precipitation of the Iron.—The processes involved in the precipitation, as limonite, of the ferrous salts contained in swamp waters, are somewhat complicated. Oxidation by atmospheric oxygen which is adsorbed at the surface of the water forms, perhaps, the simplest possibility. The following reaction, according to Van Hise,[41] illustrates such a process:

$$4FeCO_3+O_2+3H_2O=2Fe_2O_3.3H_2O+4CO_2$$

Evaporation also may be a factor, especially along the shores. Ascham[42] recently has suggested that under certain conditions bacterial action may assist in the precipitation. It has been well known for some time that certain low forms of life, notably Crenothrix, have the power of extracting iron from water and depositing it as the hydroxide.

No doubt all of these factors were in operation and they slowly formed a considerable body of bog iron ore, probably much more extensive than the present deposits. The clay be-

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[40] Clarke, F. W., Data of Geochemistry: Bull. U. S. Geol. Survey No. 491, p. 505.
[41] Treatise on Metamorphism: Mon. U. S. Geol. Survey, Vol. 47, p. 826.
[42] Zeitschr. fur. prakt. Geol., 1907, pp. 56-62.

neath the bog also contained some ferric oxide which had accumulated during the weathering process, and which had not been removed by the subsequent leaching.

At the close of the Pliocene the crustal movements which affected all of the Mississippi Valley caused the peneplain to be uplifted. This uplift, as shown above, was not less than 600 feet in all, but there is some evidence that it took place in two stages, the first including a movement of about 200 feet. At this time the drainage of the Mississippi probably was in much the same direction as now, namely, toward the Gulf of Mexico. Since the Lafayette gravels, which are terrestrial in origin and of Pliocene age, extend down to the present shore line of the Gulf, it may be safely assumed that this line has not changed materially since the Pliocene.

Northeastern Iowa, then, was uplifted a maximum of 600 feet above sea level, for as a peneplain it must have reached an approximate base-level, and according to accepted theories its streams were rejuvenated. But rejuvenation begins in that portion of a stream which is nearest the sea. Since the Driftless Area is some 800 miles from the nearest point on the Gulf coast, it is evident that the fall produced by the uplift was less than nine inches per mile and during the first stage may have been less than three inches per mile. With such a low gradient the effects of rejuvenation in Allamakee county must have been very slow in appearing, and the drainage of the swamps, when it did occur, was very gradual.

It was in this period between the first uplift and the renewal of downward cutting produced by the second uplift, that the present ore deposits were formed. Much of the drainage of the bogs was downward,, and even after they themselves were drained the meteoric waters continued to flow through the same channels. Thus the bog deposits were leached by descending waters, the iron carried down into the residuum, and there deposited, partly by precipitation and partly by replacement[43] of the residual material. The precise conditions of this replacement are not now apparent. Much of the residuum, as well as the material in solution in the circulating waters, was of colloid

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[43] Lindgren, Mineral Deposits, p. 803.

nature, and the explanation of the replacement probably involves colloid chemistry. Recently it has been shown[43a] that colloidal ferric hydroxide carries a positive electrostatic charge, whereas colloidal kaolin and clays carry negative charges. Colloidal particles of opposite sign may combine through the process of mutual adsorption and form larger particles whose sizes prevent them from remaining in suspension. The intimate relation between the iron oxide and the clay in the ore suggests strongly that these processes were the most important factors in the precipitation.

SUMMARY.

The theory of origin of the ore as brought out in the present investigation may be summed up as follows:

(1) Northeastern Iowa became a land area at the close of the Niagaran epoch and was subjected to continuous erosion until late in the Tertiary, at which time it had been reduced practically to base-level.

(2) Drainage on this peneplain was sluggish, weathering exceeded transportation, and a thick mantle of clayey residuum accumulated.

(3) The iron oxide occurring in the residuum was dissolved through the agency of organic acids, carbon dioxide, and other means. This iron was then deposited in a large bog through the agency of other organic acids, atmospheric oxygen and the action of organisms.

(4) At the close of the Tertiary the region was uplifted a total of about 600 feet, causing the rejuvenation of the streams. The marshes were drained slowly owing to their distance from the sea, and for a long time the waters, both of the normal drainage and those which fell as rain on the surface of the old bog, passed through the ore deposit, leached out the iron oxide, and deposited it by precipitation and replacement in the residuum beneath. As the streams cut downward the action became slower, but appears to have been carried to approximate completion, since but little totally unchanged clay remains. The continued downward cutting of the streams left the more resistant ore to

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[43a] Ostwald, Wo., Grundriss der Kolloide Chemie, p. 233.

form a cap over the hill. The unsymmetrical position on the hill is probably due, as suggested by Calvin, to more rapid weathering on the southern slope.

This explanation seems to account for the topographic position of the ore and for its stratigraphic unconformity. The presence of chert, limestone bowlders and unworn fossils is common in all accumulations of residuum or geest. Lower Galena fossils, rather than those of younger beds, are to be expected, for the younger beds have suffered erosion for a much longer time and their fossils may have become disintegrated. Furthermore, the fossils of the upper part of the Galena are casts and would not persist in a geest. It is worthy of note that silicified fossils are common in geest in many places, even though no silicified forms occur in the rock from which the geest was formed. Silicification of the fossils seems to occur during the weathering process.

Angular pieces of quartz occur in the massive ore and within the unbroken nodules, an association that can be explained in no other way than by replacement of a residuum. The high alumina content, the presence of unchanged clay in the cores of the nodules (which clay is shown by microscopic examination to be residual in origin), as well as the layer of clay between the base of the ore body and the bedrock, appear convincing bits of evidence in favor of this view.

The crevices in the ore are believed to be due largely to settling as solution continued beneath the protecting cap of ore. The sand pockets and beds of gravel were deposited over the surface of the original bog ore before, or immediately after the uplift, and have been cemented by secondary processes within the ore. It is noticeable that the sand ore is very lean, and that the highest phosphorus content noted in the entire deposit is in the neighborhood of a gravel bed. Hence it is possible to conceive that this really is part of the original bog, later covered by the gravels, which it cemented together.

Crane[44] regards analagous limonite deposits in southeastern Missouri as having had a similar origin, except that he assumes the replacement of a cherty, rather than a clayey residuum. The Missouri ores also are overlain by Tertiary gravels and occur on the ridges, hence their age may be considered to be approxi-

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[44] Missouri Bur. Geol. & Min., 2d Series, X, pp. 78-79.

mately that of the Waukon ores. No fossils have been found there and the field evidence appears much less conclusive than at Iron Hill.

TREATMENT OF THE ORE.

Attempts to exploit the Iron Hill ore have been made at intervals for several years, but the first really serious effort seems to have been made in 1899 when the Waukon Iron Company was organized among residents of the town and work actually was begun. In 1901 a complete ore washing plant[45] of the McClanahan-Stone type was installed and an effort made to concentrate the ore by the washing process. Crude methods of handling were used and the fact that the physical nature of the ore made the washing treatment unsuccessful assisted in rendering the entire venture a failure.

The property of the Waukon Iron Company was taken over in 1907 by the present operators, the Missouri Iron Company, of St. Louis, Missouri. They have accomplished much additional exploratory and experimental work; the deposit has been carefully studied by means of a great number of drill holes and test pits, and new methods of treatment and handling have been developed to fit the needs of the situation. At the present time they state that they have reduced the process to a point at which the ore can be marketed in competition with the northern ore and can be produced at a profit.

The pit and plant in which present operations are carried on was opened in 1913, but the property has been operated only a short time in the period which has since elapsed.

Present Development.—Development is at present being carried on through a single open pit located near the crest of Iron Hill and on its southern exposure. This opening has a length of about 400 feet and a width about one-third as great (figure 7). A thickness of only twenty-two feet is now being taken off as it is the intention eventually to work a lower level for the remainder.

It is the intention of the management to work through the ore body at about the present level, forming what is known as a "thorough cut," and following the contour of the bedrock. Oth-

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[45] Beyer, Iowa Geol. Survey, XIII, p. 59.

er benches can be run parallel to this cut and having access to it for the convenient handling of ore to the plant without the necessity of constructing other track.

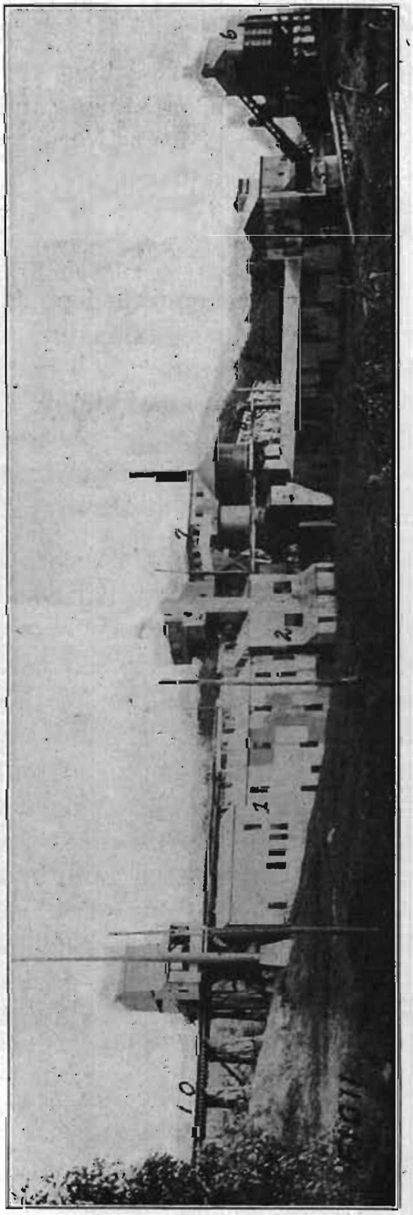

FIG. 11—General view of concentrating plant. 1, Dryer; 2, Roaster; 3, Air Washer; 4, Reducer; 5, Magnetic separator; 6, Loading bins; 7, Screens; 8, Bridge giving access to main tracks; 10, Bridge leading to pit.

The power plant and other buildings of the concentrating plant are located at a distance of about 550 yards south of the pit and a 7 per cent grade of the tracks favors the loaded cars on their way to the bridge. The following are the chief buildings composing the plant (figure 11):

Drying and Crushing house.
Roaster.
Air Washer.
Reducer.
Magnetic Separator.
Loading bins.
Refuse bins.
Coal storing and drying house.
Power House and Machine Shop.
Office and Laboratory.

Power is furnished by a well equipped plant developing 440 horsepower by means of producer gas engines, direct connected to 220 volt Direct Current generators. All machinery is motor driven and each unit has an individual motor. There is also an emergency power plant consisting of a 200 horsepower motor-generator set, current for which is secured from the hydroelectric plant on the Upper Iowa river at Decorah.

Mining.—The bowlder character of the ore makes it rather difficult to mine and handle. A churn drill located on the brow of the pit is used in sinking holes to the level of the pit floor and in these holes are placed rather heavy charges of 60 per cent dynamite. The holes are set at distances of twelve inches from center to center and the charges are fired simultaneously by means of batteries. This blasting has the effect of loosening the ore for a considerable distance and breaking it up into fine material and into bowlders, some of which are of large size. That portion of the ore which is sufficiently small in size is loaded by steam shovel and hauled immediately to the crusher and dryer. Those bowlders that are too large to be handled by the shovel are broken by light charges of dynamite. Jackhamers operated by means of compressed air are used in drilling the "plugholes" for this work.

The overburden is nowhere of great thickness, and on account of this fact and of the appreciable amount of intermingled pebbles of ore, it has been found economical to omit stripping and to send the entire body through the plant.

Loading in the pit is accomplished by a seventy-five ton Vulcan steam shovel.

Haulage.—The ore is loaded by the steam shovel onto twelve ton, standard gauge, electrically propelled dump cars, the motors of which are mounted on the axles. The haulage system is double tracked, with power transmission through central third rails. The system is divided into sections, by whch the movements of the cars may be readily controlled. Central control of the cars while they are outside of the pit is obtained from a tower which is located above the bridge at the north end of the plant, and from which a view of the entire tracks may be had. On entering the pit the cars leave the control of the operator on the bridge and pass, by their own momentum, on to a section which is controlled from the steam shovel, and from which they may be obtained as desired for loading. Automatic brakes are provided which will prevent runaways from crashing through the plant.

The ore from the bridge and from many of the bins is handled by gravity, and in fact this method is used whenever it is possible. Where it is necessary to lift the ore, however, bucket conveyers are used.

A switch some three miles in length has been constructed from the mine property to the Chicago, Milwaukee and St. Paul railroad, connecting with the latter in the southeastern part of Waukon. The loading bins are located over a spur of the switch and this is connected also with the trackage in the pit, so that ballast or additional machinery may be taken to the scene of operations without unloading. All track about the plant and in the pit is of standard gauge. A small switch engine, coal burning, is used for switching, and for conveying the employes to and from Waukon.

Concentration.—In the early efforts to market the Waukon ore the operators sought to obtain a separation of the ore from the gangue by washing to remove the clay, and subsequently by getting rid of the chert and other larger impurities by hand picking as the material passed along a belt. By this method, however, the ore could not be brought to a sufficient degree of concentration, nor was the process economical. Furthermore the necessary addition of water to the porous ore materially increased freight charges.

After a few years of trial this treatment was abandoned, and when the Missouri Iron Company took possession they instituted a series of experiments to develop a process which should produce a marketable and profitable product. The first experimental plant was located at Waukon Junction, but the method of treatment used there (washing and jigging) was not successful, and it was realized also that whatever the treatment used, it would be economy to apply it at the mine, in order to avoid the expense of shipping the gangue.

As a result of several years of experiment the present plant has been constructed and the management state that the process in use will produce a satisfactory concentrate at a cost which will permit a good profit. The treatment used is known as the "Goltra beneficiation process."

Following is a brief sketch of the Goltra process:

1. The ore is hauled from the mine to a bridge or tipple where, after weighing, it is dumped on to fourteen inch grids, the larger lumps being broken with sledges, and the sized material passes to the dryer, which is located immediately beneath.

2. The dryer is of the horizontal tubular type, 10 by 125 feet, and is driven by a motor at the rate of one revolution per minute. The fuel used is powdered coal, which is blown in at the lower end by an Aero pulverizer. At the upper end of the dryer is a large fan with a capacity of 35,000 cubic feet of air per minute, and this draws the heated air through the cylinder and discharges it, together with the fine sand and dust, into a dust catcher. A temperature of about 300° F. is maintained and here about 99 per cent of the free or mechanically held water is driven off.

3. The dried ore then passes to a movable grid set to 2½ inches, the oversize going to a No. 8 gyratory crusher which reduces it to 2½ inches. The crushed material meets the undersize at a common point from which it is hoisted by a pivoted bucket conveyer to a triple concentric trommel from which the succeeding flow is by belt conveyer to the bins. The fines below 1-16 inch pass to the waste pile, the middlings go to the storage

bin, while the lumps pass over the cobbing belts, where the chert and other float is removed, after which the lump ore goes to the storage bin. From here the ore is fed to the roaster.

4. The roaster is similar to the dryer except that it is of slightly smaller size, measuring 8 by 125 feet. In it also powdered coal is used as fuel and the roaster is operated at a temperature of 1600° to 1800° F. At this temperature limonite loses combined water according to the formula

$$\underset{\text{limonite}}{2Fe_2O_3.3H_2O} = \underset{\text{hematite}}{2Fe_2O_3} + \underset{\text{water}}{3H_2O}$$

leaving all of the ore in the form of the anhydrous hematite.

5. The dehydrated ore, still at a temperature not less than 1100° F., leaves the lower end of the roaster and is conveyed to a double jacketed trommel. All material above ½ inch goes to the shipping bins, while that which is below ½ inch goes into a closed reducer, 6 feet in diameter by 70 feet in length, and turning at a rate of three revolutions per minute. Here it is sprayed with crude oil under 125 pounds pressure.

On striking the heated ore the oil is broken up into its component gases, chiefly hydrogen and the lighter paraffins. These gases have a very high reducing power and remove one-half an atom of oxygen from the hematite:

$$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$$

The above reaction is much simpler than the one which actually occurs in the process, but it serves to illustrate the principle involved. Because of the large number of compounds entering into the reduction the exact formula cannot be given.

6. After passing through the reducer the ore is raised by an elevator to a rotary cooler, from which it passes to a trommel (42 inches by 18 feet) whose jackets are 1/16 inch, ⅛ inch and ¼ inch mesh. The sized ore drops directly into bins.

7. From the bins the sized ore goes directly to magnetic separators of the Ball-Norton type. The ¼ inch to ½ inch material is not concentrated but goes directly to the loading bin where it meets the larger size ore from the roaster. The tailings are thrown on the dump.

Results of the Treatment.—The recovery by the above treatment is from 37 per cent to 62 per cent, depending on the grade of ore worked, and the average is approximately 50 per cent. From this it will be seen that from 1/3 to 1/2 of the deposit may be classed as gangue. The average, so far as concentration tests have been made, is 55 per cent ore.

In American metallurgical practice it is considered that iron ore should contain not less than 35 to 50 per cent metallic iron at the furnace, and the process in use at Waukon is designed to produce such a concentration. The product is not allowed to fall below a content of 55 per cent metallic iron and manganese. The following analyses will illustrate the character of the concentrate:

AVERAGE OF 8,000 TONS CONCENTRATES. ANALYSIS BY MISSOURI IRON COMPANY.

	PER CENT.
Fe	55.52
SiO_2	12.02
*Insoluble	15.34
Phosphorus	.1044
Loss on ignition	.201
CaO	.69
MgO	.504
Sulphur	.024
Mn	.88

*Insoluble chiefly Al_2O_3, with some Si and Fe.

AVERAGE OF 200 CARS CONCENTRATES.

	MINE ASSAY. PER CENT.	UMPIRE. PER CENT.
Fe	55.38	55.18
Mn	1.04	1.02
SiO_2	14.03	13.15

The highest analysis of a daily sample of the concentrate has shown a metallic content of 62.3 per cent. When very rich ore is being worked the monthly average has been as high as 61.9 per cent.

DISPOSITION OF THE ORE.

The low sulphur and phosphorus content of the ore make it very suitable for the manufacture of all classes of pig iron except Bessemer, and a ready market has been found for it in ordinary times. It has been used chiefly in furnace mixtures.

The results of a test of the Waukon ore by the Sligo Furnace Company, of Sligo, Missouri, are of interest. During an eight day run on Waukon ore alone the furnace was found to handle easily on various grades of iron, ranging from .09 per cent to 3.25 per cent silicon, most of the metal produced being 1.25 per cent. The addition of manganese to the burden was found to be unnecessary, as sufficient of this element was present in the ore.

In comparison with a ten months previous run on Missouri ores carrying 54.5 per cent Fe., the Waukon ore was found to give a 25 per cent increase in production, with a decrease in fuel consumption of 22 per cent. Charcoal was used as fuel in these tests.

Phillips[46] states that "The finished product obtained by this process (the Goltra process) is excellently adapted for use in the blast furnace. The free and combined water are completely, and the clay, sand, etc., almost completely, removed. The sulphur, except in the case of some magnetic concentrates, is eliminated. The physical nature of the ore is greatly improved, particularly in respect to its porosity and easy reducibility in the blast furnace."

The article from which the above extract is taken contains a very complete discussion and analysis of the process, and should be consulted for further details.

The concentrates have been shipped to Milwaukee, Chicago and St. Louis, at all of which places it competes with the northern non-Bessemer ores. Freight rates to Chicago and Milwaukee are $1.00 per ton gross, and to St. Louis $1.50.

Profitable operation of a deposit of this kind must depend very largely on the condition of the markets. With the price of pig-iron at or above normal the Waukon property may be expected to remain a profitable producer. The plant was operated for a short time after its completion in 1913, but the depression in the iron industry made it necessary to shut down until prices should be more favorable. Operations were resumed in November, 1915, at which time shipments to South Chicago furnaces were reported. Production at present is 350 tons per day.

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[46] Iron Age, Nov. 12, 1914, p. 1150.

The present development was begun in 1913 and the total production, up to the time of the recent resumption, has been 27,000 long tons. The capacity of the plant on full time is 450 tons per day.

The available tonnage in the deposit amounts probably to ten million tons at least. The property, which is held in fee simple, by the Missouri Iron Company, consists of approximately 258 acres.

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PLATE I.

Chert Nodules from the Ore.

Figure 1.—Chert nodule showing concentric weathering and partial replacement by limonite.

Figure 2.—Chert nodule showing advanced weathering and some replacement by limonite.

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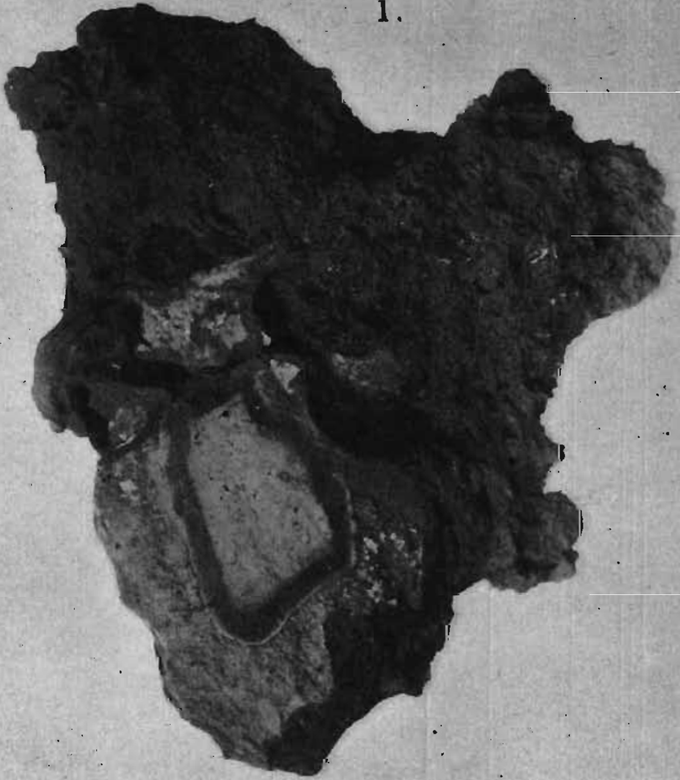

2.

PLATE II.

Fossils from the Iron Ore.

1-16, 31. *Plectambonites sericea.*

17-30. *Dalmanella testudinaria.*

Fossils from Decorah Shale.

32-39. *Plectambonites sericea.*

40-53. *Dalmanella testudinaria.*

Note perfect preservation of specimens from the ore. Also note that size and general appearance of the Decorah individuals are almost identical with those of the fossils in the ore. The Decorah specimens are not silicified.

PLATE II.

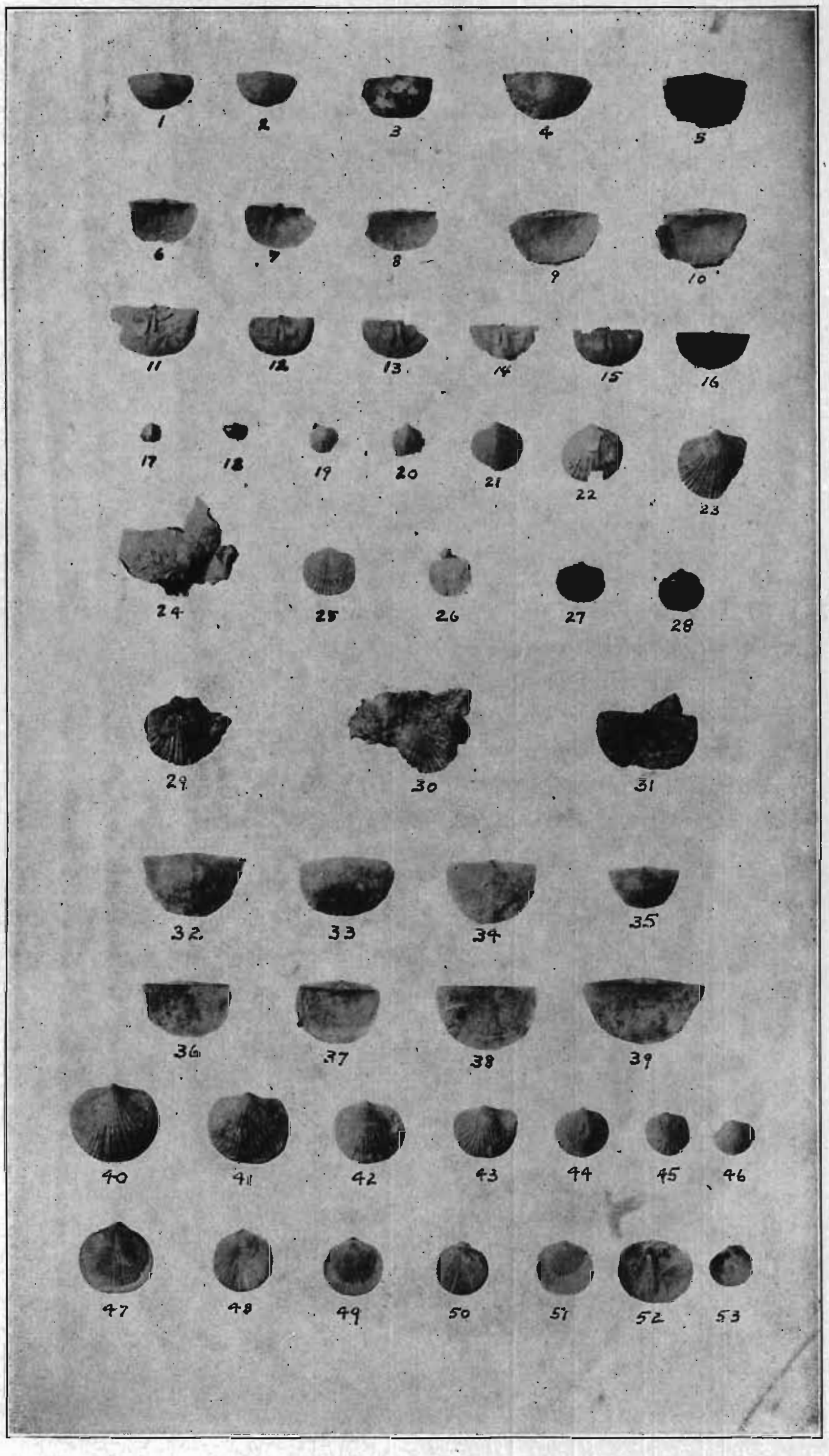
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PLATE III.

1-3. *Platystrophia lynx.*
4. *Orthis bellirugosa.*
5. *Rafinesquina minnesotensis.*
6. *Rhynchotrema capax.*
8. *Streptelasma profundum.*
7, 9-12, 14. *Streptelasma corniculum.*
13. *Prasopora simulatrix.*

Iowa Geological Survey. PLATE III.

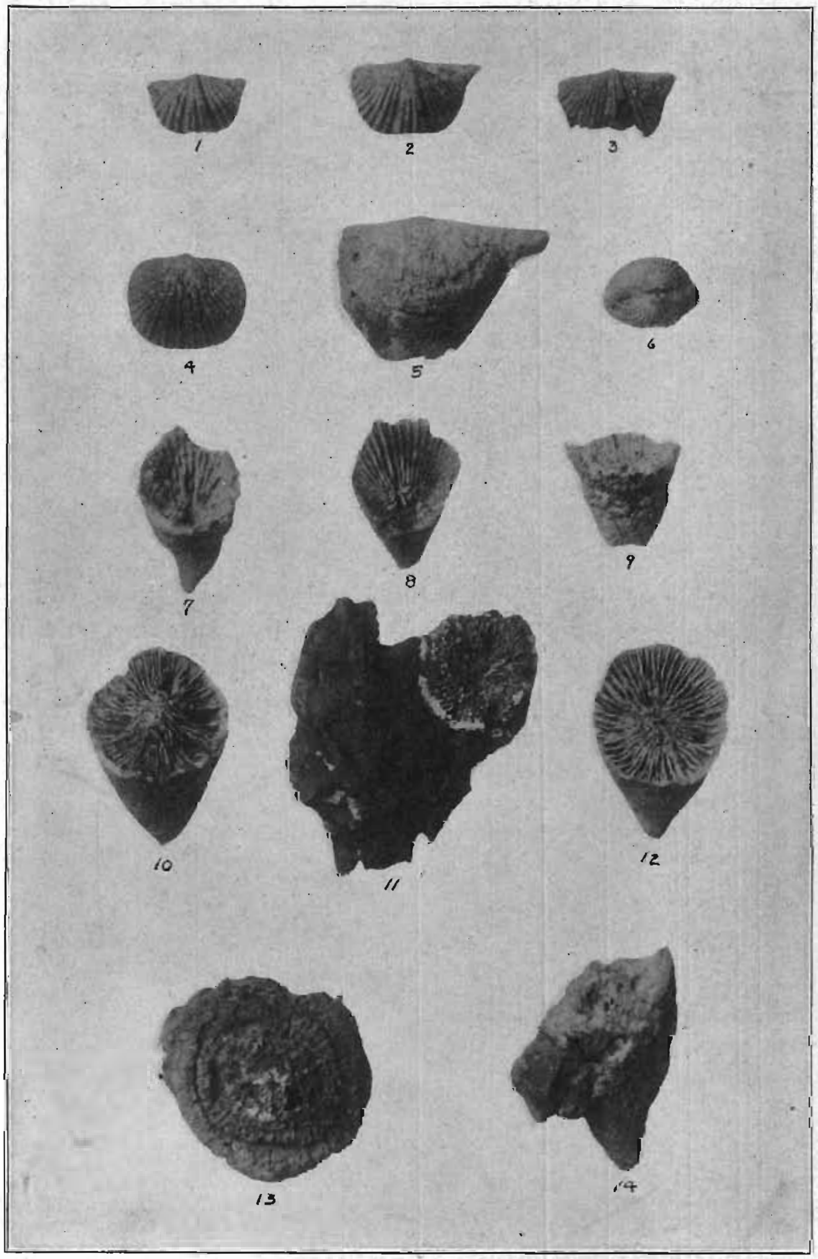
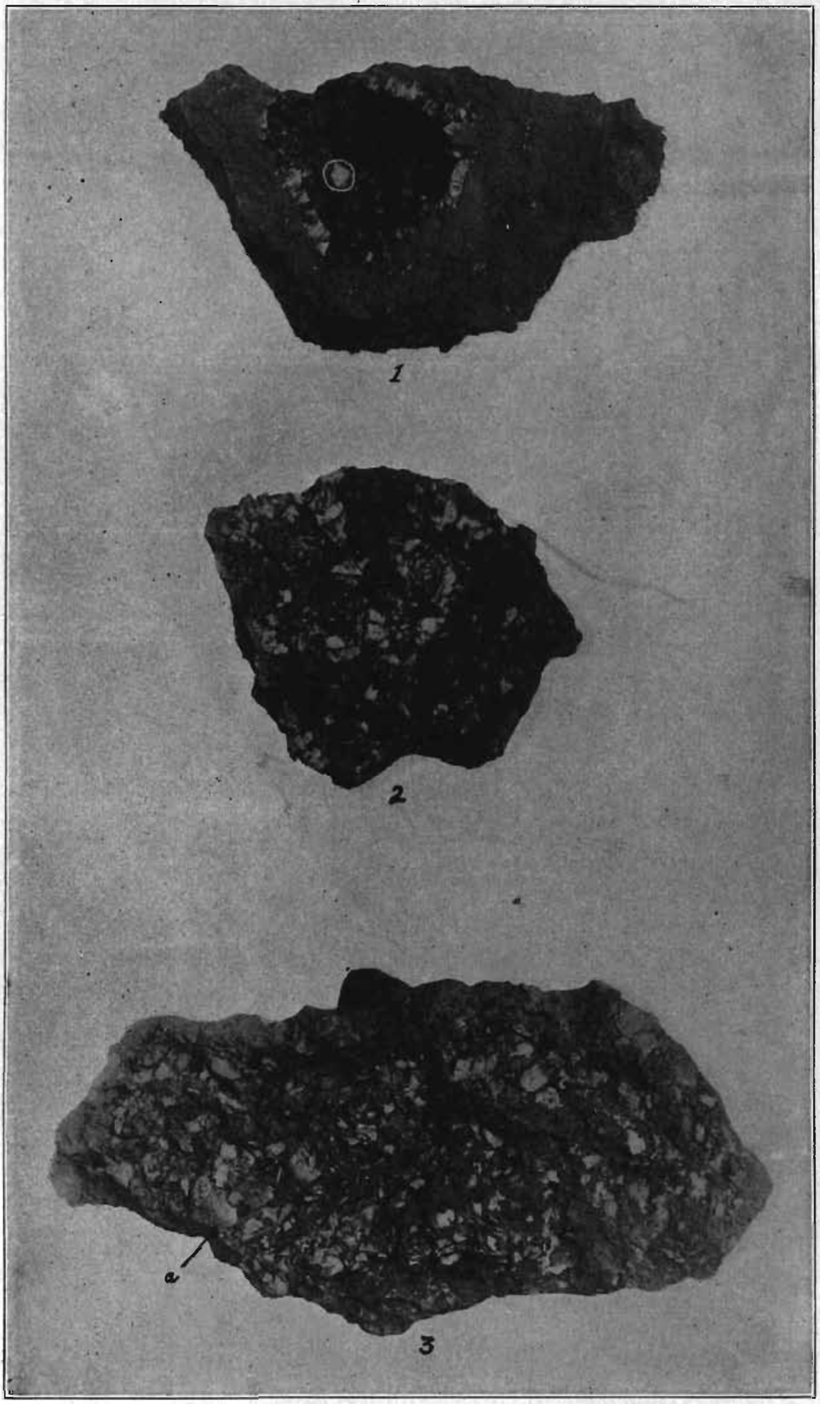


PLATE IV.

1. Interior of cavity in ore showing dense limonite surrounding band of fibrous, radiating limonite. Interior surface botryoidal. Also (in circle) small mass of hyalite.

2, 3. Pieces of very fossiliferous ore, showing silicified and un-replaced shells. Complete *Dalmanella testudinaria* at "a."

PLATE IV.



THE PLEISTOCENE HISTORY OF IOWA RIVER VALLEY, NORTH AND WEST OF IOWA CITY IN JOHNSON COUNTY

BY

M. M. LEIGHTON

OUTLINE.

THE PLEISTOCENE HISTORY OF IOWA RIVER VALLEY

Introduction.

LOCATION.

That portion of Iowa river valley to be considered is in Johnson county, Iowa.

Physiographically, the region lies within the great area of Kansan drift, and also includes the North Liberty Lobe of the Iowan drift-sheet as mapped by the late Professor Calvin. The topography of this and adjacent areas is shown on the Fairfax and Stanwood topographic maps.

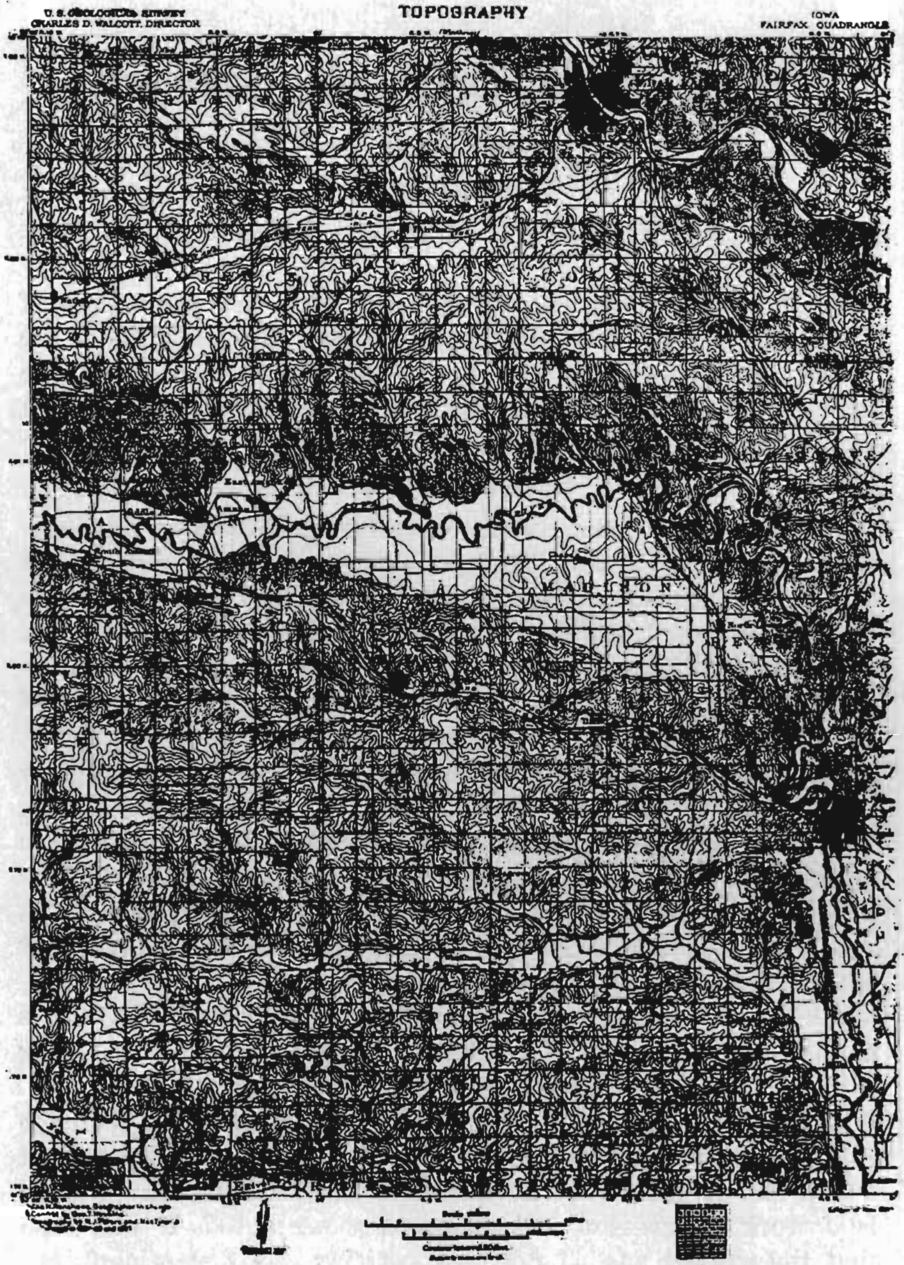
THE PROBLEM.

The discrepant features of the valley of Iowa river in Johnson county, as shown in Plate V, have been in the past objects of unusual interest from a physiographic and geologic standpoint. The great elbow of the stream within the county's boundaries, the gorgelike features of the great turn, the remarkable width of the valley above and below the gorge, the absence of rock in the south wall above the upper constriction to the gorge, and a similar absence in the west wall below the gorge, together with certain well records west of Iowa City showing deep glacial fill—these data had given rise to the theory that a change in drainage had occurred at some time in the history of Iowa river valley. Though this seemed to be the true explanation, yet it was held with that degree of tentativeness which is necessary when not confirmed by sufficient data.

Hence, it was with the hope of successfully working out a positive knowledge of the situation, impartial to all preceding conceptions, that the problem was undertaken.

At first, the problem was thought to involve merely a drainage change. Accordingly data were sought that would throw light on its cause, date, and the course of the old channel. But as field work progressed and evidence accumulated, it was seen that the subject needed not only revision in its statement, but amplification in order that the whole Pleistocene history of Iowa river valley might be included.

PLATE V.



Topographic map of Fairfax Quadrangle, showing the discrepant development of the valley of Iowa river in Johnson county.

METHODS USED IN COLLECTING DATA.

The area involved in the study of relevant data includes roughly the whole of Johnson county; most of the field work, however, was done north and west of Iowa City.

Practically all of the data, excepting the well records, were collected by personal detailed investigation in the field. The river valley was carefully surveyed from Iowa City above Curtis, together with Pardieu creek, a part of Clear creek, and many of the minor tributaries. Elevations of bedrock, drift, gravel, and loess along the river were taken and many sections of materials examined. The North Liberty Plain was generally traversed with the exception of the extreme western border. One drive was taken to the southern part of the county for the purpose of studying the distribution of the loess in that direction and ascertaining its relations to the underlying surface.

Most of the well data were obtained from well drillers of experience and eight have contributed such knowledge as was relevant. They were Messrs. D. A. Jones, Henry Buck, H. A. Hemmerle, all of Iowa City; M. H. Eaton, of Shueyville; Bert Eastland, of North Liberty; Frank Novatny, of Solon; Alf. Campbell, of Oxford; and Wm. Brown, of Wellman (Washington county). In certain instances where their territory overlapped their records of depth to bedrock closely agreed.

ACKNOWLEDGMENTS.

The writer wishes to express his appreciation to Professor A. C. Trowbridge for his advisory opinions and verifications, and to Professor G. F. Kay and Mr. A. O. Thomas for helpful suggestions and encouragement. Mr. Thomas also contributed several score of well records which he had formerly collected.

PRE-PLEISTOCENE EROSION.

The Indurated Rocks.—The indurated rocks exposed along the gorge of Iowa river are Devonian limestones and isolated patches of Carboniferous sandstone and shale.

Shales, presumably of Mississippian age, are penetrated by deep wells toward the southern part of the county, and sandstones of the same general age are exposed along English river beyond the south county line.

Upon the indurated rocks, the drift rests unconformably.

Pre-Pleistocene Topography.—While it is impossible from the available well records to reconstruct the subdrift surface accurately, some knowledge concerning it can be gained from a study of well records. Approximate elevations of the rock surface can be determined by subtracting from the altitude of the well-site, as obtained from the topographic map, the distance to rock, or the depth of the well where bedrock is not reached.

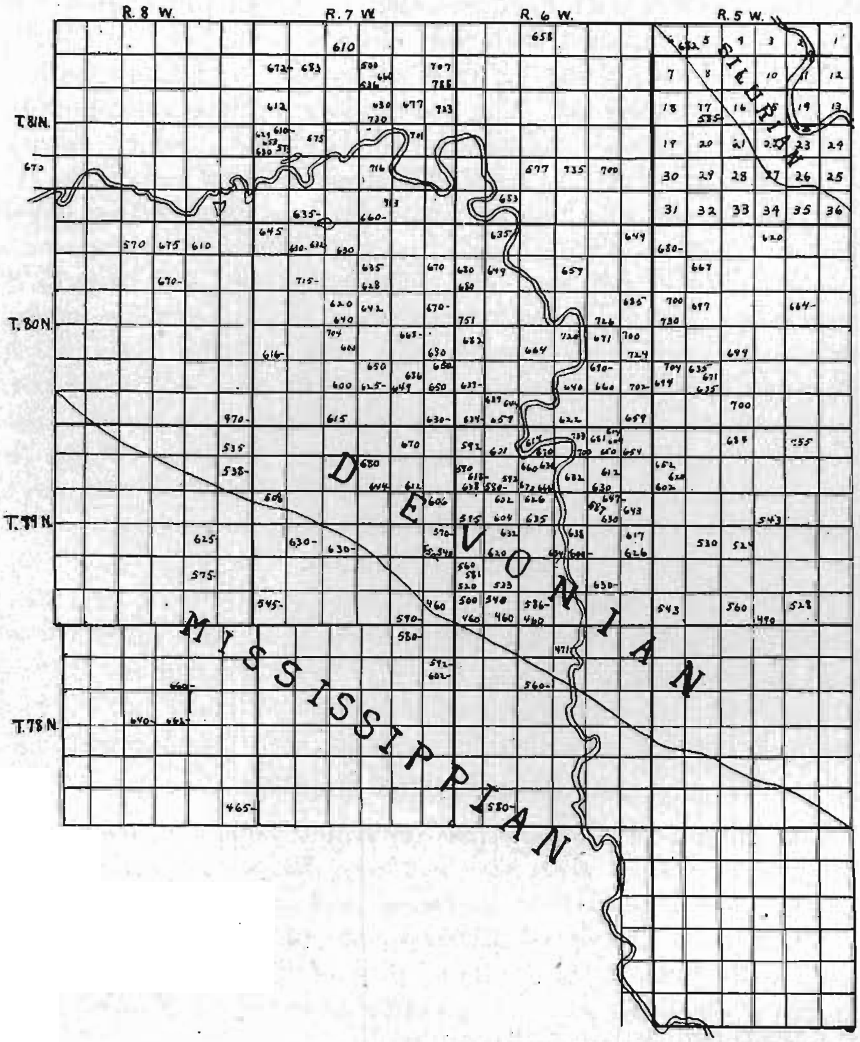


FIG. 12. Map of Johnsn county showing locations of well records collected, the approximate elevations of bedrock, and the distribution of the indurated formations according to Calvin.

These data show that the bedrock surface has marked irregularities (see figure 12). Over an irregular area in the central, northern, and northeastern parts, and along the extreme southern border of the county, bedrock is high; but between these two areas there is a northwest-southeast belt in which the bedrock surface is low. Well records, numbered 85, 86, 89, and 106, reveal bedrock as low as 460 feet above sea level.[1] Besides these, there are wells, as for instance 1, 2, 3, 83 and 104, which, though they do not penetrate rock, go down to points respectively 471 feet, 560 feet, 580 feet, 535 feet, and 545 feet above sea level.

The former group of wells penetrate shale which is perhaps the basal portion of the Kinderhook.

To the north, the bedrock surface rises on Devonian limestone and projects through the drift just north of the Rock Island trestle at Iowa City, on the west side of the river. The average elevation of the rock surface in its higher part is about 700 feet above sea level. To the south the bedrock rises on Kinderhook sandstone which overlies the basal shale. It outcrops along English river at several places:[2] (1) at Wassonville, 706 feet above sea level; (2) at Kalona, 665 feet above sea level; (3) at Riverside, 648 feet above sea level.

The distance from the outcrop at Iowa City to that at Riverside is about eleven miles. This gives an idea of the width of the buried valley. In the southwestern part of the county it seems to be even wider. Figure 12, which shows also the distribution of the indurated formations in the county, makes it evident that the north wall of the buried valley follows more or less closely the boundary between the Devonian and Mississippian formations. The lower resistance of the shale in comparison with that of the limestone on the north and the sandstone on the south undoubtedly accounts for this parallelism.

Another buried channel exists in the vicinity of Shueyville, but its relation to the large one is not clear.

It is interesting at this point to note that through the middle of the high bedrock area, as shown in figure 12, is the course of the gorge of Iowa river. On either side of the gorge, for a distance of seven to eight miles, well records show in general

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[1] The logs of the wells are given in detail at the close of this paper.
[2] Bain, Iowa Geological Survey, V., p. 119.

a high rock surface. There are a few, however, that register valleys deeper than the present bed of the stream in the same latitude. This fact is significant of the partial dissection of the old divide before it was buried.

The rock surface is not necessarily wholly preglacial. If there was a long interval of erosion in the Pleistocene period preceding the heavy Kansan deposit, it is possible that bedrock was still further modified at that time.

THE PLEISTOCENE DEPOSITS.

The Pleistocene deposits of Iowa have been classified by Calvin as follows,[3] the oldest being placed at the bottom:

SERIES	STAGE
Pleistocene	Wisconsin
	Peorian
	Iowan
	Sangamon
	Illinoian
	Yarmouth
	Kansas
	Aftonian
	Nebraskan (Pre-Kansan)

Those which occur in Johnson county will be considered in the following pages.

The Nebraskan or Pre-Kansan Till and Aftonian Interglacial Deposits.

No exposures of Nebraskan till and Aftonian interglacial deposits occur within the county. The overlying drift is so heavy that if the oldest deposits are present, they can be detected only in well records. In view of the widespread distribution of known deposits over various parts of the state, it would be surprising if, among the well records collected, there were not some which strongly suggest their presence. In order better to identify them in the records, a review of their characteristics as noted by Shimek may be helpful.[4] The Nebraskan drift "con-

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[3] Calvin, "Iowa Geological Section," Iowa Geological Survey, XVII, p. 192.
[4] Shimek, Iowa Geological Survey, XX, pp. 304-307.

sists chiefly of a dark blue-black joint clay which when dry is hard and brittle.....It is almost impervious to water, and when wet is very tough, tenacious, 'rubber-like,' and so difficult to work that it is the abomination of well-diggers and road-workers, being the most despised of all 'gumbos.' Scattered through this joint-clay are relatively few, usually dark colored pebbles and small bowlders."

As for the Aftonian deposits, they comprise both sand and gravel and peat and forest beds, though these do not necessarily occur together.

The well records which indicate the presence of Nebraskan and Aftonian below the thick Kansan are given below. In the records, those materials which appear to belong to the pre-Kansan deposits are italicized.

[5]Lone Tree, town-well: Soil and yellow clay, about 30 feet; blue clay, about 95 feet; *sand, about* 5 to 8 feet, *with pieces of wood and bark at top.* The driller penetrated a *bluish tough clay* below the sand for some distance, but withdrew the drill and made the sand the water bed.

[6]No. 61: Yellow clay and sand, 50 feet; blue clay, 40 feet; *hard pan,* 15 feet, to rock.

No. 65: Yellow clay, 50 feet; blue clay, 70 feet; *sand and wood,* 8 feet.

No. 84: Yellow clay, 40 feet; blue clay, 200 feet; *sand and tough clay* to rock.

No. 104: Yellow clay, 80 feet; blue clay, 100 feet; *black muck,* 5 feet.

No. 107: Yellow clay, 100 feet; coarse gravel, 3 feet; blue clay, 40 feet; *black hard pan with pebbles,* 122 feet.

No. 110: Yellow clay, 65 feet; blue clay, 65 feet, *log* at 125 feet; *gravel,* 5; *blue clay,* 25; *sand,* 5.

No. 173: Sand, 20 feet; blue clay, 118 feet; well in top of gravel, *wood came up with gravel.*

No. 178: Yellow clay, 50 feet; blue clay, 40 feet; *sand and wood,* 4 feet; *blue clay,* 86 feet; rock, 7 feet.

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[5]Thomas, Iowa Geological Survey, XXI, p. 514.

[6]See records of wells following this paper for locations.

No. 181: Yellow clay, 30 feet; blue clay, 100 feet, to *gravel containing wood.*

No. 206: Yellow clay with bowlders, 30 feet; blue clay, 50 feet; *sand,* 68 feet.

No. 220: Same as No. 221.

No. 221: Yellow clay, 50 feet; blue clay, 20 feet; *sand,* 20 feet, *with red cedar log at* 85 feet; *blue clay,* 54 feet; sand, 6 feet, rock.

The presence of the wood, noted in the records, is not necessarily a true indication of Aftonian deposits. They may represent forest-growth upon that portion of the pre-Pleistocene surface evaded by the Nebraskan glacier, but advanced upon by the Kansan. Or, possibly they are remnants of forests which grew close to the edge of the Kansan ice-sheet or even upon it—as is the case to-day on the Malaspina glacier of Alaska— and were overridden or buried by a new accession to the glacier.

As for the sands, they may be deposits from the waters of the ice during a temporary retreat and then later buried by a re-advance. They may also be esker-like deposits, laid down beneath the ice.

The above interpretations might be preferred but for three opposing factors of note: (1) the kind of till underlying the sands and forests beds; (2) the mode of occurrence of the latter; and (3) their general distribution. In wells 61 and 107, the material in the bottom was distinguished from the blue clay above as "hard-pan" by two different well drillers, and in well No. 84 as "tough clay" by a third well driller. One of these drillers, especially, remarked about the difficulty of drilling through the "hard-pan." In the Lone Tree well, the driller penetrated a bluish tough clay to some distance below the wood-bearing sand, and in well No. 104, five feet of "black muck" was encountered. Of the seven wells striking wood, six encountered it in the sand or gravel layer and but one in the till, though that one was just above the gravel. Another fact indicating the presence of the Nebraskan and Aftonian deposits is the quite general distribution of the sand and wood over the county. Figure 13 illustrates this point clearly.

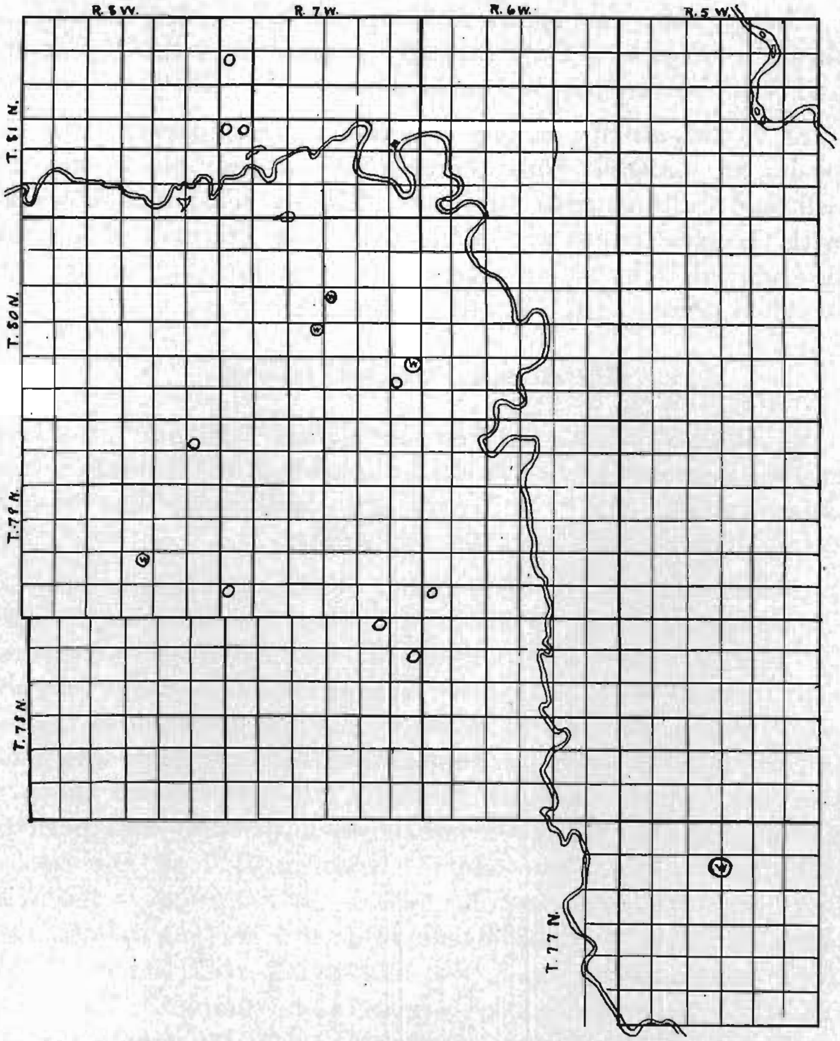

FIG. 13. Map of Johnson county showing location of wells which probably encountered Aftonian and Nebraskan materials. Those wells in which wood was found are marked by "w" within a circle.

An additional point of merit is the collection of similar records by McGee[7] in other counties in northeastern Iowa, and the occurrence of typical outcrops in areas to the south (Muscatine county) and to the southwest (Union, Harrison and Monona counties).

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[7] McGee, W J, Pleistocene History of Northeastern Iowa: 11th Ann. Rept. U. S. Geol. Survey, pt. 1, pp. 514-542.

Though these evidences are not conclusive, they are by no means negligible. They strongly suggest that the Nebraskan and Aftonian deposits are present.

In so far as this county offers evidence, however, the deposits are patchy. Only thirteen well records among the 238 collected indicate their presence. This is consistent, however, with the conclusions of Calvin, that "the Aftonian was a real interglacial interval, an interval of long duration, an interval of moist climate and swollen streams."[8]

The Aftonian Erosional Interval.

In counties to the southwest, the name "Aftonian" has been applied to gravel and sand which lie between the Nebraskan and Kansan drifts, and which represent a considerable time interval between the deposition of the two drifts.[9]

Considering (1) that the sand, gravel, and wood, noted in the foregoing wells of Johnson county are Aftonian in age; (2) that the interval was long; (3) that conditions of erosion were quite ideal; (4) that thick beds of sand and gravel were derived from a till lean in pebbles; (5) that portions of the till remain, it seems probable that the original drift-sheet was not a thin one. If this was so, the drift doubtless buried the preglacial drainage lines, the minor ones at least, and perhaps the major ones of the county. Granting that the Nebraskan drift was once thick and its surface flat-lying (as is the Wisconsin), then as erosion developed on this surface the channels were superimposed upon the underlying rock-divides. This tended to make the bedrock surface more complex. The width of the buried valley in the southern part of the county may be due partly to such modifications. Figures 14 to 17 are illustrative.

Pre-Kansan Topography.—As a result of such an interval of erosion the topography finally became an erosional one, and only patches of the former drift were left upon the surface. Hence, when the Kansan ice-sheet advanced, it moved upon a

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[8] Calvin, Present Phase of the Pleistocene Problem in Iowa: Bull. Geol. Soc. America, XX, p. 139.

[9] Calvin, Bull. Geol. Soc. America, XX, pp. 341-342.

rather rough topography, a topography that had developed by the superimposition of a post-Nebraskan drainage upon a pre-Nebraskan one without harmony.

The Kansan Drift.

The Kansan drift is either at or beneath the surface over the whole county excepting in stream valleys that are cut to bedrock. It lies beneath a thin younger drift in the northern part of the county, and under loess for some distance south from the borders of the new drift plain, but in the southern part of the county it comes to the surface along the hill slopes and at

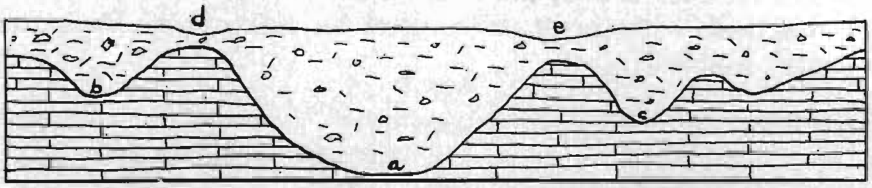


FIG. 14. Cross section of preglacial surface buried by drift: "a" the former principal drainage line, "b" and "c" two former tributaries, and "d" and "e" two incipient drainage lines on the new surface.

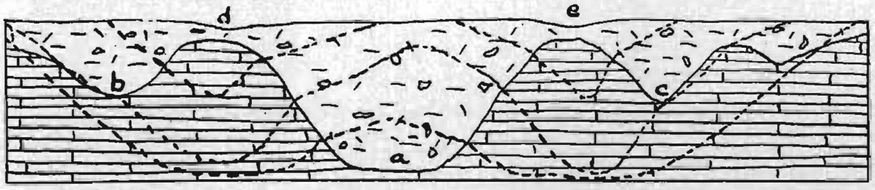


FIG. 15. Cross section showing modificafion of bedrock surface by deepening of valleys "d" and "e," and how in consequence the former valley walls might be widened and drift remnants still remain in the old valley.

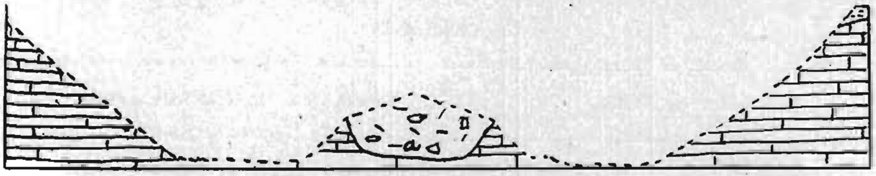


FIG. 16. Cross section of topography before incursin of a later ice-sheet. Note how it differs from the preglacial surface in Fig. 14.

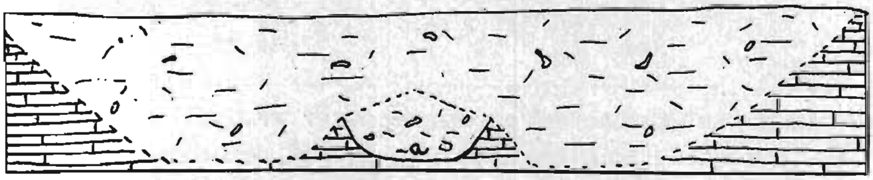


FIG. 17. Cross section showing burial by the later drift and illustrating how impossible it would be to trace out any valley that is strictly pre-Pleistocene or strictly interglacial.

the crests of divides. Alluvium and sand on the flood plains of Iowa river and of some of the minor streams also limit its exposure somewhat. But there are numerous natural exposures in the valley wall of Iowa river, a few along the smaller streams, and two artificial ones along the Cedar Rapids and Iowa City Interurban Railway.

Thickness.—The Kansan drift (including the Buchanan gravel) has a range in thickness from zero to at least 250 feet. It is thinnest where bedrock is high and thickest where bedrock is low. From the southern and west central part of the county where the rock is low, the following records in Table I are selected to show the great thickness of the Kansan, the Buchanan gravel included:

TABLE I.

No. of Well.	Thickness of Kansan Drift.
	FEET
37	162
79	197
81	190
85	250
86	250
106	250
210	224
218	228

The foregoing should be contrasted with the following typical logs in Table II, taken from the area of high bedrock:

TABLE II.

No. of Well.	Thickness of Kansan Drift.
	FEET
30	30
43	20
45	10
47	10
204	47

In the Interurban cut across the river west of Iowa City, the Kansan drift (including Buchanan gravel) is sixteen and three-fourths feet thick. From the numerous exposures of Kansan drift along the river, a similar impression is gained, namely, that the drift is thin on top of high bedrock.

From the foregoing, it is evident that the Kansan drift as deposited was thick enough to bury all previous drainage lines, and that the surface of the area immediately after the melting of the ice probably was level, undoubtedly similar to the Wisconsin area at the present time.

Kinds of Materials.—The Kansan till has two phases, the weathered and the unweathered. The upper part of the sheet is weathered to a rusty yellow, deep red, or brown color. It contains but few calcareous constituents, and much decayed material. The unweathered, forming the body of the drift sheet, is dark blue when damp and pale blue upon drying. Clay, containing small pebbles, comprises the main body of the till. Most of the pebbles in the blue clay are greenstone and limestone. Vertical jointing and polyhedral fracture are characteristic of the deposit. According to well drillers, there are not many bowlders in the blue clay, but in some of the gullies tributary to Iowa river in the Kansan area, as for instance in the ravines north of Iowa City, they are numerous. They comprise granites, dolerites, basalts, and quartzites, most of which are fresh. It is possible that these were derived from the Iowan ice-sheet by glacio-fluvial drainage. Most of the bowlders that occur above high bedrock on the valley slope are altered.

No line exists between the weathered and the unweathered portions of the Kansan. A zone marks the transition from the yellow down into the blue. This zone, however, varies in thickness at different points. In the Interurban cut across the river from Iowa City the zone of transition is about three feet thick. In contrast to this, well record No. 1 (see list of wells) shows the yellow grading into blue in a vertical distance of thirty feet.

Likewise, the thickness of the wholly oxidized portion varies. In the above mentioned cut, the yellow clay is but two feet thick, whereas in logs Nos. 62, 79, 86, and 98, it is fifteen feet, twenty feet, thirty feet, and fifty-eight feet, respectively, below the red gravel. This difference may be due to various factors: (1) the thickness of the overlying gravel; (2) the texture of the gravel; (3) the compactness of the gravel; (4) the facility with which the rain-water is drained off.

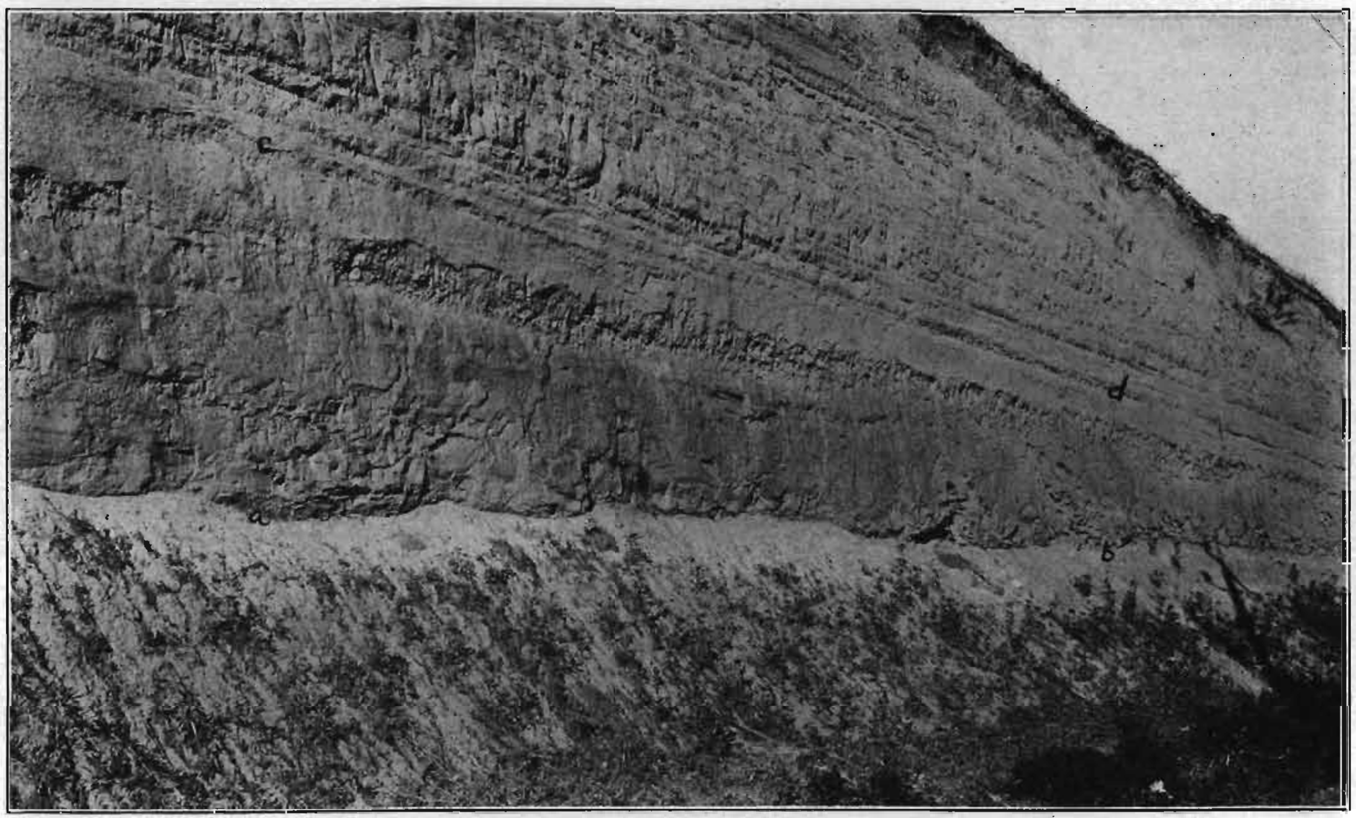
The Buchanan Gravel.—The Buchanan gravel is exposed at several places: (1) in the Interurban cut across the river from Iowa City; (2) above Saunders' northernmost sandstone quarry, three-fourths of a mile north of Iowa City; (3) one-half mile southwest of Black Springs in a ravine beside the Chicago, Rock Island & Pacific railway; (4) at Lovers Leap, one-half mile east of Coralville; (5) on the valley slope of Iowa river opposite the mouth of Rapid creek; (6) in the Interurban cut one-eighth mile north of the upper Interurban bridge.

The gravel is noted also in many of the well records following this paper as lying stratigraphically above the blue clay with yellow clay intervening.

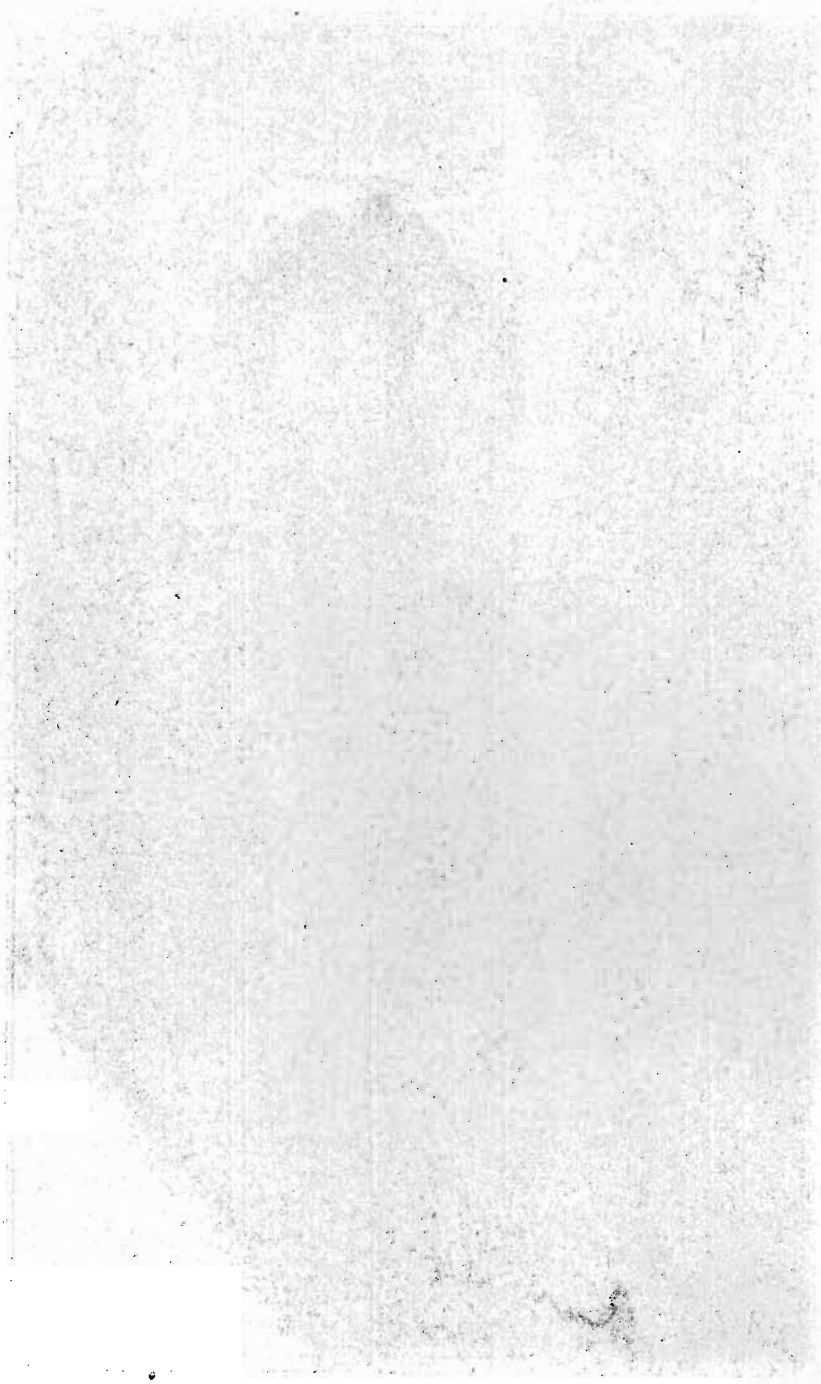
Professor Calvin in reports of the northern counties has described two phases of the gravel: the coarse, bowldery gravel he named the upland phase, and the sand and pebbly gravel the valley phase. It was his conception that the upland phase was deposited near the edge of the ice on divides and the valley phase along drainage lines some distance from the ice.

The gravel in the Interurban cut across the river from Iowa City is quite bowldery; it, therefore, has the aspects of an upland phase. The deposit comprises four layers of stratified gravel alternated by a dark reddish, compact, sandy layer, the one near the top being more distinctly reddish and compact than the one near the bottom. In the coarse gravel beds, the range in texture is from fine sand to small bowlders eight inches in diameter. The whole mass aggregates from four to eight feet in depth and the layers pinch out from below toward the east end of the cut. The gravel is much oxidized and decayed. This extent of weathering is comparable to that of the underlying material but is strikingly more than that of the overlying loess. Upon this basis, therefore, the gravel lies conformably upon the till and unconformably below the loess. The reddish appearance of the body of gravel makes it distinguishable from the loess for some distance. See Plate VI.

In the ravine one-half mile southwest of Black Springs, near the Chicago, Rock Island & Pacific railway, there are two exposures of Buchanan gravel overlain by loess with an irregular horizon between the two. The east exposure shows from four to twelve feet of gravel lying below two to eight feet of loess.



North face of Interurban cut, across the river west of Iowa City. "a" to "b" marks the division between the Kansan drift below and Buchanan gravel, and "c" to "d" the line between the gravel and the yellow loess above.



The gravel is stratified in the lower part and one stratum shows cross-bedding. The average texture of the materials is that of coarse sand or small pebbles, although a few small bowlders six or eight inches in diameter occur. Incidentally, from this standpoint, this deposit represents Calvin's valley phase. On the other hand, it lacks only about seven feet of being as high above the river as the upland phase in the Interurban cut opposite Iowa City. The gravel has been much weathered. The upper part grades into a pale drab, sandy and silty material containing a few scattered pieces of gravel and small cobbles and showing no sign of stratification. The contact with the loess above is an irregular one, and in one place a pebbly band divides them. This irregular contact crosses the ends of some of the gravel strata and reduces the thickness of the gravel from twelve feet to four feet. Similar relations and characteristics exist in the exposure to the west. Here the gravels vary in thickness from fifteen feet to zero. The loess above bears none of the weathered aspect of the gravel. It is therefore evident that in this cut the gravel is unconformable below the loess both on the basis of contact and on the basis of weathering. See Plate VII.

The history recorded by this exposure seems to be (1) deposition of the Buchanan gravel; (2) a time interval in which the upper part of the material was altered by slopewash and burrowing animals, and the constituents became altered; (3) a period of loess deposition during which the old surface was buried.

The other exposures of Buchanan gravel show the same degree of weathering as those that have been described. The distribution of the gravel is notable. Besides those places already named, the gravel was encountered in wells at various points, as follows: In No. 1 in township 78 north, range 6 west; in Nos. 37, 38, 40, 61, 62, 64, 67, 68, 79, 80, 81, and 86 in township 79 north, range 6 west; in Nos. 95, 96, 98, 106 in township 79 north, range 7 west; in No. 109 in township 79 north, range 8 west; in No. 111 in township 79 north, range 9 west; in Nos. 183, 189 in township 80 north, range 7 west. The locations of these points are shown on the accompanying map (figure 18). Evidences of even a wider distribution might have been secured had all the well drillers distinguished the materials. Neverthe-

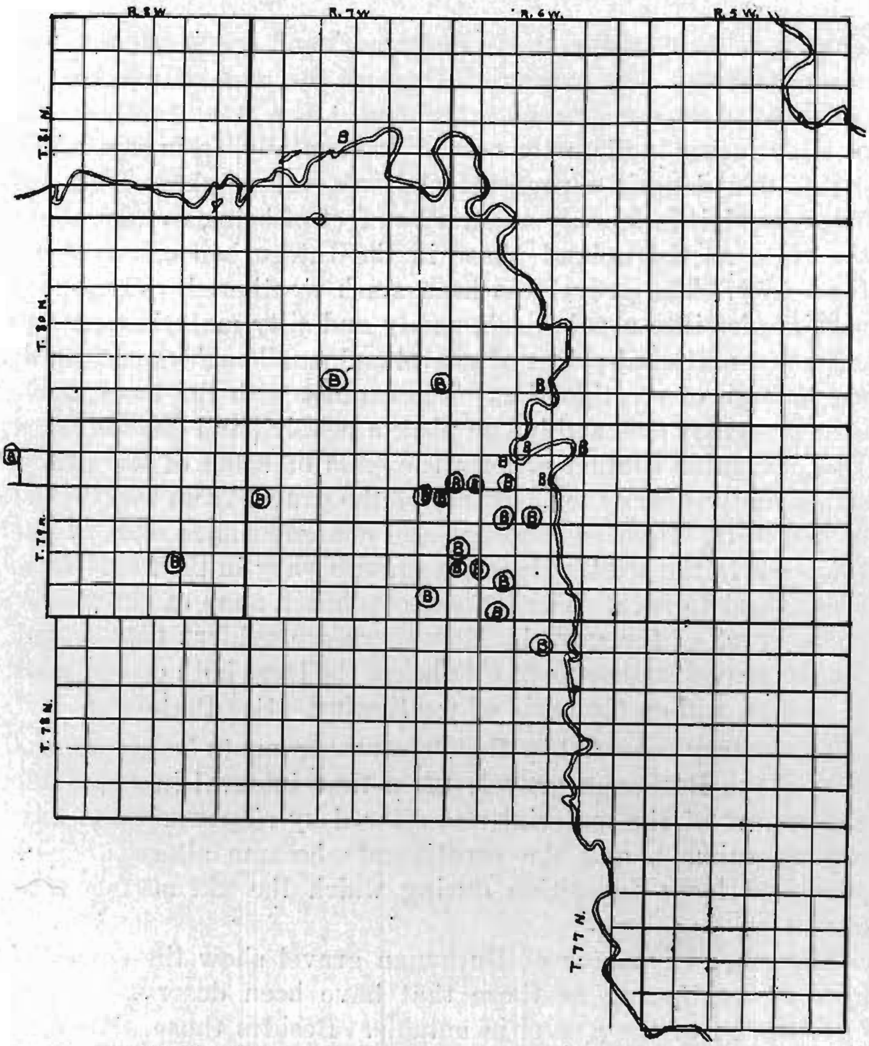


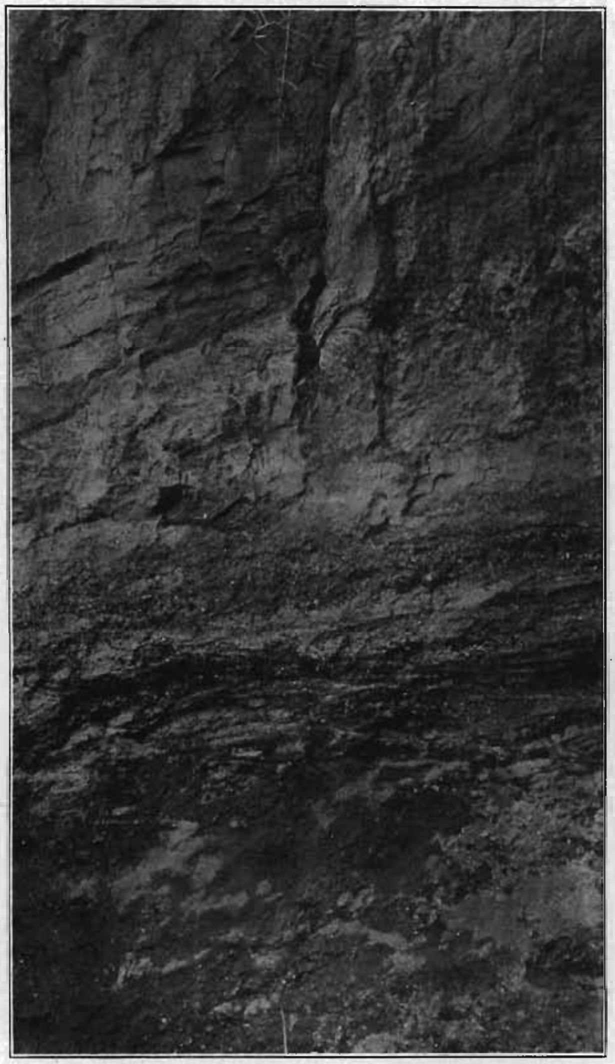
FIG. 18. Map showing distribution of Buchanan gravel in Johnson county as revealed by well records designated by "B" within a circle, and by exposures marked B.

less, the distribution herein noted is sufficiently widespread, together with their occurrence on top of the Kansan drift and apart from present drainage lines, to consider them as outwash from the retreating Kansan glacier.

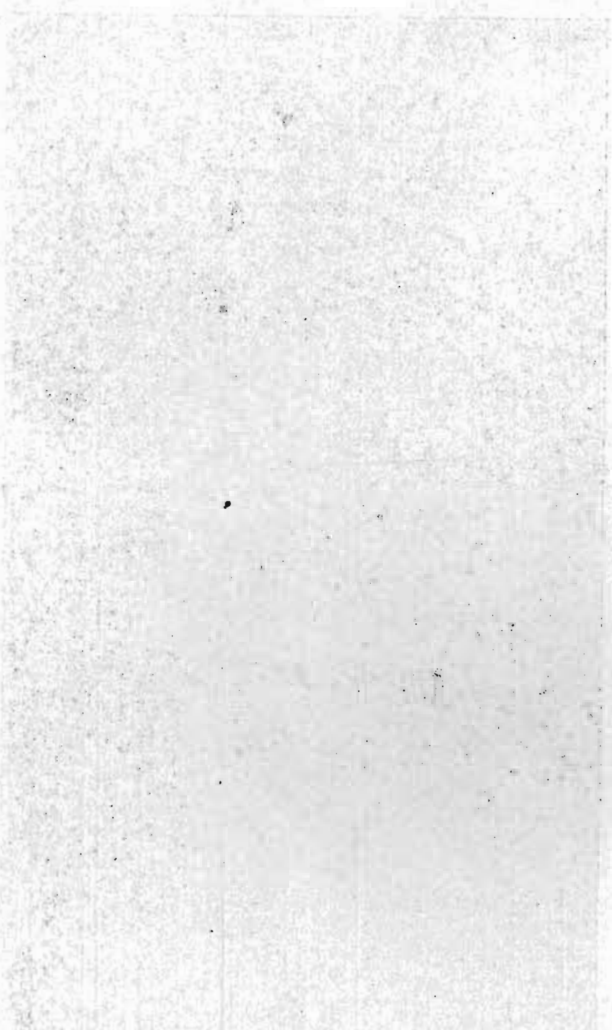
Iowan Drift.

EVIDENCES OF THE IOWAN DRIFT-SHEET.

The apparent presence of a drift-sheet in the northeast quarter of Iowa, younger than the Kansan and older than the Wis-



Cross-bedded Buchanan gravel grading up into residual material which, in turn, is overlain by yellow loess along a diagonal line, as exposed in the ravine one-half mile southwest of Black Springs.



[illegible]

consin, was detected by Calvin. He considered the evidence sufficient to indicate the existence of a distinct drift which he named Iowan. Lobular extensions of this drift were thought by him to reach into the northern part of Johnson county and these he named the North Liberty Lobe, the Shueyville Lobe, and the Solon Lobe. Figure 19 shows the area covered by these as mapped by Calvin.[10]

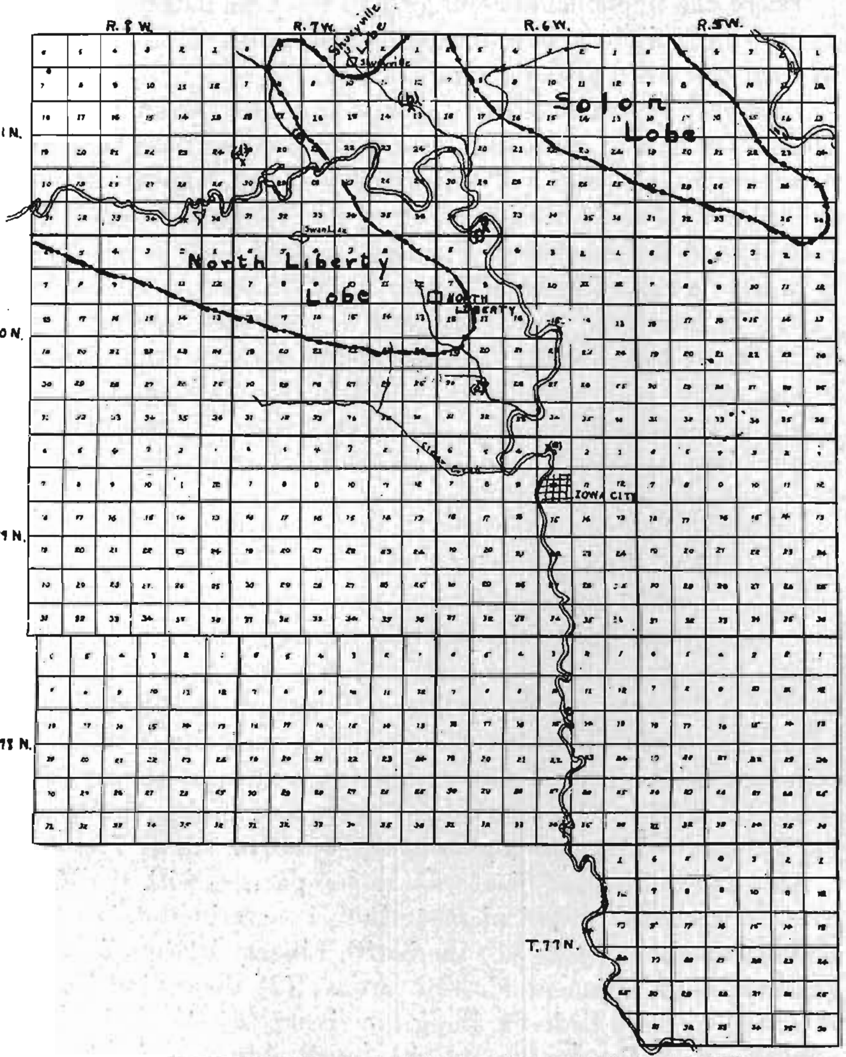


FIG. 19. Map showing the lobes of Iowan drift as mapped by Calvin.

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[10] Calvin, Iowa Geological Survey, VII, opp. p. 92.

In view of the fact, however, that the existence of such a drift-sheet has been called into question by Mr. Frank Leverett, of the United States Geological Survey, the evidence as shown in Johnson county will be considered.

There are phenomena belonging to the area mapped as Iowan drift which, when taken together, distinguish it from the Kansan drift-sheet. These are as follows:

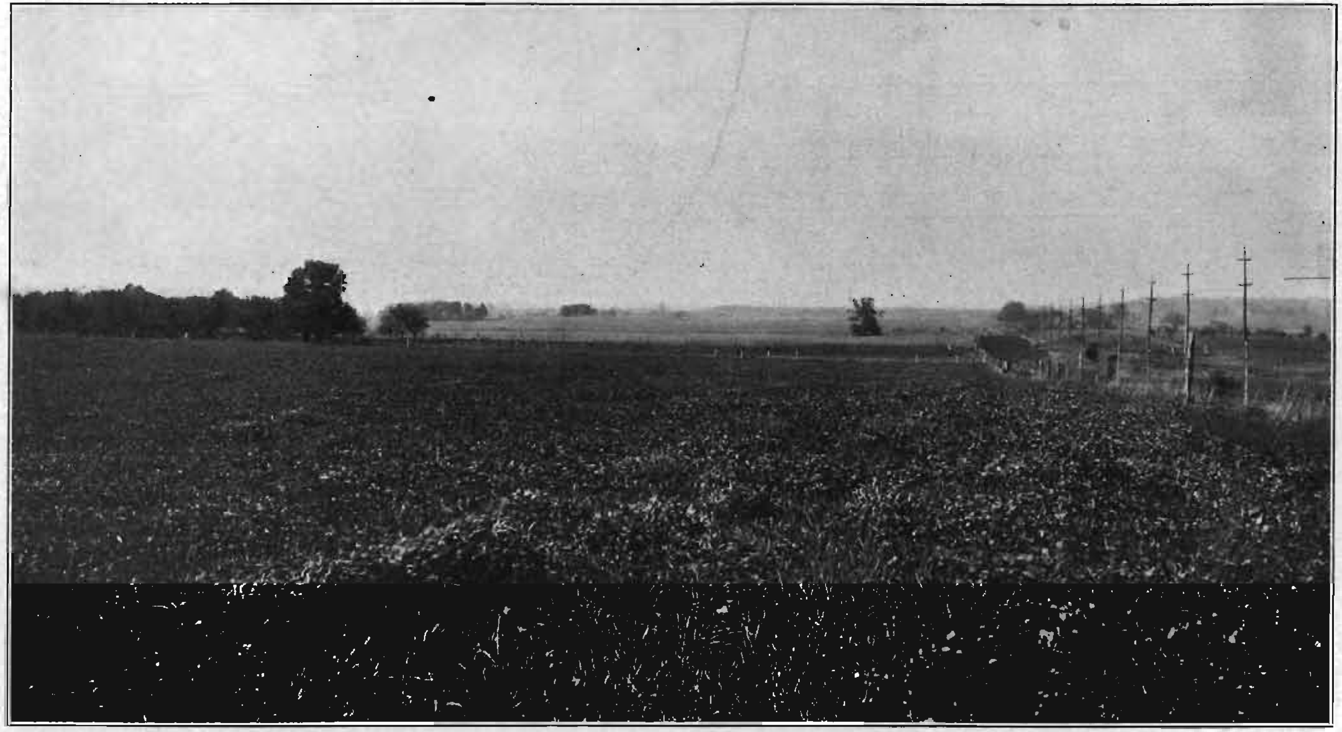
Topography.—The North Liberty Lobe is a gently undulating plain. Its lack of dissection offers striking contrast to the surrounding rough erosional topography of the Kansan as shown in Plates VIII and IX. Northwest of the village of North Liberty, just beyond the reaches of Pardieu creek, the surface is typically of the "swell and swale" type. Farther northwest is a topography of unrelated elevations and depressions, having a relief of not more than twenty feet nor slopes greater than twelve degrees. One depression is occupied by a small pond of water whereas the others are of a slough character. Many undrained depressions exist in the northeastern quarter of the plain, notable among which is Swan lake.

Drainage has not affected the area except near the borders. The heads of the tributaries to Pardieu creek and Clear creek have encroached somewhat upon the southeast end of the lobe, but their indentions immediately change, after crossing the border, to broad, shallow sags. This makes the surface south of North Liberty gently rolling. However, on the divides between the forks of these drainage lines, undrained depressions occur in drift. One of these is in the southwest corner of section 13, township 80 north, range 7 west, and another in the north central part of section 23, township 80 north, range 7 west.

This general lack of dissection in comparison with the Kansan area to the south might at first sight, be considered due to any one of several causes: (1) the North Liberty Plain offers lower gradient than adjacent Kansan areas; (2) dissection has been retarded by high bedrock along the river; (3) the plain may be younger than the surface to the south, due to a later glacial invasion. The adequacy of these explanations will now be considered.

(1) Nearly all the southeast one-half of the North Liberty Plain is at least 100 feet above Iowa river and in but few places

PLATE VIII.



View of the North Liberty Plain.

View showing the erosional topography of the Kansan, taken near the border of the North Liberty Plain.

is the river more than one mile distant from the margin, thus making the average gradient about 100 feet per mile. The other half of the plain, toward the north, slopes toward the river with an average gradient of about thirty feet per mile. These gradients are now to be compared with those afforded by the Kansan upland to the south, where the area has been well dissected. The highest table-land along the western line of the county is 840 feet above sea level. This is 220 feet above Iowa river at the mouth of Old Man creek, fifteen miles distant. This affords a gradient of fifteen feet to the mile. In other words, the Kansan area with the mature topography has a gradient ranging from fifteen feet to eighty-five feet less per mile than the plain without dissection. It is obvious, therefore, that the difference in topography is not a matter of gradient.

(2) The bedrock along the river may have impeded the drainage of the plain and prevented dissection. If this be true, the streams that lead down to the river should give corresponding evidence. Had the streams that now lead down to the river, cut their channels through rock after the plain was made, the surface of the plain should have been lowered as the cutting took place, inasmuch as the plain is made of soft material. As a consequence, the gradient of the stream ought to be greater where it flows over bedrock than where it flows over the plain. Neither, however, is true; the streams do not have their greatest gradients where flowing over bedrock but where flowing over drift leading down to bedrock. Hence, the channels through the bedrock were made before the present plain was made, and the possibility originally considered must be ignored.

These fatal objections to the first two possible explanations add to the probability of the third, namely, later glacial invasion, as the efficient cause of difference in topography. Though windwork is in evidence along the southern edge of the plain, it is not conceivable that wind has been more than a minor modifying agent. The youthfulness of the North Liberty Plain, as contrasted with the mature Kansan surface surrounding it, can best be explained on the basis that the plain was made more recently than the Kansan plain.

Drift at the Surface.—Coextensive with the level topography of the North Liberty Lobe drift comes to the surface. At one time the plain was dotted with numerous bowlders, but with the progress of settlement they have been mostly cleared from the fields. Mr. D. A. Jones, a well driller of some twenty years' experience and a resident in this region for thirty years, remarked to the writer that bowlders were plentiful in the vicinity of North Liberty in the early days, but that now most of them have been removed. Also on the Solon lobe, between Ely and Shueyville, fences of bowlders were common thirty years ago. Even at the present time it is not unusual to see bowlders along fences or in the middle of fields.

Such conditions, however, do not exist within the area conceded to be Kansan. In addition to the coextensiveness of the drift over the North Liberty Plain, the character of the drift is different from the Kansan. The till, where exposed on the plain in the shallow Interurban cuts, is more porous, arenaceous, and distinctly yellower than the weathered Kansan, lacking in the rusty tinge that oxidation has given the latter.

Marginal Deposits of Loess.—From the border of the North Liberty Lobe and extending out in all directions for many miles are thick deposits of yellow loess that have added to the sharpness of the Kansan topography. These deposits begin right at the break between the plain of youthful topography and the area in maturity. They thin out and become finer in texture as distance increases from the plain. Such relations strongly suggest that the loess has an origin intimate in its relation to the origin of the North Liberty Plain, that perhaps it was picked up from the mud-flats on that surface during the retreat of the post-Kansan ice-sheet and deposited around the borders of the plain.

Valley-train Terraces.—In valleys leading down from the North Liberty Plain, from the Shueyville Lobe, and along Iowa river from Curtis to Iowa City, are the following terraces of sand and gravel:

(1) A notable one of these occurs on the west side of the valley of Pardieu creek about one mile below the North Liberty Plain, in the west central part of section 29, township 80 north, range 6 west. The terrace is about one-fourth mile long, fifteen

feet high and from twenty-five to seventy-five yards wide. Except where dissected, it has a flat top, and is backed by a hill that rises to a height of about sixty feet above the terrace.

FIG. 20. View of the terrace in Pardieu Creek.

Several exposures in the side of the terrace show stratified sand and gravel, with a few small lenses. The sand is dominant, but gravel, ranging in size up to three inches, is mixed with the sand. They show no alteration, no oxidation and no rusting, and they are so loose that they will not stand with steep faces. In every way they have a fresh appearance.

There are no terraces on the east side of the valley.

The deposition of the sand and gravel took place, it is clear, after Pardieu creek had cut its valley. Whether the overloading took place by drainage waters from the North Liberty Plain or from a wash into the valley from the west, the significance is the same. The material is of glacial origin, and the fact that Pardieu creek was changed from an eroding stream to a depositing one for a period sufficiently long to aggrade its bed fifteen feet, and the fact that it drains from the North Liberty Lobe, are indications that Pardieu creek received a valley train from an ice-sheet after its valley was eroded.

(2) Two deposits, apparently of similar character, occur in other drainage lines leading from the North Liberty Plain. One of these is in a tributary to Clear creek, about the central part

of section 26, township 80 north, range 7 west; the other lies in a tributary leading east from the Plain to Iowa river, about one and one-half miles east of the village of North Liberty.

(3) From the Shueyville Lobe, a tributary flows southeastward through the village of Shueyville joining Hoosier creek just above its junction with Iowa river. In this tributary, on the south side, where it is crossed by a north-south road, in the northwest quarter of section 13, township 81 north, range 7 west, there is a terrace that extends for about one-eighth of a mile, and is twenty feet high and 50 to 100 yards broad. The material is not exposed in good sections, but in a side-wash and along the slopes sand is evident, suggesting that it is a sand terrace. This terrace probably has the same relation to the Shueyville Lobe that the terrace in Pardieu creek has to the North Liberty Lobe.

(4) Along the north side of the ravine running parallel with the Cedar Rapids and Iowa City Interurban from Swisher to Cou Falls, there is a benchlike feature averaging as much as thirty feet above the present stream. Apparently it has lost some of its former distinctiveness by lateral dissection. In the excavations made by the Interurban, sands, mixed with some coarse gravel, and in places cross-bedded, are exposed. This eliminates wind action and affirms deposition by running water. The material is the same in character as that in the Pardieu creek terrace and probably is of similar origin.

Three or four miles west of Cou Falls, in the southwest quarter of section 19, township 81 north, range 7 west, an intermittent creek has cut down a straight-walled channel ten feet deep into a very gently sloping area which leads up to some morainic-like hills of drift capped with loess. The materials are outwash and afford the following section:

		FEET.
3.	Soil and clay, unstratified	2-4
2.	Gravel parting, apparently residual	0-3
1.	Sands, stratified in long lenses, yellow, medium-grained, arkose	2-4

(5) At the Helman sand-pit, situated on the north side of the bend of Iowa river just north of Iowa City and on the west side of the tributary that dissects the valley wall, is an exposure of silt, sand, and gravel, overlain by loess.

FIG. 21. View of terrace-like feature at the Helman sand-pit one mile north of Iowa City.

The site, illustrated in figure 21, resembles a remnant of a terrace. On both sides of the tributary, particularly on the east, the summit is flat-topped for some little distance back to the higher land. The uniform elevation to the west for a quarter of a mile, with higher land to the north, as shown in figure 21, still further suggests a terrace. Were it not for the break in continuity by the tributary, the semblance would undoubtedly be even more perfect.

In the bottom of the cut, to the left of the picture, as shown in Plate X, are distinct pockets and lenses of gravel, sand, and some silt, with a range in texture from very fine to pebbles the size of a walnut. The outlines of the pockets depict well the channels of rapid currents, which afterward became filled with the sand and gravel. About four feet higher in the cut, the material grades into sand and silt. The sand is quite dominant in the lower part (represented in the picture by the light streaks), in fact, so much so that the sand lenses are separated by yellow silt-partings. This relation, however, gradually changes within a height of two feet until the main lenses are no longer of sand but of silt and the partings are not of silt but of sand. In this zone, which is three feet in thickness, one terrestrial molluscan shell, characteristic of the yellow loess, was found by Professor Trowbridge. Above this where the mass is mainly silt, save for a few thin scattering lenses of sand, loess fossils are common, and their presence requires the term "loess" to be applied to the silt even though it has precisely the same appearance as the silt bands below. This loess constitutes the upper ten feet of the exposure. All of the material is arkose—unconsolidated, unstained, and unaltered.

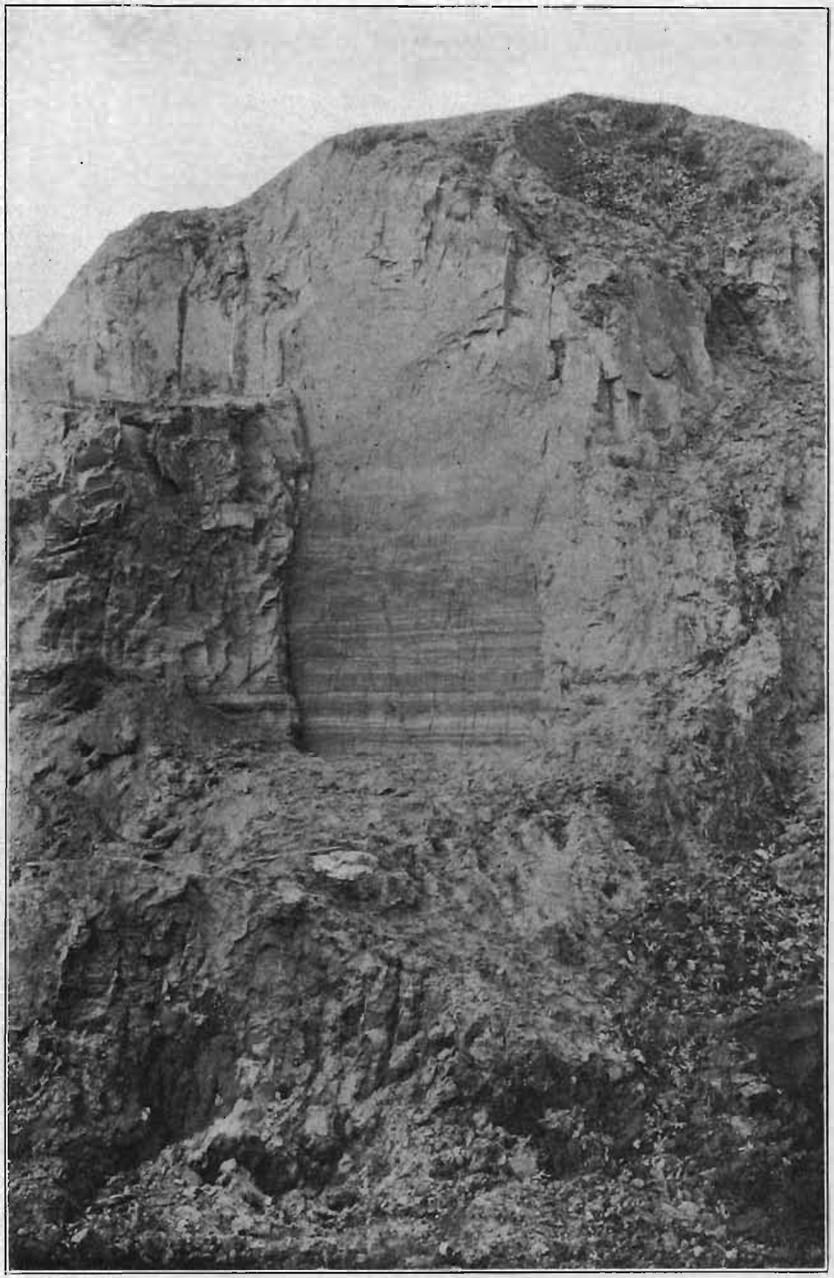
Stated briefly, there are here exposed three feet of fresh, water-laid gravel and sand at the bottom grading intimately upward through the zone of sand and silt bands into loess that is undoubtedly of wind origin.

The coarse texture of the gravel below and the pocket structure (which could not be shown in the photograph) render it impossible to refer the gravel to wind action or to deposition in still water. The material at the bottom is unquestionably a running water deposit, that at the top is clearly æolian, but no line can be drawn between them.

This deposit lies within the valley wall and hence seems to be younger than the valley. At present it is separated from Iowa river by a "second flat" one-eighth of a mile wide and by a vertical distance of twenty-four feet. Even the "second flat" appears not to be the present flood plain of the stream, although it once was, as evidenced by the channel scars on its surface.

From the foregoing, the history that can be read is as follows: Iowa river eroded its valley to a depth at least as low as the bottom of the gravel deposit. Conditions then became such that the degradational process was succeeded by aggradation. More material was given to the flowing stream than it could carry, and hence some was deposited. Inasmuch as the materials in the deposit are of glacial character and similar to those in Pardieu creek and other tributaries, and inasmuch as there must be an adequate source of these materials, it seems best to refer them to the same origin, namely, the ice-sheet that encroached upon the North Liberty Plain.

It is implying only normal glacial conditions to assume that during the maximum melting of the ice, great floods flowed forth, loaded with gravel, sand, and rock-flour, and that deposition in the stream-bed took place because of overloading or decrease in gradient. Also as the glacier disappeared, there were oscillations in the volume of water, the periods of flood-cessation af-



View showing the upper part of the aqueous sand and silt grading up into loess. Helman sand pit, one mile north of Iowa City.

fording conditions for wind-deposits, and the periods of flood-renewal causing a changing back to aqueous deposits, thus affording an alternating series in which the flood conditions grew less frequent and wind-action more prevalent until the deposit became wholly loess.

There are several other terraces along the course of the river between the one mentioned above and the upper Interurban bridge which might be mentioned, some of which are quite perfectly developed. One especially deserving of mention occurs just above the Mehaffey bridge, in the southeast quarter of section 32, township 81 north, range 6 west. It is about thirty feet high, one-fourth mile long, one-eighth mile wide at a maximum and is backed by a distinct valley-wall forty to sixty feet high. A well by the house on the east end of the terrace has the following log, as given by the digger: depth 63 feet (dug 27 feet, driven 36 feet); yellow clay, 16 feet; river sand and gravel, about 27 feet; hard-pan, 20 feet.

Structureless Ferruginous Gravel.—At the southeastern border of the North Liberty Lobe, about one-half mile north of Stewart, on a slope between the forks of a ravine tributary to Pardieu creek, is an artificial exposure of ferruginous gravel. The exposure is about ten feet long and six feet high, and is the site from which gravel has been taken for local use. Southward along the slope of one of the forks, reddish gravel outcrops in a continuous belt from the artificial exposure. Above the gravel is a thick deposit of loess, and in the stream-bed below is undoubted Kansan till. The gravel has a high textural range and the constituents are more or less rounded, and weathered. In character and position the body resembles ordinary deposits of Buchanan gravel, with certain exceptions. There are no lines of stratification, and the body contains angular fragments of both unoxidized and oxidized till, apparently Kansan.

Because of the dominance of the gravels and their rounding it seems quite clear that they show water-sorting, and, in view of their relations to the gravel outcropping continuously along the slope, that they were laid down as a Buchanan deposit and weathered in place. The lack of stratification and the angular inclusions of weathered and unweathered Kansan indicate disturbance and intimate mixing by a later ice-sheet.

Contorted Buchanan Gravel.—An excellent exposure of folded and contorted Buchanan gravel in intimate relations to weathered and unweathered Kansan and overlain by till is shown in the first Interurban cut north of the upper Interurban bridge across Iowa river. The railroad grade here runs through the south end of a divide projecting somewhat into Iowa river valley, the summit of the divide at the surface of the cut being about thirty feet above the valley flat. The physiographic setting is shown in Plate XI. This is within the area mapped as Iowan drift by Calvin.[11]

The cut is about 250 yards long and attains a maximum depth of twenty feet. For about 120 yards, the east end is till, and for 100 yards at the west end the material is yellow, fossiliferous loess. Between these are contorted folds and rolls of Buchanan gravel in peculiar relation to the Kansan till below and overlain by two to eight feet of till. The arrangement of the materials is shown in figure 22.

The oldest material in the cut is Kansan till—blue at the bottom and grading up in places into a grayish to yellow color according to the degree of weathering. The blue drift is very clayey, contains small pebbles many of which are greenstone, and breaks with polyhedral fracture. Joints are prevalent in the yellow clay and in the upper part of the blue, but instead of being vertical they dip toward the west, which suggests that they are the result of pressure from that direction. In that case they might be regarded as slight shear-planes resulting from the same force that produced the distortion of the gravel above. Overlying this, in a peculiarly folded and contorted manner, is Buchanan gravel the textural range of which is from fine flour to bowlders one foot in diameter. The gravel exhibits the usual oxidized, weathered, and decayed character, ironstones being not uncommon and cementation by iron oxide sufficiently prevalent to have preserved stratification lines at many points.

At the west end of this section (left end of figure 22), the gravel appears in a narrow band in the lower part and rises to the east at an angle of about forty-five degrees, reaching a height of sixteen feet. From this point the gravel follows a horizontal

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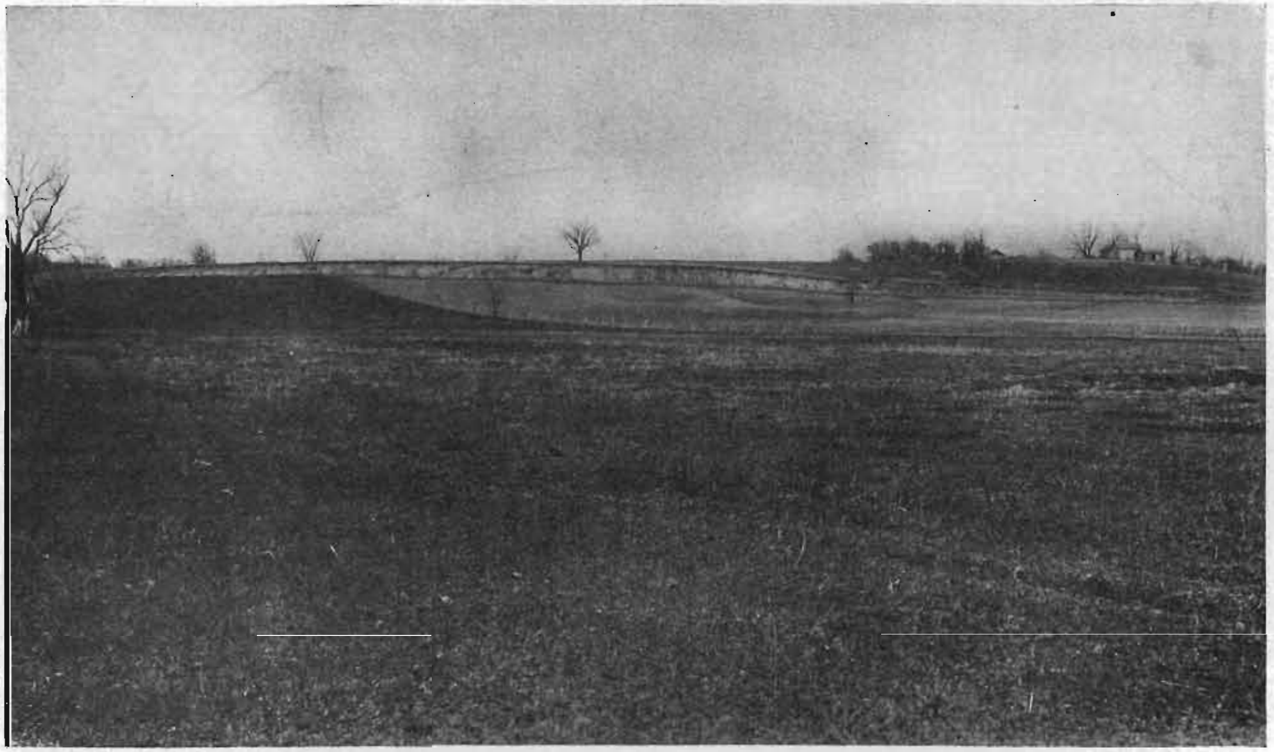
[11] Calvin, Iowa Geological Survey, VII, opp. p. 92.



View showing the topographic setting of the Interurban cut, one-eighth mile north of the upper Interurban bridge.

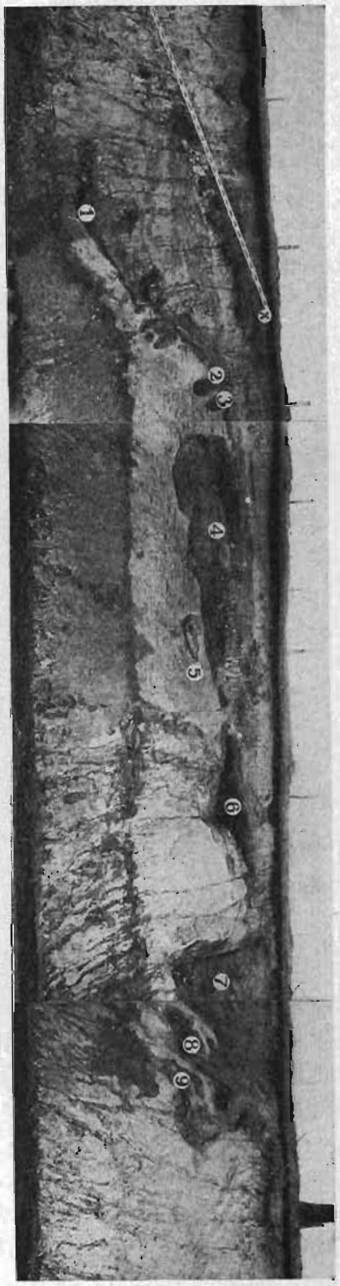


FIG. 22. View showing the folded and contorted Buchanan gravel in the first Interurban cut, one-eighth mile north of the upper Interurban bridge across Iowa river.

course eastward for about seventy-five feet and ends rather abruptly against till. In this middle portion there is a peculiar series of contortions in the gravel. Reference to the photograph shows that (2) and (3) are two small, almost perfect, synclines of the closed type; (4) is a large, elongate body twenty-seven feet long with an accumulation of small bowlders and gravel at the east end; (5) is a small elliptical roll having a nucleus of gravel with wrappings of till, all of which is surrounded by till; (6) marks a protruding compact body of gravel that has withstood slope wash; (7) is a large downward loop seven feet deep; and (8) and (9) appear as stringers projecting from the main body of the gravel into the till below. The horizontal line below the gravel is an artificial line.

At (1) and around the lower part of (7), the gravel, so altered that some cobbles can be picked to pieces by the fingers, rests against the blue unweathered till, and along the lower contact of (4) and around the lenticular body (5), the edge of a knife-blade can mark the separation of the oxidized gravel from the much less oxidized till. Till that is scarcely changed lies high in the arches between (7) and (8), and between (8) and (9). It is also striking that the gravel deep in the cut is as much weathered as that near the surface.

Overlying the gravel is a yellow, blue-streaked till, two to four feet thick across the summit, and attaining a thickness of at least eight feet along the west monoclinal limb. On the western slope of this, beginning at the point (X) and lying in contact with the drift along a diagonal line (made clearer by dotting), lies yellow, fossiliferous loess which is not contorted but which shows deposition after the disturbance of the gravel. This body of loess is in the west end of the cut.

To account for such folds, rolls, and contortions of Buchanan gravel into Kansan till in such a way as is revealed here, there can be but one possible interpretation. The sharp contact of the oxidized, altered, and rotten bowldery gravel upon unchanged till at points (1) and (7) and between (7) and (8), and between (8) and (9), and the sharp break below the elongate body (4) and around the lens (5) prove that the folding took place after the gravel was weathered. If the weathering had taken place since their disturbance, there should be at least a narrow gradation-zone between the weathered and the unweathered portions. Such, however, does not occur. Besides the foregoing significant relations, the gravel is uniformly weathered at different depths, but the till is not.

The conclusion is therefore clear that an ice-sheet, capable of distorting and molding this hill of material, invaded this region after the Buchanan gravel and some of the Kansan till were much weathered.

In view of the above interpretation there are four important points embodied in this cut: (1) the Kansan drift and the Buchanan gravel record the invasion and retreat of the Kansan ice; (2) the weathering of the same represents a considerable lapse of time after the Kansan invasion; (3) the contacts record the close of that interval and the folds give identity to the presence of a later ice-sheet and its movement; (4) the yellow loess, at least in this exposure, was deposited subsequent to the advance and retreat of the later ice-sheet.

CONCLUSIONS.

In view of the positive character of this evidence, together with the foregoing corroborative phenomena, it is quite clear that a post-Kansan drift lies within the limits of the North Liberty Plain. The distinctive features that were noted preceding the last evidence—such as the topography of the North Liberty Lobe, the drift at the surface, the marginal deposits of loess, the valley-train terraces, and the structureless ferruginous gravel—add the corroborative phenomena to be expected. In this paper, therefore, the existence of the Iowan drift sheet will be considered as substantially proven.

Loess Deposits.

Two kinds of loess exist in the region. These have been identified by Professor Shimek as pre-Iowan and post-Iowan in age. The pre-Iowan differs from the post-Iowan essentially in color, the former being blue to gray, the latter yellow. A molluscan fauna is common to both.

An exposure of pre-Iowan loess occurs in the northeast part of the old brick-yards in north Iowa City and another along the north slope of Iowa river at the fork of the roads below the Iowa City Country Club.

The post-Iowan loess is the common loess found bordering the Iowan area. It is yellow in color, fine in texture, flourlike between the fingers, gritty in constitution, variably stratified, quite compact, and has the ability to stand on steep faces. Columnar structure is visible where crumbling from steep slopes has taken place. Calcareous nodules, familiarly known as "loess-kindchen," and limonite concretions, sometimes called "pipe-stems," are quite numerous. Molluscan shells have a variable distribution through the loess where the deposit is silty. Near the Iowan drift-area the loess is sandy and coarse, but assumes its characteristic texture as distance increases.

In the excavation of some of the cuts along the Interurban from Coralville to Oakdale, not less than thirty feet of loess were exposed and its base was not reached. In the cut across the river from Iowa City the loess has a maximum thickness of thirty-four feet.

Stratigraphic Relations.—There are few sections through the loess that make clear its relations to the surface below. A study of the topography of the loess where erosion has proceeded through it into the Kansan below cannot yield conclusive results. If one were to consider, on the one hand, the result of thick loess being deposited upon a flat surface and then dissected, and, on the other hand, the result of loess being deposited upon an erosional surface, the possibility of a satisfactory discrimination between the two modes of deposition would become hopeless. Slope wash and rehandling during dissection in the first case would not only conceal the relations that originally existed, but would give the same apparent relations as would exist genetically in the second case.

The exposure of loess and Buchanan gravel one-half mile southwest of Black Springs, near the Chicago, Rock Island & Pacific Railway, mentioned on p. 120, is important in this connection. The exposure shows a residual material of silt and gravel of varying thickness which grades into the Buchanan gravel below and into the loess above. The residuum has no marks of stratification and lies across the truncated ends of the gravel strata. Because of this the gravel varies in thickness from twelve feet to four feet in the east section, and from fifteen feet to zero in the west section. In some places along the contact between the residuum and the loess above, a narrow pebble band exists, and at one point some woody substances were found. In the basal portion of the loess near this contact loess fossils also were found.

The best interpretation of the above seems to be as follows: After the deposition of the gravel a period of weathering and erosion ensued which resulted in the alteration of the gravels and a partial dissection of them. Along the slopes of dissection, residual material collected by slope-wash, creep, thawing and freezing, plant growth, etc., after which the loess was deposited on the erosional surface. If this is correct, the loess is unconformable upon the material below.

Another suggestive exposure is in the quarry of the Chicago & North Western Railway in the southeastern outskirts of Cedar Rapids, just outside the region especially studied. The quarry-men have stripped back a portion of the drift and loess overlying bedrock and cut a steep face from fifteen to fifty feet high. At the point in question the loess overlies oxidized Kansan drift along a line that resembles the depression and slopes of a former drainage line. This contact is conspicuous because of the red ferretto zone. The loess above is fossiliferous and its upper surface is that of a drainage line resembling the one below. By the deposition of the loess the depression and slopes seem to have been aggraded and raised to their present position, allowing the drainage line to retain its course but with higher and higher level.

At the Interurban cut across the river from Iowa City, the loess rests upon a level surface and there is no sharp line between the Buchanan gravel below and the loess above. The oxidized character of the gravel and the unoxidized loess is in this case the only suggestion of an unconformity between them. But due to the contrast in colors the one is distinguishable from the other for some distance.

From the foregoing evidence the idea of an unconformity between the loess and the Kansan seems conclusive.

Another method of attacking the stratigraphic relations is an investigation of the loess-covered terraces along Iowa river. In the exposure of Iowan gravel and loess in the north curve of the bend of Iowa river, one mile north of Iowa City, described on pages 136 to 141, the fluvial sands grade up into the fossiliferous yellow loess and thereby prove a conformity. The loess at this point was, therefore, deposited immediately following the cessation of waters from the Iowan ice.

The terrace just above the Mehaffey bridge also is covered with loess, as the well record, hereinbefore recorded, shows sixteen feet of yellow clay. Sand and gravel underlie the loess. There are other terraces along the river, the upper parts of which, at least, are loess.

On page 146, it is pointed out that the loess overlying the distorted Buchanan gravel in the cut north of the upper Interurban bridge was deposited after the disturbance.

These facts also strongly suggest that the yellow loess is not only post-Kansan, but post-Iowan and at least the beginning of its deposition closely followed the disappearance of the Iowan ice. This assigned age is further supported by the relation of the loess to the Iowan drift-surface, since here the loess surrounds the area and encroaches upon it only along its borders.

POST-KANSAN EROSION.

Inasmuch as the Kansan drift is thick and widespread in the county and comes to the surface excepting where covered by loess or by Iowan drift, a study of post-Kansan erosion is in general a study of present drainage. The question arises, however, as to whether all of the drainage is post-Kansan or whether part of it dates back to pre-Kansan erosion.

All of the tributaries of Iowa river are cut in either Kansan drift, Iowan drift, or Iowan loess, and hence are post-Kansan. Concerning this there has been no doubt. It has been thought previously, however, that Iowa river valley is in part antecedent to the Kansan invasion, and in part subsequent.[12] Conclusions bearing upon this are possible only after considering the river's features in detail.

Features of Iowa River Valley.

General Course.—Iowa river enters Johnson county five miles south from the northwest corner. For a distance of thirteen miles it pursues an eastward course, after which it changes to a southward direction, forming the notable elbow of the stream. It leaves the county near the southeast corner, the exact point being in the southern part of section 32, township 78 north, range 5 west. These and other features to be described are shown in Plate XII.

Tributaries.—Above Iowa City there are nine permanent streams from the north and east joining Iowa river on the outside of the elbow, and but two on the inside. Those on the outside of the elbow are Rapid creek, Turkey creek, Mill creek, Hoosier creek, Knapp creek, and some unnamed ones. On the

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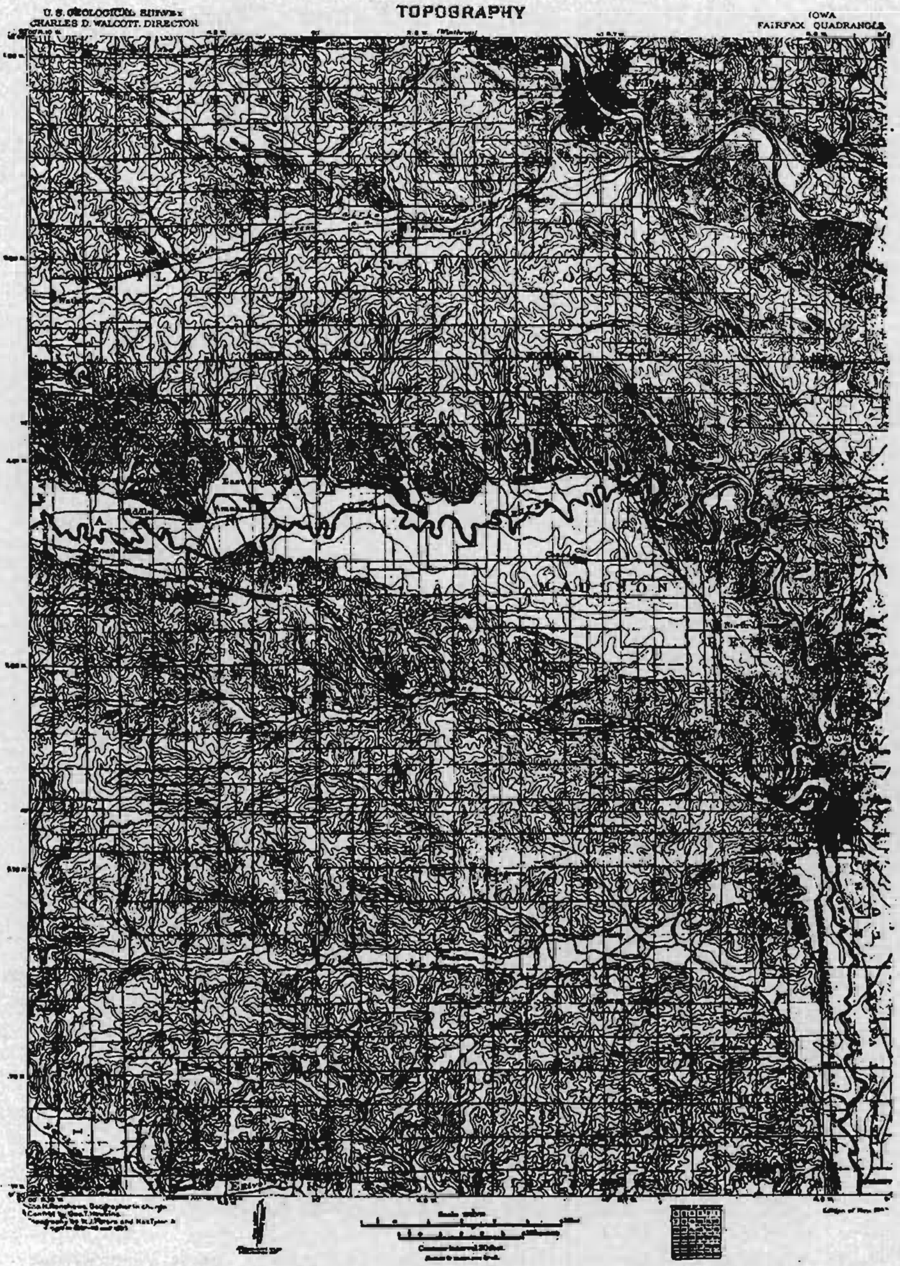
[12] Calvin, Iowa Geological Survey, VII, p. 48; Thomas, Iowa Geological Survey, XXI, p. 505.

Iowa Geological Survey. PLATE XII.



Topographic map of Fairfax Quadrangle, showing the discrepant development of the valley of Iowa river in Johnson county.

inside are Clear creek and Pardieu creek. The scarcity of tributaries from the south and west may be due in part to a smaller drainage territory, but it is also very probable that the Iowan ice eradicated certain tributaries ~~which~~ headed westward from the river. The short tributary that joins Iowa river in the northern part of section 21, township 80 north, range 6 west, is a strong suggestion of this. It heads into the southeastern part of the Iowan drift plain for only a short distance, being but a mile in length. It is remarkable in that its lower portion is cut in thirty-five feet of limestone in spite of its being an intermittent stream. The portion toward the head is filled with Iowan drift. The tributary heading into the plain east of North Liberty is equally suggestive.

Varying Development.—Above the upper Interurban bridge at Curtis the valley has all the characteristics of old age (see Plate XIII). It is one and one-half to two and one-half miles wide and 80 to 140 feet deep, and has a valley flat many times as broad as the stream that meanders upon it. There are meander scars and oxbow lakes which represent former channels of the stream, but which have been abandoned or cut off.

In the westernmost five miles of the valley in the county, the north and south walls are of equal height, but the south wall has a gentler slope as shown in (a) of figure 23. Eastward, along that portion within the Iowan area, the north wall continues steep but the south wall gives way to a low, gently sloping surface that blends with the topography of the North Liberty Lobe

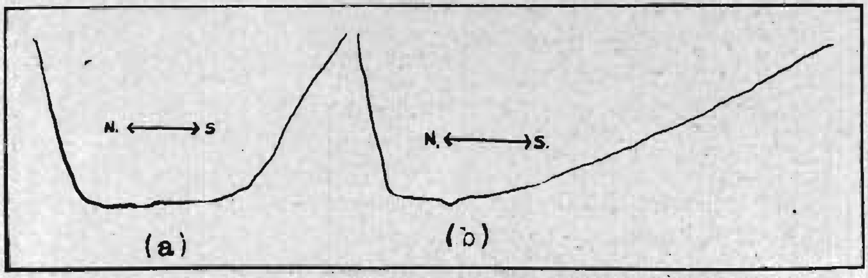
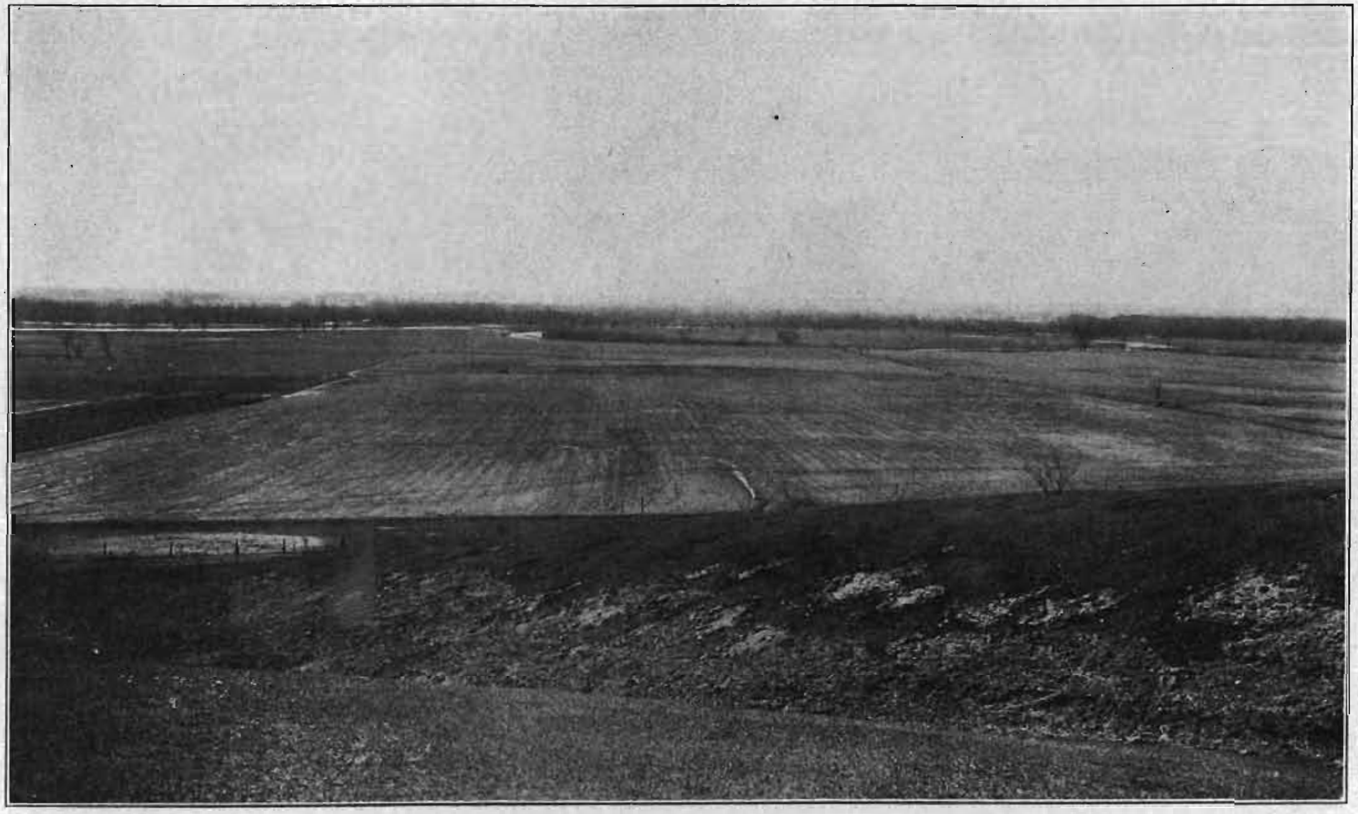


FIG. 23. (a) Cross section of valley wall four and one-half miles east from the west county line; (b) cross section four and one-half miles farther east at foot of North Liberty Lobe. In each figure the horizontal scale is one inch to a mile, and the vertical scale one-eighth inch to twenty feet.



View across the wide segment of Iowa River Valley, above the upper Interurban bridge. The opposite valley wall is dimly visible in the distance.

(shown in (b) of figure 23). This effect is undoubtedly due to the Iowan glacier having eroded more on the south side than on the north side.

The material in the walls is drift, mainly Kansan, overlain more or less by Iowan drift and yellow loess. It is possible that in some places the Kansan is underlain by Aftonian and Nebraskan. The only place where soft material is not the sole constituent of the valley wall is at the small point which protrudes out into the valley, west of the mouth of Knapp creek. Here the lower part is rock of Carboniferous age.[13] Apart from this, rock is not exposed but lies below the level of the present stream, as shown in the last column of Tables III and IV. The data incorporated in these tables are from wells situated on the slope and on top of both walls.

TABLE III.

WELL RECORDS ALONG THE NORTH WALL.

No.	LOCATION	Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Depth below river[14]
	T. 81 N., R. 7 W.	*Ft.*	*Ft.*	*Ft.*	*Ft.*	*Ft.*
219	Steve Dean, S. W. Qr., Sec. 19....	800	177	171	629	71
221	R. L. Potter, S. part, Sec. 19......	780	165	150	630	70
223	W. B. Strang, E. part, Sec. 19....	710	140	137	573	127
224	Jos. Coufal, N. E. Qr., Sec. 20....	700	135	125	575	125
225	C. R. & I. C. Ry., at Cou Falls....	740	205	192	548	152
	T. 81 N., R. 9 W.					
234	Amana Society, Amana	720	1,640	50	670	50

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[13] Calvin, Iowa Geological Survey, Vol. VII, map opp. p. 104.

[14] The datum plane for the river is taken as 700 feet above sea level, except near Amana, which is 720 feet above sea level.

TABLE IV.

WELL RECORDS ALONG THE SOUTH WALL.

No.	LOCATION	Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Depth below river
	T. 81 N., R. 7 W.	*Ft.*	*Ft.*	*Ft.*	*Ft.*	*Ft.*
231	C. Grabin, W. part, Sec. 27........	740	86	86	654	26
232	D. F. Gould, S. E. Qr., Sec. 32...	715	80	80	635-	65
	T. 80 N., R. 7 W.					
165	F. Cochran, N. E. Qr., Sec. 6......	720	85	75	645	55
	T. 80 N., R. 8 W.					
192	Wm. Novak, S. W. Qr., Sec. 2....	740	130	130	610	90
193	Jno. Shebetka, S. W. Qr., Sec. 3..	760	85	85	675	25
194	Jos. Tomas, S. E. Qr., Sec. 4......	740	440	170	570	130
196a	Amana Society, Homestead	868	2,224	300	568	152

By plotting the foregoing in longitudinal sections according to the direction of the river's course, and showing the elevation of the river and the elevation of bedrock, the bedrock surface will be seen to lie considerably below the bed of the stream (see figure 24).

At the upper Interurban bridge, the valley becomes restricted to a gorge in early maturity, and continues narrow and tortuous to the Rock Island trestle at Iowa City, a distance of some twenty-five miles. Not far below the head of the gorge, the river

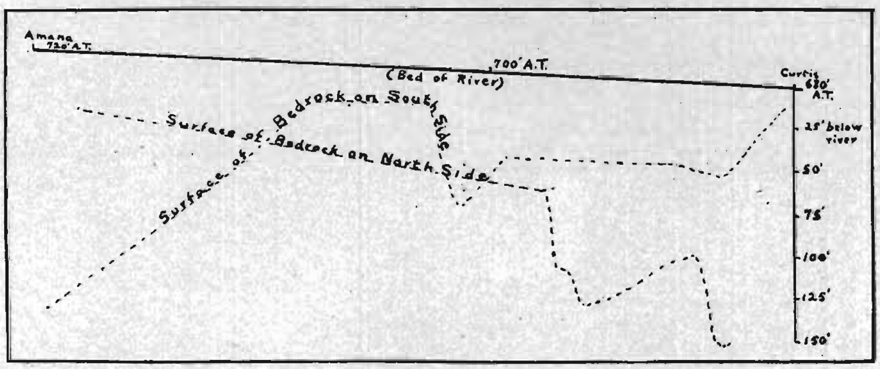

FIG. 24. Profile showing elevation of bedrock along walls of Iowa River Valley.

begins its sinuous bends and changes from an eastward to a southward direction. The valley varies from one-eighth to one-half a mile wide and from 60 to 160 feet deep. A flood plain, rarely wider than 100 yards, exists in most places but in some is totally lacking.

The stream is hemmed in by conspicuous cliffs of Devonian limestone. These are of varying height. A vertical face one-half mile above Turkey creek is ninety feet high; another on the west side of the gorge, two and one-fourth miles east of North Liberty, is seventy feet high; another of equal height occurs just below Mehaffey's bridge; and many others all along the gorge average from thirty to fifty feet in height. Overlying the rock is Kansan drift which is in turn overlain by loess. The rock, however, does not outcrop continuously, and where it is missing the drift and loess make up the valley wall from top to bottom. Where the wall on one side is of rock and the wall on the other is of soft material, the valley is asymmetrical, as shown in figure 25. This is characteristic all along the gorge and seems to be due to the lesser resistance of the soft material. And where drift is on both sides, the valley is distinctly wider than where rock occurs, as is the case four miles north of North Liberty, in the southern part of section 19 and the northern part of section 30, township 81 north, range 6 west.

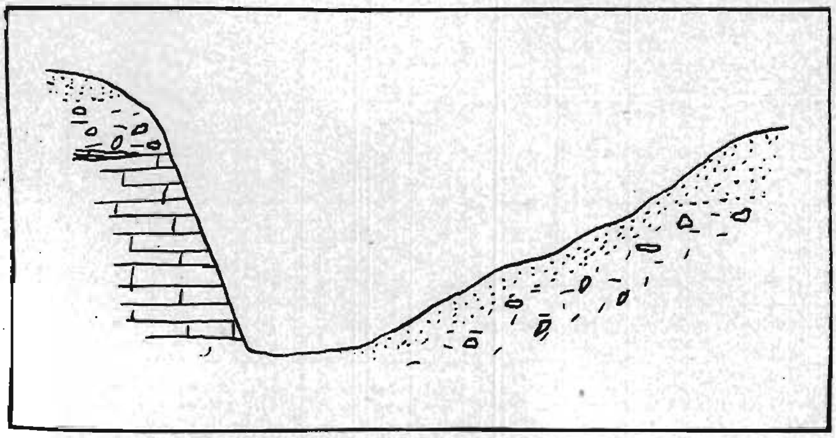

FIG. 25. Cross section of the gorge east of North Liberty at a point where rock outcrops on the side designated in the diagram but is absent in the other side.

Just below the Rock Island trestle at Iowa City, the walls diverge and the stream once more occupies a broad valley, which, in its stage of development and the materials in its walls, is similar to the old-aged portion above the upper Interurban bridge, save that the material is wholly Kansan drift and yellow loess. Bedrock lies below the river. This is indicated both by its failure to outcrop in the valley wall, and by the following tables of records taken from wells within and on top of the valley wall.

TABLE V.

WELL RECORDS ALONG THE WEST WALL.

No.	LOCATION	Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Depth below river[15]
	T. 79 N., R. 6 W.	*Ft.*	*Ft.*	*Ft.*	*Ft.*	*Ft.*
61	C. S. Ranck, W. part, Sec. 16....	740	250	105	635	5
62	J. P. Jones, W. part, Sec. 16.....	720	124	124	596	44
63	Henry Bird, S. part, Sec. 16.....	680	100	80	600	40
73	Jas. Paden, S. W. Qr., Sec. 22.......	660	31	26	660	6
	T. 78 N., R. 6 W.					
1	J. Glaspy, S. E. Qr., Sec. 4......	700	229	229	471-	149
2	J. Fellin, S. E. Qr., Sec. 9......	620	60	60	560-	60

TABLE VI.

WELL RECORDS ALONG THE EAST WALL.

No.	LOCATION	Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Depth below river[15]
	T. 79 N., R. 6 W.	*Ft.*	*Ft.*	*Ft.*	*Ft.*	*Ft.*
72	Sanders Bros., N. part, Sec. 22...	680	70	42	638	2
75	J. McCollister, S. part, Sec. 22...	640	40	40	600-	40
78	C. A. Vogt, S. part, Sec. 26......	660	30-	30	630	10

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[15] The datum plane for the river is taken as 640 feet above sea level, except near wells 1 and 2, in which cases the river is 620 feet above sea level.

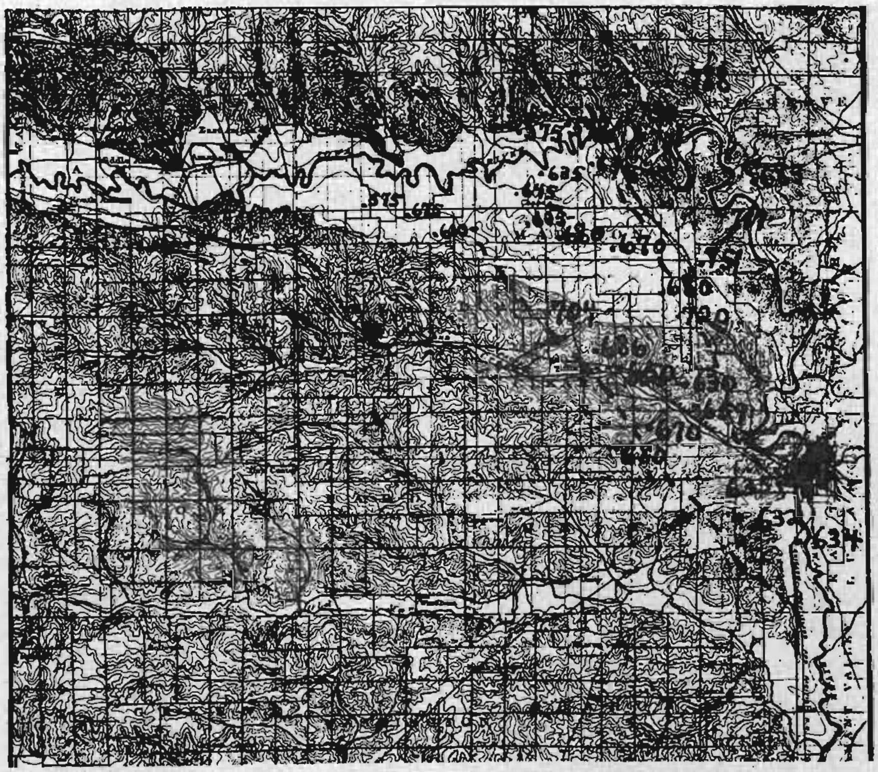

FIG. 26. Fairfax topographic map on which is marked the course of the supposed buried channel, together with elevations of bedrock in the area involved. Note that bedrock attains a higher elevation throughout the supposed old course than in the present valley, both above and below.

Cause of the Varying Development.—It is thus seen that the valley of Iowa river in Johnson county comprises three segments, two in old age and one in early maturity, the latter of which intervenes between the other two. To account for this discrepancy in development it was previously conceived that Iowa river had suffered a change in drainage.[16] It was thought that the segment which once connected the wide portions from the upper Interurban bridge to the Rock Island trestle (as marked in figure 26) lies buried beneath Kansan drift, and that because of the clogging of the channel the course of the river was deranged, forcing it to cut a new one. The gorge, therefore, was conceived to be post-Kansan in age and the wide segments pre-Kansan.

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[16] Calvin, Iowa Geological Survey, VII, p. 48; Thomas, Iowa Geological Survey, XXI, p. 505.

If the above be true, it should be possible to trace the buried channel by the aid of well records. The well records in the involved area, as shown in figure 26, show, however, that no such connecting channel exists. For almost seven miles on either side of the gorge, bedrock is much higher than the bedrock below the stream in the upper segment, and there is no continuity of low bedrock surface excepting in the southern part of the county.

Hence, there could have been no change in drainage in this immediate area so far as Iowa river is concerned.

Inasmuch as it has been shown (1) that the original Kansan surface probably was level (see page 119), and (2) that the valley of Iowa river throughout its course has Kansan drift in its walls, the valley undoubtedly is wholly post-Kansan in age. The difference in valley-development is, therefore, due not to difference in age, but to some other factor or group of factors. Recalling the kinds of materials in the valley walls of the broad segments and of the gorge, it will be remembered that where the valley is wide, the materials are drift, and where narrow the material is mainly limestone. The effect of difference in materials upon the symmetry of the gorge has also been pointed out: its gentle slopes are on soft material, its steep ones on hard; and where the gorge is widest, rock is missing. Furthermore, the point of Carboniferous rock that projects into the valley of the upper segment is evidence *in situ* of the difference in degree of resistance between rock and drift.

The varying development of Iowa river valley is not due to difference in time but to difference in materials. Iowa river started originally upon the Kansan drift surface. As the stream eroded deeper it became superimposed across one area of high bedrock, while above and below, it continued to flow across drift. Due to the difference in resistance of these materials, the valley-development in drift resulted in the wide segments while that in rock resulted in the narrow gorge.

Stream Terraces.—The fact that stream terraces of Iowan age occur within the valley has been noted on pages 134 to 141. They prove that the valley is pre-Iowan in age.

Pot-holes.—At several places along both sides of the valley wall, pot-holes and eddy-scars occur at the top of bedrock. On the west side of the river at Iowa City, about twenty-five yards below Iowa Avenue bridge, there is a group of pot-holes at the top of the bedrock, thirty feet above the river. Some of them are still intact, whereas only parts of others remain. The almost perfect ones are from six to twelve inches in diameter, one to two feet deep, circular at the top and well smoothed. The remnants also exhibit the curved and smoothed surfaces.

FIG. 27. View showing the smoothed surface associated with the pot-holes at Lovers Leap.

Others equally well preserved occur at Lovers Leap, on the south side of the bend of the river one-fourth mile east of Coralville, and at a point on the west side of the river two miles east of North Liberty. The former is at the top of bedrock, thirty-four feet above the river and the latter sixty-eight feet. Much gravel is associated with the former. Figure 27 shows the smoothed surface associated with the pot-holes at Lovers Leap.

A very distinct eddy-scar occurs on top of a prominent cliff-like protrusion about one and one-fourth miles below the upper Interurban bridge at the east bend of the river. It is about eight feet long, eight to twelve inches wide and six to ten inches deep, and is somewhat sinuous as shown in figure 28. The walls are smooth, as is also the surface of the rock bordering the scar. The feature seems to have been a series of pot-holes which later

FIG. 28. A sinuous eddy-scar on top of the valley wall, one and one-fourth miles below the upper Interurban bridge at the east bend of the river.

were united. Rounded gravel and one flattened piece one and one-half inches in diameter were found in the bottom. This scar is fifty feet above the river.

There are two other places where pot-holes occur, but the preservation has not been perfect. One of these is just west of the Country Club along the top of the bedrock, forty feet above the river. The other is on top of the northeast valley wall, one mile below the upper Interurban bridge, fifty-two feet above the river. Scattered gravel occurs along the edge of the cliff.

The fact that these pot-holes are distributed all along both sides of the gorge from Iowa City to Curtis is especially significant. They undoubtedly have a connection historically with the early formation of the gorge, and represent levels at which Iowa river once flowed after it possessed a stream of sufficient permanence and currents of such velocity as to condition eddies at these places. Without doubt, flints and cherts of Buchanan gravel, which are associated with nearly all of the pot-holes, were ready tools in the carving of the limestone. Solution also may have aided.

According to this interpretation important conclusions can be drawn in regard to the amount of rock-cutting that Iowa river has done. In every case, the pot-holes are found at the top of the rock. Hence, the distance of the pot-holes above stream represents at each place the amount of cutting that has been accomplished since the pot-holes were made. Across the river at Iowa City, this amount is twenty-nine feet; at the Country Club, forty feet; at Lovers Leap, thirty-four feet; at the point east of North Liberty, sixty-eight feet; at the point one and one-fourth miles below the upper Interurban bridge, fifty feet; at the point one mile below the same bridge, fifty-two feet.

The foregoing figures do not include the thickness of the drift through which the stream cut before it reached bedrock. Nevertheless, sixty-eight feet of rock is in itself suggestive of the age of Iowa river and of the length of time since the disappearance of the Kansan ice-sheet.

The pot-holes probably were not made contemporaneously, inasmuch as those farthest upstream are not so high as those near North Liberty. But whatever their respective dates of formation they indicate that Iowa river had a high gradient in its early history.

EVENTS ATTENDING THE DEVELOPMENT OF IOWA RIVER VALLEY.

It has been shown in the foregoing data that (1) the preglacial surface was an eroded surface, made up of valleys and divides; (2) the Aftonian erosion probably added to the complexity of the bedrock surface, destroying the possibility of distinguishing pre-Pleistocene drainage lines; (3) the Kansan drift is thick and widespread and its original surface undoubtedly was a plain, covering both low and high bedrock; (4) Iowa river valley is wholly post-Kansan and pre-Iowan in age; (5) its varying development is due to difference in materials and not to change in drainage; (6) Iowa river possessed rapids at various points in its early history and perhaps small falls.

Based on these important facts the history of Iowa river is interpreted in the following pages.

At the time of the encroachment of the Kansan ice-sheet, the topography and drainage were entirely different from the

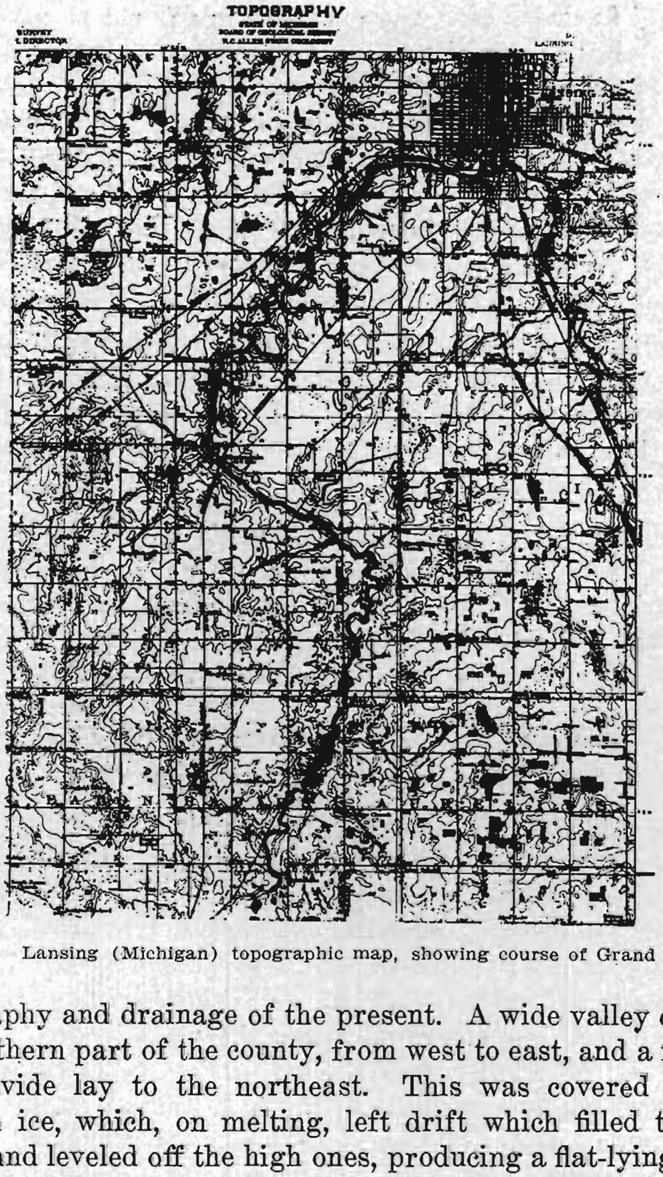

FIG. 29. Lansing (Michigan) topographic map, showing course of Grand River.

topography and drainage of the present. A wide valley crossed the southern part of the county, from west to east, and a notable rock divide lay to the northeast. This was covered by the Kansan ice, which, on melting, left drift which filled the low places and leveled off the high ones, producing a flat-lying plain. Upon this the surplus waters of the undrained depressions and surrounding areas sought the lowest outlet and ultimately established Iowa river. The course that the river now has is in general the course that marked the lowest outlet in the beginning. The great elbow represents the place where there was a change

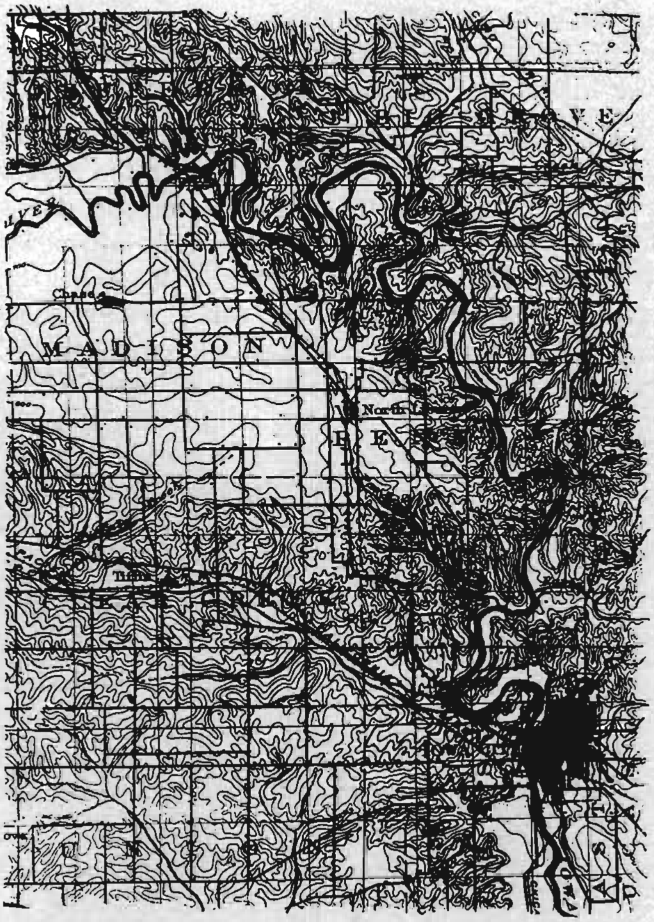

FIG. 30. Fairfax (Iowa) topographic map, showing course of Iowa River.

in slope on the original surface, and the windings of the gorge indicate the rambling of the drainage from lake to lake or around minor irregularities.

Examples of streams which have chosen their courses similar to the above are to be found on the ground moraine of the Wisconsin drift. Figure 29 is a photograph of a portion of the topographic map of Lansing quadrangle, Michigan, showing the course of Grand river on the young plain. Figure 30 is a photograph of the topographic map of Fairfax quadrangle, Iowa, showing the course of Iowa river at the great elbow. The aimlessness of the two courses is strikingly similar. The loops of Iowa river might be used to illustrate how the windings of Grand river will appear if they become entrenched in bedrock.

As Iowa river channeled its course deeper through the drift, it superimposed itself upon the rock-divides in the area of high bedrock. Having established its course it could not avoid them. The drift in the segment upstream and in the segment downstream from high bedrock, being much softer than the rock, offered extraordinary conditions for variable development of the valley. The resistance of the limestone permitted the river, in the upper segment of drift, to reach grade and to widen the valley by lateral planation while the gorge was being cut. In the segment downstream from bedrock, conditions worked differently, but the result was quite similar. The river cut so much more rapidly in the drift than it did in the rock that it reached grade sooner and had time to widen that segment to an old-aged stage of development. This difference in rate of cutting also resulted in a break in gradient at the junction of drift and rock, and rapids were developed. Even low falls may have existed. Such, however, were the conditions under which the pot-holes were made. These conditions existed first on the highest divides of the bedrock surface, which were the first ones to be reached by the stream, and other rapids developed on lower points as the stream entrenched itself more and more.

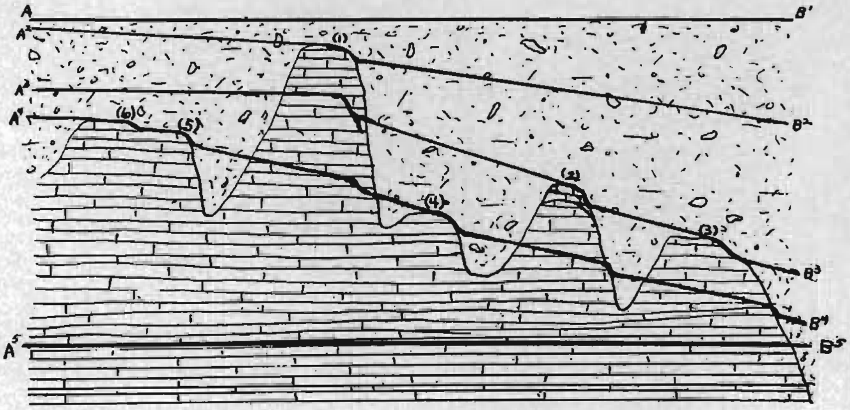

FIG. 31. Diagram illustrating progressive changes in gorge—cutting of Iowa river.

Figure 31 illustrates diagrammatically the progressive changes that characterized this period of gorge-cutting.

In the above figure A^1B^1 represents the gradient of the stream when young. A^2B^2 is the profile after the stream had reached bedrock for the first time. At (1) the profile was broken because of the resistance of the limestone, and pot-holes were formed. A^3B^3 is a later profile, after the stream had cut down to (2) and (3). At this stage Iowa river may have possessed a cascade of three rapids or falls. Pot-holes were then made at (2) and (3). A^4B^4 is the profile after all the divides, that now appear above the river, were exposed. There may or may not have been cascades at all these points, although at (4), (5), and (6) there were eddies of sufficient permanence to make pot-holes and eddy-scars. As the stream cut down from A^4B^4 it approached nearer and nearer grade. A^5B^5 represents the profile of the present stream after a cutting of at least sixty-eight feet through rock, where the rock is highest. Lateral planation within the gorge has been limited because of the limestone walls. But wherever drift occurs between the outcrops of rock it has yielded to slope wash and some planation.

Contemporaneously with the carving of the valley, tributaries developed. Some of those tributary to the gorge cut considerably into rock whereas those tributary to the wide portions of the valley are cut mainly, if not altogether in drift. The result of the development of all these has been to dissect the original Kansan plain into many valleys and divides, and so completely to change its glacial aspect to an erosional one.

Sometime after the present valley had been formed, a lobular extension of a late ice-sheet, called Iowan by Calvin, crossed Iowa river valley west of the great elbow and moved southeastward to the headwaters of Pardieu creek. It seems to have performed considerable erosion on the south valley-wall, at least an amount sufficient to blend the new drift surface with the flood plain of the river. The north side of the valley was not greatly affected erosionally, but some of the older drift was contorted and new material added. Its height and declivity perhaps was increased rather than decreased. The maximum advance of this glacier is known to have been at least six miles beyond the river, and in the course of its movement it obliterated the erosional topography of the Kansan and moulded a new plain, known as the North Liberty Plain.

From the melting of the ice Iowa river received floods of valley train material. Part of this was received directly from the ice-sheet while the rest was derived through the drainage agencies of Pardieu creek, Clear creek, Hoosier creek, and perhaps others. The load of silt, sand, and gravel being greater than the carrying power of the stream, it converted Iowa river into a stream of an aggrading or anastamosing character. The bed was built up at least twenty-four feet above the level of the present stream.

Coincident with the closing stages of melting, fine silty material was picked up from sources prepared by preceding conditions and distributed as loess over the region bordering the new drift area. These deposits ultimately increased the height of the immediate walls of the valley by at least one-half, save in certain places within the area of the young drift. This made the depth of the valley deceptively greater than the actual cutting previously accomplished by the river.

After the complete disappearance of the ice, Iowa river became once more a degrading stream. It cut through the valley train material and laterally planed it until, at the present time, only patches remain in protected places in the form of terraces. The stream again has reached grade and has developed a flat of varying width which is nowhere more than two or three times as wide as the stream.

Records of Wells in Johnson County and Adjacent Townships.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
	T. 78 N., R. 6 W.					
1	John Glaspy, SE. ¼ sec. 4.	700	229	229+	471—	Yellow clay, 73; red sand, 3; yellow clay, 14; blue clay, 139. Graded from yellow to blue, 90-120.
2	Jno. Tellin, SE. ¼ sec. 9.	620	60	60+	560—	About all blue clay.
3	Jno. Kuebel, NW. ¼ sec. 32.	700	120	120+	580—	Yellow clay, 30; blue clay, 85; sand.
	T. 78 N., R. 7 W.					
4	J. R. Hughes, NE. ¼ sec. 2.	700	120	120+	580—	Yellow clay, 40; blue clay, 75; dirty sand to clean sand, 5.
5	R. R. Hughes, NE. ¼ sec. 12.	730	128	128+	602—	Yellow clay, 40; blue clay, 80; sand, 8.
6	W. J. Davis, NE. ¼ sec. 12.	720	128	128+	592—	Same as No. 5.
	T. 78 N., R. 8 W.					
7	Jno. Fry, SE. ¼ sec. 10.	800	140	140+	660—	Very similar to No. 8.
8	J. P. Wagner, SE. ¼ sec. 15.	800	138	138+	662—	Yellow clay, 45; blue clay, 90.
9	C. Swartzendruber, SE. ¼ sec. 16.	780	140	140+	640—	Same as No. 8.
10	J. C. Benter, NW. ¼ sec. 36.	740	275	275+	465—	
	T. 79 N., R. 5 W.					
11	Sam Bowers, NW. ¼ sec. 2.	770	117	115	655	
12	C. R. I. & P. Ry., NW. ¼ sec. 4.	800	116	116	684	
13	Ed. Balluf, NW. ¼ sec. 7.	760	213	108	652	
14	Jas. Silas, SW. ¼ sec. 7.	690	188	88	602	
15	J. T. Struble, E. part sec. 7.	720	224	100	620	Yellow and blue clays.
16	Jacob Wentz, SE. ¼ sec. 15.	760	242	217	543	
17	Frank Lord, NE. ¼ sec. 20.	730	220	200	530	

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*Altitudes were determined from the Fairfax and Stanwood topographic maps.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
18	Benj. Price, E. part sec. 21.	740	260	216	524	Yellow clay, 36; blue clay, 180; rock.
19	Jos. Bowers, NW. ¼ sec. 31.	680	317	137	543	
20	Harry Hagenbuch, NW. ¼, sec. 33.	740	226	180	560	Light blue clay, 36; sand, 1; blue clay, 20; yellow clay, 60; blue clay, 63; sand with shells, 10; hard dark blue clay, 30; coarse sand, 5; rock, 1.
21	Edw. Grier, SW. ¼ sec. 34.	730	260	240	490	Yellow clay, 36; blue clay, 180; rock.
22	Jos. Lacina, NW. ¼ sec. 35.	760	232	232	528	Yellow and blue clay.
	T. 79 N., R. 6 W.					
23	Mary Mendenhall, NE. ¼ sec. 2.	760	152	146	614	
24	Jno. Zimmerman, NE. ¼ sec. 2.	760	234	156	604	
25	Wm. Ruppert, NE. ¼ sec. 2.	800	153	146	654	Yellow clay, 96; blue clay, 50; rock.
26	L. Kessler, NW. ¼ sec. 2.	800	131	119	681	Yellow and blue clay.
27	Albert Reha, NW. ¼ sec. 2.	800	232	132	668	Yellow and blue clay.
28	D. V. Conklin, SW. ¼ sec. 2.	720	195	70	650	Yellow and blue clay.
29	Jas. Eisenhofer, NE. ¼ sec. 3.	760	174	27	733	
30	J. J. Englert, SE. ¼ sec. 3.	770	220	70	700	Yellow clay, 40; thin red sand, blue clay, 30; sandy shale, 30; limestone.
31	Mrs. Wm. Black, SE. ¼ sec. 4.	720	192	40	680	
32	Ben Hanber, SW. ¼ sec. 4.	640	126	26	614	
33	Mr. Drisdla, SW. ¼ sec. 4.	680	195	46	634	
34	Frank Awlwine, SE. ¼ sec. 5.	670	74	69	601	
35	J. K. Hemphill, E. part sec. 6.	700	108	108	592	Yellow and blue clay, gravel on top of rock.
36	J. P. Mullin, SW. ¼ sec. 7.	725	137	135	590	Yellow clay, 75; blue clay, 60; rock.
37	M. H. Clear, SW. ¼ sec. 7.	740	202	202	538	Yellow clay, 40; gravel, 10; yellow clay, 3; blue clay, 149, to rock.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
38	S. O. Fry, SE. ¼ sec. 7.	740	122	122+	618—	Yellow clay, 40; red gravel, 10; blue clay, 50; fine sand, 20; coarse sand, 2.
39	Edw. Rohret, SW. ¼ sec. 8.	720	140	140+	580—	Yellow clay, 30; blue clay, 100; fine to coarser sand.
40	-------------- SE. ¼ sec. 8.	720	128	128	592	Yellow clay, 30; red gravel, 10, with some yellow clay below; blue clay, 88, to rock.
41	Chas. Dayton, NE. ¼ sec. 9.	700	254	64	636	Yellow clay, 54; blue clay, 10; rock.
42	Wm. Wilson, NW. ¼ sec. 9.	720	200	60	660	
43	J. U. Plank, N. part sec. 9.	720	222	50	670	Yellow clay, 30; sand and blue clay, 20, to rock.
44	Folsom Bros., SW. ¼ sec. 9.	740	224	68	672	
45	Geo. Ruppert, NE. ¼ sec. 9.	720	254	64	656	Yellow clay, 54; blue clay, 10; rock.
46	Folsom Bros., SE. ¼ sec. 9.	720	206	54	666	
47	Welch, Dunlap, Bradley and Rogers, SE. ¼ sec. 9.	720	190	40	680	Yellow clay, 30; blue clay, 10; rock.
48	Byington, Smith, Teeters, SE. part sec. 9.	720	194	40	680	Yellow clay, 30; blue clay, 10; rock.
48a	S. U. I. Hospital, Iowa City.	700	170	68	632	Yellow clay (loess), 30; sand, 38; rock.
49	Jno. Slodic, NE. ¼ sec. 11.	710	234	98	612	
50	J. J. Metzger, SE. ¼ sec. 11.	680	207	50	630	
51	Stewart Sisters, SE. ¼ sec. 11.	680	182	42	638	
52	Ed. Riley, W. part sec. 13.	680	55	37	643	
53	Chas. Lyons, NE. ¼ sec. 14.	680	76	33	647	
54	Jas. Greasel. NE. ¼ sec. 14.	680	82	51	629	
55	Cal. Williamson, SE. ¼ sec. 14.	680	71	50	630	
56	Vandenburg, SE. ¼ sec. 14.	680	39	39	641	
57	Jno. Kreg, NW. ¼ sec. 14.	680	93	93	587	
58	Frank Frauenholz, NW. ¼ sec. 14.	700	72	67	633	

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
59	F. Eggenberg, NW. ¼ sec. 16.	740	116	114	626	Yellow clay, 70; blue clay, 44.
60	A. R. Payne, NW. ¼ sec. 16.	740	116	116	624	Yellow and blue clay and gravel to rock.
61	C. S. Ranck, W. part sec. 16.	740	250	105	635	Yellow clay and sand, 50; blue clay, 40; hardpan, 15, to rock.
62	John P. Jones, W. part sec. 16.	720	124	124	596	Yellow clay, 10; red gravel, 15; yellow clay, 15; blue clay, 84.
63	Henry Bird, S. part sec. 16.	680	100	80	600	Yellow clay streaked with blue, 35; some sand, blue clay to rock.
64	Jno. Burns, S. part sec. 17.	640	276	136	604	Yellow clay, 40; red sand, 2; blue clay to rock.
65	Chas. R. Lee, NE. ¼ sec. 17.	730	156	128	602	Yellow clay, 50; blue clay, 70; sand and wood, 8.
66	Mrs. E. S. Carson, SE. ¼ sec. 18.	735	153	140	595	
67	E. S. Carson, SE. ¼ sec. 18.	740	150	150	590	Yellow clay, 10; red gravel, 12; yellow clay, 10; blue clay, 63; sand, 4; blue clay, 51, to shaly rock.
68	Mr. Miers, SW. ¼ sec. 19.	740	134	134	606	Yellow clay, 10; red gravel, 10; yellow clay, 15; blue clay, 109.
69	T. H. Morford, SW. ¼ sec. 20.	740	120	120	620	
70	W. J. Davis, SW. ¼ sec. 20.	740	120	120	620	
71	Owen Davis, NE. ¼ sec. 20.	740	108	108	632	
72	Sanders Bros., N. part sec. 22.	680	70	42	638	
73	Jas. F. Paden, SW. ¼ sec. 22.	660	31	26	634	Mostly sand and gravel.
74	Harry Holsworth, SW. ¼ sec. 22.	660	64	24	636	Mostly sand and gravel.
75	Jas. McCollister, S. part sec. 22.	640	40	40±	600±	
76	Peter Lenz, NW. ¼ sec. 24.	680	78	63	617	
77	Jos. Fuhrman, SW. ¼ sec. 24.	810	88	84	726	
78	Chas. A. Vogt. S. part sec. 26.	660	30	30+	630—	
79	J. W. Jones, S. part sec. 29.	740	207	207	533	Yellow clay, 10; red gravel, 10; yellow clay, 20; blue clay, 167.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
80	Willard Edwards, NE. ¼ sec. 30.	760	179	179	581	Yellow clay, 10; red gravel, 10; yellow clay, 15; blue clay, 165.
81	Wm. Hastings, NW. ¼ sec. 30.	760	200	200	560	Yellow clay, 10; red gravel, 10; yellow clay, 15; blue clay, 165.
82	H. Rowland, SW. ¼ sec. 30.	760	240	240	520	
83	D. W. Jones, SW. ¼ sec. 30.	740	205	205+	535—	Yellow and blue clay.
84	S. E. Pate, N. part sec. 31.	760	400	260	500	Yellow clay, 40; blue clay, 200; sand and tough clay to rock.
85	Jos. Stover, SE. ¼ sec. 31.	720	296	260	460	Same as No. 86.
86	R. E. Jones, cent. part sec. 32.	720	306	260	460	Yellow clay, 10; red gravel, 20; yellow clay, 30; blue clay, 200; shaly rock.
87	Jas. M. Jones, NW. ¼ sec. 32.	700	400	160	540	Yellow clay, 40; blue clay, 120.
88	Matt. Howell, NW. ¼ sec. 33.	720	134	134+	586—	Yellow clay, 60; blue clay, 74.
89	Richard Peant, Sw. ¼ sec. 33.	720	410	260	460	Yellow clay, 40; blue clay, 214; sand, 6, to rock.
	T. 79 N., R. 7 W.					
90	Newman Hudson. E. part sec. 2.	770	244	100	670	Yellow clay, 80; blue clay. 20; rock.
91	John Hradek, NW. ¼ sec. 10.	780	340	100	680	
92	Geo. Wicks, SE. ¼ sec. 10.	770	126	126+	644—	Yellow and blue clay.
93	Evan Williams, SE. ¼ sec. 11.	780	318	168	612	Yellow clay, 40; blue clay, 128; rock
94	R. Williams, SE. ¼ sec. 11.	760	282	174	586	Yellow and blue clay.
95	Johnson Co. Poor Farm, NE. ¼ sec. 13.	780	182	174	606	Yellow clay, 40; red sand, 5; blue clay, 129; rock.
96	Aug. Schnare, NW. ¼ sec. 13.	740	174	174	566	Yellow clay, 40; red sand, 5; blue clay, 129 to rock.
97	Henry Schnare, NE. ¼ sec. 13.	760	187	180	580	Yellow clay, 70; blue clay to rock.
98	W. J. Seitman, NW. ¼ sec. 18.	760	390	252	508	Yellow clay, 40; red sand, 2; yellow clay, 58; blue clay, 150; rock.
99	Chas. Rohret, W. part sec. 20.	760	130	130+	630—	Yellow clay about 60; blue clay, 120.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
100	J. R. Breese, SW. ¼ sec. 21.	720	90	90+	630—	
101	John Lloyd, SW. ¼ sec. 24.	750	100	100+	650—	Yellow and blue clay.
102	Anna Zingula, NE. ¼ sec. 24.	740	170	170+	570—	Yellow and blue clay.
103	W. E. Hastings, SE. ¼ sec. 24.	760	220	220	540	
104	Wm. Buck, NW. ¼ sec. 31.	730	185	185+	545—	Yellow clay, 80; blue clay, 100; black muck, 5.
105	A. A. Rarick, SE. ¼ sec. 35.	670	80	80+	590—	Yellow clay, 20; blue clay to sand.
106	Julius Tudor, NW. ¼ sec. 36.	720	260	260	460	Yellow clay, 10; red gravel. 10; yellow clay, 15; blue clay, 225.
	T. 79 N., R. 8 W.					
107	Jos. Springmeyer, SW. ¼ sec. 1.	800	265	265+	535—	Yellow clay, 100; coarse gravel, 3; blue clay, 40; black hardpan with pebbles, 122.
108	Wm. Quinlon, NE. ¼ sec. 12.	800	262	262+	538—	Yellow clay. 125; gravel, 5; yellow clay, 10; blue clay, 75; sand, 57.
109	J. Frichly, NE. ¼ sec. 22.	780	155	155+	625—	Yellow clay, 50; gravel, 5; blue clay, 95; sand, 5; log at 135 (walnut).
110	Jno. O'Brien, NE. ¼ sec. 27.	740	165	165+	575—	Yellow clay, 65; blue clay, 65; log at 125; gravel, 5; blue clay, 25; sand 5.
	T. 79 N., R. 9 W.					
111	Charley Frost, NE. ¼ sec. 11.	880	165	165+	715—	Yellow clay, 100; sand, 10; blue clay, 50; sand, 5.
	T. 80 N., R. 5 W.					
112	Jas. Peters, NW ¼ sec. 3.	820	202	200	620	Yellow clay, 40; sand, 2; yellow clay, 70; blue clay, 88; rock.
113	G. C. Rossler, SW. ¼ sec. 6.	820	140	140+	680—	
114	Sam Spinden, NW. ¼ sec. 8.	810	217	143	667	
115	Fred Zimmerman, N. part sec. 14.	820	156	156	664—	Yellow clay, 39; red sand, 1; yellow clay, 10; yellow-blue clay, 20; blue clay. 80; sand, 6.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
116	Chas. Dvorsky, NW. ¼ sec 17.	830	128	123	697	
117	Lucy Hempstead, NE. ¼ sec. 18.	820	128	120	700	
118	J. J. Krall, S. part sec. 18.	820	217	90	730	
119	Sam Bowers, SE. ¼ sec. 21.	780	87	81	699	
120	Michael Donovan, NE. ¼ sec. 29.	780	130	109	671	
121	Frank Kobela, SE. ¼ sec. 29.	760	127	125	635	Yellow and blue clay.
122	Sullivan Estate, NE. ¼ sec. 29.	760	90	70	690	
123	Ed. Dvorsky, NE. ¼ sec. 30.	670	79	67	703	
124	Jos. Swaner, W. part sec. 30.	720	78	26	694	
125	Jerome Earnest, NW. ¼ sec. 33.	780	163	80	700	
	T. 80 N., R. 6 W.					
126	Jos. Dvorsky, NW. ¼ sec. 1.	780	229	131	649	
127	Anton Slaby, NE. ¼ sec. 5.	720	120	85	635	Yellow clay, 30; blue clay, 55; rock.
128	J. W. Andrle, W. part sec. 7.	760	236	80	680	Yellow clay, 20; blue clay, 60.
129	T. E. Murphy, SW. ¼ sec. 7.	770	248	90	680	Yellow clay, 20; blue clay, 70.
130	R. H. Alt, NW. ¼ sec. 8.	780	131+	131	649	Yellow clay, 40 to blue clay.
131	Jas. Shimma, NE. ¼ sec. 10.	790	231	131	659	
132	Geo. Suatos, NW ¼ sec. 13.	800	115	115	685	
133	Vincent Rounner, SE. ¼ sec. 14.	790	207	64	726	
134	Albert Krall, SE. ¼ sec. 14.	790	211	81	709	
135	Jno. Zeller, SW. ¼ sec. 18.	770	200	19	751	Yellow clay to rock.
136	Sam Green, SW. ¼ sec. 18.	740	200	19	721	Black loam, 3; yellow clay, 16, to rock.
137	M. Bowman, NE. ¼ sec. 19.	780	288	98	682	High knoll.
138	Besdek Bros., SE. ¼ sec. 20.	780	116	116	664	Yellow clay, 30; sand, 10; blue clay to rock.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
139	Anton Linder, NW. ¼ sec. 26.	770	80	80+	690—	Sandy yellow clay, 20; blue clay, 60, to gravel.
140	Geo. Gressel, NE. ¼ sec. 22.	710	219	77	633	
141	Chas. Plashel, NW. ¼ sec. 23.	750	218	74	676	
142	Jas. Hotka, cent. part sec. 23.	760	108	108+	652—	
143	Frank Kott, NW. ¼ sec. 24.	800	85	80	720	
144	Chas. Dvorsky, NW. ¼ sec. 24.	800	100	100	700	
145	Mrs. Dohrer, SE. ¼ sec. 24.	800	146	76	724	
146	Albert Hemmer, SE. ¼ sec. 25.	730	128	28	702	
147	Vincent Anton, SE. ¼ sec. 26.	740	224	80	660	
148	Jno. Sedlacek, SE. ¼ sec. 26.	740	95	95	645	
149	Jas. Sedlacek, SE. ¼ sec. 26.	730	118	79	651	
150	Wm. Vogt, W. part sec. 26.	700	111	111	589	
151	Henry Eicher, E. part sec. 27.	720	188	80	640	
152	Jno. Dolmage, SE. ¼ sec. 30.	760	123	123+	637—	Yellow clay, 40; blue clay, 83, to sand.
153	Jno. Hemphill, SE. ¼ sec. 31.	760	126	126+	634—	
154	Jos. Kile, NW. ¼ sec. 32.	660	121	121+	639-	Yellow clay, 71; blue clay, 50; sand.
155	---- Kile, NE. ¼ sec. 32.	760	120	116	644	
156	Jno. Williams, SE. ¼ sec. 32.	760	256	101	659	
157	Jno. Eicher, SE. ¼ sec. 34.	760	243	138	622	
158	Homer Johnson, SE. ¼ sec. 34.	760	120	115	645	
159	Wm. Ruppert, SW. ¼ sec. 35,	720	156	151	569	Yellow clay, 100; blue clay, 51; rock.
160	A. Greasel, SW. ¼ sec. 36.	720	219	61	659	
	T. 80 N., R. 7 W.					
161	F. D. Myers, SE. ¼ sec. 4.	760	150	80	680	Yellow clay, 40; blue clay, 40.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
162	M. F. Snavely, SE. ¼ sec. 5.	750	118	118+	632—	Yellow clay, 25; blue clay, 90; gravel, 3.
163	W. J. Davis, S. part sec. 5.	720	128	128+	592—	Yellow clay, 40; blue clay, 80; sand, 8.
164	W. W. Muskgrove, SW. ¼ sec. 5.	750	120	120+	630—	Yellow clay and sand, 30; blue clay, 90.
165	Fred Cochran, NE. ¼ sec. 6.	720	85	75	645	Yellow sand, 30; blue clay and sand, 45; rock.
166	T. M. Thompson, cent. part sec. 8.	780	65	65+	715—	All sand.
167	M. M. Snavely, NE. ¼ sec. 8.	750	115	115+	635—	Yellow clay and blue clay to sand.
168	Jos. Lininger, NW. ¼ sec. 10.	770	278	135	635	Yellow clay, 25; blue clay, 110; rock.
169	Geo. Hoover, N. part sec. 10.	770	262	142	628	Loam and blue clay.
170	H. Lininger, SW. ¼ sec. 10.	780	90	90+	690—	Loam and blue clay; ends in sand.
171	Alex. Morland, NW. ¼ sec. 12.	760	233	90	670	Black loam, 5; yellow clay, 20; blue clay, 65; rock.
172	J. Bridensteine, NW. ¼ sec. 13.	730	90	90+	670—	Black loam, 5; yellow clay, 25; blue clay, 34; layered sand, 26.
173	Paul D. Dodt, NW. ¼ sec. 15.	780	138	138+	642—	Sand, 20; blue clay to gravel, 118; wood came up with gravel.
174	J. C. Bowman, SE. ¼ sec. 16.	760	312	120	640	
175	M. A. Stoner, NE. ¼ sec. 16.	780	160	160	620	
176	J. D. Colony, SW. ¼ sec. 19.	760	144	144+	616—	Yellow and blue clay.
177	Caroline Dodt, NW. ¼ sec. 21.	780	210	76	704	Black soil, 5; yellow clay, 25; blue clay, 40; hard sand, 6; soft blue clay with shells, 134; soapstone.
178	W. B. Brown, E. part sec. 21.	780	187	180	600	Yellow clay, 50; blue clay, 40; sand with some wood, 4; blue clay, 86; rock.
179	Jas. Swaner, NE. ¼ sec. 23.	780	112	112+	668—	Yellow clay, 30; blue clay, 82, to gravel.
180	Chas. E. Colony, SW. ¼ sec. 24.	780	100	100	680	To rock.
181	Jno. A. Koser, NE. ¼ sec. 25.	780	130	130+	650—	Yellow clay, 30; blue clay to gravel containing wood, 100.
182	State Sanatorium, SE. ¼ sec. 25.	800	380	150	650	Yellow clay, 70; blue clay, 80, with sand.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
183	State Sanatorium, SE. ¼ sec. 25.	800	350	150	650	Yellow clay, 40 (bowlders at bottom); red gravel and clay mixed, 12; yellow clay, 20; blue clay, 44; ledge of rock, 6; sand and gravel with lots of bowlders, 28; rock.
184	Gaugh, SW. ¼ sec. 25.	800	156	140	660	Yellow and blue clay, 100; dirty sand, 40.
185	Anthony Klein, E. part sec. 26.	780	96	94	686	Sandy loam, 5; yellow clay, 20; blue clay, 69; rock.
186	Ed. Craig, SW. ¼ sec. 26.	700	100	51	649	Yellow clay, 20; red sand, 1; blue clay, 30; hard shaly rock, 3; soapstone to "iron rock," 46.
187	J. J. Craig, NE. ¼ sec. 27.	750	213	100	650	
188	Edw. Craig, SE. ¼ sec. 27.	690	65	65+	625—	
189	Jno. Falkner, cent. part sec. 28.	750	310	150	600	Yellow clay, 40; gravel, 10; blue clay, 90; sand, 10; rock.
190	Rich. Reeve, SW. ¼ sec. 33.	800	195	185	615	Sand, 40; blue clay, 145; rock (well on hill).
191	Walter Cox, SW. ¼ sec. 36.	680	50	50+	630—	Drive well.
	T. 80 N., R. 8 W.					
192	Wm. Novak, SW. ¼ sec. 2.	740	130	130+	610—	Sand, 40; yellow clay, 40; blue clay, 50.
193	Jno. Shebetka, SW. ¼ sec. 3.	760	85	85	675	Sand, 30; yellow clay, 30; blue clay, 10; sand, 15.
194	Jos. Tomas, SW. ¼ sec. 4.	740	440	170	570	Yellow sand and clay, 90; blue clay, 80; limestone.
195	Thos. Tranter, SW. ¼ sec. 10.	860	190	190+	670—	Yellow clay, 90; blue clay, 96; sand, 4.
196	M. Pitlock, SW. ¼ sec. 36.	770	300	300+	470—	Yellow clay, 100; blue clay, 150; sand, 50.
	T. 80 N., R. 9 W.					
196a	Amana Society, SW. ¼ sec. 3.	868	2,224	300	568	
	T. 81 N., R. 5 W.					

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
197	W. Verba, E. part sec. 6.	830	160	132	682	Reddish clay, 20; blue clay and yellow sandy clay and red clay, 98; black soil, 2; brownish clay and yellow clay to rock.
198	Jno. A. Hemck, SE. ¼ sec. 17.	820	235	235+	585—	Yellow sandy clay, blue clay to 145; yellow sandy clay to 200; sand, 35.
	T. 81 N., R. 6 W.					
199	J. Pesarek, NE. ¼ sec. 4.	730	158	72	658	Loam, yellow clay, blue clay, sand on rock. Log at 60.
200	Jas. A. Ulch, NE. ¼ sec. 25.	760	282	60	700	
201	Mrs. M. Kessler, N. part sec. 26.	740	120	5	735	
202	Jacob Kessler, NW. ¼ sec. 26.	740	78	11	729	
203	Zeidchek, NW. ¼ sec. 28.	720	143	143	577	Yellow clay, 40; blue clay, 100; sand, 3, to rock.
204	L. W. Mehaffey, NE. ¼ sec. 32.	750	100	67	683	Yellow clay, 20; blue clay, 47; rock.
	T. 81 N., R. 7 W.					
205	H. H. Hanson, SW. ¼ sec. 4.	760	160	150	610	Yellow clay, 40; blue clay, 110, to rock.
206	Wm. Pudil, NW. ¼ sec. 7.	820	148	148+	672—	Yellow clay with bowlders, 30; blue clay, 50; sand, 68.
207	C. R. & I. C., NW. ¼ sec. 8.	800	140	117	683	Yellow clay, 30; blue clay, 87.
208	J. E. Bowersox, NW. ¼ sec. 10.	840	345	340	500	
209	Frank Novstny, N. part sec. 10.	840	285	285+	555—	
210	J. C. Baylor, SW. ¼ sec. 10.	820	294	284	536	Yellow clay, 60; dirty sand, 6; blue clay and sand, 134; sand, 10; blue clay, 74, to rock.
211	J. K. Fordice, E. part sec. 10.	840	185	180	660	
212	Frank Chalonpka, NW. ¼ sec. 12.	840	148	133	707	Yellow clay (bowlders), 30; sand, 3; blue clay, 100, to rock.
213	Frank Novstny, SW. ¼ sec. 12.	800	74	12	788	Yellow clay, 12.
214	Anna Becicka, NE. ¼ sec. 13.	800	77	77	723	Yellow clay, 20; blue clay, 57, including thin gravel bed.

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
215	Frank Holub, NW. ¼ sec. 14.	840	170	163	677	
216	Jos. Kivonek, E. part sec. 15.	820	195	190	630	Yellow clay, 45; blue clay, 145.
217	Jos. Turecek, SE. ¼ sec. 15.	800	80	70	730	Yellow clay, 20; blue clay, 50.
218	C. Michalek, NE. ¼ sec. 18.	840	346	228	612	Blue clay, 228.
219	Steve Dean, SW. ¼ sec. 19.	800	177	171	629	
220	John Sawford, SW. ¼ sec. 19.	800	157	147	629	Same as No. 221.
221	R. L. Potter, S. part sec. 19.	780	165	150	630	Yellow clay, 50; blue clay, 20; sand, 20, with red cedar log at 85; blue clay, 54; sand, 6; rock.
222	W. B. Strang, E. part sec. 19.	760	150	150+	610—	
223	W. B. Strang, (at barn) E. part sec. 19.	710	140	137	573	
224	Jos. Coufal, NE. ¼ sec. 20.	700	135	125	575	
225	C. R. & I. C. (Cou Falls).	740	205	192	548	Yellow clay, 40; sand, 15; blue clay, 137.
226	King Tooby, NE. ¼ sec. 21.	780	80	70	710	Mostly yellow clay, some blue.
227	Mike Petracek, NW. ¼ sec. 23.	720	265	19	701	
228	C. R. & I. C. (Mid. River Park).	740	184	27	713	Yellow clay to rock.
229	M. Herdlika, NE. ¼ sec. 27.	740	156	24	716	High ridge, water rose within 36 ft. of top.
230	Flora Meyers, NW. ¼ sec. 27.	710	184	50	660	Sand, 50.
231	C. Grabin, W. part sec. 27.	740	86	86	654	
232	D. F. Gould, SE. ¼ sec. 32.	71	80	80+	635—	Sand, 30; blue clay, 50.
233	Alex. Reinhardt, SW. ¼ sec. 34.	700	90	40	660	Mainly sand.
	T. 81 N., R. 9 W.					
234	Amana Society NW. ¼ sec. 25.	720	1640	50	670	
	T. 82 N., R. 7 W.					

No.	Location of Well	*Altitude of site above sea level	Depth	Depth to rock	Altitude of rock above sea level	Materials
		Feet	Feet	Feet	Feet	
234	Jos. Benesh, SW. ¼ sec. 32.	840	212	112	728	Yellow clay, 50; blue clay, 62, to rock.
235	Jno. Benesh, S. part sec. 32.	840	98	98	742	Yellow clay, 20 (bowlders); blue clay, 50; sand, 28, to rock.
236	David Silver, SE. ¼ sec. 32.	820	172	166	656	
237	Jno. Lopata, SE. ¼ sec. 33.	820	105	105	715	Blue clay, 100; sand, 5.
238	Jos. Witrowsex, NW. ¼ sec. 35.	740	162	160	580	

TRILOBITES FROM THE MAQUOKETA BEDS OF FAYETTE COUNTY, IOWA

BY

ARTHUR WARE SLOCOM

OUTLINE.

TRILOBITES FROM THE MAQUOKETA BEDS OF FAYETTE COUNTY, IOWA

Introductory.

The specimens upon which this paper is based represent the results of two visits to Fayette county, Iowa, made by the writer, in the interests of the Field Museum of Natural History of Chicago, one in July, 1910, and the other in October, 1912, supplemented by specimens from the collection of Mr. A. G. Becker of Clermont, Iowa, and from the collections of the State University of Iowa.

The Maquoketa beds constitute the uppermost deposits of the Ordovician system found in the state of Iowa. In a few localities they are overlaid, unconformably, by Niagaran limestones, but usually they underlie the drift. These beds have been worked out by Savage in his "Geology of Fayette County."[1] He divides the formation into Lower, Middle and Upper Maquoketa beds. The Lower member attains a maximum thickness of 95 feet and consists of alternating layers of shale and argillaceous limestone. Some of the layers are quite fossiliferous. The Middle division consists of 40 to 60 feet of cherty limestone with few fossils. No trilobites have been observed from these beds. The Upper division has a thickness in some places of 125 feet. It is composed of a plastic blue-gray shale. In the upper portion occurs a zone 8 to 12 feet in thickness, in which are thin calcareous layers composed almost entirely of fossil shells. Below this zone the shale is practically barren of fossils, but contains numerous crystals of selenite. The lithological characters of the various divisions of the Maquoketa beds are quite constant at the various exposures studied.

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[1] Iowa Geological Survey 1904, Vol. XV, pp. 433-546.

The Maquoketa beds of Fayette county afford a fauna of unusual interest both as to the number of species represented and the excellent state of preservation of the specimens. Other localities afford a greater number of individuals, but few, if any, excel it in the quality of the material. Savage[2] reports 68 species divided as follows: Sponges 2, Corals 2, Brachiopods 31, Pelecypods 4, Gastropods 11, Pteropods 2, Cephalopods 7, and Trilobites 9.

In the material collected and identified by the writer, the number of species obtained in the various groups agrees practically with the above list with the exception of the trilobites. Of these twenty species were determined. A number of species of crinoids and cystoids, probably six or eight species of which Savage made no mention, were also found. Of the twenty species of trilobites twelve were found to be new and are here described and figured. Five of the eight species which have been previously described are here redescribed and figured. The remaining three species were too fragmentary to admit of description.

Thus far the only group that has been critically studied by the writer is the trilobites and the finding of so many new species in that group would indicate that when the other groups are studied new material will be discovered. A beginning has been made on the echinoderms, and so far none of them appears to be referable to known species. If they prove to be new, they will probably be described in a future paper.

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[2] Loc. cit., p. 486.

Classification and Terminology.

The classification here used is that prepared by Prof. Charles E. Beecher and given in the English edition of Zittel's Text-book of Paleontology. For definitions of the various orders and families the reader is referred to that work.

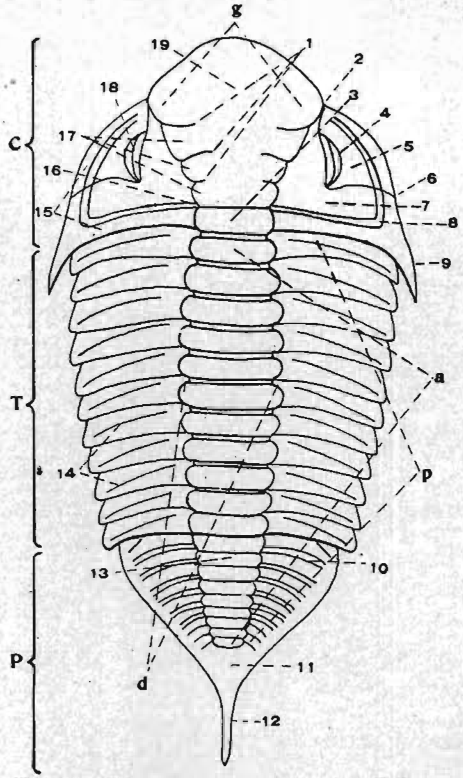

FIG. 32. Diagrammatic figure of a Trilobite.

In order to make clear in what sense various terms are used by the writer, the following glossary is given. The letters or figures in parentheses refer to text figure 32.

Annulations: The ring-like divisions of the axis of the pygidium. (13)

Anterior: Situated in front.

Anterior limb of the facial suture: The portion of the facial suture lying in front of the eye. (2)

Axis: The median longitudinal lobe of a trilobite. (a)

Carapace: The hard shell covering the dorsal surface of a trilobite.

Caudal spine: A spine at the posterior extremity of the pygidium. (12)

Cephalon: The head of a trilobite. (C)

Cheeks: The two lateral portions of the head or cephalon of a trilobite, divided into fixed (7) and free (5) cheeks by a facial suture.

Compound eyes: Eyes commonly present upon the free cheeks of trilobites; they are made up of a large number of small facets. (4)

Cranidium: The portion of the head or cephalon of a trilobite lying between the facial sutures, comprising the glabella and the fixed cheeks.

Distal: Away from the median line.

Dorsal: Pertaining to the back.

Dorsal furrows: The furrows or depressions bounding the axial or medial longitudinal lobe of a trilobite; same as the axial furrows. (d)

Doublure: The infolded margin of the trilobite test.

Facial suture: The suture in the head or cephalon of a trilobite separating the fixed from the free cheeks. (2, 6)

Fixed cheek: The portion of the cephalon or head of a trilobite lying between the glabella and the facial suture. (7)

Free cheek: Lateral portion of the cephalon or head of a trilobite, lying between the facial suture and the lateral cephalic border. (5)

Frontal lobe: That portion of the glabella anterior to the first lateral furrows. (19)

Genal angles: The postero-lateral angles of the cephalon or head of a trilobite.

Genal spines: The posterior prolongation into spines of the genal angles of a trilobite. (9)

Glabella: The central or axial portion of the cephalon or head of a trilobite. (g)

Holochroal eyes: Compound eyes of a trilobite whose visual area is covered with a continuous horny integument.

Hypostoma: The under lip of a trilobite.

Lateral furrows: The transverse furrows or grooves of the trilobite glabella, sometimes continuous across the glabella and sometimes greatly modified. (1) These furrows define the lobes of the glabella. (17)

Marginal border: The thickened or otherwise differentiated external border of the cephalon and pygidium of a trilobite. (15)

Marginal furrow: The groove or depression lying just within the marginal border of the cephalon and pygidium of a trilobite. (8)

Occipital furrow: The posterior transverse groove or furrow of the glabella of a trilobite, lying in front of the occipital segment. (16)

Occipital lobes: Small, lateral lobes of the occipital segment present in some trilobites, which are morphologically different from the lateral lobes of the glabella.

Occipital or neck segment: The posterior transverse segment of the trilobite glabella, lying between the posterior margin and the occipital furrow. (3)

Ocular ridges: Ridges extending from near the anterior extremity of the glabella to the eyes in some trilobites. The eye lines.

Palpebral lobes: Lobes of the fixed cheeks within the margins of the eyes. The eye lobes. (18)

Pleuræ: The two lateral longitudinal lobes of a trilobite, applied chiefly to the thoracic region and the pygidium. (p)

Pleural grooves: Grooves on the pleuræ of the thoracic segments. (14)

Pleural ribs: The fused segments in the lateral lobes of the pygidium. (10)

Post-axial region: The flattened area occupying the median portion of the pygidium of some trilobites, posterior to the elevated axis. (11)

Post-cephalic margin: The posterior margin of the head or cephalon.

Posterior cheek furrow: The marginal furrows or grooves present in some trilobites, which extend across the cheeks from the extremities of the occipital furrow of the glabella towards the genal angles. (8)

Posterior limb of facial suture: That portion of the facial suture extending from the posterior extremity of the eye to the posterior or lateral margin of the cephalon. (6)

Proximal: Toward the median line.

Punctate: Having minute depressions or pits.

Pustulose: Covered with pustules or blister-like prominences.

Pygidium: The tail or posterior region of the trilobite test. (P)

Schizochroal eyes: Compound eyes of the trilobites in which the visual area is occupied by small openings for the separate facets.

Segments: The transverse divisions of the thorax or pygidium.

Test: The hard outer covering of the trilobite.

Thorax: The central segmented region of the body of trilobites. (T)

Ventral: Pertaining to the under surface.

Description of Genera and Species.

Order **OPISTHOPARIA.**

Family **ASAPHIDAE,** Emmrich.

Genus **ISOTELUS** DeKay 1824.

Cephalic and caudal shields of nearly equal size with broad infolded margins; glabella nearly smooth, not lobed; free cheeks large, sometimes meeting in front of the cranidium; eyes prominent holochroal; hypostoma deeply forked; thoracic axis wide; pygidium obscurely lobed, segmentation often obsolete at maturity. This genus is distinguished from *Asaphus* by the absence of the lobation of the glabella, the distinct segmentation of the pygidial axis and the wider thoracic axis.

ISOTELUS GIGAS DeKay.

1824,*I. gigas* DeKay, Ann. Lyceum Nat. Hist. N. Y., Vol. I, p. 174 Pl. 12, fig. 1, Pl. 13, fig. 1.

1897, *I. gigas* Clarke, Pal. Minn. Vol. III, pt. 2, pp. 701 and 706.

A portion of a pygidium from the Lower Maquoketa at Clermont and one from the Upper Maquoketa at Patterson's Springs, on account of their size are doubtfully referred to this species. These are the representation of this species from Fayette county in the Field Museum collection. The State University of Iowa has in its collection a nearly complete individual of this species from the Maquoketa of Florenceville, Howard county, Iowa, so that the species may be looked for in Fayette county.

ISOTELUS MAXIMUS Locke.

1838, *I. maximus* Locke, Sec. Ann. Rept., Geol. Surv., Ohio, p. 246, figs. 8, 9.

1841, *I. megistos* Locke, Trans. Am. Geol. and Nat., p. 221.

1897, *I. maximus* Clarke, Pal. Minn. Vol. III, pt. 2, pp. 701 and 706.

This species is represented in the Field Museum collections by one cephalon in which the specific characters are well shown and several pygidia which probably belong to the species. They were found near the top of the Lower Maquoketa beds at Clermont. Most of the specimens of *Isotelus* from this locality which have been referred by other authors to *I. maximus* are here referred to *I. iowensis* Owen. (See remarks under that species.)

Isotelus iowensis Owen, Plate XIV, figs. 1-2.

1852, *I. iowensis* Owen, Rept. Geol. Surv. Wis., Ia. and Minn., p. 577, Pl. IIa, figs. 1-7.

1913, *I. iowensis* Slocom, Field Mus. Nat. Hist., Geol. Ser. Vol. 4, p. 48, Pl. XIII, figs. 1, 2.

"The general form and contour of the cephalic shield closely resemble that of *I. gigas* DeKay; but the facial sutures do not converge in front to form a distinct angle, but describe three parts of a circle as in *Asaphus expansus.* The eyes are reticulated and the middle lobe of the caudal shield is defined (though sometimes somewhat indistinctly), but the segments are only obscurely pronounced. The glabella is but obscurely defined, and the genal angles are produced into spines. The thorax consists of eight segments.

"From *I. megistos,* it differs in the eyes being set closer together; in the spines being longer, extending as low as the caudal shield; the pygidium more regularly elliptical, and its axial lobe more distinctly defined.

"From the bituminous limestone, mouth of Otter creek, Turkey river, Iowa."

The original description, of which the above is practically a copy, is so incomplete that it seems advisable to redescribe the species in more detail.

Body subelliptical, length about twice the greatest breadth, moderately convex, trilobation not well developed. Entire surface finely punctate, the punctæ being larger and more pronounced on the free cheeks and less conspicuous on the marginal borders than on other parts of the test.

Cephalon semi-oval in outline, marginal border defined by a marginal furrow which originates on the genal spines as an angular groove and develops into a shallow concave furrow gradually widening to the front of the glabella. Dorsal furrows shallow, converging toward the median line in passing the palpebral lobes, then diverging to about their original distance apart. Cranidium moderately convex, greatest convexity just in front of the eyes, concave where the marginal furrow crosses it. The anterior margin of the cranidium forms the margin of the cephalon. Fixed cheeks very small, not well defined. Free cheeks large, with long genal spines, convex near the eyes, not produced in front of the glabella. The facial sutures originate on the posterior margin of the cephalon about midway between the dorsal furrows and the lateral margins, from whence they converge forward in a sigmoid curve to the crest of the eye lobes, which they follow, thence forward and outward in an arcuate curve, meeting the anterior margin of the cephalon in front of the anterior angles of the eyes; here the sutures bifurcate, one fork following the anterior margin until it meets the fork from the other side in a continuous curve or slight angulation, never in a distinct angle; the other fork passes over the margin and curves across the doublure to the base of the hypostoma (Plate XIV, figure 2). Hypostoma forked posteriorly, only slightly constricted at the base, greatest width about three-fifths the length. Compared with *I. gigas* the forks point more directly backward making the notch between them narrower. Eyes lunate, prominent, situated less than their own length in front of the posterior margin of the cephalon, rather near together for the genus. A rather indistinct posterior cheek furrow extends across the fixed cheeks. Occipital ring and furrow obsolete.

Thorax composed of eight segments. Dorsal furrows shallow, ill-defined; axial lobes depressed convex, not tapering, occupying more than one-third but less than one-half the width of the thorax; pleural lobes curving gently upward from the dorsal furrows, then more abruptly downward to the lateral margins; each segment arching gently forward on the axial lobe, and curving slightly backward towards the extremities of the pleuræ.

A shallow concave furrow crosses the axial lobe, originating on the posterior margins at the dorsal furrows. A more pronounced subangular furrow originates on the anterior margin of each pleura at the dorsal furrows and passes diagonally outward and backward about three-quarters the length of the pleura. The distal portion of each pleura is distinctly flattened anteriorly. The flattening occupies nearly the entire width at the rounded extremity of the pleura but gradually narrows towards the dorsal furrow until it disappears.

Pygidium slightly narrower and longer than the cephalon, rather more convex, with a marginal border of uniform width. Axial lobe tapers abruptly near its anterior margin, thereafter only moderately to its prominent, rounded termination, no annulations visible. The segmentation of the pleural lobes is obscure although three or four segments may be distinguished on young individuals. All markings are more distinct on young than on older individuals.

Measurements.—The figured specimen (Field Mus. No. P 11241) (Plate XIV, figure 1) measures: Cephalon 36.5 mm. long, 63.5 mm. wide, thorax 33 mm. long. Another (Field Mus. No. P 6969) measures: Cephalon 21 mm. long, 36 mm. wide, thorax 18.5 mm. long, 36 mm. wide. Pygidium 24.4 mm. long, 34 mm. wide, entire length 63.9 mm.

Remarks.—Specimens of this species have been usually referred to *I. maximus* Locke, but the writer is convinced that they belong to Owen's species as the Field Museum collection contains one nearly complete individual and quantities of less complete ones that were collected at the type locality which agree with Owen's description. The character which most easily distinguishes *I. iowensis* from *I. maximus* is the position of the facial sutures. In *I. iowensis* they follow the anterior margin of the cephalon and unite in a curve or indistinct angle. In *I. maximus* the sutures run subparallel to the anterior margin and meet in a distinct angle so that the free cheeks are produced in front of the glabella, while in *I. iowensis* the cheeks terminate in front of the eyes. Owen describes the genal spines as extending the entire length of the thorax, but his original figures show the spines much shorter. In the specimens before the writer the length of the spines seems to be a variable character.

Locality and horizon.—"Isotelus Zone" near the base of the Lower Maquoketa beds near where Otter creek empties into Turkey river at Elgin, and at Clermont. An hypostoma, undoubtedly belonging to this species, was found on a slab at the top of the upper Maquoketa beds at Patterson's Springs.

Genus **MEGALASPIS** Angelin 1878.

Cephalon having its anterior portion large and flattened. Glabella short, more or less prominent, in front of which the facial sutures unite, usually, in a long drawn out point. Doublure of the cephalon divided by a median suture. Hypostoma arched, not forked, emarginate or drawn out in a point posteriorly. Thoracic axis small, pleuræ rounded at the ends. Pleuræ of the pygidium grooved, doublure of the pygidium narrow with a channel-like excavation. Range, Ordovician, Europe and North America.

This generic description is adapted from Schmidt's[3] discussion of the Asaphidæ. Beecher[4] makes the presence of a well-defined, cylindrical glabella the distinguishing feature of the genus, but a study of the various European species discloses the fact that the form and definition of the glabella are variable characters.

MEGALASPIS BECKERI[5] Slocom, Plate XV, figure 5.

1913, *M. beckeri* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 50, Pl. XIV, fig. 5.

Type specimen in the collection of Mr. A. G. Becker.

General outline of the test subelliptical with its anterior margin produced into a long acuminate process, trilobation only moderately well developed. Entire surface appears smooth to the unaided eye, but under a lens, minute, rounded pustules are visible scattered over the surface. These pustules are larger and nearer together in the axial region, especially just in front of the glabella.

Cephalon subtriangular in outline, with all sides of the triangle concave, marginal border narrow and not well defined. The posterior portion of the cephalon is convex, the anterior

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[3] Rev. Ostbaltischen Sil. Trilobiten Abt. V, lief. 1 and 4.

[4] Zittel-Eastman Text-book Pal., p. 630, 1st. Ed.

[5] This name was proposed by Mr. E. O. Ulrich and the figure is from a photograph furnished by him.

portion flattened and produced into a long acuminate process pointing obliquely upward. Dorsal furrows visible only in the occipital region. Glabella not defined laterally or anteriorly, depressed convex, greater elevation at its posterior margin, which is the greatest elevation of the entire test. Fixed cheeks not defined. Free cheeks large, widest near the eyes, where they slope abruptly to the lateral margins; the genal angles are produced into short spines, extending directly backward as far as the sixth thoracic segment; the anterior portions narrow gradually forward until they meet at the anterior margin. The facial sutures originate on the posterior margin of the cephalon about midway between the dorsal furrows and the genal angles, converging slightly to the eyes; in front of the eyes they converge more rapidly, extending subparallel to the antero-lateral margins of the cephalon and meeting in front of the glabella. The palpebral lobes are prominent, their proximal edges being produced towards the median line of the glabella and interrupting the dorsal furrows; the transverse ridges thus formed appear to be comparable to lateral glabella lobes rather than ocular ridges. Form of the eyes not known, but one of the palpebral lobes on a cranidium (Field Mus. No. P 16998) indicates that they were elevated similar to those of *Nileus vigilans.* Occipital segment and furrow obsolete. Shallow posterior cheek furrows extend laterally from the dorsal furrows, meeting the lateral furrows near the genal angles.

Thorax composed of eight segments. Dorsal furrows shallow; axis depressed convex, slightly tapering posteriorly; occupying somewhat more than one-third the width of the thorax; no transverse furrows; the pleuræ curve outward and then abruptly downward to the lateral margins; distal extremities rounded; angular furrows originate at the dorsal furrows and cross the pleuræ diagonally.

Pygidium slightly narrower and much shorter than the cephalon, marginal border defined only near the posterior margin. Axis tapering to a prominent rounded termination well within the margin. The pleural lobes curve abruptly to the lateral margins. The segmentation of the pygidium is not visible on the outer surface of the test, but on its inner surface some traces may be found on both axis and pleuræ.

The measurements of the type specimen are as follows: Length over all 89.1 mm.; width at genal angles 37.2 mm.; length of the cephalon on median line 42.5 mm.; length of cephalon including genal angles 57 mm.; length of thorax 21.3 mm.; width of thorax at anterior segment 33 mm.; length of pygidium 26.5 mm.; width of pygidium at anterior margin 29.5 mm.

So far as known to the writer, only two American species have been referred to this genus. These are *M. ? gonioceras* Meek from the Quebec group of Utah and *M. belemnura* White from a similar horizon in Nevada. These species were described from pygidia only, so that their reference is somewhat doubtful. Judging from the descriptions and figures of the above species, neither of them closely resembles the pygidium of *M. beckeri;* so that comparison must be made with European species. In general form *M. beckeri* most closely resembles *M. extenuata* Angelin from Gothland, Sweden, but is distinguished from that species by not having the glabella defined laterally or anteriorly, by having its genal spines less flaring and by having much narrower marginal borders of the pygidium.

The specific name is given in honor of Mr. A. G. Becker, whose collection contains the type specimen.

Localities and horizon.—The species is known to the writer by a practically complete specimen, the type, and a nearly complete cranidium (Field Mus. No. P 16998). The type is from the Lower Maquoketa beds at Clermont and the cranidium from a similar horizon at Postville Junction.

Genus **NILEUS** Dalman 1826.

"Corpus breve, convexum læve, sulcis dorsalibus longitudinalibus nullis; segmentis trunci 8. Oculi maximi, laterales." (*Palæden oder die Sogenannten Trilobiten, p. 70.*)

The above is Dalman's original description of the genus and may be somewhat elaborated as follows: Body elliptical, convex, smooth. Cephalon twice as wide as long, convex, genal angles broadly rounded. Glabella undefined laterally, no lateral furrows. The facial sutures originate on the posterior margin of the cephalon, curve forward to the eye lobes, over which they pass, thence with a sigmoid curve to the anterior margin, where they meet. Eyes large, lunate, holochroal. Rounded hypostoma with elevated border. Eight thoracic segments, indistinctly tri-lobed, axial lobe the broader. Pygidium twice as broad as long, neither lobed nor segmented, broadly rounded posteriorly. Range, Ordovician of Europe and North America.

NILEUS VIGILANS (Meek and Worthen). Plate XV, figures 9-15.

1875, *Asaphus vigilans* M. & W., Geol. Surv. Ills., Vol. VI, p. 497, Pl. XXIII, fig. 6.

1897, *Nileus vigilans* Clarke, Pal. Minn., Vol. III, pt. 2, p. 712, figs. 17-19.

1913, *N. vigilans* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 52, Pl. XIV, figs. 9-15.

Body convex, trilobation very obscure, subelliptical in outline, lateral margins nearly parallel. Surface smooth to the naked eye, but under a magnifier the extremities are ornamented with transverse impressed lines. These lines are most distinct on the doublure and anterior portion of the glabella and rather indistinct on the pygidium. Free cheeks finely punctate.

Cephalon sublunate in outline, somewhat depressed on the anterolateral margin, convex, frontal slope inflated but not projecting. Margin marked by a slight recurved elevation; genal angles obtusely rounded; free cheeks large, produced in front of the cranidium nearly or quite to the median line. Eyes small for the genus but prominent, situated at points each one-third the transverse diameter of the cephalon, and about their own diameter from the posterior margin. The facial sutures originate on the posterior margin of the cephalon at about one-third the distance from the dorsal furrows to the genal angles, curve obliquely forward over the palpebral lobes, thence in sigmoid curves to the anterior margin, where they meet. Glabella furrows, dorsal furrows and occipital ring and furrow are obsolete on the surface of the test, but on casts the location of the dorsal furrows is indicated on each side by pits at the posterior margin of the cephalon. These pits are connected by a shallow occipital furrow, running parallel to the posterior margin until near the median point, where it arches forward.

Thorax composed of eight broad, flat segments, trilobation very obscure; axis about three-fourths the entire width, depressed convex; pleural lobes curving regularly to the lateral margins; segments arched slightly forward on the axial lobe, somewhat curved backward. On enrolled specimens this backward curve appears greater than it really is on account of the flattening of the anterior portion of the pleuræ, which originates at the dorsal furrows and gradually widens distally. On the anterior border at the dorsal furrow of each segment are small projections which point forward and fit into corresponding notches of the preceding segment. The segments are without grooves on the test, but on the casts a shallow groove connects the dorsal furrows.

Pygidium somewhat narrower but longer than the cephalon, depressed convex, sloping equally to the margins, trilobation and segmentation wanting on the surface of the test but faintly discernible on the casts.

Remarks.—The Maquoketa specimens, above described, appear to correspond in practically all points to the original description and are from a similar horizon to the type. The Galena and Trenton specimens referred to this species and described by Clarke appear to differ as follows: The facial sutures reach the margin of the cephalon in front of the eyes, while in the Maquoketa specimens the sutures reach the anterior margin near the median line of the cephalon. The front part of the cranidium is more inflated in the Maquoketa specimens.

Locality and horizon.—This species was described originally from the Cincinnati shales of Carroll and Kendall counties, Illinois. It has been collected by the writer from the Lower Maquoketa beds at Clermont, Elgin, and Bloomfield, and from the Upper Maquoketa bed at Patterson's Springs near Brainard.

Genus **BUMASTUS** Murchison 1839.

"General characters.—*Pars anterior; capitis rotundato-convexa, subæqualis; oculis lunatis, glabris, remotis. Pars costalis s. corpus, sulcis longitudinalibus vix apparentibus, costis decem. Pars posterior maxima, rotundato-tumida, æqualis. Omnes testæ partes ultro citroque, linearum sulcatarum subtilisimis ambagibus punctulisque confertis, insignitæ.*" *Silurian System* 1839, p. 656.)

(TRANSLATION)

Generic characters.—Anterior part; (cephalon) rotund, convexity of the head subuniform; eyes lunate, smooth, situated far apart. Segmented part of the body; (thorax) longitudinal furrows scarcely discernible, ten segments. Posterior part (pygidium) large, roundly, uniformly tumid. All parts of the test irregularly marked by impressed lines, interspaces finely and obscurely punctate.

The above is the original description of the genus. The author states later that the surface markings may be of only specific importance and that he has added them to the generic definition provisionally.

BUMASTUS BECKERI Slocom, Plate XV, figures 1-4.

1913, *B. beckeri* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 54, Pl. XIV, figs. 1-4.

Type specimens.—Holotype in collection of Mr. A. G. Becker, one paratype in collection of State University of Iowa, and the other No. P 16708 Field Museum.

Description.—Body oblong, slightly ovate, width at the genal angles about half the entire length. Dorsal furrows nearly obsolete on the cephalon and thorax and entirely so on the pygidium. Surface, except in the region of the palpebral lobes, dorsal furrows and the anterior central portion of the glabella, marked with indented, transverse lines, more or less parallel to each other and to the transverse divisions of the test. These lines are conspicuous and close together on the doublure, somewhat less so on the cephalon and anterior segments of the thorax. On the posterior segments and pygidium they are inconspicuous and discernible only with a magnifier.

Cephalon strongly convex, semicircular in outline; the location of the dorsal furrows indicated by two almost imperceptible grooves leading up to longitudinally elongate depressions situated just in front of a line joining the anterior edges of the eyes and somewhat nearer to the eyes than to the median line of the cephalon. These depressions appear as sublunate grooves on the casts, but on the surface of the test only as a slight flattening. The regular curvature of the cephalon, aside from the flattening just referred to, is interrupted only by the palpebral lobes. Eyes far apart, situated at about half their length from the posterior margin of the cephalon. Facial sutures originate on the posterior margin of the cephalon on a level with the lower edges of the eyes, from whence they pass forward and upward around the eyes, thence obliquely downward to the antero-lateral margin of the cephalon. Free cheeks small, genal angles obtusely rounded. Occipital ring not discernible on either test or cast.

Thorax composed of ten segments, smooth and flat, gradually narrowing to the almost obsolete dorsal furrows, at which points they bend backward and downward to the lateral margins; the axis occupies about two-thirds of the width of the thorax; dorsal furrows appear on the casts as two parallel grooves.

Pygidium strongly arched, transversely oval, length about two-thirds the width, no trace of the dorsal furrows.

Five specimens were used by the writer in making this description. The holotype (Plate XV, figure 1) is an enrolled specimen having a portion of the front of the cranidium missing. It is in the private collection of Mr. A. G. Becker. A paratype (Plate XV, figures 2-3) consists of a complete cephalon attached to nine complete thoracic segments and a portion of the tenth. This specimen was collected by Professor Calvin and is a part of the geological collection of the State University of Iowa. The other paratype (Plate XV, figure 4) is a pygidium attached to the seven posterior thoracic segments. It belongs to the Field Museum collections (Field Mus. No. P 16708). Two somewhat distorted natural casts (Field Mus. No. P 16854) were also used in making this description. These casts were presented to the Field Museum by Mr. Becker. The dimensions of the type specimens are as follows: Holotype: Cephalon 18 mm. long, 31.5 mm. wide; pygidium 15 mm. long, 26.4 mm. wide; distance around the coiled specimen 74.5 mm. Allowance for the convexity of the cephalon and pygidium would make the length, if the specimen were unrolled, about 60 mm. Specimen from the State University of Iowa: Cephalon 19.6 mm. long, 32.3 mm. wide and 18 mm. thick. Specimen P 16708: Pygidium 11 mm. long, 19 mm. wide, length of pygidium and the seven posterior segments of the thorax 33 mm.

Remarks.—Specimens of this species have been referred to *B. orbicaudatus* Billings, by Calvin, Savage, and others in the various Iowa reports. *B. orbicaudatus* was originally described[6] from a pygidium only and a complete specimen was afterwards[7] figured by Billings. Referring to this description and figure, it is evident that *B. beckeri* is quite distinct from *B. orbicaudatus.* The cephalon and pygidium are much longer in proportion to their width, and the dorsal furrows are much more distinct in *B. orbicaudatus.* The orbicular axis of the pygidium, which is the distinguishing character of *B. orbicaudatus,* is missing in *B. beckeri. B. beckeri* seems to be most closely related to *B. billingsi* Raymond and Narraway, from the Trenton limestone of Canada, but it is considerably narrower in proportion to its length, the trilobation is much less pronounced and no mention is made in the description of *B. billingsi* of any transverse lines on the test.

The specific name is given in honor of Mr. A. G. Becker, whose collection contains the holotype.

Locality and horizon.—All specimens observed are from the Lower Maquoketa beds of Clermont.

Genus **THALEOPS** Conrad 1843.

"Ovate, profoundly trilobed, lateral lobes wider than the middle lobe; buckler (cephalon) lunate, with very remote oculine tubercles, not reticulated; abdomen (thorax) with 10-articulations; ribs without grooves and not alternated in size; outer half of lateral lobes suddenly depressed; post-abdomen (pygidium) without ribs or grooves and profoundly trilobed."

"This genus is remarkable for the great width of the buckler, and the very prominent laterally projecting smooth oculine tubercles. It differs from *Bumastus* in being profoundly lobed, and in having the side lobes as in *Asaphus* much wider than the middle lobe. From *Illænus* it may be distinguished by its ovate form, want of reticulated eyes, the width of the lateral lobes, and the profound lobes of the tail." (*Proc. Acad. Nat. Sci. Phil.,* 1843, Vol. I, p. 331.)

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[6] Can. Nat. Geol., Vol. iv, p. 379.
[7] Cat. Sil. Foss. Anticosti, p. 27.

The above is Conrad's original description of the genus and to it should be added that the free cheeks are produced laterally at the genal angles into blunt spines.

THALEOPS OVATA Conrad, Plate XV, figures 6-8.

1843, *T. ovata* Conrad, Proc. Acad. Nat. Sci. Phil., Vol. I, p. 332.

1882, *Illænus ovatus* Whitfield, Geol. Wis., Vol. IV, p. 238, Pl. 5, figs. 1-2.

1897, *T. ovata* Clarke, Pal. Minn., Vol. III, pt. 2, p. 716, figs. 17-19.

1913, *T. ovata* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 56, Pl. XIV, figs. 6-8.

Body broadly ovate, widest at the base of the cephalon, distinctly trilobed, length about equal to the width at the eye lobes.

Cephalon broadly semicircular on the anterior margin, very highly convex. Dorsal furrows clearly defined on the posterior third of the cephalon, obsolete in front. Glabella convex between the dorsal furrows, not defined in front. Eyes small, pedunculate, extending laterally and horizontally. Occipital segment and furrow very faintly marked, rounded backward. Free cheeks small, produced laterally at the genal angles into blunt spines. The facial sutures rise rapidly from the posterior margin to the summit of the eye lobes, thence round gradually forward to the anterior margin, which they intersect in front of the dorsal furrows.

Thorax wider than long, tapering, composed of ten smooth, slightly convex segments. Axial lobe depressed convex, narrower than the lateral lobes, segments arched forward. Pleuræ flat for more than half their width from the axis, then bent downward, segments strongly recurved toward their extremities.

Pygidium nearly flat on top and curving abruptly to the margins, short, subquadratic. The posterior margin forms a very broad curve, width about twice the length. Axis prominent, narrower than the thoracic axis, tapering slightly and terminating bluntly in an elevated extremity, which is faintly bilobed; axis entirely surrounded by the dorsal furrows; annulations of the axis nearly obsolete.

The surface of the cephalon is covered with epidermal punctæ except in the dorsal furrows and on the palpebral lobes. On the cheeks and anterior portion of the glabella the punctæ are vertical and isolated, on the posterior surface of the glabella they are oblique and crowded. The surface of the thorax appears to be smooth. Doublure marked with prominent lines parallel to the anterior margin. Pygidium sparsely punctate on the posterior margin but on the anterior portion the punctations are deep, coarse, and arranged in transverse rows.

The foregoing description is based on a practically complete specimen from the Platteville beds at Mineral Point, Wisconsin, in the paleontological collection of the University of Chicago. The Fayette county specimens have been compared with the Platteville specimen and agree so well that they must be considered to be specifically identical, although previously *T. ovata* has been found only at lower geological horizons.

This species is represented in the Field Museum collections from Fayette county by a nearly complete cranidium from the Lower Maquoketa at Clermont and another from the Upper Maquoketa at Patterson's Springs.

Family **LICHADIDAE**, Barrande.

Genus **AMPHILICHAS** Raymond 1905.

(Platymetopus[8] Angelin 1854, Paralichas Reed 1902.)

By combining the various characters enumerated in previous descriptions this genus may be described as follows:

Cephalon broadly subtriangular, tuberculate. Anterior lobe of the glabella dominating the other lobes, and continuous with the axis; a single pair of lateral glabella furrows opening directly into the occipital furrow; no third lobes; all lobes depressed convex, all furrows narrow; dorsal furrows concave inward; occipital ring forming a band. Pygidium with two rings on the axis; post-axial piece not defined posteriorly; three pairs of pleuræ, each with pleural furrow and free point; third pair incompletely defined from post-axial piece, points short and blunt.

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[8] Platymetopus Angelin, 1854, preoccupied by Dejean, 1829, for genus of Coleoptera. Paralichas Reed, 1902, suggested in its place, preoccupied by White, 1859, also for Coleoptera.

AMPHILICHAS RHINOCEROS Slocom, Plate XVI, figures 5-6.
1913, *A. rhinoceros* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 58, Pl. XV, figs. 5-6.

Type specimen No. P 11181 Field Museum.

Glabella large, occupying nearly the entire width of the cranidium, depressed convex posteriorly, inflated in front, subpentangular in outline, rounded anteriorly, greatest width just in front of the eyes; the single pair of glabella furrows originates on the lateral margins, curves gently inward and backward for about half the length of the glabella, thence backward subparallel until they join the occipital furrow. They thus divide the glabella into a median and two lateral lobes. Median lobe broad in front, posterior half only slightly convex, anterior half abruptly inflated, length about two and one-half times the width at the occipital furrow. Lateral lobes undivided, margins subparallel, width about equal to that of the median lobe, moderately convex except in front where they bend outward and downward to the lateral margins; greatest elevation near the dorsal furrows in line with the palpebral lobes, where large nodes rise abruptly from the dorsal furrows but elsewhere gradually; these nodes form the bases of the two, long, lateral spines. The occipital segment forms a wide, depressed, transverse band, widest in the middle and gradually narrowing towards the dorsal furrows; posterior margin slightly concave, with a well developed doublure. Dorsal furrows, as well as glabella and occipital furrows, narrow but well defined. Fixed cheeks small, depressed, convex, aside from the palpebral lobes, which rise abruptly; the only portion of the palpebral lobes observed is that attached to the fixed cheek. This is elevated, lunate in form with the convex side toward the dorsal furrows. The marginal border of the cephalon is represented by only a single, somewhat crushed fragment, but this fragment indicates that there was a narrow marginal border similar to that of *A. bicornis* Ulrich. Eyes and free cheeks not preserved. Surface of the cephalon finely papillose, with tubercles of various sizes more or less regularly arranged thereon. Two of the larger of these tubercles occur along the median line of the glabella, one on each lateral lobe, and three form a transverse row on the occipital segment; aside from these tubercles, the inflated anterior portion of the glabella supports a pair of recurved hornlike processes, 2.5 mm. in diameter and 29 mm. long (measured on the outer side of the curve); these processes diverge somewhat and curve upward, then backward. Another pair of processes of about the same size occurs; one on each lateral lobe of the glabella, near the dorsal furrow, in line with the eyes. Exact length of the lateral pair of processes not known.

Thorax and pygidium unknown.

The specimen (Field Mus. No. P 11181) on which the above description is based consists of a nearly complete cranidium of which the inner surface of the test is exposed with one of the anterior horns complete and in natural position and one of the lateral ones bent outward with the end missing. The dimensions are as follows: Length of cranidium, along the median line, 32 mm.; greatest width of glabella (in front of eyes) 42 mm.; width of median glabella lobe on anterior margin 18 mm.; width at occipital furrow 11.5 mm.; width of lateral lobes 11.5 mm.; width of occipital segment on median line 7 mm.; width at dorsal furrows 5.5 mm.

Remarks.—In general form and proportion the cranidium above described approaches *A. bicornis* Ulrich, from a similar horizon in Minnesota, but is distinguished from that species by the number and position of the hornlike processes as well as by the variation in size of the surface tubercles; also in a side view of the glabella of *A. bicornis* the outline of the surface is convex, while in *A. rhinoceros* the outline near the middle is concave, due to the inflation of the anterior portion.

Locality and horizon.—Upper layers of the Lower Maquoketa beds at Elgin.

AMPHILICHAS CLERMONTENSIS Slocom, Plate XVI, figure 7.

1913, *A. clermontensis* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 59, Pl. XV, fig. 7.

Type specimen No. P 11257 Field Museum.

Cephalon subtriangular, broadly rounded anteriorly, much shorter in proportion to the width than *A. rhinoceros.* Glabella convex, greatest elevation just in front of the center, to which point it rises gradually from the posterior and lateral margins and much more abruptly anteriorly; subpentangular in outline, widest in front of the eyes; a single pair of glabella furrows originates on the lateral margins, curves abruptly inward and upward, then converges backward until it meets the occipital furrow, forming a large median lobe and two smaller lateral lobes. Median lobe very broad anteriorly, more than twice the width at the occipital furrow. It comprises nearly two-thirds of the glabella. Lateral lobes undivided, margins subparallel, conforming to the general convexity of the glabella, abruptly bent downward anteriorly. Occipital segment a flat or slightly concave, transverse band, widest at the juncture of the occipital and glabella furrows, narrowing slightly to the median line and more so laterally. Occipital and glabella furrows narrow but distinct. Surface smooth to the naked eye, but a magnifier shows it to be covered with variously sized pustules. No nodes or spines interrupt the regular curvature of the cephalon.

Thorax and pygidium unknown.

The specimen here described (Field Mus. No. P 11257) consists of an incomplete glabella. The cheeks and marginal border are entirely missing. The median lobe and one lateral lobe are nearly complete, and the other lateral lobe is somewhat less so. The occipital, one dorsal and the glabella furrows are well indicated and the median portion of the occipital segment is intact. While the specimen leaves much to be desired, yet the generic characters are well shown and the specific characters fairly well.

The dimensions are as follows:

Length of glabella on median line (exclusive of occipital segment)	24.5 mm.
Greatest width of glabella (in front of the eyes)	30 mm.
Width of glabella at occipital furrow	26 mm.
Width of median glabella lobe on anterior margin, about	24 mm.
Width of median glabella lobe on occipital furrow	11.5 mm.
Width of lateral glabella lobes	8.5 mm.
Length of lateral glabella lobes	17 mm.
Width of occipital segment on median line	3.5 mm.

Width of occipital segment behind glabella furrows. 4.2 mm.

Amphilichas clermontensis is distinguished from the other members of this genus by the much greater width of the glabella in proportion to its length and by its more nearly arcuate curvature both longitudinally and transversely. In surface ornamentation it resembles *A. circullus* from the Trenton, but in form it is quite distinct from that species.

Locality and horizon.—Lower Maquoketa Beds, Clermont.

Order **PROPARIA.**

Family **ENCRINURIDAE**, Linnarsson.

Genus **ENCRINURUS** Emmrich 1844.

"Cephalon tuberculate; glabella pyriform, prominent; free cheeks narrow, separated in front by a small rostral plate; eyes small, elevated on conical prominences; thoracic segments eleven; pygidium triangular, numerous annulations on the axis, pleuræ with few ribs." Range, Ordovician and Silurian, Europe and America. (*Zittel-Eastman Text-book Pal., p. 634.*)

Vogdes[9] divided the above genus by placing all species without genal spines in *Cryptonymus* Eichwald, but his point does not appear to be well taken for two reasons. (1) In 1825 Eichwald described the genus *Cryptonymus* with *C. scholotheimi* as genotype. Seven other species were placed in the genus. The genotype and three others were found to belong to the genus *Asaphus* Brong., the balance to *Illænus* Dahlman. In 1840 Eichwald again used the name *Cryptonymus* for a genus entirely different from the one described in 1825, thus using a preoccupied name. (2) The presence or absence of genal spines does not appear to the writer to be of generic importance.

ENCRINURUS PERNODOSUS Slocom, Plate XVII, figures 5-7.

1913, *E. pernodosus* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 61, Pl. XVI, figs. 5-7.

Type specimens Nos. P 17038 and P 16930 Field Museum.

Body ovate in outline, trilobation distinct, without genal or caudal spines.

Cephalon sublunate in outline, anterior margin inflated, width more than twice the length. Glabella subhemispherical, width

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[9] Trans. San Diego Soc. Nat. Hist. Vol. I, No. 2, p. 74.

somewhat less than the length, slightly protruding beyond the anterior margin; three pairs of indistinct lateral glabella furrows define the lateral lobes; these furrows rapidly decrease in depth from the dorsal furrows and become obsolete among the tubercles; a well-defined furrow originates on the dorsal furrows about midway between the anterior lateral glabella furrows and the anterior marginal furrow and bends slightly forward in crossing the anterior lobe of the glabella; anterior glabella lobe large, comprising nearly half the glabella, lateral lobes quadrangular, decreasing rapidly in size posteriorly; occipital segment narrow, resembling the axial portion of one of the thoracic segments in size and form; occipital furrow narrow, angular, well-defined; dorsal furrows deep, angular, diverging somewhat from the occipital furrow to the anterior marginal furrow; cheeks subtriangular in outline, depressed conical in form, sloping gradually to the palpebral lobes; eyes small, pedunculate, holochroal; facial sutures originating at the genal angles, passing directly to the palpebral lobes, which they cross, thence obliquely forward, crossing the dorsal furrows and subparallel to the furrow crossing the glabella, until they meet the rostral plate, where they bend abruptly forward to the anterior margin; free cheeks large, more than twice the size of the fixed cheeks; marginal borders well-defined by the marginal furrows, those of the posterior margin narrow, those of the lateral margins wide, gradually narrowing to the anterior margin; genal angles rounded, ending in a large tubercle. Surface of the glabella covered with large rounded tubercles, that of the cheeks near the dorsal and lateral marginal furrows tubercular, other portions covered with elongated pits radiating from the eyes; surface of the occipital segment and marginal borders finely granulose. Hypostoma broadly elliptical, convex.

Thorax composed of eleven segments; axis convex, about the same width as the pleuræ; tapering slightly posteriorly, pleuræ curving regularly to the lateral margins; surface of the thoracic segments finely granulose, ornamented with indistinct nodes; these vary from two to four on the axis and one or two on each pleura; no pleural grooves.

Pygidium triangular, convex, width somewhat greater than the length, rounded posteriorly, no caudal spines. Axis convex, conical, occupying about one-third the anterior margin of the pygidium, with many annulations, which diminish in size and distinctness posteriorly so that the number visible depends to a great extent on the amount of abrasion to which the specimen has been subjected; most of the annulations bear two to four rounded nodes, having decided pits in their apices. Pleuræ composed of seven distinct ribs, which curve slightly upward and then downward and backward to the margins; each rib ornamented with two or more rather indistinct nodes near the dorsal furrows and with a prominent knoblike distal end.

Dimensions of the type specimen:

Length of cephalon	10 mm.
Width of cephalon at genal angles	17.5 mm.
Length of glabella exclusive of occipital segment	8.4 mm.
Width of glabella on anterior margin	8.0 mm.
Width of glabella on occipital furrow	5.0 mm.
Entire length of body measured on a coiled specimen	32.0 mm
Length of pygidium (Field Mus. No. P 16930)	8.2 mm.
Width of pygidium	9.6 mm.
Width of axis at anterior margin	3.6 mm.

The species is known from the holotype (Field Mus. No. P 17038) in which the cephalon, about two-thirds of the thorax and most of the pygidium are preserved, from five detached pygidia and from one specimen in which the entire pygidium is attached to all but the anterior segment of the thorax.

In general form and proportions the species here described resembles *E. variolans,* Brongniart, from the Wenlock Limestone of England, but the tubercles are much larger, the transverse furrow on the glabella is missing and the annulations of the pygidia are fewer in number. *E. sexcostatus* Salter possesses the transverse furrow, but that seems to be about the only resemblance with this species.

Locality and horizon.—The holotype is from the top of the Lower Maquoketa beds at Bloomfield. The species has been found at a similar horizon at Clermont and Elgin, and at a somewhat lower horizon at Clermont.

Genus **CYBELOIDES** gen. nov.

Body distinctly trilobate, outline, aside from the spines, subovate. Cephalon sub-lunate; genal angles produced into spines. Glabella divided by two longitudinal furrows into a central and two lateral lobes; the lateral glabella furrows are indicated by three pits situated in each longitudinal furrow. Eyes small, pedunculate; the facial sutures originate on the lateral margins somewhat in front of the genal angles. Thorax consists of twelve segments; the five anterior segments are faceted at their distal extremities. The sixth segment, and in some specimens the sixth to the twelfth, is abruptly bent backward at the lateral margin of the thorax and produced into long spines. Pygidium small, axis conical with many annulations, pleural lobes with few ribs.

Genotype, *Cybeloides iowensis.* Range, Ordovician of North America.

This genus differs from *Cybele* Loven as exhibited in *C. bellatula,* the genotype, in the form of the glabella furrows and in the genal angles being produced into spines instead of being rounded.

Four American species have been referred to the genus *Cybele; C. ella* Narraway and Raymond, *C. prima* (including *C. valcourensis*) Raymond, *C. winchelli* Clarke, and a portion of a pygidium referred to the genus without specific determination by Ruedemann. Of the first two only is the form of the glabella known, but both of these agree with *C. iowensis* Slocom. Narraway and Raymond called attention to the difference of the form of the glabella of this species from that of the European species, but still referred their species to *Cybele.* While the presence or absence of genal spines would not be of generic importance, the fact that the glabella is divided longitudinally into three lobes appears to be ample reason for separating the American from the European species generically. This is the character which distinguishes *Chasmops* from *Dalmanites* and the various genera of the Lichadæ are based on the variations of the glabella furrows.

Of the eleven European species of *Cybele* known to the writer, two have only the pygidium described or figured; the other nine all have well-marked lateral glabella furrows. Three of these species described by Schmitz, viz., *C. grewingki, C. kutorgæ* and *C. revaliensis,* exhibit a tendency toward the American forms. The lateral furrows are separated from the dorsal furrows by a narrow lateral margin of the glabella, but there are no traces of longitudinal glabella furrows.

The bibliography of the genus is as follows:

Cybeloides ella Narraway and Raymond.

1906, *Cybele ella* N. & R., Ann. Carnegie Mus., Vol. 3, No. 4, p. 598, fig. 1. Black River, Ottawa, Canada.

Cybeloides iowensis Slocom, genotype, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 64, Pl. XVI, figs. 1-4. Lower Maquoketa, Iowa.

Cybeloides prima Raymond.

1905, *Glaphurus primus* Raymond, Ann. Carnegie Mus., Vol. 3, No. 2, p. 362, pl. 14, figs. 7-8.

1905, *Cybele valcourensis* Raymond, ibid p. 362, pl. 14, fig. 9.

1906, *Cybele prima* Narraway and Raymond, Ann. Carnegie Mus., Vol. 3, No. 4, p. 601. Chazy, N. Y.

Cybeloides ? winchelli Clarke.

1897, *Cybele winchelli* Clarke, Pal. Minn., Vol. 3, pt. 2, p. 742, fig. 59. Galena Limestone, Minn.

Cybeloides ? sp. ? Ruedemann.

1901, *Cybele* sp. ? Ruedemann, N. Y. St. Mus. Bull. 49, p. 66, pl. 4, fig. 12. Trenton, N. Y.

The last two species are placed in the genus provisionally until the characters of the glabella are known.

CYBELOIDES IOWENSIS Slocom, Plate XVII, figures 1-4.

1913, *C. iowensis* Slocom.

Type specimens Nos. P 16631, 16633 and 17039 Field Museum.

Body depressed convex, distinctly trilobed, outline, aside from the spines, subovate, tapering rather rapidly to a small pygidium. Surface finely granular with many more or less prominent rounded nodes.

Cephalon short, width nearly three times the length, outline sublunate with the anterior lateral margins inflated. Glabella convex, inflated anteriorly, somewhat longer than wide, widest across the lateral lobes; median lobe clavate, narrow at the occipital furrow, gradually widening for about half its length then abruptly widening until its greatest width is reached, rounded in front; lateral lobes longitudinally oval; longitudinal glabella furrows originating in deep pits on the occipital furrow, converging slightly, then curving forward and outward; the positions of the lateral glabella furrows are indicated by three pits in the longitudinal furrows; occipital ring prominent, more elevated than any other part of the cephalon, wide between the glabella furrows, abruptly narrowing towards the dorsal furrows, bearing a large median node with a smaller one on each side of it; occipital furrow shallow and ill-defined in the median portion, deepened into pits near the dorsal furrows. Surface of the glabella finely granular with many prominent rounded nodes arranged in more or less uniform transverse rows; the two largest nodes are close together near the anterior margin and point forward. On the median line of the glabella just in front of a line connecting the anterior pair of glabella pits is a circular, well-marked pit. Cheeks large, depressed convex, not rising as high as the glabella, genal angles produced into long spines, which extend backward more than half the length of the thorax. Marginal borders convex; posterior marginal furrows narrow and deep, lateral marginal furrows not well-defined. The facial sutures originate on the lateral margin just in front of the genal angles, pass almost straight to the palpebral lobes, after crossing which they extend forward for a short distance, then curve abruptly toward the median line and again forward to the anterior margin. Eyes small, pedunculate and very prominent (Plate XVII, figure 4), situated on a line with the anterior pair of glabella pits near the dorsal furrows; a pair of ocular ridges connects the eyes with the anterior lobe of the glabella. Surface of the cheeks inside the marginal borders reticulated, or covered with rows of pits; surface of the marginal borders granular like the glabella, many nodes irregularly distributed over the cheeks; these nodes average somewhat larger than those on the glabella; the larger ones are on the posterior margin and point backward instead of outward.

Thorax composed of twelve segments, rather rapidly tapering posteriorly, distinctly trilobed; axis convex, less than one-third the width of the thorax; the pleural lobes curve gently for about half their width and then more rapidly to the lateral margins. Each segment is divided unequally by a furrow extending nearly from one margin of the thorax to the other. The posterior portion, which is the wider, bears numerous nodes, four of which occur on the axis and two or more on each pleura. The nodes on the pleuræ are much larger than those on the axis and their location on different segments is not always uniform. The five anterior segments terminate at the lateral margins of the thorax, but the seven posterior ones are abruptly bent backward at the lateral thoracic margins and are produced into spines. The spines of the sixth segment extend more than one-third their length beyond the pygidium; the spines of the other segments are considerably shorter.

Pygidium small but too poorly preserved in the specimens at hand for a detailed description.

The dimensions of the type specimens are as follows:

Length of the holotype along the axis 23.6 mm. Length of body, including pleural spines, 31.3 mm.; width at genal angles 19.6 mm.; length of cephalon, including genal spines, 16 mm.; length of glabella 7.8 mm.; width of anterior portion of glabella 4.7 mm., across lateral lobes, 5.3 mm.; length of thorax 12.8 mm.

Width of paratype at genal angles 27.8 mm.; length of glabella 10.7 mm.; width of posterior portion 8.0 mm., across lateral lobes, 8.7 mm.

This description is based upon the holotype (Field Mus. No. P 16631, Plate XVII, figure 1), a nearly complete specimen, a practically complete cephalon (Field Mus. No. P 17039, Plate XVII, figures 2-3), somewhat larger than the holotype, and a detached free cheek with eye (Field Mus. No. P 16633, Plate XVII, figure 4).

Localities and horizon.—The holotype was collected by the writer from the top of the Lower Maquoketa beds at Elgin, the two paratypes from a similar horizon at Bloomfield. More or less complete cranidia are not uncommon at a similar and somewhat lower horizon at Clermont.

Family **CALYMENIDAE,** Brongniart.

Genus CALYMENE Brongniart, 1822.

"Complete body sub-oval in outline, possessing the power of complete enrollment; cephalon sub-crescentiform with thickened margin, genal angles usually rounded; glabella strongly convex, narrowed in front, with three pairs of deep lateral furrows; occipital segment well defined; posterior limb of the facial sutures originating just in front of the genal angles; free cheeks elongate, separate, usually with a free plate between their anterior extremities in front of the glabella; eyes small; hypostoma sub-quadrate, notched. Thorax with thirteen segments; axis strongly convex and bounded by deep axial furrows; pleural lobes wider than the axis, bent down laterally. Pygidium distinctly marked off from the thorax, with six to eleven segments, axis prominent and margin entire." (*Weller, Pal. Chicago Area,* p. 261.)

CALYMENE FAYETTENSIS Slocom, Plate XVII, figures 8-9.

1913, *C. fayettensis* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 67, Pl. XVI, figs. 8-9.

Type specimen No. P 16755 Field Museum.

Body strongly trilobate, subovate in outline, greatest breadth at the genal angles, narrowing gradually to the anterior border of the pygidium, thence abruptly to the posterior extremity of the pygidium. Surface finely papillose with small rounded tubercles more or less regularly distributed thereon.

Cephalon sublunate in outline, anterior border arcuate, except between the anterior limbs of the facial sutures, where it is somewhat produced. Glabella moderately convex, not prominent anteriorly, slightly elevated above the cheeks, well defined by the dorsal furrows, broadest across the posterior lobes where the width nearly equals the length, gradually narrowing towards the front, which is truncated; frontal lobe quadrangular, occupying less than one-fourth the length of the glabella; first lateral lobes small, hardly separated from the frontal lobes; second lateral lobes larger and nodelike; posterior lobes much larger, forming a pair of conspicuous nodes at the base of the glabella. The lateral furrows do not cross the glabella, first pair indistinct, transverse; second pair well defined and bent backward;

posterior pair broader and deeper than second pair, curved backward so as to nearly, but not quite, isolate the posterior lobes; occipital furrow arched forward in the middle, somewhat deeper and narrower back of the posterior glabella lobes, where it merges into the posterior cheek furrows; occipital segment prominent, widest in the middle, gradually narrowing to the dorsal furrows. Cheeks convex, with rounded lateral and sharp posterior marginal borders, greatest elevation at the palpebral lobes; marginal borders defined by shallow, concave furrows; free cheeks subtriangular, about half the size of the fixed cheeks. Facial sutures originate at the genal angles which they unequally bisect; from thence they pass obliquely forward until opposite the posterior glabella furrow; thence curve abruptly over the eye lobes to the anterior border, which they cut almost in front of the eyes. A small free plate to which the hypostoma is attached occupies the space between the anterior extremities of the sutures. Eyes small, lenses not preserved, situated well forward, about opposite the second glabella furrows.

Thorax composed of thirteen segments, length about three-fifths the entire length of the test, strongly trilobed; segments arched forward on the axis, each one bearing a pronounced rounded node on either side just within the dorsal furrows, and a smaller, more pointed one on each pleura, pointing forward, situated on the anterior margin at the crest of the convexity, when the body is rolled up; on the posterior margin is a notch or indentation into which the node from the next posterior segment fits; each pleura is provided with a well-marked groove which originates at the dorsal furrow and extends on to the flattened distal portion of the segment. The pleural segments curve regularly upward for about one-third their length, then abruptly to the lateral margins.

Pygidium transversely suboval in outline with posterior portion produced into an obtuse angle, strongly trilobed. The convex axis tapers posteriorly and terminates on a rounded extremity near the posterior margin, marked by seven annulations. The pleural lobes slope abruptly from the dorsal furrows to the margins, each lobe consisting of five or more segments, the anterior ones being distinct and the others becoming less so until they are entirely obsolete at the posterior extremity of the pygidium; each segment is marked by a shallow longitudinal groove which originates at the lateral margins and becomes obsolete before the dorsal furrow is reached.

The dimensions of the type specimen are: Length of cephalon 10.5 mm.; width 18.3 mm.; length of thorax 21.5 mm.; length of pygidium 3.5 mm.; width 9.3 mm.; entire length of the body 39 mm. measured around an enrolled specimen, but if the test was unrolled it would measure 3 or 4 mm. less. The cephalons of two specimens in the collection of Mr. A. G. Becker measure respectively 13.5 mm. long, 24 mm. wide, and 9.5 mm. long, 15.6 mm. wide. All of the specimens on which the description is based are enrolled specimens so that it is difficult to take accurate measurements of some of the parts.

Remarks.—This species has been referred by most writers and collectors to *C. senaria* of the Ohio Valley region, but upon comparing practically perfect specimens from the two localities they are found to be distinct. The glabella in *C. senaria* is shorter and more convex, the pleural segments of the pygidium do not have a longitudinal furrow, the liplike process on the anterior margin of the glabella is shorter and the surface of the test does not possess the rounded tubercles. *C. mammillata* was described from the Maquoketa of Dubuque county, Iowa, and specimens from the type locality loaned to the Field Museum for study from the collection of the State University of Iowa by Prof. George F. Kay prove *C. fayettensis* to be quite dissimilar. The frontal lip is very large in *C. mammillata* and bears a low, rounded tubercle just in front of each dorsal furrow. The surface ornamentation also is quite different. *C. fayettensis* resembles *C. christyi* in the outlines of the glabella, but there the similarity ceases as it does not possess the genal spines or the curvature of the thoracic segments, and the form and size of the pygidium are entirely unlike. The surface ornamentation of *C. fayettensis* is similar to that of *C. niagarensis,* but in the form of the glabella and many other characters it is entirely distinct.

Locality and horizon.—The type (Field Mus. No. P 16755) was collected by the writer in July, 1910, in the Lower Maquoketa shale at Clermont. Other specimens were collected by the writer from the Lower Maquoketa beds at Clermont, Elgin, and Bloomfield.

CALYMENE GRACILIS Slocom, Plate XIX, figure 9.

1913, *C. gracilis* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 69, Pl. XVIII, fig. 9.

Type specimen No. P 17065 Field Museum.

Body small, in form and general proportions similar to other species of the genus. The surface of the test appears smooth to the naked eye but under a magnifier it appears very finely papillose.

Cephalon sublunate, width of the genal angles somewhat less than twice the length on the median line, ratio about as 7 to 4. Anterior border flat, projecting obliquely forward and upward, not recurved; separated from the glabella by a deep, narrow, marginal furrow. The dorsal furrows, in passing forward from the occipital ring, diverge slightly near the posterior glabella lobes, then converge until they meet the anterior marginal furrow. Here the dorsal furrows become nearly obsolete on account of a large rounded node on each fixed cheek, opposite the anterior lobe of the glabella. Glabella convex, elevated above the cheeks, shorter than is usual in this genus, widest at the posterior lobes where the width is equal to the length, including the occipital ring, much narrower anteriorly; anterior lobe transverse, width less than one-third the length; first lateral lobes well defined, about the width of the anterior lobe and terminating about the same distance from the median line; second lateral lobes larger and node-like; posterior lateral lobes much larger, forming a pair of conspicuous nodes at the base of the glabella. Lateral furrows well defined but not crossing the glabella. The first pair transverse; second pair somewhat larger, but bent slightly backward; posterior pair broader and deeper, curved backward towards, but not reaching, the occipital furrow; at about two-thirds of their length from the dorsal furrows they bifurcate; the shorter fork extends toward the median line of the glabella, forming a well-defined node between the second and posterior lobes. The facial sutures originate just in front of the genal angles, curve forward and inward over the palpebral lobes and thence forward to the anterior margin. Occipital ring prominent, slightly wider in the middle, separated from the rest of the glabella by a well-defined occipital furrow. Cheeks only moderately convex aside from the palpebral lobes, which are long for this genus and rise very abruptly from the dorsal furrows; lateral marginal borders wide and well rounded, posterior border much narrower; all are defined by deep marginal furrows.

Thorax known only by a few detached segments which indicate that it was narrow and elevated.

Pygidium subtriangular, terminating in a rounded obtuse angle, strongly elevated and trilobed. Axis convex, marked by six or seven annulations; it tapers gradually and is truncated posteriorly so that the dorsal furrows instead of meeting at a point posteriorly are joined by a short transverse furrow; the pleural lobes slope abruptly from the dorsal furrows to the margins; each lobe consists of five segments, faintly grooved on their distal portion; the segments merge into a smooth undefined, marginal border.

The type specimen is a perfect cranidium with the following dimensions: Length on median line 7.8 mm.; length including genal angles 9.0 mm.; width 14.0 mm.; length of glabella including occipital ring 5.4 mm.; length of glabella without occipital ring 4.5 mm.; width of glabella at anterior lobe 3.5 mm.; width of glabella at posterior lobes 5.4 mm. A detached pygidium gives the following measurements: Length 3.4 mm.; width 6.4 mm.; thickness 4.8 mm.

Remarks.—This species was considered by Savage to be identical with *Calymene fayettensis* of the lower beds, but it is distinguished from that species by its surface ornamentation, its shorter glabella, its larger anterior margin, its longer and more prominent palpebral lobes, the transverse furrow connecting the dorsal furrows on the pygidium and its smaller size. In surface ornamentation this species resembles *C. senaria* but is distinguished from it by its longer palpebral lobes, its relatively short and more elevated glabella. It is distinguished from all species known to the writer by the nodes, which are situated in the dorsal furrows on each side of the anterior lobe of the glabella. *C. mammillata* bears two nodes, but they are situated on the anterior margin.

Locality and horizon.—Limestone layers of the Upper Maquoketa beds at Patterson's Springs near Brainard. No complete specimens have been observed by the writer, but cranidia, free cheeks, thoracic segments and pygidia are comparatively abundant.

Family **CHEIRURIDAE,** Salter.

Genus CERAURUS Green, 1832.

"Entire body subovate in outline. Cephalon subsemicircular or subsemielliptical in outline, genal angles produced into spines; glabella strongly convex, broadest in front, with three pairs of deep lateral furrows; posterior limbs of the facial sutures cutting the lateral margins well in front of the genal angles; eyes small. Thorax usually with eleven segments, rarely nine to thirteen; axis prominent, narrower than the pleura, bounded by strong axial furrows. Pygidium small, pleural segments produced into points or spines." (*Weller, Pal. Chicago Area,* p. 263.)

CERAURUS PLEUREXANTHEMUS Green.

1832, *C. pleurexanthemus* Green, No. Amer. Jour. Geol., Vol. I, p. 560, Pl. 14, fig. 10.

1847, *C. pleurexanthemus* Hall, Pal. N. Y., Vol. I, p. 242, Pls. 65-66.

1847, *C. pleurexanthemus* S. A. Miller, Cin. Quar. Jour. Sci., Vol. I, p. 132.

This species is said to occur in Fayette county, but so far has not been observed by the writer. A specimen in the collection of the University of Iowa appears to belong to this species. It is said to come from the Maquoketa beds of an adjoining county, but the exact data are missing.

CERAURUS MILLERANUS Miller and Gurley, Plate XVIII, figures 1-3.

1894, *C. milleranus* Miller and Gurley, Bull III, Ill. St. Mus. Nat. Hist., p. 80, Pl. 8, fig. 10.

1913, *C. milleranus* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 71, Pl. 17, figs. 1-3.

Type specimen No. 6062 University of Chicago.

General outline of the carapace, exclusive of the spines, subovate, abruptly narrowed posteriorly; moderately convex, trilobation distinct.

Cephalon semielliptical, width nearly three times the length; dorsal furrows well marked. Glabella convex, narrower than the cheeks at the occipital ring, gradually widening anteriorly until its width about equals its length, abruptly bent downward at the frontal margin; anterior lobe constituting about one-third the length of the glabella; the three pairs of lateral furrows are short and about equidistant, forming three pairs of small convex lateral lobes; the two anterior pairs of furrows extend slightly forward, but the posterior pair is transverse for a part of its course and then bends abruptly backward until it meets the occipital furrow isolating the posterior lateral lobes. Occipital segment arched upward, higher than the anterior portion of the glabella, greatest height at the posterior margin, sloping gradually into the occipital furrow. This furrow is narrow and deep behind the posterior lateral glabella lobes but wider and shallow in its median portion. Cheeks convex with well-defined rounded marginal borders, posterior angle produced into spines, which point backward; eyes prominent, globular, placed near the center of the cheeks; the palpebral lobes bear a pit near the base on the side nearest to the dorsal furrows; the facial sutures originate on the lateral margins about in line with the occipital furrow, curve forward and inward to the palpebral lobes, which they traverse, thence pass forward with a sigmoid curve to the anterior margin of the cephalon.

Thorax composed of ten segments; axis convex, about the same width as the pleuræ; pleuræ flattened for one-third to one-half their width from the dorsal furrows, then bent downward and backward, tapering to a point; each pleural segment is ornamented with a prominent tubercle situated near the point where the pleuræ curve downward; an angular furrow originates on the anterior margin of each pleural segment at the dorsal furrow and crosses it obliquely, reaching the posterior margin behind the tubercle; dorsal furrows distinct, nearly parallel from the first to the eighth thoracic segment, then converging posteriorly.

Pygidium short, much narrower than the posterior segment of the thorax, consisting of three segments; the anterior segment bears a pair of stout spines, which extend posteriorly with the points somewhat converging; axis undefined.

Surface of the cephalon, within the marginal borders, covered with irregularly placed tubercles; on the cheeks the tubercles are somewhat farther apart and the interspaces are pitted; the marginal borders and genal spines are finely granulose; two or more conical tubercles are situated on the posterior borders of the cheeks; the entire thorax is finely granulose, as is also the pygidium, but the granulations are more conspicuous on the caudal spines.

Measurements of the type are as follows:

Length on median line	28.7 mm.
Length including caudal spines	35.4 mm.
Width at genal angles	21.6 mm.
Width at points of genal spines	23.6. mm.
Length of cephalon including genal spines	11.5 mm.
Length of glabella	8.0 mm.
Width of posterior lobes of glabella	6.0 mm.
Width of anterior lobe of glabella	7.5 mm.
Width of pygidium	7.4 mm.
Length of pygidium	2.7 mm.

The above description is based on the type specimen from Cincinnati, Ohio, No. 6062 of the paleontological collection of the University of Chicago. The species is known to the writer from Fayette county by twelve more or less complete cephalons and two pygidia. These agree with the type except that in the type the genal spines are somewhat shorter, the tubercles on the posterior border are less conspicuous and the longitudinal curve of the glabella is somewhat more abrupt in front, making its anterior lobe appear shorter in dorsal view. This last feature may be due to distortion.

C. milleranus is distinguished from *C. pleurexanthemus* by its proportionally shorter cephalon, its less flaring genal spines, and by its eyes being globular and situated about equidistant from the dorsal furrows and from the posterior margin of the cephalon. The eyes of *C. pleurexanthemus* are conical and nearer the dorsal furrows. Further, the spines of the pygidium in *C. millcranus* converge at their points instead of diverging as in *C. pleurcxanthemus*.

Locality and horizon.—Lower Maquoketa shales of Clermont and Elgin.

CERAURUS ELGINENSIS Slocom, Plate XVIII, figures 4-5.

1913, *C. elginensis* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 73, Pl. XVII, figs. 4-5.

Type specimens Nos. P 16630A, 16630B, 17030 Field Museum.

Cephalon sublunate, width more than three times the length, anterior lateral margins arcuate, posterior margin transverse in the median portion, gently bent backward near the genal angles. Glabella convex, clavate, less than half the width of the cheeks at its posterior margin but gradually widening anteriorly until its width nearly equals its length; anterior lobe constituting about one-fourth the entire length of the glabella; three pairs of lateral furrows rather short, well defined, defining three pairs of convex lateral lobes, diminishing in size posteriorly; the two anterior pairs of furrows are transverse, the posterior pair are transverse for part of their length, then bent backward until they join the occipital furrow, isolating the posterior lobes; occipital segment elevated at the posterior margin, sloping into the occipital furrow; occipital furrow shallow, concave in the median portion, narrower, deeper and bent backward behind the glabella lobes; dorsal furrows deep, angular, forming deep angular pits where they merge into the marginal furrows; cheeks large, convex, posterior angles produced into long, stout spines, flattened anteriorly and pointing almost directly backward; palpebral lobes elongated, large for the genus, placed well forward, about midway between the dorsal furrows and the lateral margins but nearer the posterior margins than the dorsal furrows. Near the base of each lobe on the side toward the dorsal furrow is situated a decided pit; an indistinct furrow extends from this pit to the crest of the lobes; the ocular ridges extend from the anterior angle of the palpebral lobes to the pit in the dorsal furrows; the facial sutures originate on the lateral margins about in line with the posterior marginal furrow, curve forward and inward to the palpebral lobes which they traverse, then forward to the anterior margin, which they reach in front of the glabella; marginal borders prominent, defined by shallow furrows; the posterior furrows curve into the lateral furrows just within the genal angles; free cheeks small, less than one-third the size of the fixed cheeks. The surface of the glabella, with the exception of the occipital segment and the cheeks, is covered with more or less regularly distributed rounded tubercles; a larger, more conical tubercle is situated on each fixed cheek, just in front of the posterior furrow, at about one-third the distance from the dorsal furrow to the genal angle. A row of spine-like tubercles traverses the posterior marginal borders of the cheeks, and similar tubercles are distributed over the flattened portions of the genal spines, gradually diminishing in size posteriorly until they become obsolete.

Thorax not known.

Pygidium transversely sub-elliptical in outline, aside from the spines length less than half the width; composed of three segments, the extremities of the anterior segment produced into long, stout, flattened spines, which curve outward and backward; second and third segments much smaller; axis not well defined. The surface of the caudal spines is covered with sharp conical tubercles similar to those on the genal spines. The pygidium above described (Plate XVIII, figure 5) was not associated with the cephalons but came from the same horizon at Bloomfield. Its size and the form and ornamentation of the spines are such as might accompany these cephalons and no other cephalons have been observed to which this pygidium could well be referred.

Measurements	P 16630A	P 16630B
Length of cephalon on median line	13.7 mm.	12.3 mm.
Width of cephalon at genal angles	38.5 mm.	36.3 mm.
Width of cephalon including genal spines (estimated)	40.0 mm.	38.0 mm.
Length of glabella	13.0 mm.	11.0 mm.
Width of anterior lobe of glabella	11.5 mm.	9.6 mm.
Width of posterior lobes of glabella	8.8 mm.	6.7 mm.
	P 17030	
Width of pygidium	10.7 mm.	
Length of pygidium	5.5 mm.	
Length of caudal spines (estimated)	20.0 mm.	

C. elginensis differs from all other species known to the writer in having extremely long genal spines with spinelike tubercles on their flattened portion. It is also distinguished from *C. millerانus* and *C. pleurexanthemus* by having the eyes farther apart. It is most nearly related to *C. dentatus* Raymond and Barton, but the ocular ridges are not present in that species and the eyes are not so far forward.

Locality and horizon.—The species is known to the writer from two cephalons from the top of the Lower Maquoketa beds at Elgin, and a pygidium, which is referred with some doubt, from the same horizon at Bloomfield. Fragments of genal spines and other parts of the test have been observed on slabs from the Upper Maquoketa beds at Patterson's Springs which, from their size and ornamentation, appear to belong to this species.

Genus **CERAURINUS** Barton 1913.

"Ceraurinus is in general appearance and size much like Cheirurus (genotype *C. insignis* Beyrich). The glabella is subrectangular or expands only slightly. The posterior of the three pairs of glabella furrows are straight, about one-third the width of the glabella in length and slope gently backward. Their inner ends are connected with the neck-furrows by curving constrictions which are about parallel to the axis of the glabella. The constrictions are strong in some species and very faint in others. The middle part of the axial portion of the neck-furrow is parallel to the posterior edge of the neck-segment. The outer thirds each slope gently backward. The eyes are large for a cheirurid and are somewhat Asaphus-like.

The thorax is presumably of eleven segments. The axial lobe is slightly less than one-third of the width of the thorax and tapers gently backward. Each pleuron is divided by a node-like constriction into a large inner third and a small outer two-thirds. The inner third bears a deeply impressed diagonal pleural furrow.

The pygidium, well known only in *Ceraurinus icarus* (Billings), is composed of three (four) segments ending in six free spines, which are of about equal length."

Genotype *C. marginatus* Barton. Range, Ordovician, America, Europe and India? *(Barton, Bul. Mus. Comp. Zool., Vol. LIV, p. 548.)*

CERAURINUS ICARUS (Billings), Plate XVIII, figures 6-9.

1860, *Cheirurus icarus* Billings, Can. Nat. and Geol., Vol. 5, p. 67, fig. 2.

1873, *Ceraurus icarus* Meek, Pal. Ohio, Vol. I, p. 162, Pl. 14, figs. 11a-c.

1889, *Ceraurus meekanus* S. A. M., N. Am. Geol. and Pal., p. 537.

1913, *Eccoptochile meekanus* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 75, Pl. XVII, figs. 6-9.

Body subovate in outline, moderately convex, distinctly trilobed. Surface smooth to the naked eye but under a magnifier the cephalon appears finely granulose.

Cephalon subsemicircular, somewhat flattened anteriorly, genal angles produced into short spines, posterior margin nearly straight until it merges into the genal spines, where it is bent nearly at right angles (Plate XVIII, figure 8). Glabella subquadrate, rounded in front, length in front of the occipital furrow about equal to the width, depressed convex. Anterior lobe of the glabella transversely oval, about twice as wide as long, lateral lobes nearly transverse and about equal in size. Glabella furrows distinct, length about one-third the width of the glabella, anterior pair bent backward; middle pair nearly at right angles to the axis of the glabella; posterior pair similar to the middle pair for most of the length but having the inner ends abruptly bent backward until they meet the occipital furrow, isolating the posterior glabella lobes; occipital segment arched upward somewhat higher than the rest of the glabella, wider in the median portion, tapering towards the dorsal furrows; occipital furrow deep and narrow, arched forward. Dorsal furrows deep and narrow, diverging slightly at the posterior margin of the cephalon, thence passing to the front of the glabella, which they surround, leaving a narrow anterior border. In each furrow just in front of the anterior glabella furrow is a distinct pit. Cheeks large, sloping anteriorly and laterally from the eyes; posterior cheek furrows narrow; near the genal angles they meet the lateral furrows, which are wider and extend forward parallel to the margins until they meet the dorsal furrows; marginal borders somewhat concave on account of shallow marginal furrows, which originate on the genal spines. Eyes of moderate size, situated opposite the second glabella furrows, visual surface sublunate, palpebral lobes moderately prominent, approaching in height that of the glabella. The facial sutures originate a short distance in front of the genal angles, curve obliquely forward, then abruptly inward to the posterior angles of the eyes, follow the inner margin of the eyes and again forward with a broad curve, cutting the anterior margin of the cephalon in front of the glabella (Plate XVIII, figure 8).

Thorax somewhat longer than wide, consisting of eleven segments, distinctly trilobed. Axis narrower than the pleuræ, regularly arched upward. Pleural lobes flattened for about one-third their width, thence abruptly curved to their lateral margins; each segment marked by a deep groove across the axis; another smaller groove originates on the anterior margin of each pleura near the dorsal furrows and crosses the pleura obliquely; on the anterior margin of each pleura, near the point where the pleura is bent downward, a still smaller groove defines a low oblong node which points forward, not upward. The segments are nearly transverse across the axis and about half the length of the pleuræ; their distal portions curve gently backward to the falcate extremities.

Pygidium small, transversely subelliptical, width more than twice the length, posterior curve much flattened. Axis small with three well defined annulations. Two shallow pits occur just back of the termination of the axis. Pleural lobes large, composed of three segments which are produced posteriorly into flattened spines. The anterior pair is the largest; carinate on top, strongly curved backward and obtusely rounded at the extremities; the other two pair decrease in size inward and are more pointed.

Remarks.—Of the specimens here figured and described, figures 6 and 7 are two views of an enrolled individual, complete with the exception of the genal spines, in the collection of Mr. A. G. Becker, from the Lower Maquoketa shale, Clermont; while figures 8 and 9 (Field Mus. No. P 11130) show specimens collected by the writer in the top of the Lower Maquoketa beds at

Clermont. In figure 8 the position of the facial suture and the angle formed by the posterior margin of the cephalon and the genal angles are well illustrated.

In my previous paper I referred these forms to *Eccoptochile? meekanus* S. A. Miller, with a footnote stating that Barton had a paper in press in which he created a new genus to which this species should be referred. My judgment in using Miller's species was based upon a rather incomplete description and figure of the Canadian species, which led me to believe that the two forms were distinct. Dr. Raymond has since informed me that, after comparing the Canadian specimens with those from the Mississippi Valley, he considers them to be identical, so that they are here referred to *C. icarus* Billings.

Locality and horizon.—The specimens here described are from the Lower Maquoketa beds, Clermont.

Genus **SPHAEROCORYPHE** Angelin 1852.

Cephalon convex, genal angles spined; glabella spheroidal anteriorly, lateral lobes obscure; eyes prominent; facial sutures cut the lateral and frontal margins. Thorax composed of 8 to 10 segments; axis narrower than the pleuræ; pleural segments terminate in short reflexed spines. Pygidium composed of three segments, the extremities of the anterior one produced into long spines. Type *S. granulata*. Range, Ordovician, Europe and North America.

SPHAEROCORYPHE MAQUOKETENSIS Slocom, Plate XVI, figures 1-4.
1913, *S. maquoketensis* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 77, Pl. XV, figs. 1-4.

Type specimens Nos. P 11152A, 11152B, 16954 and 17051 Field Museum.

Cephalon sublunate in outline, convex, distinctly trilobed; anterior margin truncated; posterior margin nearly transverse. Glabella very prominent, anterior lobe globular, produced beyond the anterior margin; comprising fully three-fourths the bulk of the glabella; a single pair of shallow, transverse, lateral furrows meet just behind the lateral lobe of the glabella and separate it from a pair of indistinct lateral lobes; occipital segment arched slightly forward, its posterior margin abruptly elevated, surface sloping into the furrow; occipital furrow shallow, not well-defined except at its extremities. Dorsal furrows well defined, much wider and deeper at the junctures with the occipital and glabella furrows, diverging somewhat in passing forward from the posterior margin of the cephalon until near the anterior margin where they abruptly converge until they meet, forming the anterior marginal furrow; cheeks depressed convex, greatest elevation at the palpebral lobes which are situated about midway between the posterior and anterior margins and one-third the distance from the dorsal furrows to the genal angles; antero-lateral margins of the cheeks forming an elongate sigmoid curve; free cheeks triangular, small, less than one-half the size of the fixed cheeks; eyes large, prominent, globular; the facial sutures originate on the lateral margins well in front of the genal angles, pass inward and slightly backward over the palpebral lobes, thence forward to the anterior margin; the genal angles merge into stout, recurved spines; the posterior marginal furrows are continuations of the occipital furrow but narrower and deeper; they terminate abruptly before the genal angles are reached; a deep elongate pit on each fixed cheek and a longer, shallower one on each free cheek represent the lateral marginal furrows.

Thorax not observed.

Pygidium small, sub-triangular in outline, aside from the spines; not distinctly trilobed, composed of three segments; the first of these has its extremities produced into long, diverging, slightly recurved spines; margin entire, with its ventral surface forming a thick doublure.

Surface of the globular portion of the glabella pustulose; pustules rounded, larger near the transverse glabella furrow and gradually diminishing in size anteriorly; balance of cephalon smooth or finely granulose; surface of pygidium pustulose, pustules more prominent on the spines.

Measurements of cephalon	Holotype P 11152A	P 11152B
Length on median line from posterior to anterior margins	4.6 mm.	
Length from posterior margin to front of glabella	7.4 mm.	10.4 mm.
Length from front of glabella to points of spines	13.0 mm.	
Length of anterior lobe of glabella	5.0 mm.	7.7 mm.
Width of anterior lobe of glabella	4.7 mm.	7.5 mm.
Width of cephalon at genal angles	10.2 mm.	14.6 mm.
Width of cephalon at points of spines	15.8 mm.	
Length of occipital segment	2.3 mm.	3.3 mm.
Width of occipital segment	1.0 mm.	1.2 mm.
Measurements of pygidium	**P 16954**	**P 17051**
Width of anterior margin	3.4 mm.	6.7 mm.
Length on median line	1.5 mm.	3.2 mm.
Length including spines	4.2 mm.	10.3 mm.

This species is the most abundant trilobite in the shales of the Lower Maquoketa beds, but a great majority of the individuals are represented only by the globular portion of the glabella. They range in size from 2.5 mm. to 7.5 mm. in diameter. The writer was fortunate enough to obtain about twenty more or less complete cephalons and three pygidia. No thorax has been observed that can be referred to this species so that it is not certain that these pygidia belong to the cephalons, yet from their form and the conditions under which they were collected, there is little doubt that they belong to this species.

S. maquoketensis differs from all previously described species in possessing large pits in place of the lateral marginal furrows. It resembles *S. granulata* Angelin in the form of the marginal outline, but in *S. maquoketensis* the cephalon is longer in proportion to the width and the pustules on the glabella are finer. *S. salteri* Billings is from a similar horizon, but in *S. salteri* the width of the glabella at its posterior margin is three-fourths of its greatest width, and it has tubercles at the juncture of the occipital and dorsal furrows; in *S. maquoketensis* the glabella is twice as wide anteriorly as posteriorly and the tubercles are wanting.

Localities and horizons.—Abundant in the top layers and somewhat less so in the middle layers of the Lower Maquoketa shales of Clermont, Elgin, and Bloomfield.

Family **PHACOPIDAE**, Salter.

Genus PTERYGOMETOPUS Schmidt 1881.

Cephalon obtusely angular in front. Glabella enlarging anteriorly, lateral furrows well defined. Eyes large, schizochroal. Posterior limb of the facial suture cuts the margin well in front of the genal angles, and the anterior limb crosses the lateral expansions of the frontal lobe of the glabella. Pygidium rounded, margin entire, without caudal spine. Range, Ordovician of Europe and North America.

PTERYGOMETOPUS FREDRICKI Slocom, Plate XIX, figures 1-5.
1913, *P. fredricki* Slocom, Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 79, Pl. XVIII, figs. 1-5.

Type specimen No. P 17024 Field Museum.

Test elongate-ovate in outline, trilobation distinct. Cephalon sublunate in outline, convex, anterior border rather thick and rounded, posterior margin concave, genal angles rounded. Glabella large, convex, greatest elevation and greatest width near the anterior margin, well defined by the dorsal furrows; anterior lobe large, transversely elliptical, rising abruptly from the anterior border; it comprises more than half of the glabella; anterior pair of lateral furrows originating at the anterior angles of the eyes, passing obliquely backward but not crossing the glabella; second pair of lateral furrows smaller than the first and directed obliquely forward forming a pair of triangular lateral lobes; the third pair of lateral furrows bifurcate, the anterior forks extending forward parallel to the second lateral furrows defining the quadrangular second lateral lobes; the posterior forks extending backward until they join the occipital furrow isolating the small, posterior, glabella lobes; occipital segment elevated at its posterior margin sloping to the occipital furrow; occipital furrow narrow, distinct. Dorsal furrows narrow and deep, nearly parallel from the posterior margin of the cephalon to the third, lateral glabella furrows, thence diverging to the antero-lateral margins. Cheeks slope regularly to the lateral margins; marginal borders wide at the genal angles, narrowing in each direction, marginal furrows shallow on the lateral margins, deeper on the posterior margins; palpebral lobes large, prominent, but not equaling the glabella in height; marked by a distinct furrow just within and parallel to the borders of the eyes; eyes large, lunate, extending from the posterior cheek furrows to the anterior glabella furrows, eye facets arranged in vertical rows of five facets each; the facial sutures originate on the lateral margins in front of the genal angles, curve inward with a sigmoid curve to the posterior angles of the eyes, follow the inner margin of the eyes to their anterior angles and thence pass forward to the anterior margin of the cephalon.

Thorax distinctly trilobed, composed of eleven segments. Axis convex, occupying somewhat more than one-third the width of the thorax; the pleural segments extend outward from the dorsal furrows for a little more than one-third their length, from which point they bend backward and abruptly downward to the lateral margins; extremities rounded; a straight groove originates near the anterior edge of each of the pleural segments at the dorsal furrows, extends slightly backward and outward and becomes obsolete on the flattened surface of each segment. The dorsal furrows converge slightly to the ninth thoracic segment, then more rapidly to the pygidium.

Pygidium subsemicircular in outline, slightly produced posteriorly, strongly trilobed. Axis narrow, convex, margins slightly incurved, abruptly rounded posteriorly; there are ten sinuous annulations; dorsal furrows narrow and deep, entirely surrounding the axis; the pleural lobes, consisting of six to eight segments, each bearing a median groove, curve slightly upward in their anterior portion, then downward to the margins. The segments are defined by grooves which are distinct in the anterior portion of the pygidium but gradually become obsolete posteriorly. This feature is more noticeable in young specimens. Both segmentation and median grooves become obsolete a short distance from the margins, thus leaving a smooth, undefined, marginal border.

The surface of the thorax and pygidium appears smooth to the eye, but under a magnifier is finely punctate, without nodes or spines. The surface of the cephalon is pustulose, the pustules on the glabella being somewhat more prominent than on other parts.

The dimensions of the type specimen (Field Mus. No. P 17024) are as follows: Length, 24.2 mm.; width at genal angles 11.5 mm.; length of cephalon on median line 6.7 mm.; length including genal angles 7.4 mm.; length of thorax 11.5 mm.; length of pygidium 6 mm.; greatest width of pygidium 8.7 mm. A detached pygidium (Field Mus. No. P 16923A) measures, length 11.0 mm.; greatest width 14.6 mm.; it has ten annulations in the axis and eight segments in each pleural lobe, the last two being visible only with a magnifier. This is the largest pygidium observed and appears to belong to an old individual.

A small coiled specimen (Plate XIX, figures 4-5) in the collection of Mr. A. G. Becker, found associated with typical specimens, is doubtfully referred to this species. It differs from the type in having a smooth instead of a pustulose glabella and the pygidium appears to be shorter in proportion to its width. Considering these characters in connection with its small size, it is probable that they only indicate the immaturity of the specimen. Its dimensions are: Length of cephalon 5 mm.; length of thorax 10.4 mm.; length of pygidium 3.3 mm.; width at genal angles 6.8 mm.; width at anterior margin of pygidium 4.9 mm.

P. fredricki is distinguished from *P. larrabeei* by having five rows of eye facets instead of eight, by its more inflated anterior portion of the glabella, by its thicker and shorter anterior margin, by its shorter pygidium and fewer annulations on its axis, and by the anterior limbs of the facial suture being less divergent. So far as is known to the writer, the number of rows of eye facets has not previously been used as a specific character, but it seems to be a constant character in the thirty specimens of the two species which he has observed. Specimens of *P. callicephalus* from the Trenton of Ottawa, Canada, which appear to be typical, have eight rows of eye facets. *P. fredricki* appears to be related to *P. callicephalus,* but aside from the eye facets, the glabella is more inflated anteriorly and the anterior margin is smaller and less angular in *P. fredricki*.

The specific name is given in honor of Dr. Fredrick Becker, who was one of the first collectors of fossils in Fayette county and who gave the writer much valuable information as to localities.

Localities and horizon.—The type is from the top of the Lower Maquoketa beds at Bloomfield. The species has been observed in beds somewhat lower down at Clermont and at Postville Junction.

PTERYGOMETOPUS LARRABEEI Slocom, Plate XIX, figures 6-8.
1913, *P. larrabeei* Slocom. Field Mus. Nat. Hist., Geol. Ser., Vol. 4, p. 81, Pl. XVIII, figs. 6-8.

Type specimen No. P 11256 Field Museum.

Cephalon sublunate in outline, anterior margin produced into a thin subangular lip, genal angles well back of the occipital ring, rounded. Glabella large, depressed, convex, about twice as wide in front as at the occipital ring, anterior lobe transversely elliptical, sloping gently towards the front, comprising fully half the glabella; anterior pair of glabella furrows originating at the anterior angles of the eyes and passing obliquely backward but not meeting at the median line of the glabella; second pair of glabella furrows shorter and shallower than the first, directed obliquely forward; third pair of glabella furrows directed towards the axis of the glabella for a short distance, then bifurcating, the posterior forks bending abruptly backward and joining the occipital furrow leaving the small posterior lobes entirely detached; the anterior and larger forks bending obliquely forward defining the third glabella lobes; occipital segment wide, slightly rounded, of about uniform width until near the dorsal furrows where it is abruptly constricted; occipital furrow shallow but distinct. Dorsal furrows narrow and deep, nearly parallel from the posterior margin of the cephalon to the posterior glabella furrows, thence diverging in a regular curve to the anterior angle of the eyes where they become obsolete. Palpebral lobes large, prominent, exceeding the glabella in height, marked with a distinct furrow just within and parallel to the border of the eye; eyes large, lunate, extending from the posterior cheek furrows to the anterior furrows of the glabella; eye facets arranged in vertical rows of eight facets each; the cheeks curve regularly to the lateral margins, marginal borders rather wide on their lateral margins, narrow on their posterior margins, marginal furrows shallow on their lateral margins, narrower and deeper on the posterior margins. The facial sutures originate on the lateral margins well in front of the genal angles, curve inward and backward to the posterior angles of the eyes, follow the inner margin of the eyes to their anterior angles and thence curve outward to the margin of the cephalon, almost in line with the anterior furrows of the glabella. Surface of the glabella distinctly pustulose; that of the palpebral lobes, cheeks, occipital ring and anterior projection finely granulose.

Thorax not known.

Pygidium subtriangular, somewhat rounded posteriorly, distinctly trilobed. Axis narrow, convex, margin slightly incurved, abruptly rounded posteriorly; there are thirteen sinuous annulations; the dorsal furrows entirely surround the axis; the pleural lobes, marked by seven or eight segments each bearing a median groove for part of its length, curve regularly to the lateral margins; both segmentation and grooves become obsolete a short distance from the margin, leaving a plain, undefined marginal border. The entire surface of the pygidium is finely punctate.

Measurements.—Type specimen (Field Mus. No. P·11256). Length of cephalon on median line 9.5 mm., length including genal angles 10 mm., width of cephalon 14.5 mm.; length of pygidium 9.2 mm., width 10.6 mm., width of axis on anterior margin of pygidium 3 mm., length of axis 7 mm. Another complete cephalon gave the following: Length on median line 11 mm., length including genal angles 12.5 mm., width 17.5 mm.

Remarks.—The above description is based on the type specimen (Field Mus. No. P 11256) consisting of a complete cephalon and a nearly complete pygidium. In general form this species resembles *P. callicephalus* but differs from it in the following characters: In *P. larrabeei* the cephalon is longer in proportion to the width; the cheeks do not curve so abruptly to the lateral margins; the glabella is less inflated anteriorly; the pygidium is longer and has more annulations and segments; the pustulose surface occurs only on the glabella; the surfaces of the palpebral lobes, occipital ring and cheeks are punctate. The pygidium of *P. larrabeei* appears to be midway between *P. callicephalus* and *P. intermedius* in form. The specific name is given in memory of the late Ex-Governor William Larrabee on whose property some of the specimens were collected.

Locality and horizon.—More or less complete cephalons and pygidia are comparatively abundant in the Lower Maquoketa beds at Clermont, Elgin, and Bloomfield. The type specimen came from Clermont.

Acknowledgments.

The generic descriptions used in this paper have been derived from a number of sources. Where practicable a copy of the original description of the genus has been given; in other cases the best descriptions available have been used. In nearly all cases the descriptions have been rewritten, but where copied due credit has been given.

The writer is under obligations to Mr. A. G. Becker of Clermont for the loan of specimens and assistance given while in the field. Mr. Becker not only placed his private collection at the disposal of the writer, but spent much time with him in actual collecting and gave valuable information as to localities to be visited. Also to Prof. George F. Kay for the loan of specimens from the paleontological collections of the State University of Iowa, and to Prof. Stuart Weller of the University of Chicago for the loan of type specimens and publications which materially aided in the preparation of this paper, grateful acknowledgments are given.

This paper is a republication, with some revisions by the author, of Part 3, Volume IV, Geological publications of the Field Museum of Natural History of Chicago, and the plates used herein are kindly loaned by that institution.

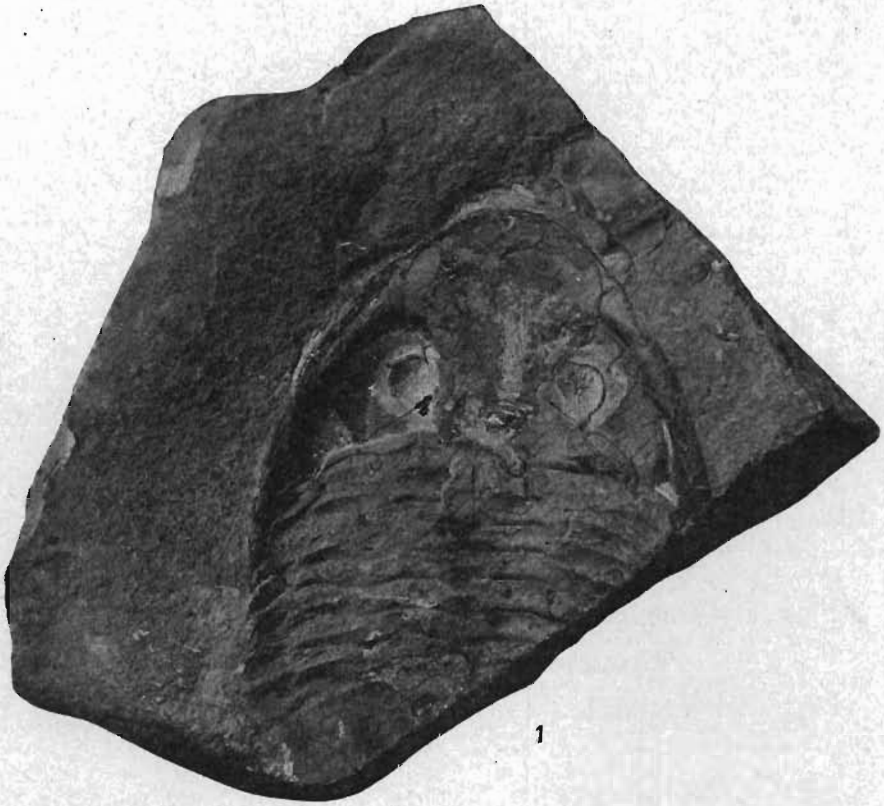
Walker Museum,
The University of Chicago,
February 4, 1916.

Explanation of Plate XIV.

Isotelus iowensis Owen, page 193.

Fig. 1. View of the inner surface of the test, showing position of the facial suture. Field Mus. No. P 11241. × 1.

Fig. 2. Ventral view of a cephalon in the paleontological collection of the State University of Iowa, showing form and position of the hypostoma and sutures. × 6/7.



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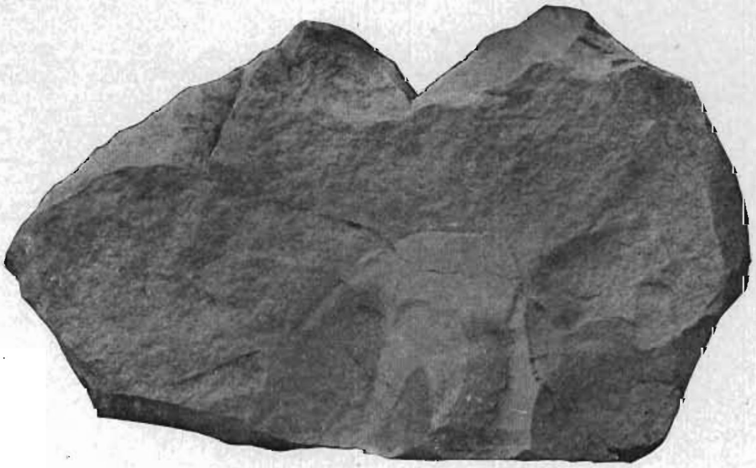

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Explanation of Plate XV.

BUMASTUS BECKERI Slocom, page 201.

Fig. 1. Lateral view of the holotype. × 7/8.

Figs. 2, 3. Dorsal and lateral views of the paratype in the paleontological collections of the State University of Iowa. × 4/3.

Fig. 4. Dorsal view of the paratype. Field Mus. No. P 16708. × 7/8.

MEGALASPIS BECKERI Slocom, page 196.

Fig. 5. Dorsal view of the type specimen. × 14/15.

THALEOPS OVATA Conrad, page 204.

Fig. 6. Cranidium. Field Mus. No. P 11259, Clermont. × 13/14.

Fig. 7. Dorsal view of a nearly complete specimen from Mineral Point, Wisconsin. No. 6901 University of Chicago. × 13/14.

Fig. 8. Cephalon showing cheek spines, from Dixon, Illinois, No. 12584 University of Chicago. × 13/14.

NILEUS VIGILANS Meek and Worthen, page 199.

Figs. 9-15. Series illustrating variations in size. × 1.


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Explanation of Plate XVI.

Sphaerocoryphe maquoketensis Slocom, page 229.

Figs. 1, 2. Dorsal and lateral views of the holotype. Field Mus. No. P 11152A. × 9/5.

Fig. 3. Dorsal view of pygidium from Elgin. Field Mus. No. P 16954. × 1.

Fig. 4. Ventral view of a larger pygidium from Elgin. Field Mus. No. P 17051. × 1.

Amphilichas rhinoceros Slocom, page 206.

Fig. 5. View of the inner surface of the shell of a cranidium. The type specimen. Field Mus. No. P 11181. × 6/7.

Fig. 6. Outline restoration from the type specimen. × 6/7.

Amphilichas clermontensis Slocom, page 207.

Fig. 7. Dorsal view of the type specimen. Field Mus. No. P 11257. × 6/7.

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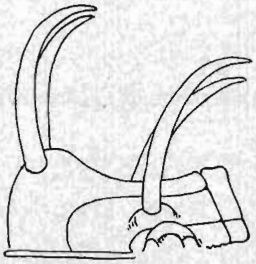

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Explanation of Plate XVII.

Cybeloides iowensis Slocom, page 213.

Fig. 1. The holotype. Field Mus. No. P 16631. × 5/4.

Figs. 2, 3. Dorsal and anterior views of the paratype. Field Mus. No. P 17039. × 1.

Fig. 4. A detached free cheek showing form and position of the eye. Field Mus. No. P 16633. × 5/4.

Encrinurus pernodosus Slocom, page 209.

Figs. 5, 6. Dorsal and lateral views of the holotype. Field Mus. No. P 17038. × 3/2.

Fig. 7. A detached pygidium. Field Mus. No. P 16930. × 1.

Calymene fayettensis Slocom, page 216.

Figs. 8, 9. Dorsal and lateral views of the type specimen. Field Mus. No. P 16755. × 3/2.

PLATE XVII.


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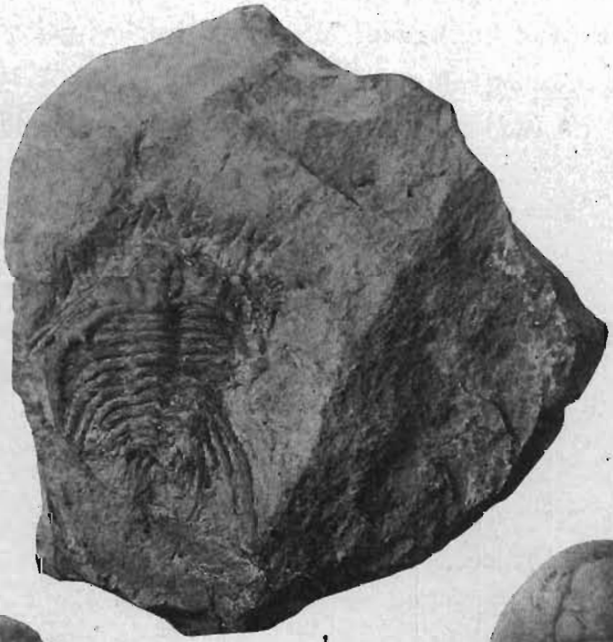
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Explanation of Plate XVIII.

CERAURUS MILLERANUS Miller and Gurley, page 221.

Fig. 1. A complete cranidium. Field Mus. No. P 16853. × 1.

Fig. 2. A pygidium with one spine missing. Field Mus. No. P 16925. × 1.

Fig. 3. The type specimen. No. 6062 University of Chicago. × 1.

CERAURUS ELGINENSIS Slocom, page 224.

Fig. 4. The holotype. Field Mus. No. P 16630A. × 1.

Fig. 5. A pygidium referred to this species. Field Mus. No. P 17030. × 1.

CERAURINUS ICARUS (Billings), page 227.

Figs. 6, 7. Two views of a coiled specimen in the collection of Mr. A. G. Becker. × 1.

Fig. 8. An imperfect cranidium showing the form of the facial suture and the posterior margin. Field Mus. No. P 11150. × 1.

Fig. 9. Ventral view of a complete pygidium. Field Mus. No. P 11150. × 1.


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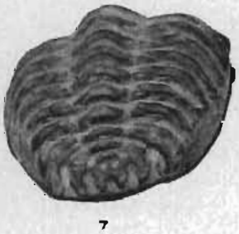
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Explanation of Plate XIX.

PTERYGOMETOPUS FREDRICKI Slocom, page 232.

Fig. 1. The type specimen. Field Mus. No. P 17024. × 3/2.

Fig. 2. Dorsal view of the cephalon of the above. × 3/2.

Fig. 3. Outline drawing of a lateral view of the same showing the form of the glabella. × 3/2.

Figs. 4, 5. Dorsal and lateral views of a young specimen referred to this species, in the collection of Mr. A. G. Becker. × 3.

PTERYGOMETOPUS LARRABEEI Slocom, page 235.

Fig. 6. The holotype. Field Mus. No. P 11256. × 5/4.

Fig. 7. Outline drawing of a lateral view of the same showing form of the glabella. × 5/4.

Fig. 8. Pygidium associated with the holotype. × 5/4.

CALYMENE GRACILIS Slocom, page 219.

Fig. 9. The type specimen. Field Mus. No. P 17065. × 5/4.

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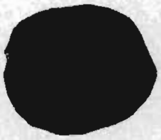

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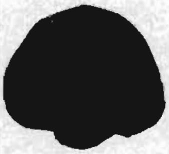

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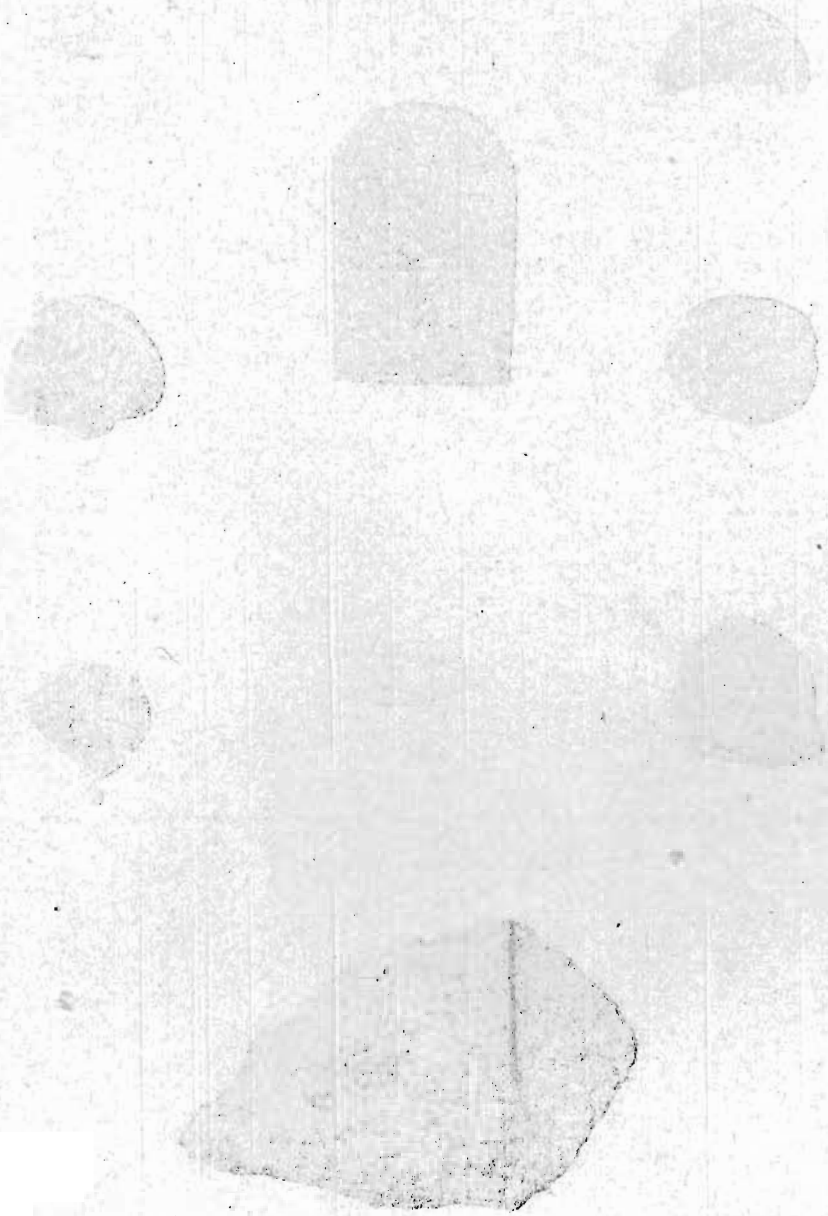

THE ORIGIN OF DOLOMITE

BY

FRANCIS M. VAN TUYL

CONTENTS

THE ORIGIN OF DOLOMITE

Introduction.

Bischof has well said: "No rock has attracted greater attention than dolomite." The problem of the origin of this rock has long occupied the minds of geologists and many theories have been advanced for its formation.

The Tyrol has always been classic ground for dolomite study. As early as 1779, before dolomite as such was recognized as a distinct rock, the Italian geologist, Arduino,[1] called attention to the magnesian limestones which occur in this region in association with rocks of volcanic origin. Two years later Dolimeu[2] remarked upon the peculiar magnesia-bearing limestones of the same region and described some of their properties. But it remained for Saussure[3] in 1792, to make a comprehensive study of the physical and chemical properties of the rock and to give it the specific name "dolomite" in honor of its first describer. Since this time dolomite has been found to have a widespread distribution in both time and space and to constitute one of the most important rocks of the earth's crust. But the mode of formation of the rock has remained from the first a disputed question and in spite of the fact that a voluminous literature has grown up on the subject, the last word has not yet been spoken. It is the purpose of the writer to review the existing theories of the origin of dolomite and to weigh each of these carefully in the light of additional evidence gathered in the course of his investigations.

Field studies were first undertaken in connection with the problem in northeastern Iowa and adjacent parts of Illinois and Wisconsin in 1912, under the auspices of the Iowa Geological Survey, and from this time were carried on privately at intervals in southeastern New York state and New Jersey

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[1] Cited by Morlot, Haidinger's Naturw. Abh., Vol. 1, 1847, p. 305.
[2] Idem., p. 306.
[3] Idem., p. 306.

until early in 1914, when a grant from the Esther Herrman Research Fund of the New York Academy of Sciences made possible much more extensive observations during the remainder of that year in Vermont, New York State, Pennsylvania, Ohio, Michigan, Missouri, Illinois and in the province of Ontario. In addition the writer has more recently obtained a large amount of data bearing on the subject in southern Iowa while engaged in a study of the stratigraphy of the Mississippian formations of this region for the State Geological Survey.

OCCURRENCE.

Dolomite frequently occurs as a gangue mineral in ore deposits and commonly forms veinlets and druses in dolomitic limestones. Magnesian spring deposits likewise have been recorded. Vein dolomites formed by the dolomitization of limestone along fissures also are known and several examples of limestones mottled with patches of dolomite in such a way as to give the appearance of a breccia have been described within recent years. It is with the stratified deposits of dolomite, however, that we are chiefly concerned. These are predominantly marine formations, or at least the alteration products of formations originally marine. But fresh-water dolomites also are known. Thus, Leube[4] has described dolomite beds bearing as much as 44.94 per cent of $MgCO_3$ which alternate with less dolomitic and with clayey beds in a Cretaceous fresh-water formation near Ulm in Bavaria, and Knapp[5] has found from 38 to 49.6 per cent of $MgCO_3$ in a fresh-water limestone of the brown coal series at Rödgen near Geissen.

The stratified dolomites may in themselves constitute entire formations ranging up to several hundred feet in thickness, or they may represent only portions of formations, in which case they are interbedded with limestone, sandstone, shale and gypsum. They are widely distributed on the continents and occur in many of the coral islands of the sea.

They range from several shades of gray to buff or yellow in color, and are usually massive and nearly structureless but in

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[4] Neues Jahrb. 1840, p. 371.

[5] Jahresber. Chemie. 1847-1848, p. 1298.

places they are thinly and regularly bedded. In fossil content they also exhibit considerable variation. Some dolomites show few or no traces of fossils, while others are highly fossiliferous. In the fossiliferous varieties the fossils in some instances are preserved intact in a silicified condition, but in most cases they are in the form of moulds or casts. Again they vary much in porosity. Some dolomites are very compact, but most of them are vesicular and porous. The size of grain is likewise subject to great variation. The fine-grained, dense varieties are often distinguished from limestone only with difficulty, but the coarser-grained types are more distinct by reason of their tendency to break down into a dolomite sand upon weathering.

With regard to the relation of dolomites to time, they occur in every geological system of the stratigraphic column and are being formed in the seas today. They attain their maximum development, however, in the early Paleozoic systems and roughly decrease in importance with time. This has been demonstrated by Daly,[6] who, by a compilation of a large number of analyses of limestones and dolomites of known age, calculated the ratio of dolomite to limestone in the different geologic periods. (See Table I.)

TABLE I.

PERIOD	NO. OF ANALYSES	RATIO OF $CaCO_3$ TO $MgCO_3$	RATIO OF Ca TO Mg
Pre-Cambrian:			
(a) From North America except those in (b)	28	1.64:1	2.30:1
(b) From Ontario (Miller)	33	4.92:1	6.89:1
(c) Average of (a) and (b)	61	2.93:1	4.10:1
(d) Best General Average	49	2.58:1	3.61:1
Cambrian (including 17 of the Shenandoah limestone)	30	2.96:1	4.14:1
Ordovician	93	2.72:1	3.81:1
Silurian	208	2.09:1	2.93:1
All pre-Devonian	392	2.39:1	3.35:1
Devonian	106	4.49:1	6.29:1
Carboniferous	238	8.89:1	12.45:1
Cretaceous	77	40.23:1	56.32:1
Tertiary	26	37.92:1	53.09:1
Quaternary and Recent	26	25.00:1	35.00:1
Total	865		

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[6] Bull. Geol. Soc. America, Vol. 20, 1900, p. 153.

TABLE

HORIZON	LOCALITY.	CONSTITUENTS				
		$CaCO_3$	$MgCO_3$	Al_2O_3 + Fe_2O_3	Insol. Matter	SiO^2
Missourian......	Independence, Mo......	97.41	....	0.92	....	1.46
Stones River....	Murat P. O., Va.......	94.88	1.03	1.24	....	2.54
Chambersburg...	Strasburg, Va..........	84.64	1.68	1.48	12.10	....
Beekmantown...	Harrisburg, Pa.........	92.14	3.15	0.06	5.08	....
Wapsipinicon...	Cedar County, Ia.......	93.61	4.20	0.58	1.52	....
Platteville......	Dixon, Ill.............	83.93	5.02	4.44	....	4.78
Elbrook........	Waynesboro, Pa........	83.23	6.03	1.16	8.80	....
Triassic........	Southern Tyrol........	91.50	7.40	...	1.13	....
Kinderhook.....	Marshall County, Ia....	90.04	8.08	0.50	1.22	....
Plattin.........	Cape Girardeau, Mo....	87.23	9.26	0.45	....	2.93
Clinton.........	Wilmington, Ohio......	83.77	10.20	2.68	....	2.32
Jurassic........	French Jura...........	82.00	11.22	...	6.88	....
Trenton........	Nat. Gas Belt, Ind.....	83.21	12.48	1.23	2.14	....
St. Louis.......	St. Louis, Mo..........	78.97	13.36	0.53	....	2.40
St. Louis.......	St. Louis County, Mo..	78.98	14.12	0.99	....	3.39
Wapsipinicon...	Bettendorf, Ia.........	79.60	15.40	0.70	4.46	....
Onondaga......	Bloomville, Ohio.......	62.30	13.18	1.54	....	22.76
Triassic........	Southern Tyrol........	80.50	18.20	...	1.26	....
Beekmantown...	Harrisburg, Pa........	76.10	19.00	1.10	4.70	....
Beekmantown...	Harrisburg, Pa........	76.33	19.88	0.64	2.41	....
Clinton.........	New Jasper, Ohio......	75.27	20.60	2.40	....	2.54
Onondaga......	Owens Sta., Ohio......	74.00	21.46	1.85	....	1.92
Onondaga......	Owens Sta., Ohio......	72.85	22.38	2.65	....	1.65
Onondaga......	Owens Sta., Ohio......	64.00	20.47	2.30	....	12.50
Beekmantown..	Harrisburg, Pa........	64.28	22.32	1.30	11.61	....
Beekmantown..	Harrisburg, Pa........	64.99	23.59	1.57	10.60	....
Onondaga......	Kelley's Island, Ohio...	71.17	26.82	0.40	....	1.60
Niagara........	Lynchburg, Ohio........	64.55	25.51	5.18	....	4.88
Clinton.........	Yellow Springs, Ohio...	68.20	28.44	2.40	....	0.72
Niagara........	New Paris, Ohio.......	67.00	29.32	1.32	....	2.50
Beekmantown..	Harrisburg, Pa........	58.53	27.44	2.09	11.90	....
Onondaga......	Spore, Ohio...........	56.04	27.82	3.99	....	8.92
Kinderhook.....	Cooper County, Mo.....	55.54	29.09	2.61	....	11.99
Niagara........	Stone City, Ia.........	63.56	34.76	0.72	0.96	....
Onondaga......	Defiance, Ohio.........	55.30	32.21	1.58	....	11.86
Burlington.....	Ash Grove, Mo.........	61.44	37.68	0.50	....	0.40
Kinderhook.....	Sedalia, Mo...........	49.21	31.57	1.08	....	17.69
Wapsipinicon...	Cedar Valley, Ia.......	58.20	39.50	0.90	1.20	....
Cedar Valley....	Bremer County, Ia.....	55.23	39.03	2.12	3.28	....
Beekmantown...	Strasburg Jct., Va.....	51.07	37.80	1.00	10.06	....
Kittatinny......	Easton, Pa............	54.40	42.40	2.22	....	1.84
Niagara........	Lannon, Wis..........	52.29	42.27	1.68	....	3.96
Niagara........	Springfield, Ohio......	53.44	44.49	0.54	....	1.37
Niagara........	New Madison, Ohio....	51.70	45.26	2.70		....
Niagara........	Cedar Valley, Ia.......	51.27	48.09	0.35	0.23	....
Niagara........	Springfield, Ohio.......	46.40	47.53	4.90		....
Niagara........	Greenville, Ohio.......	44.60	50.11	4.60		....
Niagara........	Hillsboro, Ohio	35.57	49.00	2.00	....	13.30

II.

Recalculated on basis of 100% $CaCO_3$+ $MgCO_3$		Authority
$CaCO_3$	$MgCO_3$	
100.00	....	Mo. Bur. Geol. and Mines, Vol. 6, 2d ser., p. 235
98.93	1.07	Wm. M. Thornton, Jr., Va. Geol. Survey, Bull. II A, p. 107
98.05	1.95	J. H. Gibboney, Va. Geol. Survey, Bull. II A, p. 60
96.70	3.30	Pa. Sec. Geol. Survey, Rept. M. M., p. 330
95.71	4.29	N. Knight, Ia. Geol. Survey, Vol. 17, p. 531
94.36	5.64	Ill. Geol. Survey, Bull. No. 17, p. 99
93.25	6.75	C. O. Jones, Analysis made for the writer
92.52	7.48	E. W. Skeats, Quart. Jour. Geol. Soc., London, Vol. 61, p. 107
91.76	8.24	G. E. Patrick, Ia. Geol. Survey, Vol. 17, p. 534
90.40	9.60	Mo. Bur. Geol. and Mines, Vol. 6, 2d ser., p. 111
89.14	10.86	S. V. Peppel, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 145
87.96	12.04	F. Pfaff, Neues Jahrb. Beil. Bd. 23, p. 540
86.96	13.04	F. W. Clarke, Bull. U. S. Geol. Survey No. 148, p. 263
85.53	14.47	Mo. Bur. Geol. and Mines, Vol. 6, 2d ser., p. 239
84.83	15.17	Mo. Bur. Geol. and Mines, Vol. 6, 2d ser., p. 237
83.79	16.21	C. E. Ellis, Ia. Geol. Survey, Vol. 17, p. 535
82.54	17.46	S. V. Peppel, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 161
81.56	18.44	E. W. Skeats, Quart. Jour. Geol. Soc. London, Vol. 61, p. 105
80.02	19.98	W. S. Smith, Analysis made for the writer
79.34	20.66	A. S. McCreath, Pa. Sec. Geol. Survey, Rept. M. M., p. 306
78.51	21.49	S. V. Peppel, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 144
77.52	22.48	N. W. Lord, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 163
76.50	23.50	N. W. Lord, Idem, p. 163
75.77	24.23	S. V. Peppel, Idem, p. 161
74.23	25.77	Pa. Sec. Geol. Survey, Rept. M. M., p. 340
73.37	26.63	Idem, p. 331
72.63	27.37	N. W. Lord, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 163
71.67	28.33	S. V. Peppel, Idem, p. 151
70.57	29.43	S. V. Peppel, Idem, p. 145
69.56	30.44	S. V. Peppel, Idem, p. 151
68.08	31.92	Pa. Sec. Geol. Survey, Rept. M. M., p. 330
66.83	33.17	S. V. Peppel, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 163
65.63	34.37	Litton, Mo. Bur. Geol. and Mines, Bull. 6, 2d ser., p. 133
64.65	35.35	A. O. Anderson, Ia. Geol. Survey, Vol. 17, p. 534
63.19	36.81	S. V. Peppel, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 161
61.99	38.01	Mo. Bur. Geol. and Mines, Vol. 6, 2d ser., p. 133
60.92	39.08	Idem, p. 236
59.57	40.43	N. Knight, Ia. Geol. Survey, Vol. 17, p. 531
58.59	41.41	N. Knight, Idem, p. 531
57.47	42.53	J. H. Gibboney, Va. Geol. Survey, Bull. II A, p. 51
56.20	43.80	F. B. Peck, Econ. Geol. Vol. 3, p. 42
55.30	44.70	G. M. Prentiss, Wis. Geol. and Nat. Hist. Survey, Bull. 4, p. 275
54.57	45.43	N. W. Lord, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 151
53.32	46.68	Wormley, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 151
51.60	48.40	N. Knight, Ia. Geol. Survey, Vol. 17, p. 531
49.40	50.60	Wormley, Ohio Geol. Survey, 4th ser., Bull. No. 4, p. 151
47.09	52.91	Wormley, Idem, p. 151
42.06	57.94	Wormley, Idem, p. 153

COMPOSITION.

Normal dolomite, $CaMg(CO_3)_2$, is composed of the carbonates of calcium and magnesium combined in equivalent proportions, and hence consists of 54.35 per cent of $CaCO_3$ and 45.65 of $MgCO_3$. But perfectly pure dolomite is rarely found in nature. Siliceous or argillaceous impurities are commonly present; iron and related metals may replace a portion of the calcium and magnesium; and most important of all, the calcium in many dolomites is far in excess of the normal amount. This, in fact, is true to such a degree in dolomitic limestones that it is often impossible to say where dolomite leaves off and limestone begins, and some confusion has arisen regarding the place where the boundary should be drawn between these two rocks. At present the terms limestone and dolomite are very loosely used, and no attempt is made by many to distinguish between them. Thus, many rocks which are nearly true dolomites are described as limestones by some, while others refer to a rock as dolomite when really it is very low in magnesia; again, still others use the term magnesian limestone freely, regardless of the amount of magnesia present. The attempted classifications of limestone and dolomite show this same uncertainty and lack of regard of the importance of the magnesia content of the rock. For example, Forchhammer[7] concluded that a limestone containing more than 2 per cent of $MgCO_3$ could be called a dolomite. F. W. Pfaff,[8] on the other hand, after a study of a series of analyses of dolomitic limestones, decided that no limestones exist in nature which contain from 7 to 11 per cent of $MgCO_3$, and made this the basis of his classification, calling all magnesia-bearing limestones containing more than 11 per cent of $MgCO_3$ dolomite and all those containing less than 7 per cent of this constituent limestone. A careful examination of a large number of analyses of dolomitic limestones by the writer, however, has proven Pfaff's classification to be untenable, for every gradation has been found to exist in the magnesia content between pure limestone on the one hand and dolomite on the other. (See Table II.) In rare cases the magnesia even exceeds the

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[7] Jour. Prakt. Chemie. Vol. 49, 1850, p. 52.
[8] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

proportion required in normal dolomite, and in these it must be assumed that this excess is due either to the existence of $MgCO_3$ in solid solution or isomorphous mixture in the dolomite or to the presence of free crystals of magnesite.

As to the exact nature of the mixtures of calcite and dolomite in all stages of the transition from limestone to dolomite, little is as yet definitely known. Nor can this be determined except by careful mineralogical studies in conjunction with analytical work or by direct synthetic experiments. It can be safely asserted, however, that calcite and dolomite exist in solid solution or isomorphous mixture to a considerable degree, and that up to a certain point dolomite is miscible with calcite without seriously affecting the latter's mineralogical properties and that again as the composition of dolomite is approached calcite is miscible with dolomite without destroying the latter's individuality. Where the exact transitions take place it is at present impossible to state, but there is some evidence bearing on this point. Thus, Skeats[9] states that in some of the Tyrol limestones $MgCO_3$ is present to the extent of 6 or 7 per cent, without giving rise to any visible dolomite crystals, while a sample of the coral rock from Christmas Island bore over 11 per cent of $MgCO_3$ without showing visible dolomite. Similarly Cullis[10] reports that the coral rock of the Funafuti boring contained as much as 16 per cent of $MgCO_3$ without exhibiting individual crystals of dolomite. It should be noted, however, that this rock had not yet undergone recrystallization. On the other hand, Wallace[11] found that a rock composed of homogeneous crystals but containing only 23.35 per cent of $MgCO_3$ reacted for dolomite optically with Lemberg's solution. Somewhere, then, within the limits of 11, or possibly 16, and 23.35 per cent there appears to be a transition from calcite with dolomite in isomorphous mixture to dolomite with calcite in isomorphous mixture. Whether the transition is sharp or whether there is an intermediate stage in which the dolomite and calcite are present in the form of a mechanical mixture it is impossible to state. It is hoped that future studies will locate this point more accurately,

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[9] Quar. Jour. Geol. Soc. London, Vol. 61, 1905, p. 131.

[10] The Atoll of Funafuti: Published by the Royal Society, London, 1904, p. 392.

[11] Congrès Geologique International Compt. Rend. 12th Session, Canada, 1913, p. 875.

for the present confusion attending the classification of the magnesian and dolomitic limestones would then be, in part at least, eliminated. For instance, it might be found convenient to designate all limestones bearing $MgCO_3$ in excess of 3 or 4 per cent and below the limit at which individualized dolomite crystals appear as magnesian limestones, while rocks above this limit which consist wholly or in part of crystals which behave as dolomite but which still contain less $MgCO_3$ than normal dolomite might be designated dolomitic limestones. The more restricted term dolomite could then be applied to those rocks which possess the two carbonates in approximately equivalent proportions. In the present paper no attempt is made to apply any form of classification, and the term dolomite is loosely used for all dolomitic limestones which react microchemically as dolomite, regardless of their exact composition.

HISTORICAL REVIEW.

The theories of the origin of dolomite may be classified conveniently in the following tabular form.

- I. Primary deposition theories:
    - A. The chemical theory.
    - B. The organic theory.
    - C. The clastic theory.
- II. Alteration theories:
    - A. The marine alteration theory.
    - B. The groundwater alteration theory.
    - C. The pneumatolytic alteration theory.
- III. Leaching theories:
    - A. The marine leaching theory.
    - B. The surface leaching theory.

I. Primary Deposition Theories.

A. The Chemical Theory.—This theory formerly had many followers, and some geologists still adhere to it today. Boné[12] advocated this method of origin as early as 1831, and Bertrand-Geslin[13] was an early supporter of this view. Similarly Wagner,[14] in 1839, favored the view that the dolomites of the French Jura were original deposits rather than alteration products.

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[12] Bull. Soc. géol. France, Vol. 1, 1831, p. 115.
[13] Bull. Soc. géol. France, Vol. 6, 1834, p. 8.
[14] Cited by F. Pfaff, Pogg. Annalen, 1851, p. 465.

Coquand,[15] however, concluded that dolomite had a two-fold origin, being in part the product of the action of volcanic agents on limestone, and in part a regular chemical precipitate on the sea bottom. Wissmann[16] almost simultaneously expressed the view that the dolomites of the Tyrol were original deposits, and Petzholdt[17] stated it as his opinion that both the dolomite and the limestone of this region are chemical precipitates, since they grade into each other. This, he believed, would account for the predominance of limestone in the lower part of the section and of dolomite in the upper, since $MgCO_3$ is the more soluble of the two carbonates and would be the last to be thrown out of solution. Fournet[18] likewise interpreted the dolomite of the same region as original.

Forchhammer[19] soon after pointed out that certain dolomitic nodules in the Cretaceous limestones at Faxö were probably chemical. These he believed to be the product of the reaction of the $CaCO_3$ of spring water with the magnesia of sea water. The presence of material resembling travertine in the rocks and other evidences of spring action seemed to lend support to this view.

Delanoue,[20] on the other hand, was inclined to favor the chemical precipitation theory for dolomites in general, regarding secondary dolomites as only local and of little importance.

Liebe[21] in 1855 gave this theory an elaborate setting for the origin of the Zechstein dolomites. To account for these he assumed that the Zechstein sea had been visited by eruptions and violent disturbances through which magnesia was introduced from subterranean sources and the inhabitants of the sea exterminated. Carbon dioxide, possibly contributed by the volcanic action, took the magnesia into solution as $MgCO_3$, which was distributed over wide areas. This then united with the $CaCO_3$ of the sea to form minute crystals of dolomite which after being driven here and there by waves and currents were finally deposited on the sea bottom.

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[15] Bull. Soc. géol. France, Vol. 12, 1841, p. 314.

[16] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 200.

[17] Idem., p. 201.

[18] Bull. Soc. géol. France, 2d. ser. Vol. 6, 1849, p. 502.

[19] Jour. Prakt. Chemie, Vol. 49, 1850, p. 52.

[20] Compt. Rend., Vol. 39, 1854, p. 492.

[21] Zeitschr. Deutsch. geol. Gesell., Vol. 7, 1855, p. 406.

Hunt[22] also expressed himself unequivocally in favor of the chemical precipitation of dolomite, giving it as his opinion that "dolomites, magnesites, and magnesian marls have had their origin in sediments of magnesium carbonate formed by the evaporation of solutions of bicarbonate of magnesia. These solutions have been produced by the action of bicarbonate of calcium on $MgSO_4$; or by the action of bicarbonate of sodium on $MgCl_2$ or $MgSO_4$. The subsequent action of heat has cemented the sediments into magnesite or dolomite."

Cordier,[23] approaching the problem from a philosophical standpoint, was also led to believe dolomites were chemical deposits, and Leymerie[24] entertained similar views. He points out that the dominant salt in the sea today is NaCl, while $MgCl_2$ and $CaCl_2$ are accessory, but supposes that in early Paleozoic time conditions may have been reversed. If then Na_2CO_3 were brought in by rivers or introduced from submarine sources, a double decomposition would set in and dolomite might be deposited. This he believed would account for the constant association of limestone and dolomite both in different beds or layers and in the same bed, and would explain the present high NaCl content of the seas.

Von Rosen[25] about this time claimed chemical precipitation as the probable method of origin of the dolomite and dolomitic limestone of the Düna and Welikaja regions in Finland and Kurland, and Gümbel[26] applied it to the dolomites of the French Jura and of the southern Tyrol. Scheerer,[27] on the other hand, believed that all of the oldest dolomites represent chemical precipitates.

Loretz[28] also favored the view that the dolomites of the southern Tyrol are original formations and leaned towards the chemical theory. The preservation of fine and detailed structures in the rock suggested to him its primary nature.

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[22] Am. Jour. Sci., 2d ser., Vol. 28, 1859, p. 382.
[23] Compt. Rend. Vol. 54, 1862, p. 293.
[24] Mémoires de L'Academie Impériale des Sciences de Toulouse, 6th ser., Vol. 2, 1864, p. 307.
[25] Cited by Zirkel, Lehrbuch der Petrographie, 2d ed. Vol. 3, 1894, p. 503.
[26] Cited by Zirkel, Idem, p. 503.
[27] Neues Jahrb., 1866, p. 1.
[28] Zeitschr. Deutsch. geol. Gesell., Vol. 30, 1878, p. 387.

S. F. Emmons,[29] in 1886, adopted the primary theory for the origin of the dolomites of the Leadville district of Colorado. He concluded that the magnesia is an original constituent of these rocks, having been deposited at the same time as the lime. The presence of minute amounts of chlorine in the dolomites as shown by analyses led him to believe that fluid NaCl was included in the dolomite grains when they crystallized.

In still later times Vogt[30] has come out in favor of this view, stating it as his opinion that certain Norwegian dolomites are chemical. The following facts are arrayed in favor of this contention: (1) Although the dolomites are in places of great thickness, they consist in many cases of dolomite of ideal composition; (2) Dolomite layers are interstratified with limestone without transition; (3) Carbonaceous material is wanting in these dolomites, while in limestones derived from organic remains carbonaceous material is always met with.

Ulrich and Schuchert[31] have also implied that certain dolomitic limestones are chemical, as shown by the following statement:

"Except around certain areas composed of pre-Cambrian rocks and supposed to have been islands (Adirondacks and Isle of Wisconsin) where deposits were arenaceous, the upper Cambric sea laid down great beds of limestone. These limestones were chiefly dolomite, and in this case, indicate (1) remoteness from steep shores of the areas receiving them, (2) considerable depth of water, which may explain the unusual paucity of animal remains contained in them, and (3) chemical precipitation as the main source of the material composing them."

The chemical theory has had one of its greatest champions in Suess,[32] who points out that in the Plattenkalk formation beds of dolomite, often containing more than 40 per cent of $MgCO_3$ and of constant thickness and regular contacts, are interbedded with limestone, and maintains that the dolomite was deposited as such from the sea. The following statement is added in a footnote:

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[29] Mono. U. S. Geol. Survey, Vol. 12, 1886, p. 276.
[30] Zeitschr. Prakt. Geologie, 1898, p. 4.
[31] New York State Museum, Bull. 52, 1901, p. 633.
[32] The Face of the Earth, English translation, Vol. 2, 1906, p. 262.

"Gümbel has always maintained this view; the dolomitic intercalations in the Potsdam sandstone, the Waterlime of the upper Silurian of North America, the dolomitic beds of the upper Devonian of Russia, those which represent the Zechstein in England and those in the German Keuper, all of them more or less littoral deposits, are so many examples of the direct deposition of dolomite."

The chemical theory, however, has been elaborated most fully by Daly in two very suggestive papers. In the earlier paper[33] this writer points out that in pre-Cambrian time when the scavenger system of the ocean was not yet developed, the seas must have been depleted in lime and magnesia due to the precipitating effect of $(NH_4)_2CO_3$ generated from decaying organisms on the sea bottom. "The magnesium carbonate should have been most abundantly thrown down in pre-Cambrian time; its precipitation must have been lessened through Paleozoic and Mesozoic time and has reached its minimum since the abyssess of the ocean became abundantly tenanted with scavengers."

In Daly's second paper[34] this theory is developed still further. A study of nearly 900 representative analyses of limestones distributed among all the geological periods ranging from the pre-Cambrian to the recent showed that the ratio of calcium to magnesium is fairly constant for all the pre-Devonian periods, but that the ratio rises abruptly in the Devonian and continues to rise to the Cretaceous, where the maximum is reached. (See Table I, page 259.)

The average Ca:Mg ratio for the pre-Devonian limestones (3.35:1) is very close to the ratio of Ca to Mg in the rivers now draining the pre-Cambrian terranes as shown by analysis of the water of the Ottawa river at Ottawa. "This comparison of itself suggests that during the pre-Devonian time the river-borne magnesium and calcium were wholly precipitated after diffusing to the sea bottom. In fact the correspondence must be regarded as giving powerful support to the hypothesis." It is suggested that the marked rise in the Ca:Mg ratio in Devonian

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[33] Am. Jour. Sci. 4th ser., Vol. 23, 1907, p. 93.
[34] Bull. Geol. Soc. America, Vol. 20, 1909, p. 153.

and later time may be due to the development of the scavenging fishes, which would prevent organic decay and the consequent generation of $(NH_4)_2CO_3$.

To Daly the fine and monotonous grain of the pre-Ordovician limestones and dolomites means that they are neither of clastic nor of organic origin. For example, microscopic examination of samples of 7000 feet of pre-Cambrian strata exposed in the Forty-ninth Parallel section of the Rocky Mountian geosyncline showed that "the constituent particles are either idomorphic and roughly rhombohedral, or anhedral and faintly interlocking. The former are everywhere of nearly uniform average diameter, ranging from .01 millimeter to .03 millimeter with an average of about .02 millimeter. The anhedral grains range from .005 millimeter to .03 millimeter, averaging about .015 millimeter." The same uniform grain was found to prevail in the Archean dolomites at the head of Priest river, Idaho, in the Belt series of the Clarke Range and in the Siyèh and Sheppard siliceous limestones of Middle Cambrian age of Northwestern Montana. The fact that the average diameters of these carbonate granules are of the same order as the average diameter of calcite and dolomite crystals known to have been formed by chemical precipitation seems to him to be significant.

The alternation of clean-cut beds of limestone with beds of magnesian limestone or dolomite, as illustrated by the pre-Cambrian formations of British Columbia and Montana, also seemed to him to speak for the original deposition of the two carbonates as against later metamorphism.

Following closely upon Daly came Linck[35] as an advocate of the chemical precipitation theory. Basing his conclusions upon the conditions of his experimental production of dolomite, he also assumed that $(NH_4)_2CO_3$ derived from the decay of marine organisms was a competent precipitating agent.

The latest investigator to express himself favorably to the chemical hypothesis is Weigelin,[36] who applies it to the dolomites associated with salt and gypsum in the Lower Keuper of West

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[35] Monatsh. Deutsch. geol. Gesell., 1909, p. 230.

[36] Neues Jahrb., Eell. Bd. 35, 1913, p. 628.

Württemberg. The upward succession of dolomite, gypsum and salt here suggests to him that all these are the products of evaporating seas.

B. The Organic Theory.—The opinion formerly prevailed in some quarters that organisms have played an important role in the production of dolomite, and recent work has tended to revive this view somewhat.

Forchhammer[37] showed by a series of analyses as early as 1850 that the calcareous skeletons of some organisms contained considerable magnesia. In the Brachiopods he found the $MgCO_3$ to be uniformly low, not exceeding one per cent, but *Isis hippuris* yielded 6.36 per cent; *Corallium nobile* 2.13 per cent; Serpula sp. from the Mediterranean 7.64 per cent; and *Serpula triquetra* from the North Sea 4.45 per cent. Upon the strength of these results this writer concluded that such magnesia-secreting organisms might build a dolomitic limestone directly.

The chemical studies of Damour[38] also led him to support this theory. Analysis of calcareous algae ("corals") by him showed a high $MgCO_3$ content in four out of six specimens. He records a maximum of 16.99 per cent of this constituent in *Amphiroa tribulus* Lam., while Melobesia sp. nov. yielded 12.32 per cent. Damour concludes, therefore, from the development such forms take on along the shore and on the sea bottom that deposits of magnesian limestone are being formed by them today and must have been formed by them in the past.

Ludwig and Theobold[39] have also emphasized the importance of algae in the deposition of limestone and dolomite. In the travertine of the mineral spring at Nauheim, in the Wetterau, which is deposited through the agency of algae, these writers found a magnesia content ranging up to 11.69 per cent. They are led to venture the suggestion, then, that similar plants may have played an important role in the deposition of older compact limestones poor in organic remains, and perhaps also of much dolomite.

The observations of Doelter and Hoernes,[40] who held that many weakly dolomitic limestones were deposited directly in

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[37] Jour. Prakt. Chemie, Vol. 49, 1850, p. 52.

[38] Annales Chim. Phys., 3d ser., Vol. 32, 1851, p. 362.

[39] Pogg. Annalen, Vol. 87, 1852, p. 91.

[40] Jahrb. K.-k. geol. Reichsanstalt, Vol. 25, 1875, p. 293.

the sea through the activity of organisms, are also in accord with the organic theory. Much more recently Nichols[41] has sought to demonstrate the importance of organisms in dolomite formation. Thus, upon analyzing a calcareous nodule taken from the Argus Bank of the Atlantic Ocean at a depth of 28 to 30 fathoms he found a much higher $MgCO_3$ content in the outer portion of the nodule than in its inner portion, the percentages being 10.70 and 4.98 respectively. This anomaly is accounted for on the assumption that "the more highly magnesian corals, serpulae and algae of which the nodule is composed are in the central part diluted by the less magnesian gastropod material. It is probable that the magnesium of the outer part is also somewhat increased by the re-solution of the skeletal material which is always taking place." Nichols then raises the question whether the more ancient organisms may not have secreted even more highly magnesian skeletons, thus:

"If under present conditions corals, etc., secrete skeletons which may contain over ten per cent of magnesia, may they not, under Paleozoic conditions, when, as is usually conceded, the sea water was very different in composition and possibly far more corrosive than at present, have protected themselves by secreting relatively insoluble dolomite skeletons?"

As regards the origin of the nodules, it should be pointed out that Phillipi[42] dissents from the interpretation above given, holding that the higher magnesia content in their outer portion is rather to be accounted for upon the basis of recent dolomitization by magnesia which has been introduced from the sea.

Late investigations by Wallace[43] have tended to lend weight to this theory, since he believes that the occurrence of dolomitic fucoid-like markings in the Ordovician limestones of Manitoba is best accounted for on the assumption that algae bearing considerable magnesia were imbedded in the rock at the time it was deposited and that this magnesia was influential in producing local dolomitization of the limestone.

C. The Clastic Theory.—That some dolomites may represent ordinary mechanical sediments derived from the erosion of older

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[41] Field Columbian Museum, Geol. series, Vol. 3, 1906, p. 40.
[42] Neues Jahrb., Festband, 1907, Vol. I, p. 397.
[43] Jour. Geol., Vol. 21, 1913, p. 402.

dolomitic limestones, seems to have been conceived first by Lesley, in 1879,[44] who suggested this mode of origin for an interbedded series of limestones and dolomites of the "Calciferous," exposed in the old Walton quarry, in the west bank of the Susquehanna river, opposite Harrisburg, Pennsylvania. Here "a consecutive series of the beds, all conformable, and all dipping regularly about 30° to the southward afforded a good opportunity for collecting two sets of specimens for analysis, one at the bottom and one at the top of the cut." In all 115 distinct beds with an aggregate thickness of 371 feet were carefully measured and separately sampled both at the bottom and at the top of the opening. The analyses were then carried out in the Survey laboratory at Harrisburg. On the whole, each bed in itself showed remarkable uniformity in composition; but when compared with the associated layers, striking differences were noted. This is well illustrated by the accompanying table compiled from Lesley's report.

TABLE III.

NUMBER OF BED	THICKNESS		$CaCO_3$		$MgCO_3$		INSOLUBLE	
	Feet	*Inches*	*Bottom*	*Top*	*Bottom*	*Top*	*Bottom*	*Top*
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
46	3	6	97.2	90.6	1.7	7.6	0.7	1.8
47	0	10	63.4	68.2	29.5	27.1	6.4	3.6
48	0	5	94.3	95.3	1.9	2.2	3.5	2.2
49	0	2	57.8	66.2	33.2	26.9	8.0	5.7
50	0	6	60.4	62.0	32.1	31.7	5.3	5.1
51	1	11	92.6	95.7	3.2	2.9	3.0	1.7
52	4	0	61.4	68.9	31.9	23.7	5.3	7.2
53	0	5	81.1	88.7	10.0	7.0	4.7	3.4
54	5	2	98.2	97.9	1.3	1.2	1.2	0.7
55	0	11	79.8	79.5	10.8	13.4	8.6	6.9
56	1	0	66.9	66.0	24.2	23.2	7.4	9.7
57	1	10	91.6	91.0	2.4	2.3	5.9	6.8
58	2	0	64.8	60.1	27.4	29.9	7.2	8.6
59	1	10	97.1	99.3	1.8	1.3	1.1	0.2
60	0	10	75.1	76.3	20.9	19.9	3.1	2.4
61	2	4	89.3	95.1	1.5	1.8	8.9	2.1

In a few instances, however, notable variations in the $MgCO_3$ content were found in the same layer. These are indicated in the table below.

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[44] Pa. Second Geol. Survey, Rept. M. M., 1879, p. 311.

TABLE IV.

NUMBER OF BED	THICKNESS		$CaCO_3$		$MgCO_3$		INSOLUBLE	
	Feet	*Inches*	*Bottom*	*Top*	*Bottom*	*Top*	*Bottom*	*Top*
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
14	12	8	95.85	83.70	2.40	11.85	1.80	3.40
17	2	8	96.60	60.20	1.10	33.40	1.10	5.90
68	14	10	85.1	96.00	10.40	2.30	3.20	1.90

Some of Lesley's conclusions are quoted in full:

Sometimes a bed of limestone only 5 or 6 inches thick crosses the exposure between two equally thin beds of dolomite, yet there is no appearance of gradation in the deposits, nor in their chemical composition. The same percentages of carbonate of magnesia are found at both extremities of the exposure.

In a few cases there is a decided difference in the amount of magnesia at one or other end of the exposure; but whether this be due to some error in the investigation or to a radical change of composition along the bed which exhibits it, is not certain.

There are thick masses of limestone strata with comparatively thin magnesian layers in their midst; and vice versa, there is sometimes a considerable thickness of magnesian rock parted by thin layers of nearly pure limestone.

There are a few layers of an intermediate species; but these are not numerous enough to destroy the remarkable and sudden contrasts of alternate layers of limestone with 2 or 3 per cent of magnesia and layers with 25, 30, 35 or more per cent. In fact the extreme limits are often directly and repeatedly in contact with each other.

The largest percentage of silicate of alumina is almost invariably found in the high magnesian layers.

The only generalization I can make from the above data is a negative one, namely: that no theory of percolation can account for the facts; that no theory of more rapid dissolution of carbonate of lime leaving a growing charge of magnesia behind, will apply to rocks which are neither honeycombed or visibly porous, nor unusually cleft, nor otherwise disturbed; and that any theory to account for the presence of magnesia must treat the layers of both species as equally mechanical sediments; especially, seeing that the larger part of the insoluble matter resides in those which contain most magnesia; while magnesia is present in all of both kinds.

Such a theory of origin is favored also by Phillipi[45] to account for certain impure dolomites associated with clastic sediments in the Muschelkalk of Germany. He believes that the material constituting these dolomites probably was derived from the residuum of a limestone originally low in magnesia. This view has been adopted lately by Grabau[46] also, who holds that the upper Silurian waterlimes and certain dolomitic intercalations in the Salina are clastic deposits derived from the erosion of older limestones. The same writer[47] is of the opinion that certain interstratifications of limestone and dolomite likewise are explainable upon the basis of the clastic theory, remarking that the relationship is most satisfactorily explained as a primary difference in the materials deposited, that both the limestone and the dolomite are clastic but are derived from different sources, or that the limestone is organic and the dolomite clastic.

II. Alteration Theories.

A. The Marine Alteration Theory.—The theory that dolomite has had its origin in the alteration of limestone before it emerged from the sea has had many followers and probably is most widely held today. Among the supporters of this view there has been almost unanimous agreement that the sea-water contributed the magnesia, and the only exception to this is the view of Favre[48] who, basing his suppositions upon the conditions of the experimental production of dolomite by Marignac, concluded that the dolomites of the Tyrol were formed in part at least by the alteration of limestone at a temperature of 200° C., and at a pressure of fifteen atmospheres, corresponding to a depth of 150 to 200 meters, by magnesium compounds furnished by the action of sulphurous and hydrochloric acids of volcanic origin on the lava of submarine melaphyr eruptions.

The conception that the alteration might be effected by the magnesia of sea water was first suggested by Dana[49] in 1843, to account for the dolomitic reef rock of the coral islands of the

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[45] Frech's Lethaea Geognostica, Vol. 2, 1908, p. 31.
[46] Bull. Geol. Soc. America, Vol. 24, 1913, p. 399.
[47] Principles of Stratigraphy, 1913, p. 760.
[48] Compt. Rend., Vol. 28, 1879, p. 364.
[49] Am. Jour. Sci., Vol. 45, 1843, p. 120.

Pacific. He hinted at this time that the rock might have been formed by the introduction of magnesia through the medium of heated sea water which possibly contained a larger supply of this element than usual. Three years later[50] in discussing the origin of a dolomitic coral limestone from the Island of Metia which contained 38.07 per cent of $MgCO_3$ he says:

"We cannot account for this supply of magnesia except by referring to the magnesian salts of the ocean. It is an instance of dolomitization during the consolidation of the rock beneath sea water, and throws light upon this much vexed question."

In 1872, the same writer[51] expressed the view that the same dolomite had been formed in sea water at ordinary temperatures but perhaps in a contracting lagoon where magnesian and other salts were in a concentrated state. In the latest edition of Dana's Manual[52] this same idea is elaborated without modification, the opinion being held that the concentrated brines in the lagoon would contain $MgCl_2$ and $MgSO_4$ in a state favorable to the formation of dolomite. He then goes on to say that "if this is the true theory of dolomite-making, then great shallow areas or basins of salt-pan character must have existed in past time over various parts of the continental area and have been a result of the oscillation of the water level. Such magnesian limestones contain few fossils, partly because of fine trituration, and partly, no doubt, because of the unusually briny condition of the waters. The frequent alternation of calcite and dolomite strata would indicate alternations between the clear water and salt-pan conditions."

F. Pfaff[53] likewise regarded the marine alteration theory as the most practicable for the origin of the dolomites of the French Jura. He pointed out that the relation of the limestone to dolomite in this formation and the great variation in the composition of the rock was such as to make Wagner's application of the chemical theory to this rock untenable. He further contended that the rock could not have been produced by the action of $MgSO_4$ or $MgCl_2$ on limestone, since no trace of gyp-

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[50] Am. Jour. Sci., 2d ser., Vol. 14, 1852, p. 82.
[51] Corals and Coral Islands, 1872, p. 356.
[52] Manual of Geology, 4th ed., 1895, p. 134.
[53] Pogg. Annalen, 1851, p. 465.

sum or of $CaCl_2$ now appear as reaction products in the dolomite. He, therefore, concluded that the most plausible agent of alteration was $MgCO_3$, and that the transformation must have taken place beneath the sea subsequent to the deposition of the limestone as evidenced by the decrease in the magnesia content downwards in the limestone and by the wavy boundary between the dolomite above and the limestone below in the Wisent Valley near Muggendorf.

Sorby[54] expressed himself in favor of the marine alteration theory in 1856, when he suggested that the formation of certain dolomites was effected by the alteration of limestone through the agency of soluble magnesian salts of the sea water "under some peculiar conditions not yet clearly explained during the period when it became so far concentrated that rock salt was frequently deposited; and that the calcareous salt removed during the change had, by decomposition with the sulphates of the sea water, given rise to the accumulation of gypsum. In support of this is an important fact, that some very solid dolomite does even now still contain about one-fifth per cent of salts soluble in water, consisting of the chlorides of sodium, magnesium, potassium and calcium and sulphate of lime, doubtless retained in the minute fluid cavities, seen with the microscope to exist in great numbers. These, like those in most crystals formed from solution, must have been produced at the same time as the dolomite, and caught in some of the solution then present, which is thus indicated to have been of a briny character.

A process the very reverse of that just described is now taking place by the action of dissolved gypsum, by which sulphate of magnesia, frequently efflorescing on the surface of the rock, and carbonate of lime are produced, and this may perhaps in some cases explain why the upper beds of the Permian limestone are now more calcareous than the lower."

Similarly Von Richthofen[55] adopted this theory, in 1860, to explain the formation of the great dolomitic reef rocks of southern Tyrol. He claimed that these dolomite masses represent dolomitized coral reefs formed during a period of subsidence

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[54] Rept. Brit. Assoc. Adv. Sci., 1856, p. 77.

[55] Cited by Skeats, Quart. Jour. Geol. Soc. London, Vol. 61, 1905, p. 97.

and that the St. Cassian marly and tufaceous deposits which flank the reefs represent the deposits of lagoons, bays and channels of the coral sea.

Mojsisovics,[56] in his classic memoir on the dolomite reefs of the same region, accepted a theory not essentially different from that of Von Richthofen. He held that the dolomite masses represent altered coral reefs possibly formed in the same manner as the recent one described by Dana, but doubted if the sea which effected the alteration was concentrated in lagoons as postulated by that writer.

Hoppe-Seyler[57] was also a champion of the marine alteration theory. He believed that the magnesia for altering great limestone masses to dolomite could be furnished only by the sea. In like manner, Doelter and Höernes[58] supported this theory in their memoir on dolomite building, attributing the greater part of the dolomites more or less rich in magnesia to the action of magnesia of sea water, especially the $MgCl_2$, on limestone made up of the calcareous skeletons of organisms.

F. W. Pfaff,[59] in 1894, basing his evidence upon the conditions under which he prepared dolomite artificially, concluded that the following chemical compounds are involved in the production of dolomite and magnesite in nature: (1) $CaCO_3$, (2) basic $MgCO_3$, (3) H_2S, (4) NH_3, and (5) NaCl. He believed that coral reefs might be altered to dolomite in the following manner: H_2S derived from decaying organisms would react with $CaCO_3$ taken into solution from the reef to form the hydrosulphide of calcium. $(NH_4)_2CO_3$, also resulting from putrefaction, would change a portion of the magnesium salts of the sea to basic $MgCO_3$ which with the H_2S would form the hydrosulphide of magnesium. By the action of CO_2 on the calcium and magnesium hydrosulphides so formed there would be a tendency to form the double carbonate, especially under the concentrated conditions which might result from the drying up of the sea water during ebb movements. Through numerous repetitions of this process a dolomitic reef rock might in time result.

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[56] Die Dolomitriffe von Süd Tirol, 1879, p. 505.
[57] Zeitschr. Deutsch geol. Gesell., Vol. 27, 1875, p. 495.
[58] Jahrb. K.-k. geol. Reichsanstalt, Vol. 25, 1875, p. 293.
[59] Neues Jahrb., Beil. Bd. 9, 1894, p. 485.

Later experiments by this author[60] led him to modify this view, but he did not abandon it completely, still maintaining that it would apply frequently and that it was especially applicable to the dolomite of the Neckar in Comstalt. In this new series of experiments Pfaff found that pressure must be regarded as an important factor in dolomite formation, since he obtained the best results in his artificial production of the mineral at pressures ranging from forty to sixty atmospheres. He concluded, therefore, that dolomitization must go on most effectively at a depth beneath the sea corresponding to this pressure. Thus, ideal conditions for dolomitization should exist in a sea like the Caspian, which attains a depth of from 180 to 1800 meters and is more or less concentrated. Such conditions, according to him, may have obtained when the dolomites of the Keuper and Haupt were formed; and the dolomite which occurs along with salt and gypsum in the Rauhwacke and Raibler strata might be explained in the same manner.

The paucity of fossils in some dolomites is attributed by Pfaff to the fact that the sea may have been in a concentrated state when they were deposited. He, therefore, believes that dolomitization takes place contemporaneously with deposition in some cases and in support of this he cites analyses showing a high magnesia content in slimes dredged from a considerable depth in the modern seas. One of these, taken from Pourtales Plateau, off the coast of Florida at a depth of 150 to 500 meters, bore 12.39 per cent $MgCO_3$ and 47.11 per cent $CaCO_3$, but also was high in phosphate of lime and in iron. The dolomite of the French Jura, however, he regards as having been formed by the alteration of limestone subsequent to its deposition, agreeing in this particular with the elder Pfaff. A concentration of the sea water due to its being shut off from free intercourse with the open ocean might bring about dolomitization after limestones were formed.

The view that pressure induced by considerable depth is an important factor in dolomite formation, however, is not shared by Phillipi,[61] who points out that dolomite is associated

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[60] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

[61] Neues Jahrb., Festband, 1907, Vol. I, p. 397.

with sandy sediments in the Röt and Keuper and that the presence of calcareous algae in the dolomite of the Alpine Trias proves that this could not have been formed in a deep sea as urged by Pfaff, since algae seldom live below 80 fathoms and never so deep as 200 fathoms. Moreover, Phillipi cites evidence of dolomitization at shallow depths and at ordinary concentration in the modern seas. For instance, he believes that the calcareous nodules described by Nichols from the Argus bank, of which one was found to contain 10.70 per cent of $MgCO_3$ in its outer portion, furnish an example of recent dolomitization at a depth not greater than thirty fathoms. Moreover, certain limestone lumps dredged from the Seine bank northeast of Madeira at a depth of about 150 meters were found to bear 11 to 18 per cent of $MgCO_3$. Microscopic study showed the presence of dolomite crystals in the lumps and every stage of the alteration could be traced. In addition to the dolomite crystals scattered through the mass others appear lining cavities in the rock and these are believed to have been deposited chemically. The lumps evidently are not being formed today, because the organisms imbedded in them are not the same as those now living on the Bank, and what is more, their outer surfaces show corrosion effects. But Phillipi believes they were formed in shallow water at ordinary concentration and that they were brought to their present level by subsidence.

The dolomites of the Aspen District of Colorado are best explained upon the basis of the marine alteration theory, according to Spurr,[62] who expresses himself as follows:

"It is probable, therefore, that the Silurian dolomite of the Aspen district was originally deposited in quiet seas, and was built up from calcareous sediments; that these beds were subsequently altered to dolomite by the magnesium salts of a great evaporating shallow inland sea, and that the alteration was accompanied by the production of the crystalline structure characteristic of the rock." The same method of origin is ascribed to the overlying dolomites of the Carboniferous which Emmons had previously regarded as chemical deposits.

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[62] Mono. U. S. Geol. Survey, Vol. 31, 1898, p. 12.

Calvin and Bain[63] adopt an analogous explanation for the origin of the Galena dolomite of the upper Mississippi Valley. On page 410 they state that "it looks as if dolomitization had affected the limestone .... after the formation was complete; that the process began at the top and progressed downwards; and that the depth to which the change descended was, in some instances and to some extent at least, determined by the presence or absence of impervious beds of shale." On page 441 their views are elaborated much more fully, thus:

"It has been said that probably the Galena limestone owes its dolomitic character to the fact that, toward the close of the interval represented by the formation named, the area now occupied by the lead-bearing limestone was an isolated, or partly isolated, basin in which the sea waters were concentrated by evaporation. The City of Dubuque is located in what was the central part of this land-locked basin. In order that the concentration necessary to produce dolomitization of the limestones might be possible, it is a fair assumption that the interval was one of arid climate, one in which loss by evaporation exceeded the volume of drainage water received by the basin from adjacent lands."

Van Hise,[64] on the other hand, tends to minimize the importance of dolomitization before the limestones emerge from the sea and emphasizes the importance of ground water as a dolomitizing agent. Observe the following statement:

> While it is clear that dolomitization below the sea may locally go far, the usual facts of observation correspond with the conclusion above given, that dolomitization below the sea is usually very partial, and that the Metia example is exceptional..... It is entirely possible that locally the Cambro-Silurian limestone was dolomitized more extensively below the sea than is the case, on the average, for the later limestone formations. Indeed, it has been supposed that this has been deposited in a mediterranean sea, and that the entire sea may have had to some extent the concentrated conditions at Metia described by Dana. But it appears certain to me, even if the dolomitization was further advanced in the case of some of these formations while below the sea than can be paralleled by recent exten-

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[63] Iowa Geol. Survey, Vol. X, 1899, pp. 410 and 441.
[64] Mono. U. S. Geol. Survey, Vol. 47, 1904, p. 803.

sive formations, that they have subsequently been much further dolomitized and the magnesium extensively rearranged since the limestones emerged from the sea.

Branner[65] about this time furnished evidence of recent dolomitization through the agency of sea water in an old reef rock of the stone reefs of Brazil. This rock was found to bear 12.98 per cent of $MgCO_3$ and the assumption was made that part of the lime of the coral rock had been replaced by magnesium from sea water. The rock is still within reach of sea water, and dolomitization is believed by him to be still in progress. The structure of the rock disappears in proportion as the dolomitization proceeds.

Several examples of altered coral reefs have been described by Skeats[66] from the southern Pacific. Dolomite occurs in several of the elevated coral islands there, but attains its greatest purity in Christmas Island, where it contains as much as 43.3 per cent of $MgCO_3$. This author holds that Dana's theory with some modification probably applies here, and believes that the view that limestone is altered to dolomite at a considerable depth corresponding to a particular pressure is untenable. This is indicated by the fact that in several of the islands the highest rocks are dolomitized and the only movement of which there is evidence since their formation in shallow water is one of elevation. He states that "it seems probable that the introduction of magnesia into the limestone does take place from the waters of the lagoon under certain favorable conditions," but adds that "it is improbable that concentration to any marked extent can take place in lagoons unless they are entirely shut off from the sea." The CO_2 liberated by the decay of the animals and plants of the reef would help to dissolve $CaCO_3$, which might then react with the $MgSO_4$ of sea water to give rise to dolomite, the more soluble product $CaSO_4$ remaining in solution. He concludes that since the extent to which the alteration proceeds must depend upon the duration of the exposure of the limestones to the conditions producing dolomitization, the occurrence of dolomite at several different

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[65] Bull. Mus. Comp. Zool., Vol. 44, 1904, p. 264.
[66] Bull. Mus. Comp. Zool., Vol. 42, 1903, p. 53.

horizons in an island might be accounted for upon the basis of changes in the rate of subsidence or elevation.

In a very suggestive paper entitled "On the Chemical and Mineralogical Evidence as to the Origin of the Dolomites of Southern Tyrol"[67] the same writer elaborates his views still further. He emphasizes again that dolomitic coral reefs could not have been formed at great depths, and points out that dolomitization of coral reefs is not confined to concentrated lagoons since the outer parts of fringing reefs facing the open ocean are sometimes dolomitized. Thus, some of the fringing reefs of the Fiji Islands are altered, and the raised fringing reefs along the coast of the Red Sea are also occasionally dolomitic. He believes, therefore, that "the Schlern dolomite originated first as a limestone, composed of organisms, in a slowly subsiding area. Dolomitization of the limestone in superficial waters kept pace with the slow subsidence, so that the whole thickness of 3,000 feet or more of rock was continuously and uninterruptedly converted into dolomite during the Triassic Period." In conclusion Skeats lists the following conditions as favorable to the formation of dolomite masses:

(a) Shallow water between 0 and 150 feet in depth and corresponding to a pressure of 1 to 5 atmospheres.

(b) The presence of carbon-dioxide in comparative abundance, causing the partial solution of the limestones and the possibility of chemical interchange with the magnesium salts in sea water.

(c) Porosity of the limestones, allowing the percolation of sea water through the mass of the rocks.

(d) Sufficiently slow subsidence or elevation to render the change from calcite to dolomite complete.

Other examples of dolomitization believed to have been effected by sea water have been described recently by Dixon[68] as occurring in the Carboniferous limestones of South Wales. In the Main limestone member of the series he finds evidence of two distinct periods of dolomitization. The first of these affects certain horizons of the Mumbles Head and Laminosa divisions over wide areas and is regarded as contemporaneous, while the second

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[67] Quart. Jour. Geol. Soc. London, Vol. 61, 1905, p. 97.

[68] The Geology of the South Wales Coal Fields, Part 8: Mem. Geol. Survey, England and Wales, 1907, p. 13.

affected the limestone along fissures and hence is subsequent. The contemporaneous dolomitization produced extensive beds and pockets of dolomite and gave rise to a peculiar mottled rock designated as pseudo-breccia. This alteration is believed by Dixon to have been inaugurated so shortly after deposition that the magnesian salts were derived from the Carboniferous sea itself. He indeed asserts that at one place the alteration must have proceeded during the formation of the limestone. Thus, a conglomerate interbedded with the limestone at Pendine contains fragments of Carboniferous limestone which was dolomitized before it was incorporated in the conglomerate. This contemporaneous dolomitization is believed to have taken place in shallow seas since the limestones affected show evidence of shallow water deposition. The subsequent dolomitization is thought to have taken place much later through the agency of underground water.

Peach and Horne[69] are of the opinion that the Cambrian dolomites of the Northwest Highlands of Scotland were formed by the dolomitization of calcareous sediments on the sea bed itself; but they regard it as possible that there may have been also an enrichment of magnesia through the leaching out of the more soluble calcareous material of a slightly magnesian ooze, possibly made up of the secretions of unicellular plants of the plankton.

The marine alteration theory has been adopted likewise by Salomon[70] in recent years to explain certain nests and tongue-like extensions of dolomite in the Ladinic limestones of the Alps. Similarly Walther[71] recognizes that dolomites may be produced in this manner. Following Nadson, he suggests that the $MgCO_3$ which enters into the dolomite may be deposited through the influence of bacteria of the sea water standing in the pores of the rock.

In favor of some method of alteration capable of operating over wide areas are the observations of Weller[72] also, who, from a comparison of the faunas of the Galena and Niagaran dolomites of the Upper Mississippi Valley with their non-dolomi-

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[69] The Geological Structure of the Northwest Highlands of Scotland: Mem. Geol. Survey, Great Britain, 1907, p. 370, ff.

[70] Abh. K.-k. geol. Reichsanstalt, Vol. 21, Part I, 1908, p. 408.

[71] Geschichte der Erde und des Lebens, 1908, p. 90.

[72] Bull. Geol. Soc. America, Vol. 22, 1911, p. 227.

tized equivalents in other regions, concluded that they must have been deposited first as limestone and later metamorphosed.

Blackwelder[73] also advocates this method of origin for the Bighorn dolomite of Wyoming; but the low porosity of the dolomite (1.31 per cent) and its sharp contact with the limestone interbedded with it and underlying it leads him to favor the view that it was not formed by the substitution of magnesium for half the calcium in normal limestone, but that it has resulted from progressive alteration during deposition. Thus:

> The remaining fourth suggestion to be examined is that the material of the Bighorn dolomite was originally deposited in the form of lime carbonate growths, shells, or ooze, but was progressively altered to dolomite before actual lithification took place, in consequence of chemical reactions in the basal layer of the sea water in which deposition was proceeding. . . . If, as assumed, this process of converting lime carbonate into dolomite during crystallization took place in the loose sediment lying undisturbed on the ocean floor, there seems to be no reason why it should have affected a layer more than a few inches in depth at any one time. If this view is correct, it helps to explain the alternation of dolomites and limestones in many formations and the fact that the beds underlying the Bighorn formation are pure limestone rather than dolomite.
>
> To this hypothesis of the dolomitizing of lime carbonate deposits in the course of their deposition I find no positive objection, and as it apparently explains most of the observed facts, it seems to me the most promising of the suggestions which have made.

In this particular, then, Blackwelder follows Daly,[74] who believes that the magnesia content of the pre-Devonian limestones is original and that "in many, if not all, cases the dolomite crystals may have been formed at or near the surface of the ancient calcareous muds by the interaction of the magnesium salts of sea-water with the more easily precipitated calcium carbonate."

As regards the conditions obtaining when the Bighorn dolomite was formed, Blackwelder states that "experimental work has shown that strong solutions of magnesium salts are deleterious to the growth of animals and plants, but inasmuch as the

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[73] Bull. Geol. Soc. America, Vol. 24, 1913, p. 607.
[74] Bull. Geol. Soc. America, Vol. 20, 1909, p. 153.

Bighorn sea evidently contained abundant living organisms—many of them, like the corals, very delicately adjusted to their environment—it seems unlikely that the magnesium content could have been more than two or three times as great as in the present ocean.'' He believes that the deposits were laid down in a warm epicontinental sea less than 100 to 200 meters in depth.

The late views of Nahnsen[75] likewise are in line with the theory of the alteration of limestone beneath the sea. He describes a horizontal seam of dolomite with wavy boundaries in the Upper Jurassic limestone of North Germany, and concludes that the alteration probably took place beneath the sea before the rock solidified, since solutions would not circulate freely after recrystallization.

B. The Ground Water Alteration Theory.—That ground water is capable of accomplishing local dolomitization under favorable conditions there can be no doubt, and there has been a tendency on the part of some to believe that this method of alteration is of far-reaching significance. Most writers who have supported this view have emphasized the importance of the $MgCO_3$ of ground water as the dolomitizing agent, but some have advocated that $MgSO_4$ was very effective. For instance Collegno, as early as 1834[76] pointed out the frequent association of gypsum and dolomite in the St. Gothard region and regarded these both as transformation products resulting from the action of the $MgSO_4$ in surface water on limestone. For similar reasons Haidinger[77] advocated this method of origin, but since he found evidence that under ordinary conditions a solution of $CaSO_4$ tends to convert dolomite into $MgSO_4$ and $CaCO_3$ he assumed that the contrary change takes place at great depths and under considerable pressure. In this view Haidinger was closely followed by Morlot.[78]

That dolomite might be formed by the partial replacement of calcite by magnesium carbonate was first pointed out by Haidinger,[79] who described a dolomite pseudomorph after calcite and in-

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[75] Neues Jahrb., Beil. Bd. 35, 1913, p. 277.

[76] Bull. Soc. géol. France, Vol. 6, 1834, p. 106.

[77] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, 1859, p. 158.

[78] Haidinger's Naturw., Abh. Vol. 1, 1847, p. 305.

[79] Trans. Roy. Soc. Edinburgh, 1827, p. 36.

timated that it had been formed in this manner. It remained for Beaumont,[80] however, to put this theory into definite form. Reasoning on the basis that the replacement was molecular and that one out of every two equivalents of $CaCO_3$ was replaced by $MgCO_3$ he calculated that the transformation of limestone to dolomite should be accompanied by a decrease in volume of the rock to the extent of 12.1 per cent. This, he believed, would explain the cavernous character of the dolomites of the Tyrol. Actual porosity determinations of a sample of dolomite from the Alps by Morlot,[81] who obtained the value of 12.9 per cent, later seemed to confirm this prediction.

Scowler[82] also favored this view for the origin of the Carboniferous dolomites of Ireland, believing that the alteration might readily be accounted for by the infiltration of water charged with $MgCO_3$. He suggested that the magnesia was derived from an igneous or ancient Paleozoic rock, or from springs.

In discussing the dolomite of the coral island of Metia Jackson[83] suggested that ascending spring water bearing $MgCO_3$ might have effected the change. Likewise, Haussmann[84] believed that the dolomite of the Muschelkalk was produced by the action of $MgCO_3$ of ascending thermal springs on limestone.

Nauck[85] also cited an instance where he believed limestone had been transformed to dolomite by $MgCO_3$, and Bischof[86] pointed out that since dolomite pseudomorphs may be formed by the action of $MgCO_3$ on calcite, the substitution might also be expected to take place in amorphous carbonate of lime or in compact limestone. "Consequently dolomite would be produced whenever carbonate of lime in any state is brought into such conditions as are requisite for conversion into double carbonate of lime and magnesia. The essential conditions of this conversion are the permeation of carbonate of lime by water containing bicarbonate of magnesia, which is one of the most common constituents of spring water."

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[80] Bull. Soc. géol. France, 1836, p. 174.
[81] Compt. Rend., Vol. 26, 1848, p. 311.
[82] Jour. Geol. Soc. Dublin, Vol. I, 1838, p. 382.
[83] Am. Jour. Sci., Vol. 45, 1843, p. 140.
[84] Neues Jahrb., 1854, p. 478.
[85] Pogg. Annalen, Vol. 75, 1848, p. 129.
[86] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 166.

It will be observed that most of the foregoing advocates of the ground water alteration theory attributed the source of the magnesia to spring water. An entirely different idea, however, was entertained by Green[87] who, in 1876, suggested that the $MgCO_3$ might be furnished by the decomposition of olivene sand incorporated in the limestone at the time it was formed. He refers to the fact that in the Hawaiian Islands olivene forms the main component of the sand of the seashore wherever the sea meets the lava and that fine olivene sand is frequently mixed with the coral sand and even impregnates the coral rock. He suggests that the silica of the olivene sand so imbedded in limestone might be removed in solution and the magnesia converted into $MgCO_3$, which would then give rise to dolomitization. It is his belief that many magnesian limestones and dolomites as well as serpentinous streaks in limestone may have been formed in this manner.

There always has been a tendency to regard dolomite veins in limestone as the product of the reaction of the $MgCO_3$ of circulating ground waters on limestone. For instance Schmidt[88] expressed the view, in 1875, that the dolomitized limestone associated with the ores of the Joplin district was formed in this way. In like manner Michael[89] attributes the dolomitization of the Muschelkalk along lines of disturbance at Tarnowitz, in southeastern Prussia, to the same cause. The dolomitization there appears to be closely bound up with the mineralization phenomena, the sulphide ore deposits being limited to the dolomitic areas.

The local dolomitization effects in the Leadville limestone of the Aspen district of Colorado[90] also are attributed to the action of the magnesia of ground water by Spurr. The limestone is dolomitized along faults and fractures and "the local dolomitization almost invariably accompanies the ore." No tangible evidence as to the conditions under which these vein dolomites were formed could be obtained in the Aspen district, but at Glenwood Springs, Colorado, only forty miles away, Spurr obtained some

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[87] Jour. Roy. Geol. Soc. Ireland, 2d ser., Vol. 4, Part 3, 1876, p. 140.
[88] Trans. St. Louis Acad. Sci., Vol. 3, No. 2, 1875, p. 246.
[89] Zeitschr. Deutsch. geol. Gesell. Prot., Vol. 56, 1904, p. 127.
[90] Mono. U. S. Geol. Survey, Vol. 31, 1898, p. 208 ff.

valuable data bearing on the problem. Thermal springs, attaining a temperature of 120° F., rise through fissures in the same limestone formation here that exhibits local dolomitization effects at Aspen, and the analysis of samples of the limestone taken at intervals from the conduits of the springs outward showed a progressive, though in some cases almost an inappreciable, decrease in the magnesia content. The conclusion was reached, therefore, that the local dolomitization at Aspen is probably due to the effects of hot springs which, rising along faults and fractures, altered the limestone to dolomite by means of the $MgCO_3$ and $MgCl_2$ they held in solution.

By Van Hise[91] the importance of dolomitization through the agency of ground water is strongly emphasized, and it would appear that he gives this method of dolomite formation precedence over dolomitization beneath the sea.

Local dolomitization phenomena along fissures in the Carboniferous limestone of South Wales is attributed to the action of ground water by Dixon[92], who states that water percolating downwards from the surface effected the change. Wichmann[93] likewise has described local dolomitization effects in the Korallenoolith (Jura) which he ascribes to the action of ground water bearing $MgCO_3$.

The latest word expressed upon the efficiency of ground water in producing dolomitization is that of Steidtmann[94], who regards this method of dolomite building as capable of operating only locally.

C. The Pneumatolytic Alteration Theory.—The pneumatolytic theory of the origin of dolomite was introduced in 1779, by Arduino,[95] to whom we are indebted for the first attempt to explain the formation of the rock. Dolomite had not been fully differentiated from limestone at that time, but Arduino mentions a magnesian limestone which from its association with rocks of volcanic origin he believed to have been formed by the alteration of ordinary limestone during volcanic activity.

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[91] Mono. U. S. Geol. Survey, Vol. 47, 1904, p. 804 ff.

[92] Geology of the South Wales Coal Fields, Part 8: Mem. Geol. Survey, England and Wales, 1907, p. 13.

[93] Zeitschr. Deutsch. geol. Gesell., Vol. 61, 1909, p. 392.

[94] Jour. Geol., Vol. 19, 1911, p. 323.

[95] Cited by Morlot, Haidinger's Naturw. Abh., Vol. 1, 1847, p. 305.

Heim[96] also entertained similar views as to the origin of the rock, but it remained for Von Buch[97] to develop the theory and put it in definite form in the early twenties of the last century. In his studies in the Tyrol he observed that the dolomite was vesicular; that the bedding planes and the fossils were obliterated and that a brecciated, fissured and crystalline structure had been taken on. He, therefore, concluded that this could represent no original deposit from the sea, but that it must have been deposited at first as limestone and subsequently altered. This alteration, he believed, was accomplished by volcanic vapors bearing magnesia, which were given off by the intrusions of augite porphyry which there penetrate the rock. This view, however, was not shared by Wissmann[98] nor by Fournet,[99] who were unable to find any constant association of the dolomite with the intrusives.

In 1843, Klipstein[100] adopted the pneumatolytic theory to explain the veinlike deposits and irregular masses of dolomite in the transition limestone of the Lahn district, holding that ascending magnesian vapors had effected the transformation, although he was not able to find fissures extending downwards from the dolomite in all cases. Likewise Coquand[101] believed that dolomites associated with igneous intrusions were of pneumatolytic origin, and in support of his contention he furnishes quite convincing evidence. Thus, at Rougiers, in the province of Var, in France, samples of the limestone associated with basalt intrusions showed a progressive decrease in the magnesia content from limestone imbedded in the basalt, which contained 39.6 per cent of $MgCO_3$, to limestone two meters away which bore only 9.5 per cent. The unaltered limestone not associated with igneous rocks showed no trace of magnesia. The force of this argument, however, has been weakened by the observations of Bischof,[102] who held that this phenomenon might

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[96] Cited by Zirkel, Lehrbuch der Petrographie, 2d ed., Vol. 3, 1894, p. 505.

[97] Cited by Morlot, Haidingers Naturw. Abh., Vol. 1, 1847, p. 305.

[98] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 200.

[99] Bull. Soc. géol. France, 2d ser., Vol. 6, 1849, p. 502.

[100] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 187.

[101] Bull. Soc. géol. France, Vol. 12, 1841, p. 314.

[102] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 179.

be due to the local alteration of the limestone by $MgCO_3$ liberated by the decomposition of the basalt.

Karsten[103] also favored the volcanic theory as elaborated by Von Buch, and Frapolli[104] similarly has gone on record in favor of this view, holding that the dolomites were formed through the agency of volcanic emanations either while deposition was going on beneath the sea or after the rock was deposited. Quite the same opinion was held by Durocher[105] who, basing his supposition upon the conditions of his experimental production of dolomite, believed that vaporous $MgCl_2$ emanating from the interior of the earth had metamorphosed limestone to dolomite.

The latest writer to express himself on this theory is Linck,[106] who states that dolomite might be formed under favorable conditions by pneumatolytic action.

III. Leaching Theories.

It has been long known that when a magnesian limestone is subjected to solvent action the lime is taken into solution much more rapidly than the magnesia, thus giving rise to a concentration of the latter constituent, and many geologists have held that by the continued leaching of a limestone originally low in magnesia, either at the surface or beneath the sea, a dolomite might in time result.

A. Surface Leaching Theory.—The view that dolomite might result from surface leaching seems to have been first suggested by Apjohn[107] in 1838, who stated that the $CaCO_3$ might be removed from limestones containing some magnesia by the solvent action of carbonated waters, and that some dolomites might have been produced in this manner. Grandjean[108] subsequently was led to adopt the same explanation, in 1844, to account for the dolomites of the lower Lahn district, and pointed out that the dolomite is developed to its greatest extent near fissures and cracks in the limestone where water has had easy access.

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[103] Archiv. Min., Vol. 22, 1848, p. 545.
[104] Bull. Soc. géol. France, Vol. 4, 1847, p. 832.
[105] Compt. Rend., Vol. 33, 1851, p. 64.
[106] Doelter's Handbuch der Mineralchemie, Vol. I, 1912, p. 134.
[107] Jour. Geol. Soc. Dublin, Vol. 1, 1888, p. 368.
[108] Cited by Bischof, Elements of Chemical and Physical Geology. English translation, Vol. 3, 1859, p. 193.

The same view was accepted by Sandberger[109] the following year for the dolomites of the same district.

In support of this theory also are the observations of Bischof,[110] who showed by experiment that carbonated waters do not dissolve out of magnesian limestone more than a mere trace of magnesia and concluded that dolomite would ultimately be formed either by the action of surface water, or of sea water on limestone. He remarks that "it may be conjectured that the dolomite containing calc-spar druses is still in course of formation, while in that containing bitter-spar druses the conversion is complete" and sums up with the following statement:

> Considering all the circumstances, it appears probable that limestone containing little or no silicates, but rich in magnesia, may be converted into dolomite on the spot, by extraction of the excess of calcium carbonate.

Hardman[111] also regarded this as the plausible theory of dolomite formation, and he sought by its employment to explain the method of origin of the Carboniferous dolomites of Ireland. He actually proved experimentally that the magnesia of these limestones became more concentrated when they were subjected to the action of carbonated waters and showed by analysis that the stalactite and stalagmite deposits of caves in the magnesian limestone were extremely low in magnesia. These features, together with the porous character of the dolomite, seemed to him to speak forcibly for the leaching hypothesis.

In still later times Hall and Sardeson[112] favored this theory in their discussion of the origin of "The Magnesian Series of the Northwestern States." Thus:

> The flow of waters from the dolomitic beds, with their load of calcium carbonate, can in time produce but one result, and that is to bring into more equal proportions the quantity of calcium and magnesium carbonates. The disappearance of over 80 per cent more of the former than of the latter, which

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[109] Neues Jahrb., 1845, p. 577.

[110] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 195.

[111] Proc. Roy. Irish Acad., 2d ser., Vol. 2, (Science), 1875-77, p. 705.

[112] Bull. Geol. Soc. America, Vol. 6, 1895, p. 167.

occurs if the original rock of these beds had the composition of average modern marine deposits, must result in the removal of at least eight times as much of that material as remains behind. Under such an assumption every 100 feet of the present thickness of the Oneota and Shakopee would represent an original thickness of 1,000 feet, more or less, an extent much nearer in accord with what seems necessary in sedimentary accumulations to conform to the profound faunal changes and crustal movements so conclusively proved by the paleontologic and structural conditions of the rocks.

Phillipi,[113] in like manner, brought the leaching theory to bear, in 1899, to account for the Conchodon dolomite of the southern Alps. He points out that in the heights where the rock is subjected only to the action of water poor in CO_2 it is but little if at all dolomitized, but in situations where the water can take up CO_2 and humus acids, leaching and recrystallization have taken place. By him humus acids are regarded as the most powerful agents in transforming a weakly dolomitic limestone to dolomite.

B. The Marine Leaching Theory.—That marine leaching of calcareous deposits low in magnesia might give rise to dolomite was suggested by Bischof in 1859,[114] but he made no attempt to elaborate the idea. Eleven years later Gümbel,[115] in making a study of certain deep sea oozes, found one taken from a depth of 2,350 fathoms in the Atlantic which yielded upon analysis 1.44 per cent of magnesia. This magnesia content is accounted for upon the basis of the solution of a portion of the original calcareous material, and it is suggested that by the same method dolomitic rocks and marly intercalations might be formed.

The marine leaching theory, however, has been most fully developed by Högbom.[116] This writer regards marine leaching as far more important than surface leaching, since the latter can operate only on that portion of the limestone exposed. The results of a leaching experiment on a marl demonstrated the plausibility of this process, and the following table of analyses of deep sea deposits taken from the Challenger report also seemed to lend support to this view.

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[113] Neues Jahrb., 1899, Vol. 1, p. 32.

[114] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859,

[115] Neues Jahrb., 1870, p. 753.

p. 195.

[116] Neues. Jahrb., Vol. I, 1894, p. 262.

TABLE V.

$CaCO_3$ RANGE	$CaCO_3$ AVERAGE	$MgCO_3$	PARTS OF $MgCO_3$ TO 100 PARTS OF $CaCO_3$	NUMBER OF ANALYSES
80-100	86.7	0.7	0.8	8
60-80	68.3	1.4	2.0	8
40-60	52.0	1.2	2.4	8
20-40	32.0	0.9	3.0	3
10-20	16.2	1.6	10.0	4
5-10	6.1	0.7	11.5	1
3-5	3.7	1.6	43.0	7
1-3	2.0	2.1	105.0	9

The most convincing argument of all, however, was found by Högbom in the marine Quaternary marls of Sweden. These marls, which are believed to have been transported from a Silurian argillaceous rock by glacial waters, become progressively weaker in $CaCO_3$ and richer in $MgCO_3$ the farther southward one goes from the parent rock, as shown by analyses made by the Geological Survey. (See Table VI.)

TABLE VI.

SECTION	$CaCO_3$	$MgCO_3$	PARTS OF $MgCO_3$ TO 100 PARTS OF $CaCO_3$	NUMBER OF ANALESES
Leufsta	32.0	1.2	3.7	14
Örbyhus	23.0	1.4	6.1	6
Salsta	21.7	1.5	6.9	10
Upsala	17.8	1.3	7.2	8
Sigtuna	11.4	0.8	7.0	29
Fånö	11.9	1.9	16.0	9
Södertelje	7.6	2.8	37.0	9
Hörningsholm	3.3	1.2	36.0	17

This relationship is explained by the fact that the longer the glacial mud was in suspension and the farther it was carried from the source, the more the $CaCO_3$ was leached out and the $MgCO_3$ enriched because of its greater insolubility.

Högbom also furnishes evidence of enrichment of magnesia by marine leaching in the coral reefs of Bermuda. Analyses of the reef-building corals and other organisms showed a uniformly low magnesia content, but the lagoon muds which must have been derived from the organisms of the reef were found to be much richer in this constituent, one sample yielding 4.04 per cent of $MgCO_3$. Likewise the magnesia content was found to increase with the degree of fineness and duration of suspension. Thereupon it is suggested that if the detritus should remain in suspension long enough it would undergo thorough leaching and a true dolomitic sediment might result. The opinion is then ventured that many dolomites of older formations played an important part in the building of the Alpine dolomites.

Judd[117] is of the opinion that the dolomitic rock disclosed by the boring at Funafuti was formed, in part at least, by marine leaching. The conditions represented there are summarized briefly as follows:

> As has been already pointed out, the proportion of $MgCO_3$ rises in the first 50 feet of descent in all the borings, from the normal 1 to 5 per cent, up to a maximum of nearly 16 per cent which is attained at a depth of about 25 feet, and then declines again to what may be considered the normal amount, 1 to 5 per cent. At 637 feet the percentage of $MgCO_3$ again rises from the normal and by 660 feet has reached nearly 40 per cent. This proportion, with some small exceptions, is maintained to the bottom of the bore hole at 1,114 feet.

Cullis,[118] who made a mineralogical study of the core, states that above the 637 foot level the rock consists of aragonite and calcite without individualized dolomite. But from this depth to the bottom of the hole the rock is made up of calcite and individualized dolomite.

In reviewing the evidence in favor of marine leaching, Judd refers to the analyses of Lithothamnium by Högbom, which showed a maximum of 14 per cent of $MgCO_3$ and regards it as probable that this abnormal magnesia content is due to leaching, since the material originally secreted by these organisms probably did not contain more than one per cent of $MgCO_3$. He concludes that "it seems not improbable that the enrichment of the rock in $MgCO_3$ up to 16 per cent in the upper part of the cores may be entirely due to the leaching out of

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[117] The Atoll of Funafuti, 1904, p. 362.
[118] Idem., p. 393, ff.

the $CaCO_3$." All of the $MgCO_3$ of the rock to a depth of 637 feet, then, according to him, probably is to be ascribed to leaching, and the variation in the magnesia content at different levels is due to the varying proportions of organisms which differ in their susceptibility to the leaching out process. Judd then suggests that a rock so enriched in magnesia by leaching might exercise an attractive action on the magnesium salts of the sea water. He evidently would imply that this might account for the more highly dolomitic rock in the lower part of the boring, but he does not express himself clearly on this point.

This view, however, is not esteemed highly by Skeats,[119] who, in reference to Judd's conclusions, remarks as follows:

> The process of differential solution is one which no doubt coral-limestones undergo to a greater or smaller extent, and it is probably the correct explanation of the origin of the all but structureless limestones containing magnesium-carbonate in sufficient amount for the production of dolomite-crystals. Very extensive solution and removal of calcium-carbonate is needed, however, before the percentage of magnesium-carbonate in the residual rock is appreciably raised. Assuming the original limestone to contain 1 per cent of magnesium-carbonate, an amount which is probably near the superior limit for the fresh organisms composing the rock, and further, assuming that only the calcium-carbonate is dissolved by carbonated water 80 per cent of the original rock must be removed by solution before the magnesium-carbonate in the remainder reaches 5 per cent, 90 per cent must be dissolved before the magnesium-carbonate reaches 10 per cent, and over 93 per cent before the magnesium-carbonate reaches 16 per cent. So extensive a removal of the original substance of the rock would largely destroy the structure of the organisms that it contained. In the case of the limestones from Christmas Island, Niue, and elsewhere, examined by me, in which magnesium-carbonate was present in the rock in amounts up to 11 per cent, the structure of the contained organisms was in general wonderfully preserved; and not only was there no evidence of solution in the rock, but on the contrary secondary calcite and secondary aragonite were deposited upon the organisms to a considerable extent. I was in consequence, forced to the conclusion that in these limestones

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[116] Neues Jahrb., Vol. 1, 1894, p. 262.

the magnesium-carbonate was introduced into the rock from the sea-water, resulting in the partial replacement of calcium- by magnesium-carbonate.

Peach and Horne[120] are favorable to the idea that marine leaching may account in part for the Cambrian dolomites of the Northwest Highlands of Scotland, suggesting that unicellular plants which secreted lime may have existed in the plankton as in the sea today and that the small magnesia content of these may have been concentrated by the abstraction of the more soluble $CaCO_3$. They believe, however, that some replacement has taken place also.

Murray and Hjort[121] also concur that the explanation of enrichments of magnesia in deep sea deposits is to be sought in preferential dissolution of the lime. To them enrichment of the magnesia by reaction with sea water does not seem plausible, since this would require that the waters be concentrated with $MgCO_3$.

EXPERIMENTAL EVIDENCE.

As regards the experimental evidence of the origin of dolomite, it may be safely said that the present data are very unsatisfactory and of little value in interpreting the conditions under which this rock is formed in nature. Dolomite has been prepared repeatedly at high temperature and at high pressure, and at both high temperature and high pressure, but in only rare instances has it been prepared artificially at ordinary temperature and pressure, and then only in minute amounts and for the most part under conditions which doubtfully obtain in nature, at least on a large scale.

I. Evidence Bearing on the Primary Deposition Theories.

The experimental evidence bearing on the primary deposition of dolomite is, from the nature of the case, applicable only to the theory of chemical precipitation. The experiments bearing on this theory are for convenience classified as follows: (1) those performed at ordinary temperature and ordinary pressure; (2) those performed at elevated temperature but at ordi-

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[120] The Geological Structure of the Northwest Highlands of Scotland; Mem. Geol. Survey, Great Britain, 1907, p. 370.

[121] The Depths of the Ocean, 1912, p. 180, ff.

nary pressure; and (3) those performed at ordinary temperature but at elevated pressure. These will be discussed in their regular order.

Experiments at Ordinary Temperatures and Pressures.—All attempts to produce dolomite directly under ordinary conditions have failed, but evidence of the possible production of dolomite under these conditions in nature has been observed in several instances. Thus, Moitesser[122] found small rhombohedral crystals which had the composition of dolomite, in a badly closed flask of mineral water from a French spring. Similarly, Terreil[123] reported that rhombohedral crystals of carbonate of calcium and carbonate of magnesium were deposited upon the walls of sealed tubes which contained samples of mineral water from the region of the Dead Sea. He does not distinctly state that the double carbonate was present, but remarks that this discovery may have an important bearing on the origin of the dolomites of that region.

Certain travertine deposits also are said to be rich in $MgCO_3$. F. W. Clarke[124] states that "according to J. Giradin, the travertine formed by the mineral spring of Allyne, near Clermont, in France, is rich in magnesium carbonate. In recent travertine he found 28.80 per cent of $MgCO_3$ with 24.40 of $CaCO_3$, and in old travertine the proportions were 26.86 and 40.22 respectively. Whether this represents a dolomite or a mixture of the carbonates was not determined."

J. F. Johnson[125] has likewise described a dolomitic spring deposit on the north bank of the river Tees in England, and believes this occurrence has a direct bearing on the origin of dolomites in general. Gorup-Besanez, however,[126] states that the springs which issue from the dolomites of the Jura deposit upon evaporation the mixed carbonates of calcium and magnesium although they are present in essentially the same proportions as in normal dolomite. Bischof[127] has this to say regarding the magnesia content of spring deposits:

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[122] Jahresber. Chemie, 1866, p. 178.

[123] Cited by Lartet, Bull. Soc. géol. France, 2d ser., Vol. 23, 1866, p. 750.

[124] Bull. U. S. Geol. Survey, No. 491, p. 536.

[125] Liebig and Kopp, Jahresber., 1853, p. 927.

[126] Quoted by F. W. Clarke, Bull. U. S. Geol. Survey No. 491, p. 536.

[127] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 167.

Water extracts from a mixture of carbonates of lime and magnesia twenty-eight times as much carbonate of magnesia as carbonate of lime; consequently, when water containing about equal quantities of these carbonates, evaporates so far that the separation of carbonate of lime commences, the deposition of carbonate of magnesia cannot take place until the water has evaporated to such an extent that there remains only 1-28 of the water present when the deposition of lime commenced. When the amount of carbonate of magnesia is less than that of the carbonate of lime, it is evident that the evaporation must extend still further before the deposition of carbonate of magnesia can commence. Then since it generally happens that spring water contains less carbonate of magnesia than carbonate of lime, it is clear that by the evaporation of this water the greater part of the carbonate of lime will be deposited without any trace of carbonate of magnesia being mixed with it. When the water of a spring does not evaporate completely, but if somewhat less than 27-28 is evaporated, carbonate of lime alone will be deposited, and the whole of the carbonate of magnesia may be retained in solution. If at the same time the deposits from such spring water contain traces of magnesia, its deposition must be attributed to the tendency towards the production of a double salt with carbonate of lime. This may, perhaps, be the case with the dolomite marl, shelly limestone, and mixtures of limestone and dolomite examined by Karsten. The composition of the deposits from the water of springs shows, moreover, that true dolomite, or the compound of carbonates of lime and magnesia in equal equivalents, is never deposited from water.

As above stated, all attempts to produce dolomite artificially as a direct precipitate under ordinary conditions have been unsuccessful. Scheerer[128] failed to obtain it by mixing solutions of $CaCO_3$ and $MgCO_3$ together in different proportions and evaporating at ordinary temperatures. The two carbonates were thrown down separately as characteristic rhombohedrons of calcite and prisms of hydrous magnesium carbonate. Similar results were obtained by Gorup-Besanez and later by Hoppe-Seyler[129] when they allowed a carbonic acid solution of the two carbonates to evaporate slowly. Leitmeier[130] has repeated this experiment recently, evaporating the solutions at temperatures of from 10° to 100°, but his results also were negative.

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[128] Neues Jahrb., 1866, p. 1.

[129] Quoted by F. W. Pfaff, Neues Jahrb, Beil. Bd. 23, 1907. p. 555.

[130] Doelter's Handbuch der Mineralchemie, Vol. I, 1912, p. 395.

The experiments of the writer along this line likewise have been unsuccessful. Separate solutions of the bicarbonates of calcium and magnesium after being standardized were mixed in molecular equivalent proportions so as to give the same ratio of $CaCO_3$ to $MgCO_3$ as exists in normal dolomite. The solution was then allowed to evaporate spontaneously during a period of one month. It was noted that the carbonates came down separately with the $CaCO_3$ much in advance of the $MgCO_3$ which was deposited in the hydrous form ($MgCO_3.3H_2O$). Negative results still were obtained when a solution prepared as above was inoculated with a crystal of dolomite and allowed to evaporate. The crystal did not grow and no dolomite could be found in the residue. Nor could the double carbonate be prepared by evaporating spontaneously a solution of the two carbonates obtained by the action of carbonated waters on normal dolomite, even when a dolomite crystal was introduced and a concentrated solution of NaCl and magnesium salts was introduced.

The experiments of Murray and Irvine[131] on the power of $(NH_4)_2CO_3$ furnished by decomposing organic matter to precipitate $CaCO_3$ and $MgCO_3$ from sea water are interesting in this connection. In general these show that $CaCO_3$ may be deposited in large amount through this agency, but that little $MgCO_3$ is precipitated, thus:

Nine small crabs weighing in all 11 ounces were placed in a shallow glass vessel containing 2 litres of ordinary sea water and were fed on mussel flesh. The water was never removed nor aerated, the effete matters passing into it. At the end of fourteen days all the crabs had died and were removed. The water being then in a putrid condition, it was set aside for about three weeks at a temperature ranging from 70° to 80° Fahr. All the conditions of the last two experiments were observed and it was found that crystals of carbonate of lime had been thrown down in amount practically equivalent to all the calcium present in the sea water employed.

Similar results were obtained when the effect of urine on sea water was tried. After the mixture had stood for seven days at temperatures ranging from 60° to 80° F. the precipitate thrown out had the following composition:

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[131] Proc. Roy. Soc. Edinburgh, Vol. 17, 1889, p. 79.

	Per cent
Water and organic matter containing ammonia, 7.38 grains	31.81
Carbonate of lime	4.85
Phosphate of magnesia and ammonia	51.10
Phosphate of lime	12.24
	100.00

Upon allowing the filtrate from the above experiment to stand ten days more under the same conditions, practically all the soluble calcium salts in the sea water were precipitated. The composition of the precipitate was:

	Per cent
Water and organic matter	20.25
Carbonate of lime	75.35
Carbonate of magnesia	1.02
Phosphate of magnesia	3.38
	100.00

The results of these experiments are wholly in accord with the following statement of these investigators:

> In the laboratory, when carbonate of ammonia is added to sea water, nine tenths of the calcium in solution is thrown out as carbonate of lime, while the magnesia salts remain in solution; so that if the reaction above indicated be that which takes place in the ocean, then to this circumstance may be due the fact that carbonate of magnesia is almost wholly absent from recent coral reefs and deep-sea calcareous formations.

The efficiency of decaying organic matter as a precipitant of calcium and magnesium has also been studied by Fischer,[132] who arrived at similar conclusions. Upon placing decaying organisms in ordinary sea water he obtained a precipitate overnight consisting of 94.45 per cent of $CaCO_3$ and 5.55 of $MgCO_3$. Neither concentration of the sea water and of the decaying organic matter, nor increase in temperature served to appreciably increase the magnesia content of the precipitate.

Experiments at Elevated Temperatures and Ordinary Pressures.—Dolomite has been prepared artificially at elevated temperatures by several investigators. Forchhammer,[133] upon adding water containing $CaCO_3$ to boiling sea water, obtained a pre-

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[132] Monatsh. Deutsch. geol. Gesell., 1910, p. 255.

[133] Quoted by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 161.

cipitate containing 12.23 per cent of $MgCO_3$ and 87.77 of $CaCO_3$, and when Na_2CO_3 was added as well as $CaCO_3$, the $MgCO_3$ content of the precipitate was increased to 27.93 per cent. It is not made clear, however, whether the double carbonate was formed or not in these experiments.

An analogous experiment was performed by Hunt.[134] A solution of the chlorides of calcium and magnesium, which had been accidentally mixed with a quantity of Na_2CO_3 insufficient for its complete decomposition, was set aside for a period of five weeks. At the end of this time the solution still retained a portion of the $MgCl_2$, but possessed only a trace of $MgCO_3$. The precipitate, after heating, analyzed $CaCO_3$ 50.52, $MgCO_3$ 30.09 and water 19.39 per cent.

The experiments of Linck[135] are interesting in this connection. When one molecular weight of $MgCl_2$ and one molecular weight of $MgSO_4$ were dissolved in 500 cc. of water and mixed with a solution of one and one-half molecular weights of ammonium sesquicarbonate in 150 cc. of water, the resulting solution remained clear, but when one molecular weight of $CaCl_2$ in 100 cc. of water was added a voluminous precipitate came down. This became crystalline when warmed to about 30° C. and examination of the material showed it to consist of minute round or oval spherulitic grains which had essentially the same composition as normal dolomite, but their double refraction was weakly positive, showing that they could not be this mineral. The same reaction took place when the magnesium salts were used separately but in double the amount of the above experiment. But the effect of NaCl when added in about the same proportion as it exists in sea water was to reduce the $MgCO_3$ content of the precipitate to 12 per cent. The same effect, however, did not result when one molecular weight of Na_2CO_3 was added to the NaCl solution beforehand, for then the residue yielded 49 per cent. Briefly these results may be explained as follows: The effect of adding NaCl to the solution was to repress the ionization of the $MgCl_2$, since these two compounds have one ion in common. For the same reason the addition of

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[134] Am. Jour. Sci., 2d ser., Vol. 42, 1866, p. 56.
[135] Montash. Deutsch. geol. Gesell., 1909, p. 230.

Na_2CO_3 tends to increase the yield of $MgCO_3$. The concentration of the carbonate ions in solution is increased with the result that the $MgCO_3$ of the solution becomes less dissociated and as a consequence must be deposited, since the solution is already saturated with the undissociated salt. As above stated, the precipitate obtained in these experiments did not behave as dolomite. Nor was it transformed to this mineral even when heated to 110°. But when solutions prepared as above were warmed several hours in sealed tubes at 40 to 50° C., spherulites possessing negative double refraction and all other properties of dolomite were obtained. Analysis of these gave 44.8 per cent of $MgCO_3$ and 49.5 of $CaCO_3$. Linck, therefore, was led to suggest that dolomite might be formed in the sea in this manner, since decaying organisms give off ammonium carbonate. Meigen,[136] however, who has repeated Linck's experiment, calls this in question, since he failed to procure dolomite under these conditions, but obtained only a product easily soluble in dilute acetic acid.

Bourgeois and Traube[137] also report the production of dolomite as a direct precipitate at elevated temperature. Thus, by heating a solution of $MgCl_2$, $CaCl_2$ and KCNO (potassium cyanate) to 130° in a sealed tube dolomite was produced. But as F. W. Clarke has pointed out, this experiment has no geological significance.

The experiments of Bischof[138] have a much more important bearing on the problem, although only the mixed carbonates were produced in these. First, solutions of carbonate of calcium and of carbonate of magnesium in carbonic acid water, were mixed in the proportion of two parts of magnesium to one of calcium and evaporated at a temperature of 122° F. After one-third of the solution had evaporated the precipitate contained 1.64 grs. of $CaCO_3$ and 1.99 grs. of $MgCO_3$. When the filtrate from the above was next evaporated to one-fifth the original volume it was found to consist of only a trace of $CaCO_3$ and of .43 grs. of $MgCO_3$. It will be noted that in this experiment the

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[136] Quoted by Leitmeier, Doelter's Handbuch der Mineralchemie, Vol. I, 1912, p. 395.

[137] Quoted by F. W. Clarke, Bull. U. S. Geol. Survey No. 491, p. 537.

[138] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 168.

$MgCO_3$ was considerably in excess of the $CaCO_3$ in the solution. In the next experiment this factor was eliminated by using well water which contained only about half as much $MgCO_3$ as $CaCO_3$. Eighty ounces of this water was evaporated at 122° F. After 45 ounces was evaporated, 8.36 grs. of $CaCO_3$ had been deposited, but only a trace of $MgCO_3$. When the remaining 35 ounces was evaporated, however, the residue was found to contain 1.95 grs. of $MgCO_3$ and only .22 grs. of $CaCO_3$. When this experiment was repeated more carefully it was found that the $MgCO_3$ did not begin to deposit until seven-eighths of the water had evaporated, and almost all the $CaCO_3$ had been thrown out. Bischof then draws the following conclusions:

> It follows also from these experiments that the production of a double carbonate of lime and magnesia cannot take place to any considerable extent, if at all, by the evaporation of water similar to the above, and under analogous conditions. In evaporation at the ordinary temperature, also, the quantity of water evaporated before deposition takes place must be very considerably greater than when the evaporation takes place at a higher temperature.

The elaborate series of experiments of F. W. Pfaff[139] bearing on the direct deposition of dolomite should also be mentioned here. First Na_2CO_3 was added to solutions of $CaCl_2$ and $MgCl_2$, and of $CaCl_2$ and $MgSO_4$, and evaporation allowed to take place on the water bath. But no dolomite was obtained. Similarly the addition of ammonium carbonate to a solution corresponding to sea water in composition failed to yield the double carbonate upon addition of ammonia and evaporation. Next a saturated solution of NaCl with $CaCO_3$ and $MgCl_2$ through which CO_2 was passed was evaporated to dryness without results. The substitution of $MgSO_4$ for $MgCl_2$ was still without effect. Then carbonated solutions of $CaCO_3$ were treated separately with $MgCl_2$ and $MgSO_4$ and to each was added $(NH_4)_2CO_3$. Evaporation again yielded no dolomite. The addition of $(NH_4)_2CO_3$ to a carbonated solution of $CaCO_3$ and $MgCO_3$ was likewise without results. Negative data were still obtained when a strong solution of $CaCO_3$ and magnesia alba was treated with CO_2 and evaporated. When, however, the

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[139] Neues Jahrb., Beil. Bd. 9, 1894, p. 485.

preceding experiment was repeated using $(NH_4)_2CO_3$ instead of CO_2 and the solution evaporated on the sand bath, at a temperature which attained 140° C., towards the last, a crystalline residue difficultly soluble in dilute acid was obtained. But evaporation to dryness of a solution prepared in the same manner on the water bath yielded a readily soluble precipitate.

Another series of experiments next undertaken to determine the influence of $(NH_4)_2S$ and H_2S in the formation of dolomite met with much more success. First a saturated solution prepared by the action of $(NH_4)_2S$ on the carbonates of calcium and magnesium was evaporated to dryness with the addition of $(NH_4)_2CO_3$. The process took several days, but in the end the residue contained double refracting crystals which dissolved in strong acid only when it was heated. Since it was not certain that the temperature did not rise above 100° in this operation the experiment was repeated, and the evaporation was conducted this time on the water bath. A residue with similar properties was obtained, analysis of which showed considerable magnesia and some lime. Similar results were obtained when an H_2S solution was substituted for the $(NH_4)_2S$ solution and NaCl was added. This time the $(NH_4)_2CO_3$ was omitted, but CO_2 was passed through while evaporation proceeded at 50° to 60° C. The precipitate behaved as in the preceding experiment, and analysis showed only a small amount of lime. Pfaff suggests that this product may have consisted of magnesite with some lime. When $(NH_4)_2S$ was used in place of H_2S under somewhat similar conditions, rhombohedrons which showed diagonal extinction were obtained. These effervesced at first in strong acid, but a residue remained which dissolved only when heat was applied. An analysis of this product by Professor Hoppe-Seyler gave:

	Per cent
$CaCO_3$	12.77
$MgCO_3$	79.84
Fe_2O_3	1.74
Insoluble	4.64
H_2O	1.00

Since the magnesia was much in excess of the lime in the above experiment the operation was repeated using these constituents in the proportion of one to one, but this was no more successful, for only 6.93 per cent of $CaCO_3$ was obtained. The precipitate evidently represented magnesite with $CaCO_3$ mechanically mixed. Further trials under slightly different conditions still failed to increase the yield of the $CaCO_3$ to the normal dolomite ratio. When, however, the solutions prepared by the action of the sulphides of H_2S and $(NH_4)_2S$ on the carbonates of calcium and magnesium were mixed in the proportion of two of calcium to one of magnesium, the results were much more satisfactory. After NaCl was added to the mixture prepared in this manner and CO_2 passed through for slightly more than two months the precipitate was washed and dried at 120° C. Analysis showed it to have the following composition:

	Per cent
$MgCO_3$	43.7
$CaCO_3$	52.0
Insoluble	3.8

Recalculation to eliminate the insoluble matter gave 45 per cent of $MgCO_3$ and 54 of $CaCO_3$, almost exactly the same proportions as in normal dolomite. When the experiment was repeated without NaCl no trace of dolomite was obtained after a period of fourteen days.

Experiments at Ordinary Temperatures and Elevated Pressures.—For experiments bearing on the production of dolomite at ordinary temperatures but at elevated pressures we are indebted entirely to F. W. Pfaff.[140] His attempts to produce dolomite as a direct precipitate were unsuccessful, but he obtained it as an alteration product under a variety of conditions. It was sought to prepare the double carbonate as a direct precipitate in the following manner: $CaCO_3$ and magnesium alba were added to a saturated solution of NaCl. CO_2 was then passed through under a pressure of 2 to 2½ atmospheres. When the solution became saturated with calcium and magnesium the pressure was decreased, but seldom was a precipitate formed, and evaporation gave rise only to the deposition of $CaCO_3$ and hydrous $MgCO_3$, separately.

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[140] Neues Jahrb., Beil. Bd. 9, 1894, p. 485.

Since the basic-carbonate of magnesium obtained in such experiments is in no condition to unite with $CaCO_3$ to produce dolomite, it was attempted by Pfaff in a later series of experiments[141] to produce anhydrous $MgCO_3$. The effect of solutions of potassium and sodium carbonate on $MgCl_2$ at high pressures was tried without avail. The addition of a concentrated solution of $CaCl_2$ or of NaCl also failed to produce the anhydrous salt. The results were equally unsatisfactory when a solution of magnesium salts was subjected to the action of $(NH_4)_2CO_3$ for 48 hours at 500 atmospheres. Pfaff, therefore, concludes that dolomite and anhydrous $MgCO_3$ are not precipitated directly under high pressure.

Discussion.—To recapitulate, experiments have failed to indicate the conditions under which dolomite can be precipitated directly at ordinary temperatures and pressures. But there is convincing evidence that dolomites have been so formed, on a small scale at least, in nature. The fact that the two carbonates are found by experiment to come down separately with the $CaCO_3$ much in advance of the hydrous $MgCO_3$ cannot, therefore, be regarded as wholly opposed to the theory of chemical deposition of large masses of dolomite, for under favorable conditions the double carbonate may be precipitated directly, the dolomite molecule being continuously formed in solution while deposition proceeds. The chief objection to the chemical theory thus falls down. But the fact that experiments have failed to give rise to a magnesia-rich precipitate from sea water at ordinary temperature, even when the pressure was elevated, must be regarded as important.

The experiments carried on at elevated temperature and ordinary pressure show that the double carbonate is readily formed under these conditions, but while these may have a direct bearing on the origin of some local dolomites they cannot be considered as having an important bearing on the origin of stratified dolomites of great thickness.

II. Evidence Bearing on the Alteration Theories.

Experiments at Ordinary Temperatures and Pressures.—As regards the evidence bearing on the production of dolo-

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[141] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

mite as an alteration product under ordinary conditions, a number of experiments may be mentioned. Thus, Bischof,[142] trying the effect of a solution of $MgCO_3$ upon carbonate of lime, found that "after twelve hours there was neither any lime in solution, nor any magnesia retained by the carbonate of lime." A similar experiment was tried using small fragments of chalk instead of powdered carbonate of lime. "The closed vessel stood for several years unopened, but examination from time to time failed to reveal any action upon the edges of the chalk fragments." Scheerer,[143] however, later recorded somewhat different results from a similar experiment. When powdered chalk was treated with a carbonated solution of $MgCO_3$ for forty-eight hours with the passage of CO_2 it was found that nearly all of the $MgCO_3$ had gone into the sediment and that only a slight amount of the same remained in the solution, which was now rich in $CaCO_3$. But it is not stated that dolomite was formed.

Hoppe-Seyler[144] was unable to produce dolomite by the action of solutions of $MgCl_2$ on $CaCO_3$ for several months. The same negative result was obtained when a dilute $MgSO_4$ solution was saturated with $CaCO_3$ and a current of dry air drawn through for a long time. Even when NaCl was added to the saturated solution of $MgSO_4$ the residue yielded no dolomite and the freezing of an $MgSO_4$ solution saturated with $CaCO_3$ was equally unsuccessful. The effect of sea water on $CaCO_3$ was also tried but with no more success. Likewise when Liebe[145] immersed chalk a year and a half in $MgCl_2$ solutions of various concentrations no trace of decomposition could be detected.

More successful results, however, are reported by Leitmeier,[146] who in his experiments on the formation of aragonite claims to have prepared dolomite also. In these experiments .1 gram of powdered $CaCO_3$ in 100 grams of water was subjected to the action of .001, .005, .01 and .05 gram of $MgSO_4.7H_2O$ and $MgCl_2.6H_2O$ respectively. At low temperatures dolomite was obtained at none of these concentrations;

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[142] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 167.

[143] Neues Jahrb., 1866, p. 1.

[144] Quoted by F. W. Pfaff, Neues Jahrb., Beil. Bd. 23, 1907, p. 555.

[145] Zeitschr. Deutsch. geol. Gesell., Vol. 7, 1855, p. 431.

[146] Neues Jahrb., Vol. 1, 1910, p. 49.

but at medium temperature (10° C.) a few fine grains which reacted as dolomite microchemically were obtained at the concentration of .01 gram. At a concentration of .05 gram, however, copious crystals which did not react with iron chloride were found in the residue. These showed partly developed crystallographic boundaries and appeared to possess the distorted structure characteristic of dolomite rhombohedrons. In the .1 gram solutions a much richer mixture of "dolomite" was obtained. The effect of higher temperatures was to produce essentially the same results, for "dolomite" was obtained at the same concentrations.

The experiments performed by F. W. Pfaff[147] at ordinary conditions are also interesting in this connection. By the action of a solution of $MgSO_4$, $MgCl_2$ and NaCl on anhydrite with the passage of CO_2 a reaction product coating the anhydrite was obtained. This was soluble only in strong hydrochloric acid and had at one time the composition: $CaCO_3$ 61.7 per cent; $MgCO_3$ 38.7.

The experiments of the writer bearing on the artificial production of dolomite as an alteration product at ordinary temperatures and pressures have yielded no successful results. In these powdered aragonite was treated with solutions of known concentration of $MgCl_2$ and $MgSO_4$ and of definite mixtures of these salts. The influence of NaCl and CO_2 on the reaction was also studied and the effect of inoculating the solutions with crystals of dolomite was tried. The concentration of the magnesium solutions used ranged from two to ten times the concentration of magnesium in ordinary sea water. After a period of six months and again after nearly three years the residues of the experiments were thoroughly tested microchemically for dolomite, but without successful results. Analyses of portions of the solutions, however, showed the presence of calcium in greater quantity than the solubility of $CaCO_3$ alone would account for, and there can be no doubt that a reaction had taken place, although no $MgCO_5$ had been deposited. Evidently the easily soluble trihydrate of magnesium carbonate had been formed.

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[147] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

Experiments at Elevated Temperatures and Ordinary Pressures.—Dolomite has been prepared frequently as an alteration product at elevated temperatures and ordinary pressures. Morlot,[148] for instance, upon heating a mixture of one equivalent of sulphate of magnesium and two equivalents of powdered $CaCO_3$ to 392° F. in a sealed glass tube, obtained a mixture of dolomite and gypsum, and found that the $MgSO_4$ had been completely decomposed. Hunt,[149] however, found by repeating this experiment that the two carbonates did not crystallize out as dolomite.

The experiment of Sainte-Claire Deville[150] also should be mentioned here. A fragment of chalk after having been impregnated with a solution of $MgCl_2$ was placed in a platinum crucible and subjected to prolonged heating on the sand bath. At a temperature a little above 100° a reaction took place whereby $CaCl_2$ and dolomite were produced. By a single operation of this kind it was possible to replace only six to seven parts of lime by an equivalent amount of magnesia, but when the fragment was washed and subjected to the same procedure repeatedly the replacement went much further. Fragments of madrepores when subjected to the same treatment were replaced in a similar manner.

A somewhat similar experiment was performed by Sorby,[151] who attempted to produce a dolomite pseudomorph by the action of a solution of $MgCl_2$ on Iceland Spar at an elevated temperature. He found that only an external crust of $MgCO_3$ was formed by replacement.

The elaborate series of experiments by Klement[152] also has an important bearing on the problem of the origin of dolomite, although only the mixed carbonates were obtained.

The effect of $MgSO_4$ on aragonite was first observed. One-half gram of aragonite and 1.25 grams of crystalline $MgSO_4$ were placed in tubes, after which 10 cc. of a saturated solution

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[148] Quoted by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 158.

[149] Am. Jour. Sci., 2d ser., Vol. 28, 1859, p. 170.

[150] Compt. Rend., Vol. 47, 1858, p. 91.

[151] Quart. Jour. Geol. Soc. London, Vol. 35, 1879, p. 56.

[152] Bull. Soc. Belge géol., Vol. 9, 1895, p. 12.

of NaCl was added and the tubes were sealed. A preliminary experiment having shown that at elevated temperature a reaction took place whereby $MgCO_3$ was deposited, the influence of time and temperature was studied. At a temperature of 50° to 55° C. only a trace of $MgCO_3$ was produced after an interval of ten days. The same was true when the temperature was held at 62° for four days, but after the same experiment ran for six days 1.3 per cent of $MgCO_3$ was formed. Above this temperature $MgCO_3$ was always obtained, and the amount increased directly with the time. Thus, at 72° for twenty-four hours he obtained 1.7 per cent, for sixty-seven hours 9.8 per cent, and for ninety-five hours 12.4 per cent. The maximum amount of $MgCO_3$, 38 per cent, was obtained at 90° for sixty-eight hours. When the heating was prolonged to one hundred and forty hours no increase was noted. By using another sample of aragonite, however, Klement was able to obtain 41.1 per cent of $MgCO_3$ after heating to 91° for one hundred and forty-four hours.

The influence of the changing of the concentration of the NaCl was then tried, the same amount of aragonite and $MgSO_4$ being used as in the preceding experiments. In general it was found that increase in the concentration of this constituent had the same effect as increase in time. For instance, it was found in a previous experiment in which a 10 cc. saturated solution of NaCl was used, that 24.5 per cent of $MgCO_3$ was formed at a certain temperature after a given time, but when now the 10 cc. saturated solution was diluted with 1 cc. of water the yield of $MgCO_3$ was reduced to 8 per cent under essentially the same conditions of temperature and time, and when the NaCl solution used consisted of a 5 cc. saturated solution of NaCl plus 5 cc. of water only .6 per cent of $MgCO_3$ was obtained. When the NaCl was completely removed from the solution there was a still further reduction of the $MgCO_3$ content even when the $MgSO_4$ solution was very concentrated.

As regards the influence of the quantity of the reacting substances it was found that when each was doubled there was a marked decrease in the amount of $MgCO_3$ produced. Klement attempts to explain this on the assumption that equilibrium is soon reached under these conditions, since the volume of the solution is greater and the $CaSO_4$ produced by the reaction would not be so readily deposited. But this is difficult to understand.

The action of $MgSO_4$ on recent corals also was studied under the same conditions as in the first series of experiments. It was found that the powdered material gave even a greater yield of $MgCO_3$ than aragonite under similar conditions. The action of $MgSO_4$ on powdered calcite, however, was much less energetic. Thus, at 100° for ten hours in the presence of an excess of NaCl only a trace of $MgCO_3$ was formed, while at 90° for forty-eight hours 1.6 per cent of this compound was obtained.

The comparative efficiency of $MgCl_2$ in altering aragonite was likewise determined. When the $MgSO_4$ was replaced by an equivalent amount of this compound and 10 cc. of a saturated solution of NaCl was added the reaction proceeded very feebly, only .4 per cent of $MgCO_3$ being formed at 72° for 95 hours. When, however, only 3 cc. of a saturated NaCl solution was used instead of 10 cc. the yield was slightly increased, but it was still very low. These singular results are accounted for by Klement on the assumption that an easily soluble reaction product is formed here and that equilibrium is soon reached. This no doubt is important, but the effect of the NaCl in repressing the ionization of the $MgCl_2$ should also be taken into consideration.

Experiments at Ordinary Temperatures and Elevated Pressures.—The attempts of F. W. Pfaff[153] to produce dolomite at ordinary temperatures and elevated pressures are noteworthy in this connection. When a mixture of $CaCO_3$ and anhydrite was subjected to the action of an $MgSO_4$ solution under pressure dolomite rhombohedrons were obtained, but when gypsum was used instead of anhydrite no such reaction took place. Similarly the effect of a solution of $MgCl_2$ and NaCl on powdered anhydrite in the presence of Na_2CO_3 or $(NH_4)_2CO_3$ under pressure was to produce the double carbonate. When the latter

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[153] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

experiments were repeated, however, they were not always successful and when gypsum was substituted for anhydrite the double carbonate was never obtained.

The influence of $MgSO_4$ on $CaCO_3$ in the presence of NaCl also was tried, and the pressure was held at 100 atmospheres for eight days. The temperature varied from 4° to 14° C. The residue obtained after being treated with a two per cent solution of acetic acid for twenty-four hours analyzed 73.7 per cent of $CaCO_3$ and 26.2 of $MgCO_3$. When the experiment was repeated under the same conditions the residue yielded 80.1 per cent $CaCO_3$ and 20.7 $MgCO_3$.

When he used an apparatus to insure uniform concentration of the $MgSO_4$ and $CaCO_3$ Pfaff obtained, in a similar experiment run for ten days, under a pressure ranging from sixty to eighty atmospheres, at room temperature, a residue which after standing twenty-four hours in a two per cent acetic acid solution, tested as follows: $CaCO_3$ 53.7 per cent, $MgCO_3$ 46 per cent. When the experiment ran one day under the same conditions only 7 per cent of $MgCO_3$ was formed in the residue. Pfaff then endeavored to determine at what pressure the reaction proceeds most favorably, and arrived at the conclusion that at 40 atmospheres the reaction begins, but takes place most quickly at 60 atmospheres and still proceeds even at 200 and 500 atmospheres.

Experiments at Elevated Temperatures and Elevated Pressures.—Of the experiments carried on both at high temperatures and high pressures those of Marignac[154] are among the first. When he heated $CaCO_3$ with a solution of $MgCl_2$ in sealed tubes to 200° C. for six hours there was obtained a product which yielded $CaCO_3$ 48 per cent, and $MgCO_3$ 52 per cent. After only two hours heating, however, the amount of $MgCO_3$ obtained was less.

The experiment of Duroche[155] was also formerly regarded as important in that it seemed to lend support to the volcanic theory of the origin of dolomite. Anhydrous $MgCl_2$ and frag-

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[154] Quoted by Hunt, Am. Jour. Sci., 2d ser., Vol. 28, 1859, p. 170.
[155] Compt. Rend., Vol. 33, 1851, p. 64.

ments of porous limestone were heated to dull redness for three hours in a sealed gun barrel. When the fragments were removed they were found to be coated with a scoriaceous mass consisting of $MgCl_2$, $CaCl_2$ and a small quantity of the oxides of Ca, Mg, and Fe. When this was washed off the limestone fragments were found to be partly converted into dolomite.

Later researches by Hoppe-Seyler[156] likewise showed how dolomite might be formed at high temperatures. Thus, he obtained both the double carbonate and magnesite by heating magnesium salts or sea water with $CaCO_3$ in sealed tubes. When $CaCO_3$ was treated with a solution of magnesium bicarbonate and heated to over 100° the same result was obtained.

It will be noted that in the above experiments the pressure was induced only by the effect of high temperature on the reacting substances. In some of Pfaff's experiments,[157] on the other hand, mechanical pressure was applied and the temperature kept lower. The effect of an $MgSO_4$ solution ten times as concentrated as this salt in sea water was tried on $CaCO_3$ at a pressure of sixty atmospheres and a temperature of 40° to 50°. After an interval of six days a residue was obtained which was insoluble in two per cent acetic acid. When the experiment was repeated using $MgCl_2$ instead of $MgSO_4$ the same result was obtained, and an insoluble residue bearing considerable $MgCO_3$ was produced.

Discussion.—In summarizing the experimental data bearing on the alteration theory we find the evidence furnished by experiments carried on at ordinary conditions very conflicting, for while Pfaff and Leitmeier report the production of dolomite artificially under these conditions, all other experimenters have obtained only negative results. As regards Pfaff's experiment in which dolomite was obtained by the action of a solution of $MgSO_4$, $MgCl_2$ and NaCl on anhydrite with the passage of CO_2, it must be admitted that this can have no direct bearing on the formation of extensive dolomite deposits in nature, except in-so-far as it shows the possible production of dolomite at

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[156] Cited by F. W. Clarke, Bull. U. S. Geol. Survey No. 491, p. 537.
[157] Neues Jahrb., Beil. Bd. 23, 1907, p. 529.

ordinary temperature and pressure. The evidence furnished by Leitmeier's experiment, on the other hand, is much more important in this connection. But his results are difficult to understand, since other experimenters have consistently obtained negative results when the same constituents were employed, under almost identical conditions. Even when the magnesium solutions were many times more concentrated than those used by Leitmeier no dolomite was obtained.

In the writer's experiments in which the effect of $MgCl_2$ and $MgSO_4$ was tried on $CaCO_3$ at many concentrations, absolutely no trace of dolomite could be found in the residue when it was tested in the most careful manner with Lemberg's solution. To be sure, small transparent crystals were present which failed to take the stain and which suggested dolomite in several particulars, but these were insoluble even in hot, concentrated acids and the conclusion was forced that they represented quartz grains derived from the corrosion of the glass of the containing flasks. For the present, therefore, it seems best to hold Leitmeier's observations in question. If further work should demonstrate the correctness of his observations, then here we would have valuable data bearing on the possible dolomitization of limestone at ordinary temperature and pressure by a dilute solution of magnesium, and many puzzling features of this process would be explainable.

The high temperature experiments, although they have frequently yielded dolomite, cannot be regarded as having a direct bearing on the problem at hand, as all the evidence goes to show that high temperatures have not prevailed when the great masses of dolomite were formed in nature. The same may be said of the experiments carried on both at elevated temperatures and at elevated pressures. But the data bearing on the production of dolomite at elevated pressures are much more valuable, for in the alteration of limestone to dolomite the pressure of the water column above the scene of the replacement must be taken into consideration. It is conceivable that this has in many cases amounted to several atmospheres. All the evidence, however, is unfavorable to the view that the pressure has amounted in many cases to forty to sixty atmospheres, the pressure at which Pfaff obtained his best results, for there is almost universal agreement that the dolomites are not deep sea deposits.

III. Evidence Bearing on the Leaching Theory.

The power of carbonated waters to remove the lime more rapidly than magnesia from magnesian limestone was first actually demonstrated by Bischof,[158] who after placing the powder of magnesian limestones of known composition in water, passed a stream of CO_2 through the mixture for twenty-four hours. It was found that in case of one of the samples which contained originally 84.57 per cent of $CaCO_3$ and 11.54 of $MgCO_3$ no trace of $MgCO_3$ had been taken into solution.

Almost identical results were obtained by Doelter and Höernes[159] in a similar experiment on a dolomitic limestone from the Wengener formation, which bore 84.82 per cent of $CaCO_3$ and 13.94 of $MgCO_3$. When a powdered sample weighing 2.125 grams was placed in water and a stream of CO_2 passed through for forty-eight hours, the solution contained 0.272 grams of $CaCO_3$ and only a strong trace of $MgCO_3$. In like manner Scheerer,[160] upon exposing the powder of dolomitic limestone containing about 9 per cent of $MgCO_3$ to carbonated water obtained only a trace of $MgCO_3$ in solution, although it was rich in $CaCO_3$.

The experiments of Hardman[161] along this line are important. First a dolomitic limestone from Kilkenny was used. This had the following composition:

	Per cent
$CaCO_3$	68.21
$MgCO_3$	24.00
$Fe_2O_3+Al_2O_3$	4.32
Silica	1.92
$FeCO_3$	0.90

110 grains of the crushed limestone were placed in a jar of distilled water and only enough CO_2 passed through to keep

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[158] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 195.

[159] Jahrb. K.-k geol. Reichsanstalt, Vol. 25, 1875, p. 328.

[160] Neues Jahrb., 1866, p. 1.

[161] Proc. Roy. Irish Acad., 2d ser., Vol. 2, 1875-77, p. 705.

the water feebly acid. After an interval of seventy-two hours it was found that the carbonates were dissolved in the proportion of 68.21 parts of $CaCO_3$ to 9.32 parts of $MgCO_3$. When, however, the water was saturated with CO_2 for forty-four days the ratio was 68.21 to 20.06. A similar experiment on a limestone from Dungarnon County which bore 12.71 per cent of $MgCO_3$ yielded very similar results.

The experiment of Högbom[162] on a marl from Upsala likewise has an important bearing on the leaching theory. When this marl, which contains approximately 18 per cent of $CaCO_3$ and 1.3 of $MgCO_3$ was treated with carbonated water it was found that almost half of the former was dissolved, while only a trace of the latter was taken into solution.

The effect of carbonated waters on normal dolomite at ordinary pressure, on the other hand, is in general to dissolve the two carbonates with their ratios undisturbed. Thus, when Gorup-Besanez[163] treated dolomite powder with carbonated water for five days the solution contained 55.2 per cent of $CaCO_3$ and 47.7 $MgCO_3$, while the undissolved residue yielded 56.74 per cent $CaCO_3$ and 43.26 $MgCO_3$. When the operation was prolonged over a period of twenty-one days the results were not essentially different. The effect of elevation of pressure, however, appears to be to produce a considerable change in the relative solubility of the two carbonates in dolomite. Skeats[164] is the authority for the statement that "when dolomite is subjected to fresh water containing carbon-dioxide at a pressure of about 5 atmospheres, the magnesium carbonate is dissolved and the calcium carbonate remains almost unaffected."

The effect of dilute acetic acid upon magnesian limestones and dolomite is much the same as that of carbonated water. For instance, Karsten,[165] upon treating with cold dilute acetic acid a sample of the Muschelkalk limestone from the district of Lüneberg which contained 2 to 5 per cent of $MgCO_3$, found that there was left behind a residue which had the composition of normal dolomite. He concluded, therefore, that this rock must

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[162] Neues Jahrb., Vol. 1, 1894, p. 266.
[163] Liebig's Annalen, 8th Supp., 1872, p. 230.
[164] Quart. Jour. Geol. Soc. London, Vol. 61, 1905, p. 97.
[165] Quoted by F. W. Pfaff, Neues Jahrb., Beil. Bd. 23, 1907, p. 545.

consist of a mixture of calcite and dolomite. In like manner Forchhammer,[166] upon treating with dilute acetic acid the powder of a dolomitic limestone from Faxö, which contained 16.5 to 17 per cent of $MgCO_3$, found 41.42 per cent of $MgCO_3$ in the residue, while the solution contained 97 per cent of $CaCO_3$ and 3 of $MgCO_3$. The results obtained by Doelter and Höernes[167] by the action of acetic acid on a dolomitic limestone containing 84.82 parts of $CaCO_3$ and 13.94 parts of $MgCO_3$ for forty-eight hours were very similar. The solution contained 91.5 per cent of $CaCO_3$ and 8.5 of $MgCO_3$. But when F. Pfaff[168] employed a more richly dolomitic limestone the enrichment of the residue in $MgCO_3$ was not relatively so great. A dolomite from the French Jura of the Muggendorf region was subjected to the action of a dilute acetic acid solution for twenty-four hours. The original sample consisted of $CaCO_3$ 60.33 per cent, $MgCO_3$ 38.27, insoluble matter 1.40, while the acetic acid solution contained 69.15 per cent of $CaCO_3$ and 30.80 of $MgCO_3$. The residue left behind, however, showed a great enrichment in magnesia, as it bore 40.1 per cent of $CaCO_3$ and 59.8 of $MgCO_3$. Pfaff concluded that this residue must have consisted of a mixture of magnesite and calcite, since the $MgCO_3$ is far in excess of that in normal dolomite.

An elaborate series of experiments by Haushoffer,[169] on the other hand, showed that in the more nearly pure dolomites the $CaCO_3$ does not tend to go into solution more readily than the $MgCO_3$. Indeed, by experimenting with various concentrations of acetic acid and with dolomites of variable composition, he actually found in some cases a slightly higher proportion of $MgCO_3$ in the solution than in the original rock. He gave it as his opinion, therefore, that in normal dolomite the $MgCO_3$ is more soluble than $CaCO_3$ and that the normal order of solubility of the two carbonates is reversed.

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[166] Jour. prakt. Chemie, Vol. 49, 1850.

[167] Jahrb. K.-k. geol. Reichsanstalt, Vol. 25, 1875, p. 329.

[168] Quoted by F. W. Pfaff, Neues Jahrb., Beil. Bd. 23, 1907, p. 545.

[169] Quoted by F. W. Pfaff, Idem., p. 547.

FIELD AND CHEMICAL EVIDENCE.

I. Evidence Bearing on Primary Deposition Theories.

CHEMICAL THEORY.

There are several facts which lend strong support to the view that some stratified dolomites represent chemical precipitates. The more important of these are as follows:

(1) The occurrence of chemically deposited dolomite in veins and druses, etc.
(2) The purity of some stratified dolomites.
(3) The association of dolomite with salt and gypsum deposits.
(4) The interbedding of limestone and dolomite.
(5) The compactness of some dolomites.
(6) The preservation of fine and detailed structures in some dolomites.
(7) The paucity of organic remains in some dolomites.
(8) The great thickness of some dolomites.
(9) The relation of dolomite to limestone in certain formations.

The occurrence of Chemically Deposited Dolomite.—That dolomite can be deposited directly in nature is indicated by its occurrence as a gangue mineral and in veins and druses. The high magnesia-bearing travertines reported by Giradin[170] and by Johnson[171] must likewise represent direct deposits, and occurrences of chemically deposited dolomite on a small scale in dolomitized coral reefs have been reported. Skeats,[172] referring to the latter feature, says:

> The lining of calcite-crystals by an outer zone of clear dolomite, described by me as occurring in sections from Mango (one of the Fiji Islands) and also noticed in some of the sections of the Tyrol dolomite described above, is difficult of explanation, except on the hypothesis that the dolomite was deposited from solution in optical continuity with the calcite. It sometimes happens that one crystal is built up of successive zones, alternately calcite and dolomite. As these crystals are

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[170] See ante, p. 297.
[171] See ante, p. 297.
[172] Quart. Jour. Geol. Soc. London, Vol. 61, 1904, p. 136.

but rarely recognized in thin sections, it is clear that they were not formed under the conditions governing the general dolomitization of the mass of the rock. It may be that they were formed in cavernous parts of the rock, more or less shut off from the free passage of the sea water; and indeed, these crystals are sometimes found lining the walls of cavities. Dr. C. D. Cullis, in the mineralogical report on the Funafuti boring, describes and figures a somewhat analogous case, of the deposition of the two minerals in alternating coats lining the walls of cavities, in a way that simulates on a microscopic scale the appearance of an agate.

Phillipi[173] also states that similar chemically deposited dolomite crystals appear in the dolomitized limestone lumps from the Seine Bank of the Atlantic Ocean northeast of Madeira.

The possibility that dolomite can be formed by direct deposition in nature then must be regarded as proven. But as regards the possible extensive chemical deposition of dolomite beneath the sea either in the past or at the present time we have no positive evidence. To be sure, recent work by Drew[174] has shown that calcium carbonate is being actively deposited through the agency of marine bacteria in the American tropics, but dredging has yet failed to show the presence of dolomitic ooze on the sea bottom.

The Purity of Some Stratified Dolomites.—It has been held by some that certain pure dolomite masses which possess the carbonates of calcium and magnesium in approximately equivalent proportions probably represent chemical deposits rather than alteration products because of their definite composition, and all must agree that this is the simplest explanation of the phenomenon which may be offered. The force of this argument, however, is greatly weakened by the fact that the Niagaran dolomite of the Upper Mississippi Valley which the investigations of the writer have shown to be an undoubted alteration product is, in general, a very pure dolomite, especially in its upper portion, and many analyses show the two carbonates to exist in essentially the same proportion as in normal dolomite.

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[173] Neues Jahrb., Festband, 1907, p. 424.

[174] Carnegie Institution of Washington, Publication 182, 1914, p. 9.

Furthermore, ideally pure stratified dolomites are the exception rather than the rule in nature. By far the greater number of dolomites have an indefinite and variable composition.

The Association of Dolomite with Salt and Gypsum Deposits.—Beds of dolomite, as of limestone, frequently occur in association with salt and gypsum deposits, and the impression no doubt lingers in the minds of many geologists that both the dolomite and the limestone so associated have been precipitated chemically, like the salt and the gypsum, during the evaporation of a land-locked sea. Weigelin,[175] in fact, has frankly advocated this method of origin for a dolomite of these relations in West Württemberg. This view is supported by the fact that the dolomite and limestone normally come just below the gypsum, a relationship which we should expect upon the basis of the chemical deposition theory, since these are much less soluble than gypsum and would naturally be the first to be deposited. There can be little doubt that the limestone associated with salt and gypsum deposits is in many cases of chemical origin, and the natural inference from this would be that the dolomite is also. But it must be regarded as possible that a rock deposited originally as limestone under these conditions might later be metamorphosed to dolomite. Ideal conditions for the alteration of limestone would be furnished in evaporating seas where the magnesium salts exist in a concentrated state.

The Interbedding of Limestone and Dolomite.—The simplest and most understandable explanation of the phenomenon of interbedding of limestone and dolomite which suggests itself is found in the primary deposition theory, the limestone and dolomite both being regarded as chemical deposits, and this theory in fact has been adopted by many to account for this relationship. Wagner[176] accepted it for the interbedding in the French Jura, holding that the dolomite constitutes a definite member of the series and is of constant thickness. For the same reason Vogt[177] adopted the chemical theory for certain Norwegian dolomites, and Suess[178] for the interbedded dolomites

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[175] See ante, p. 269.

[176] Quoted by F. Pfaff, Pogg. Annalen, 1851, p. 465.

[177] See ante, p. 267.

[178] See ante, p. 267.

of the Plattenkalk. Daly[179] has cited instances of sharp and regular interstratification of limestone and dolomite in the pre-Cambrian of British Columbia and Montana which he regards as strong evidence of the chemical origin not only of these dolomites, but of dolomites in general.

There can be no doubt that the stand of these writers is well taken, but, as will be shown later in this paper, interbedding produced by chemical precipitation of limestone and dolomite, if indeed this be considered a possible method of origin, is not the whole story. In fact, all examples of interbedding examined by the writer are most plausibly explained upon the basis of the clastic deposition and alteration theories. Indeed, in most cases, the evidence in favor of these is positive. It is believed that careful field study of many of these cases of so-called interbedding of limestone and dolomite, especially where the dolomite is relatively free from insoluble matter, would bring out the fact that the dolomite layers do not possess regular, even contacts and constant thicknesses. F. Pfaff[180] long ago showed that Wagner's conclusions regarding the dolomite of the French Jura were erroneous, since this rock fails to constitute a definite member of the series.

The Compactness of Some Dolomites.—Ever since Beaumont[181] pointed out that the alteration of limestone to dolomite should be accompanied by a decrease in volume of 12.1 per cent, there has been a tendency to think of secondary dolomites as vesicular, and the opinion naturally has arisen in the minds of some that compact dolomites are original. Thus, Bischof[182] expresses himself as follows:

> The cellular character of dolomite, which, according to Elie de Beaumont and Morlot, results from the replacement of lime by magnesia, is considered to prove that the rock has been altered since its deposition, since otherwise it would be compact. There is at many places compact dolomite, which has, probably, been produced directly.

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[179] See ante, p. 269.

[180] Pogg. Annalen, 1851, p. 465.

[181] See ante, p. 286.

[182] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 159.

Doubtless many advocates of the chemical theory have entertained views similar to those of Bischof. Blackwelder,[183] however, upon finding that the Bighorn dolomite, which he believes in an alteration product, possessed a porosity of only 1.31 per cent, attempted to overcome this obstacle by assuming that the replacement took place in the ooze contemporaneously with deposition.

As far as the writer's experience goes, compactness in dolomites cannot safely be used as a criterion of either chemical deposition or contemporaneous dolomitization, since many dolomites known from their field relations to have been formed by the alteration of limestone subsequent to its deposition show only very slight shrinkage effects. For instance, the dolomitic facies of the Central bowlder bed layer of the Elvins formation, near Elvins, Missouri, has a porosity of only .97 per cent although it contains 16.18 per cent of $MgCO_3$. The pore space of the limestone facies of the same layer amounts to .20 per cent. Again a compact fine-grained limestone from the Saint Louis at Alton, Illinois, has a porosity of 1.3 per cent, while its dolomitized equivalent in the same layer, containing 32.39 per cent of $MgCO_3$, has a pore space of only 4.24 per cent, and many other known secondary dolomites are equally compact. Furthermore, certain dolomites believed to be of clastic origin are very compact. The upper Silurian waterlimes of New York state, which are most satisfactorily explained as clastic deposits, are frequently extremely dense. Compactness, therefore, is not a reliable criterion of origin, and this feature cannot be regarded as favorable to the theory of chemical precipitation of dolomite.

The Preservation of Detailed Structures.—Most dolomites which have been interpreted as secondary after limestone exhibit many signs of obliteration of the original structures of the rock, and the inference naturally follows that the dolomites in which these structures are preserved are primary. Loretz[184] for this reason was led to favor the chemical theory of origin for the dolomites of southern Tyrol, which exhibit fine and

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[183] Bull. Geol. Soc. America, Vol. 24, 1913, p. 621.

[184] See ante, p. 266.

detailed structures. Here again, however, the evidence must be regarded as uncertain, since some secondary dolomites still retain these. The Anamosa dolomite of northeastern Iowa, which unquestionably is an alteration product, as shown by its association with dolomitized coral reefs, still frequently preserves fine ribbon stratification along which the rock readily cleaves. Examples of dolomitized corals and other organisms in which the structures are more or less faithfully preserved are also known.

Moreover, dolomites of clastic origin may exhibit no obliteration effects, and these may possess fine stratification. This feature, therefore, cannot be regarded as important in interpreting the history of dolomites.

The Paucity of Organic Remains.—The paucity of organic remains in some of the more ancient dolomites is sometimes postulated as evidence of their chemical deposition under conditions unfavorable to the existence of life, due to the excessive concentration of the sea-water or to some other cause. But it should be pointed out that to advocate this view would be to oppose in a measure the arguments of the strongest supporters of the chemical theory themselves, for $(NH_4)_2CO_3$ generated by the decay of organisms is regarded by them as the precipitating agent of the carbonates of calcium and magnesium entering into the dolomite.

On the whole, this feature cannot be regarded as throwing much light on the problem, since in the first place many of the ancient limestones, low in magnesium, are also nearly barren of fossils, and in the second because in many instances in which fossils were present they were very much obscured, if not wholly obliterated, by the dolomitization of the limestone.

Great Thickness.—Since it seems improbable that the dolomitization of a thick limestone subsequent to its deposition could affect more than the upper portion of the formation, it might be contended that deposits of dolomite aggregating several hundred or even several thousand feet in thickness were laid down directly. Certain of the Cambro-Ordovician dolomites of the Appalachian region are reported to attain a great thickness and this argument might well apply to them. But if it could be shown that dolomite might be formed by the progressive alteration of limestone during its deposition, this argument would lose much of its weight. Both Skeats[185] and Blackwelder[186] have regarded this method of dolomitization as possible. Thus, Skeats holds that the Schlern dolomite of southern Tyrol, which is 3000 feet thick, and which nearly all agree is a great dolomitized coral reef, was formed by a progressive alteration which kept pace with slow subsidence. The Bighorn dolomite, for which Blackwelder advocates the progressive alteration theory, attains a maximum thickness of 300 feet.

The Relation of Dolomite to Limestone.—Several instances are known where the upper portion of a formation is represented by dolomite and the lower portion by limestone, and this might be interpreted as having resulted from the chemical precipitation of both species, during which the calcium carbonate came down first because of its greater insolubility, and later calcium carbonate and magnesium carbonate mingled were deposited, as the solutions became more concentrated. To Petzholdt[187] this seemed the most plausible explanation of such relations in the Tyrol, but later workers have shown that the dolomites of this region must be regarded as secondary.

Moreover, the evidence is all in favor of the view that the same relations in other formations have been produced by downward dolomitization. In all such examples known to the writer the boundary between the dolomite and the underlying limestone is so wavy and irregular as to preclude the view that the relationship is original.

THE ORGANIC THEORY.

In support of the organic theory of the origin of dolomite several facts may be brought to bear. These are:

1. The existence of dolomitic worm castings and fucoidlike markings in limestones.

2. The occurrence of different faunules in the limestone and dolomite in some cases of interbedding.

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[185] See ante, p. 282.
[186] See ante, p. 284.
[187] See ante, p. 265.

3. The power of some organisms to secrete $MgCO_3$.
4. The deposition of $MgCO_3$ through the agency of algae.

Dolomitic Worm Castings and Fucoids in Limestones.—In 1907 Peach and Horne[188] reported the presence of dolomitic worm castings in the Sailmohr and Croisaphuill groups of the Northwest Highlands of Scotland, and suggested that their dolomitic character was due either to the fact that "the worms were selective as to their food or that their gastric juices had the effect of predisposing the casts to be dolomitized under the influence of magnesian solutions more readily than the surrounding mud." Still more recently, R. C. Wallace[189] has described dolomitic fucoid-like markings in certain Ordovician limestones in Manitoba. He was led to conclude after careful study that this relationship had resulted from a process of local replacement produced by the magnesia contained in algae which were imbedded in the limestone at the time it was deposited.

The writer has observed several occurrences of limestones mottled and streaked with dolomitic areas similar to those described by Peach and Horne and by Wallace. But in all of these the phenomenon could be satisfactorily explained only upon the basis of selective dolomitization, since the evidence favored the view that the magnesium was introduced after the limestone was formed. This feature, therefore, cannot be regarded as having a direct bearing on the organic theory of dolomite formation.

Influence of Organisms in the Production of Interbedding.—At least one instance is known where the dolomite and limestone layers of an interbedded series bear different faunules, and this suggests that organisms may have had some influence in the production of this phenomenon. Thus, Von Bibra[190] states that in Franconia marly layers containing as much as 44.8 per cent of $MgCO_3$ and bearing fossil molluscs alternate with unaltered shelly limestone containing on the average only 1.5 per cent of $MgCO_3$ and whose fossil remains consist chiefly of fish.

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[188] The Geological Structure of the Northwest Highlands of Scotland: Mem. Geol. Survey Great Britain, 1907, pp. 366 and 379.

[189] See ante, p. 271.

[190] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 181.

Bischof,[191] in commenting on this occurrence, remarks that "altered conditions of animal life in the ocean appear, therefore, to have taken place during the deposition of these different layers, and this is not opposed to the opinion, that they have been produced by organic action." But after further discussion, the conclusion is reached by him that the high magnesia content of the marly layers has resulted either from leaching out of the lime or from later introduction of magnesia, and this explanation seems most logical. The selective dolomitization of the marly layers might be accounted for readily on the supposition that they were more readily affected than the limestone because of their fine-grained character. It must be regarded as possible also that the organic remains of the marly layers exercised a selective influence during dolomitization.

The Deposition of $MgCO_3$ through the Agency of Algae.—The power of algae to deposit $CaCO_3$ and to build up deposits of travertine about springs is well known, and that $MgCO_3$ can be deposited with the lime to a limited extent under these circumstances has been shown by the studies of Ludwig and Theobald,[192] but whether such low plant forms have ever actively deposited $MgCO_3$ in the sea to an important extent, as suggested by these investigators, remains an open question. The fact that modern marine calcareous oozes are almost invariably very low in this constituent would suggest that they have not played an important part in dolomite-building. But more evidence is needed on this point.

The Power of Some Organisms to Secrete $MgCO_3$.—That certain marine organisms have the power of secreting considerable magnesium along with the lime was early shown by Forchhammer[193] and Damour[194]. Högbom[195] in 1894 also emphasized the fact that certain calcareous algae secrete much magnesia. A table of fourteen analyses presented by him shows the composition of a number of species of Lithothamnium collected from many different seas. The $MgCO_3$ content in these ranges from a minimum of 1.95 per cent to a maximum of 13.19, with a general average of 8.17 per cent.

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[191] Idem., p. 181.
[192] See ante, p. 270.
[193] See ante, p. 270.
[194] See ante, p. 270.
[195] Neues Jahrb., Vol. 1, 1894, p. 272.

More recently Bütschli[196] has summarized very exhaustively the results of all known analyses of the calcareous skeletons of marine organisms. He found in general that the forms which secrete considerable $MgCO_3$ are those which build calcite skeletons, while the aragonite-secreting forms are rarely found to contain more than 1 per cent of this constituent.

The maximum percentage of $MgCO_3$ for each of the various groups as shown by Bütschli's tables is as follows: Algae 16.99; Protozoa 12.52; Spongiæ 6.84; Octacoralla 9.38; Hexacoralla 0.62; Hydrozoa 0.97; Vermes 7.64; Asteroidea 9.36; Echinoidea 8.53; Holothuroidea 12.10; Bryozoa 4.66; Brachiopoda 3.4; Pelecypoda 1.0; Gastropoda 1.31; Cephalopoda 5.08; Arthopoda 1.38.

Bütschli, as will be observed, does not list any analyses of recent crinoid skeletons, but several such analyses are now on record. Thus, Nichols[197] in 1906, reported 11.72 per cent of $MgCO_3$ in the skeleton of *Metacrinus rodundus* from Japan, and A. H. Clarke[198] shortly after found abundant magnesium in this same species and in one other. A much more elaborate series of analyses of crinoid skeletons, however, are furnished by F. W. Clarke and W. C. Wheeler.[199] All the recent forms analyzed were found to possess a high percentage of magnesia. Thus, the analysis of nineteen species, representing as many genera, collected from widely different localities, which include great variation in depth, temperature, and salinity, showed, when the results were recalculated to eliminate the organic matter, an $MgCO_3$ content ranging from 7.86 to 12.69 per cent. The proportion of magnesium was found to decrease with depth and with decrease in temperature, but the cause of this relation is not known.

The analysis of ten fossil species of crinoids ranging in age from the Lower Ordovician to the Eocene, however, failed to show an important proportion of $MgCO_3$ for all but one. *Encrinus liliiformis* (Lam.) from the Triassic of Braunschweig, Germany, the stem of which bore 20.23 per cent of $MgCO_3$,

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[196] Abh. Göttinger Akad, Vol. VI, No. 3, 1908, p. 90.
[197] Field Columbian Museum, Geol. series, Vol. 3, 1906, p. 49.
[198] U. S. Nat. Mus. Proc., Vol. 39, 1911, p. 487.
[199] Prof. Paper U. S. Geol. Survey No. 90D, 1914, p. 33.

yielded less than 3 per cent of this constituent. This contrast in the composition of recent and fossil crinoids is difficult to explain. Clarke and Wheeler state that it is possible that the ancient crinoids were deficient in magnesium, but they believe is more probable that the low magnesium content of these has resulted from loss due to subsequent alteration, "perhaps to the infiltration of calcium carbonate."

A study of the foregoing summary of analyses of marine invertebrates will readily show the inadequacy of these organisms in themselves to build a dolomite. It should be recalled that the magnesium content listed is the maximum one in each case except in the crinoids, and that the great majority of the species of each group show a much smaller amount of this constituent. The rather high magnesium content of some forms then would be greatly diluted in a limestone deposit by the presence of forms low in magnesium. Probably in most cases forms low in magnesium would greatly predominate in a given deposit, but it is well known that certain calcareous algae, such as Lithothamnium, are the principal lime secretors in some modern coral reefs, and it is conceivable that reefs built largely by these forms might bear from the first several per cent of $MgCO_3$.

The possibility that recent crinoids might build a magnesian limestone directly is suggested by the high magnesium content of these. But no evidence has yet been found in support of the view that the Paleozoic crinoids have built such a limestone. Certain horizons in the Burlington and Keokuk limestones of southeastern Iowa are literally filled with crinoid remains, yet these have been shown by analyses made for the writer to be nearly free from magnesium except in the lower portion of the Burlington, which has been dolomitized locally. The accompanying analysis[200] is of a sample of crinoidal Burlington limestone from Morning Sun, Iowa.

	Per cent
SiO_2	2.06
Fe_2O_3	0.64
Al_2O_3	1.62
$CaCO_3$	94.59
$MgCO_3$	1.15

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[200] Prof. A. W. Hixson, analyst.

Considering all the evidence, it seems improbable that marine organisms play an important role in dolomite-building in the modern seas, and unless we assume as Nichols[201] has suggested that the Paleozoic forms secreted dolomitic skeletons, we must conclude that they have not played an important role in the past. But Nichols' suggestion has no foundation in fact, since the experience of paleontologists is that unaltered carbonate skeletons of Paleozoic invertebrates consist of calcite and never of dolomite.

THE CLASTIC THEORY.

Several attempts have been made to apply the elastic theory of dolomite formation, and there is some reason for believing that this will hold in certain instances. Some of the facts which lend support to this view are:

1. The intimate association of some dolomites with clastic sediments.

2. The high siliceous and argillaceous content of some dolomites.

3. The calcareous fossils and thin seams of limestone included in some impure dolomites show no signs of alteration.

4. The lack of obliteration and shrinkage effects in some dolomites.

5. The interbedding of limestone and dolomite.

The Association of Dolomite with Clastic Sediments.—When dolomite is intimately associated with sandstone and shale, which are both clastic, the assumption might be made that the dolomite also is clastic. Phillipi[202] has advocated this method of origin for certain dolomite beds associated with clastic sediments in the Muschelkalk of Germany. But this is, from the nature of the case, difficult to prove, since it might be contended also that such dolomites represent chemical deposits, or have resulted from the alteration of limestone. As regards the first of these possibilities, it is difficult to conceive of dolomite being deposited chemically under these conditions. But there

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[201] See ante, p. 271.
[202] See ante, p. 274.

could be no valid objection to the last contention. Indeed, the writer has found thin layers of dolomite in the Warsaw shales at Warsaw, Illinois, which must be secondary, as shown by the fact that they locally grade laterally into limestone only partly if at all dolomitized. Moreover, some of the best known examples of dolomites, examples which exhibit many of the characteristics of clastic deposits, are not associated with sandstone or shale but rather with limestone.

When, however, the dolomite associated with shale and sandstone is impure and is seen to merge laterally into shale or into pure limestone showing no alteration effects, the evidence of its clastic origin is much stronger. Certain impure dolomitic limestones in the Keokuk formation of southeastern Iowa exhibit these relations and are believed for this as well as other reasons to represent clastic deposits.

High Siliceous and Argillaceous Content. Since it is believed by those who uphold the clastic theory that the dolomitic sediments are derived from the residuum of older limestones, we should expect clastic dolomites to be high not only in magnesia, but also in insoluble impurities. But high siliceous and argillaceous content in dolomites is in itself not a reliable indication of their clastic origin, since many limestones also are high in these constituents, and dolomitization of these would give rise to an impure dolomite. Moreover, in many instances silica has been introduced into dolomites subsequently to their formation, and this must always be taken into account. This criterion, therefore, can be used safely only in conjunction with several others.

Unaltered Fossils and Thin Limestone Seams.—In all examples known to the writer in which fragments of calcareous fossils and thin limestone seams appear in dolomites of known secondary origin, these invariably show signs of corrosion or of imperfect dolomitization. When, therefore, these are well preserved in dolomite and show no signs of alteration even under the microscope, the conclusion is at once suggested that the latter are original. This would apply especially well in the case of those dolomites which are impure and grade locally into clastic sediments. Certain dolomitic limestones of the Keokuk formation of southeastern Iowa exhibit all these relationships.

Lack of Obliteration and Shrinkage Effects.—That these features cannot be applied indiscriminately in interpreting the history of dolomites has been pointed out. Some dolomites known to be secondary after limestone locally show little or no trace of obliteration and shrinkage effects, but it is seldom that a secondary dolomite exhibits these features either throughout its thickness or over wide areas. When they are consistently wanting, therefore, some support is lent to the view that the dolomite is primary, but even then this criterion should be employed guardedly, since it has not been disproven that some stratified dolomites are primary chemical precipitates. But where dolomites exhibit several other features suggestive of their clastic origin, the absence of obliteration and shrinkage phenomena must be regarded as lending still stronger evidence of their having been formed in this manner.

The Interbedding of Limestone and Dolomite.—As previously shown, the interbedding of limestone and dolomite is most easily explained upon the basis of primary difference in the materials deposited, and many geologists who have expressed themselves on this subject have adopted the chemical theory as furnishing the most satisfactory explanation of the phenomenon. But Lesley[203] has advocated the clastic theory of origin for the interbedded series of limestone and dolomite in the "Calciferous" near Harrisburg, Pennsylvania, and Grabau[204] holds that it will apply in many cases of interbedding.

Regarding the value of this criterion, the experience of the writer is that it should be applied with care, since selective dolomitization and related phenomena may give rise to a pseudo-interbedding of limestone and dolomite which can be distinguished from true interbedding only by careful study. For instance the interbedding of limestone and dolomite described by Lesley as existing in the "Calciferous" appears to have resulted entirely from dolomitization. This is clearly indicated

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[203] See ante, p. 272.

[204] Principles of Stratigraphy, 1913, p. 760.

by the fact that some of the dolomite layers pass abruptly into limestone when followed along the dip, and by the fact that many of the interbedded layers of limestone are mottled and streaked with patches of dolomite. Furthermore, the boundaries of the dolomite layers frequently do not coincide with the bedding planes, but are wavy and undulating.

It must also be regarded as possible that some cases of interbedding have resulted from progressive dolomitization of certain beds during deposition. The dolomite of the "Lower Buff Beds" of the Upper Mississippi Valley was doubtless formed in this manner. This member of the Platteville maintains a thickness of approximately fifteen feet over hundreds of square miles and is directly overlain by compact limestones. That it represents an alteration product is clearly indicated by the occasional presence of small remnants of limestone within its mass.

It must also be regarded as possible that some interbedded limestones and dolomites represent chemical deposits, and for this reason also interbedding is not a reliable indication of clastic deposition. When, however, the dolomite layers bear considerable siliceous impurity and grade laterally into shale on the one hand and into limestone on the other by transitional stages in which interfingering is developed, the evidence is strongly in favor of their being clastic. Especially is this true if fossil fragments and thin limestone seams in the dolomite show no signs of alteration under the microscope. There are several examples known to the writer which exhibit these relations. The most notable of these is found in the Keokuk formation at Keokuk, Iowa. At two horizons in the section, separated by an interval of about twenty-five feet, beds of ash-colored, fine-grained, siliceous, dolomitic limestone appear. The lowermost of these averages about six feet in thickness, while the upper one is about fifteen feet thick. The remarkable geodes for which this locality is famous come mainly from these two beds.

The results of an incomplete analysis of the upper bed made by the writer are given below.

	Per cent
Insoluble matter	33.8
Fe_2O_3 and Al_2O_3	2.8
$CaCO_3$	39.99
$MgCO_3$	12.50
Moisture and carbonaceous matter	7.70
Undetermined	3.21
	100.00

In general these dolomitic members of the Keokuk maintain their individuality over wide areas, and the upper member is traceable over an area several hundred square miles in extent. But locally they merge wholly or in part into argillaceous shale or fossiliferous limestone, and the transitions are characterized by an intimate interfingering of the shale and dolomitic limestone on the one hand and fossiliferous limestone and unfossiliferous dolomitic limestone on the other. The transition into pure limestone is entirely a physical one resulting from original differences in sedimentation, since not the slightest evidence of dolomitization is to be found in the limestone.

Very nearly the same relations as described above are shown by the Warsaw formation in Ste. Genevieve county, Missouri. This formation attains a thickness of approximately 120 feet in this region, and the upper one-half consists of fine-grained, impure, siliceous, dolomitic limestone, with a few rare, thin layers of bluish, coarse-grained, fossiliferous limestone in the upper portion. An exposure in the west bluff of the Mississippi river one mile below Clement, Missouri, exhibits the character of this portion clearly. The succession here is as follows:

	Feet	Inches
Limestone, gray, medium-grained, slightly oölitic; the lowermost portion of the Salem (exposed)	5 ±	
Limestone, soft, buff, impure, dolomitic, contact with bed above regular and even, no fossils noted	5	10
Limestone, gray, medium-grained, fossiliferous, weathering into thin layers	2	3
Limestone, soft, buff, impure, dolomitic, no fossils noted	5	8
Limestone, gray, medium-grained, rather thinly bedded, fossiliferous	2	9
Limestone, ash-colored, fine-grained, impure, dolomitic, sparsely fossiliferous	31	6
Clay, soft, plastic, weathering yellowish, fossiliferous	6	

The pure limestone layers are sharply and regularly interbedded with the dolomitic ones over wide areas, and show no trace of alteration. Furthermore, the calcareous fossils of the dolomite are perfectly preserved.

The Upper Silurian waterlimes of New York state also exhibit many of the earmarks of clastic deposits and Grabau[205] in fact has advocated their clastic origin. These waterlimes consist of dark, fine-grained, compact, siliceous, dolomitic limestones bearing on the average 20 to 25 per cent of $MgCO_3$. In the eastern part of the state these waterlimes are interbedded with gray, compact, fossiliferous limestones, and yet the contacts are sharp and regular and continuous over wide areas. These interbedding relations are excellently shown in the region about Rosendale, where the waterlimes were formerly extensively quarried for the manufacture of natural cement.

II. Evidence Bearing on the Alteration Theories.

The field evidence furnishes a mass of data favorable to the alteration theories of the origin of dolomite, but it will not in itself always indicate the conditions under which the alteration was effected. Thus, it is not possible to say in all cases whether the dolomitization took place while the limestone was still beneath the sea, through the agency of sea water, or after its emergence, through the agency of ground water. The evidence which may be introduced in favor of the alteration theories may be classified first, as that inherent in the dolomites themselves, and second, that based on the association of limestone and dolomite.

Inherent Evidence.

(1) Dolomite pseudomorphs after calcite.
(2) The great range in composition of the stratified dolomites.
(3) Dolomitized coral reefs.
(4) Dolomitized fossils in dolomites.
(5) Dolomitized oölites.
(6) Obliteration and shrinkage effects.

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[205] Bull. Geol. Soc. America, Vol. 24, 1913, p. 399.

(7) The association of gypsum with some dolomites.

Evidence Based on the Association of Limestone and Dolomite.

(8) Vein dolomites.
(9) Mottled limestones.
(10) Remnants of limestone in dolomite.
(11) Nests of dolomite in limestone.
(12) Irregular contacts of limestone and dolomite.
(13) The lateral gradation of dolomite into limestone.
(14) Pseudo-interstratification effects.

INHERENT EVIDENCE.

Dolomite Pseudomorphs.—Dolomite pseudomorphs after calcite are not uncommon. Several occurrences of such pseudomorphs were reported long ago by Blum[206] and many more have since been described by Haidinger[207] and others. These can only have been formed by the substitution of $MgCO_3$ for a portion of the $CaCO_3$ of calcite crystals. Here, then, the validity of the alteration theory is established, and the replacement of limestone by magnesia on a much larger scale must be regarded as not only possible but highly probable.

Range in Composition.—As has been shown, there is every gradation in the $MgCO_3$ content of limestone, from pure limestone free from this constituent, on the one hand, to dolomite with an excess of $MgCO_3$ on the other (see Table II, p. 260). This great range in composition surely would not characterize a chemical deposit, nor can it be satisfactorily explained upon the basis of the clastic or leaching theories, because of the freedom of most dolomitic limestones from considerable insoluble impurities. When we consider that the alteration theory will allow all degrees of replacement of limestone by magnesia the phenomenon is readily explainable. The variable composition of the dolomitic limestones as a whole, therefore speaks strongly for their secondary origin.

Dolomitized Coral Reefs.—The existence of both recent and fossil dolomitized coral reefs indicates the possible operation

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[206] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 165.

[207] Trans. Roy. Soc. Edinburgh, 1827, p. 36.

of dolomitization on a large scale. Many examples of recent or near recent dolomitized coral reefs exist in the coral islands of the southern Pacific as shown by the work of Dana,[208] Skeats,[209] and others, and Branner[210] has reported the presence of a dolomitic reef rock in the old stone reefs of Brazil. These can have resulted only from the alteration of the calcareous skeletons of corals and other organisms of the reef. When, therefore, dolomitized coral reefs are found in the ancient dolomites, these dolomites can have had no other than a secondary origin. The most notable examples of fossil coral reefs now represented by dolomite are found in the Niagaran of Iowa and Wisconsin and in the great Schlern dolomite of Southern Tyrol.

Dolomitized Fossils.—When fossils which are known to have been originally calcareous are found to be represented by dolomite in dolomitic formations it is difficult to avoid the conclusion that these formations have resulted from the replacement of limestone. Instances where the skeletons of organisms are replaced by dolomite are not common, since the fossils are usually represented by molds in dolomites. The problematic fossil Cryptozoan, however, has been found to be represented by dolomite in several instances. In the Shakopee dolomite of the Upper Mississippi Valley dolomitized remains of this organism are sometimes met with. They have likewise been observed in the Allentown dolomite near Allentown, Pennsylvania; in the Little Falls dolomite at Little Falls, New York; and in the Joachim dolomite near Bloomsdale, Missouri. Dolomitized corals are also occasionally found in dolomites. These are not uncommon in certain dolomite beds of the Cedar Valley limestone at Fairport, Iowa, and they appear also in the Lockport dolomite at Niagara Falls, New York.

Altered Oölites.—It has been our experience that calcareous oölites, when formed, consist of pure, or nearly pure calcium carbonate. Where, therefore, oölite beds in the midst of dolomite formations are composed of dolomite, the inference is that both the dolomitic oölite and the rock inclosing it have

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[208] Am. Jour. Sci., Vol. 45, 1843, p. 120.
[209] Bull. Mus. Comp. Zoöl., Vol. 42, 1903, p. 53.
[210] Idem., Vol. 44, 1904, p. 265.

resulted from dolomitization, and where the oölite is only partly changed to dolomite, and so shows unquestionably that it was originally calcareous, the evidence in favor of dolomitization must be regarded as positive. In the course of the writer's studies several oölites have been found in the midst of dolomites, and strangely enough, these have been for the most part only partly altered, although the inclosing rock is uniformly dolomitized. The details of the alteration of these oölites will be considered in the section on the petrographic evidence.

Imperfectly altered oölite beds occurring in association with dolomite are found in the Elbrook limestone at West Waynesboro, Pennsylvania; in the Elvins formation at Elvins, Missouri; in the Allentown limestone near South Bethlehem, Pennsylvania; in the Hoyt limestone near Saratoga Springs, New York; in the basal portion of the Oneota dolomite at McGregor, Iowa; in the Tribes Hill limestone at Canajoharie, New York; and in the Monroe dolomites near Sylvania, Ohio.

Obliteration and Shrinkage Effects.—The massive and all but structureless character of some dolomites has frequently been remarked upon, and there can be little doubt that in many instances this massive character was taken on at the time of dolomitization, as the bedding planes of the original thinly-bedded limestone were largely obliterated by the welding which accompanied the recrystallization induced by dolomitization. Thus, in the Galena limestone of Clayton county, Iowa, which has suffered dolomitization locally, the limestone facies is thinly and distinctly stratified, but the dolomitic facies is heavily bedded and the thick massive layers are separated by faint planes which are often indistinctly shown even on weathered surfaces. The limestone and dolomite facies of the Niagaran in Delaware county, Iowa, exhibit similar differences.

The obliteration of structures seems to have taken place typically where the dolomitization was accompanied by shrinkage, i. e., where the alteration proceeded by molecular rather than by volume replacement. Where the replacement is truly molecular the transformation of limestone to dolomite should be accompanied by a decrease in volume of about 12.1 per cent as pointed out by Beaumont.[211] Few of the massive dolomites which are known to be secondary probably show as much shrinkage as this, but some of them are very vesicular and it is in these that the structures are most obliterated.

While indications of obliteration of structures and of shrinkage furnish good evidence of the secondary origin of the dolomites which exhibit them, it cannot be argued conversely that compact dolomites which exhibit no obliteration effects are original, for the replacement may sometimes take place after the law of equal volumes as enunciated by Lindgren,[212] as shown by the fact that certain dolomites known from their field relations to be secondary after limestone fail to exhibit these features. One of the most notable examples of this method of replacement is found in the Saint Louis limestone of southeastern Iowa. Freshly exposed surfaces of the dolomitic facies of this formation are frequently nearly or quite as thinly bedded as the limestone facies and no evidence of shrinkage is to be seen. The Allentown dolomite in the region about Allentown, Pennsylvania, also shows little or no sign of obliteration of structures or of shrinkage, yet its secondary origin is suggested by the fact that it contains both dolomitized oölites and skeletons of Cryptozoan.

Some of the well known dolomites in which the writer has observed obliteration and shrinkage phenomena are: the Leithsville dolomite at Allentown, Pennsylvania; the Oneota and Shakopee dolomites of the Upper Mississippi Valley; the Little Falls dolomite of the Mohawk Valley, New York; the Galena, Fort Atkinson, and Niagaran dolomites of northeastern Iowa; the Bonneterre, Doerun, Derby and Potosi dolomites of the Ozark region; the Monroe dolomites of Michigan and Ohio; the Cedar Valley dolomites of eastern Iowa; and the Spergen dolomites of southeastern Iowa and eastern Illinois.

The Association of Gypsum and Dolomite.—When gypsum is found occupying small pockets and filling shrinkage vugs in dolomite the suggestion at once comes to mind that this gypsum represents a reaction product of dolomitization and was pro

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[211] See ante, p. 286.

[212] Econ. Geol., Vol. 7, 1912, p. 521.

duced by the action of $MgSO_4$ on limestone. Absolute proof of this is wanting, of course, since the exact time of the introduction of the gypsum cannot be determined. As a criterion of origin, then, the value of this feature cannot be emphasized strongly. But taken in conjunction with other features it may serve to strengthen the evidence.

Examples of gypsum occurring in association with dolomite are not common, and the only case met with by the writer was found in the Lockport dolomite of the Niagara Falls region. Morlot,[213] however, has described several other instances where dolomite and gypsum appear in intimate association.

EVIDENCE BASED ON THE ASSOCIATION OF LIMESTONE AND DOLOMITE.

Vein Dolomites.—The development of dolomite along fissures in limestone furnishes positive evidence in favor of the alteration theory, provided no signs of extensive leaching are shown. Probably most vein dolomites have been produced through the agency of ground water circulating along the fissures, but there is not general agreement on this point.

Vein dolomites are of common occurrence in the Lahn district as pointed out by Klipstein,[214] who early reported that in this region the dolomite not only traverses the limestone as distinct veins or dikes, but also is imbedded in it as nests and large irregular masses. Similar phenomena were later described by Grandjean[215] from the lower Lahn district. According to him the dolomite is developed here to the greatest extent where the limestone is most subject to the penetration of water.

Other vein dolomites have been described in the same general region by Von Strombeck and by Abich. Bischof[216] summarizes their observations as follows:

Dyke-shaped masses of dolomite, generally in a vertical position, were also observed in limestone by v. Strombeck and Abich at the Kahlen-Berg, near Echte, between Göttingen and Brunswick, and in the valley of Tramonte. At several places near

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[213] Haidinger's Naturw. Abh., Vol. 1, 1847, p. 305.

[214] Cited by Bischof, Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 185.

[215] Cited by Bischof, Idem., p. 193.

[216] Idem., p. 185.

the Lahn the dolomite intersects the limestone strata and spreads out over them like a roof six or eight feet thick. In some of these dikes the dolomite is very much decomposed and presents a striking contrast with the unaltered limestone adjoining.

Similarly Harkness[217] has described cases where dolomite appears to follow joints in the Carboniferous limestones in the district about Cork, Ireland. Local masses of dolomite in the limestone here assume courses in intimate agreement with the direction of the joints. ''In some instances the line of the joint, when the joint is closed, forms the boundary between the dolomite and the ordinary limestone; the two distinct portions terminating abruptly against the sides of the joint.'' Harkness concluded that the jointing was antecedent to dolomitization, but believed the alteration to have been effected by sea water.

Vein dolomites have also been reported in the Carboniferous limestones of South Wales.[218] In the country around Abergavenny dolomitization is closely associated with faults, and the alteration effects die out on each side of these. It is suggested that waters from the Coal Measures which are known to be high in magnesium and barium salts are responsible both for these dolomites and for the associated joints and crack infillings of barytes.

Dixon[219] likewise states that vein dolomites following fissures are of frequent occurrence in the Carboniferous limestone along the coast of South Wales between Mumbles Head and Pwlldu. These were formed subsequent to pre-Triassic deformation, and are regarded as of Triassic age, and to have been caused by the downward percolation of water from the surface. The more continuous beds of dolomite in the formation must have been produced prior to the disturbance. These he interprets as contemporaneous. The vein dolomites may be distinguished from the contemporaneous ones by the fact that they show ''(1) larger average size and greater clearness of the rhombo-

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[217] Quart. Jour. Geol. Soc. London, Vol. 15, 1858, p. 86.

[218] Strahon and Gibson and others. The Geology of the South Wales Coal Fields, Part 2; Mem. Geol. Survey, England and Wales, p. 33.

[219] The Geology of the South Wales Coal Field, Part 8; Mem. Geol. Survey, England and Wales, 1907, p. 16.

hedra; (2) the inclusion of hematite; (3) the association with calcification; (4) the preference of dolomitization for oöliths and corals."

Whatever uncertainty may be entertained regarding the origin of the foregoing vein dolomites, no doubt need exist regarding the manner of formation of those closely associated with ore deposits. These can have been formed only through the agency of ground water. Several such occurrences have been described. For instance, Bischof,[220] quoting Coquand, states "that where the auriferous quartz veins of the gold mine La Gardette, extend from the gneiss into the Lias limestone, the latter is converted into black dolomite and bears auriferous galena; but, at a distance of a few centimeters, it is quite free from magnesia."

Local dolomitization is also associated with the lead and zinc deposits of the Joplin district.[221] "The ores are invariably connected with dolomite either fresh or rotten, and reach sidewise into the limestone only as far as the latter is dolomitic and crystalline." Somewhat related features are described by Spurr,[222] who states that dolomite follows fractures and faults in the upper part of the Leadville formation in the Aspen district, Colorado. The dolomitization effects gradually die out on each side of the fissures, as shown by analyses. Dolomitization is associated with the ore here as at Joplin. Spurr states that "the local dolomitization invariably accompanies the ore. Even when the latter is in blue limestone there is usually a sort of envelope of dolomite around it, which in turn is surrounded by limestone." These vein dolomites cannot be distinguished from the associated contemporaneous dolomites microscopically, according to him. It would appear, therefore, that Dixon's observations will not apply generally. The origin of the Aspen vein dolomites is ascribed to the action of hot springs such as those which still exist at Glenwood Springs nearby and which, according to his observations, are producing similar dolomitization effects today. More recently Michael[223]

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[220] Elements of Chemical and Physical Geology, English translation. Vol. 3, 1859, p. 180.

[221] Schmidt, A., Trans. St. Louis Acad. Sci., Vol. 3, No. 2, 1875, p. 246.

[222] Mono. U. S. Geol. Survey, Vol. 31, 1898, p. 208, ff.

[223] Zeitschr. Deutsch. geol. Gesell. Prot., Vol. 56, 1904, p. 127.

has shown that dolomitization has followed closely certain lines of disturbance in the Muschelkalk beds near Tarnowitz and elsewhere. The phenomenon is closely associated with mineralization here also, and the conclusion is reached that the alteration has been accomplished by ground water through the introduction of $MgCO_3$ and the removal of $CaCO_3$.

Mottled Limestones.—Within recent years several occurrences of limestone mottled with patches of dolomite have been described and commented upon. These mottled limestones are of two general types, viz.: (1) those in which the dolomite patches follow worm castings or fucoid-like markings, and (2) those in which the dolomite patches exhibit irregular shapes and relations and show no guiding influence. These types of mottling will be referred to as organic and inorganic respectively. Some attempt has been made to explain the first type, but the last has been only briefly mentioned.

Dolomitic worm castings have been described by Peach and Horne[224] from the Croisaphuill group of the Northwest Highlands of Scotland. Their description is as follows:

> Towards the base the beds consist chiefly of massive beds of dark grey limestone full of worm castings, which are now chiefly represented by dolomite, so that they stand out in mottled masses on the weathered surface of the rock, the limestone matrix having yielded to solution more readily than the dolomite. Such rocks are highly fossiliferous, but where bands of granular dolomite make their appearance fossils are rarely met with. The middle portion is made up chiefly of unfossiliferous granular leaden-colored dolomite with a few light colored bands of limestone full of worm casts. The upper part, consisting of massive sheets of fossiliferous limestone full of worm casts preserved in dolomite, resembles the lower subdivision.

Worm castings are also reported by these writers[225] to occur in the underlying Sailmohr group. But this rock is uniformly dolomitic, and is described as a massive, crystalline, granular dolomite charged with dark worm castings in a grey matrix, and known locally as the "leopard stone." The view enter-

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[224] The Geological Structure of the Northwest Highlands of Scotland: Mem. Geol. Survey, Great Britain, 1907, p. 379.

[225] Idem., p. 366.

tained by these writers as to the origin of the dolomitic worm castings is made clear by the following quotation:

> Thus up to the very top of the Cambrian series of Sutherland and Ross impressive evidence is supplied by the abundance of worm casts that the rocks must have accumulated in the state of fine mud or ooze, probably derived mainly from the minute organisms of the plankton. The fact that the worm casts in the two upper groups of the series are for the most part preserved in dolomite while the matrix remains a limestone, suggests that either the worms were selective as to their food or that their gastric juices had the effect of predisposing the casts to be dolomitized under the influence of magnesian solutions more readily than the surrounding material.

R. C. Wallace,[226] in a recent paper entitled "Pseudobrecciation in Ordovician Limestones in Manitoba," also has described dolomitic markings suggestive of organisms in limestones. The succession of formations involved there is as follows:

	Feet
Stony Mountain formation	190
Upper mottled limestone	130
Cat Head limestone (dolomitic)	70
Lower mottled limestone	70
Winnipeg sandstone	100

The dolomitic markings manifest themselves as irregularly distributed darker areas which have their greatest linear extent along the bedding planes, where they exhibit a branching structure. They are characterized by a content of iron as well as of magnesia which is higher than that of the limestone, and with the exception of a few large shells are free from the fossil fragments so numerous in the latter rock. Separate analyses of the dolomite and limestone areas yielded Wallace the following results:

	LIGHT COLORED	DARK COLORED
	PER CENT	PER CENT
SiO_2	1.56	1.56
Total iron as Fe_2O_3	0.16	1.94
(FeO	0.12	0.45)
Al_2O_3	0.06	2.27
$CaCO_3$	94.02	71.03
$MgCO_3$	4.33	23.35
Total	100.13	100.15

[226] Jour. Geol., Vol. 21, 1913, p. 402.

As is shown by the following statement, the view is entertained by Wallace that the mottling has resulted from alteration:

> A study of the margin of the darker areas leaves no doubt that we are dealing with secondary dolomitization. Although there is a definite marginal line, it shows so sharp interpenetration of dolomitized and undolomitized material that it could have been caused only by the irregular advance of waters bearing magnesian salts in solution.

After carefully reviewing the whole subject of mottling, however, the conclusion is reached that algæ imbedded in the rocks are responsible for the phenomenon, thus:

> There remains the hypothesis that the mottling is connected with algic decomposition. Analyses due to Goedechens show that the percentage of MgO in the ash of algæ collected from the west coast of Scotland may reach 11.66. If, then, the algæ of the sea bottom became buried under a thin coating of calcareous ooze before actual decomposition ensued, the liberated Mg salts might, in conjunction with the sea water of fairly high Mg content, cause such increase of Mg ions locally as to give rise to actual dolomitization. Only from such organisms and allied types could the percentage of Mg salts be increased locally to any appreciable extent. There are certain structural features of the markings that lend some support to this view of the origin of the dolomitization. They are horizontally placed, are markedly dendritic, and the sections often show a darker core which might represent the actual position of the plant; while the magnesian waters, extending outward from this central nucleus, have affected the surrounding stone. Again, thin sections of the dolomitized areas occasionally show a narrow central tube of clear, well crystallized calcite, indicating that a cavity had existed when the dolomitization took place and that this was subsequently infilled with calcite. Such cavities might be formed when, owing to decomposition, the organism disappeared. The hematite and limonite of the recrystallized dolomitic material would be attributed to the iron salts of the algæ.

It will be noted that Wallace emphasizes the importance of algæ as contributors of magnesia to the dolomitizing solutions and there can be no doubt that certain algæ do contain considerable magnesia in their tissues. It does not seem probable to the writer, however, that this constituent would ever attain the proportion sufficient to dolomitize the surrounding limestone to such a marked degree.

The data obtained in the course of the writer's studies lead him to adopt an alternative hypothesis of origin for both the organic and inorganic types of mottling. All cases of mottling examined seem to be best explained on the assumption that the magnesia was introduced from without and that the mottling has resulted from the selective replacement of fucoids in the one case and from the spreading out of the alteration from certain favorable centers in the rock in the other. Consistent with this view are the following facts:

(1) The existence of unaltered fucoid-markings containing less than two per cent of $MgCO_3$ in association with dolomitic ones.

(2) The association of both types of mottling with dolomite seams and other evidences of imperfect dolomitization.

(3) The gradation of mottled beds into beds which are uniformly dolomitic, both laterally and vertically.

(4) The existence of every gradation between limestone showing incipient mottling and true dolomite.

Thus it appears that mottling represents merely an incipient stage in the process of dolomitization, and it is believed that many dolomites have passed through such a stage in the progress of their formation. Here, then, we have a clue to the origin of all those masses of dolomite with which such mottling is associated.

Examples of Mottled Limestones.

Many examples of mottled limestones associated with dolomite have been met with in the course of this investigation. These will be described as far as possible in the order of their geologic age.

The Elbrook Formation.—The limestones of the Elbrook formation are commonly uniformly dolomitic, but mottled limestones occur at several horizons in the vicinity of Waynesboro, Pennsylvania. A hand specimen, in the writer's collection, from the quarry located in the southwestern portion of the town, consists of fine-grained dark gray limestone with irregular wavy seams of fine-grained, lighter gray dolomite ranging from about 1 mm. to 12 mm. in thickness. These are approximately parallel to the stratification of the rock, but some of them extend across the stratification planes and invade the adjacent limestone layers. Under the microscope the dolomite seams are shown to possess no definite contact lines, but to grade gradually into the limestone through transitional stages.

Elvins Formation.—The Davis member of the Elvins group, of southeastern Missouri, exhibits mottling on a large scale. This member attains a thickness of approximately 170 feet according to the measurements of Buckley,[227] and is both overlain and underlain by extensive dolomite formations. Excellent facilities for studying these beds are afforded in the cuts of the Illinois Southern Railroad between the stations of Flat River and Elvins. The upper sixty-three feet of the formation as developed here consists of dolomitic shales and limestones, while the remaining portion, with the exception of twenty-five feet of dolomite at the base, is only imperfectly altered. In this part the thinly bedded limestones are streaked and blotched with buff dolomite. The dolomite patches follow no definite pattern, but typically form discontinuous streaks along the stratification planes and irregular areas within the limestone layers. At many points the alteration has proceeded so far that only small irregular remnants of limestone entirely surrounded by dolomite remain. It seems probable that this mottled character was taken on by the Davis member at the time the overlying dolomites were formed, and that the dolomitizing solutions not only were weakened by reaction with the limestone above, but also were hindered in their circulation by the more impervious shaly beds in the upper portion of this member.

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[227] Mo. Bur. Geol. and Mines, Vol. 9, part 1, 1908, p. 38.

The Beekmantown Limestone.—An excellent exhibition of mottling is shown by the limestones associated with dolomite in the Tribes Hill member of the Beekmantown as it is developed in the Mohawk Valley of New York state. Unusually good opportunity for studying the mottled stone of this formation is furnished in the abandoned quarries at Canajoharie and at Palatine Bridge.

By previous observers the significance of the mottled character of some of these beds seems not to have been appreciated and the coarser-grained dolomitic patches have almost invariably been described as consisting of arenaceous material.

As regards the details of the mottling, two main types may be recognized. These are: first, a mottling produced by the dolomitization of the limestone in an irregular and imperfect manner by alteration along stratification lines and in irregular patches; and, second, a mottling produced by a more regular and selective dolomitization along well directed lines and apparently following fucoid markings in the limestone. In the latter type, the dolomite forms more or less cylindrical, branching pipes running indiscriminately through the limestone but having their greatest linear extent along the bedding planes. The original outline of these, however, has been obscured in a number of instances by the spreading out of the dolomitization from them into the adjacent limestone. At some points both types of mottling are developed in the same layer and there a net work of dolomite streaks appears. In both types the local alteration has been accompanied by increase in size of grain and in both the dolomitic areas tend to stand out in relief as yellowish patches on weathered surfaces of the gray limestone.

The relations of the mottled limestone are well shown in a large abandoned quarry situated about one-half mile west of the station of Palatine Bridge along the New York Central and Hudson River railroad. The following section was measured at the east end of the opening:

	Feet	Inches
7. Limestone, conglomeratic, showing no visible signs of alteration	2–3	
6. Dolomite, brownish	3	
5. Limestone, gray, compact, with dolomitic fucoid markings		8
4. Limestone, dove-colored, compact; upper two-thirds with occasional discontinuous seams of dolomite; lower one-third with dolomitic fucoid markings	9	
3. Dolomite, brownish, bearing fucoid markings of a darker tint, and resembling the "leopard stone"	3-4	
2. Limestone, gray, compact, with dolomitic fucoid markings, grading up into the dolomite above through a transition zone 2 to 3 inches thick		8
1. Limestone, gray, compact, grading up into the mottled rock above (exposed)	2	

The contact of No. 3 with the bed below is fairly sharp and regular, but the contact with the bed above is much less regular, for near the middle of the quarry face the dolomite bed thickens greatly, mainly at the expense of the mottled zone in the lower part of No. 4. Thus, No. 3 and No. 4 are each six and one-half feet thick here and the mottled zone at the base of No. 4 is reduced from three feet to one foot.

Samples of the mottled limestone, and of the uniformly dolomitized rock from bed No. 3 have been analyzed by Prof. A. W. Hixson. The dolomitic and non-dolomitic areas of the mottled limestone were tested separately.

	Limestone Area	Dolomite Area	Dolomite
	Per cent	Per cent	Per cent
SiO_2	2.90	9.28	2.82
Fe_2O_3	1.43	5.00	3.14
Al_2O_3	3.87	7.28	6.40
$CaCO_3$	84.49	62.73	55.62
$MgCO_3$	5.81	15.01	32.60
Total	98.50	99.30	100.58

Similar relations of mottled limestone to dolomite are shown in the quarries at Canajoharie. In a small quarry a short distance west of the village a layer of dolomite eighteen inches thick, overlain and underlain by mottled limestone, grades laterally into mottled limestone itself. This relationship is again shown in an abandoned quarry in the eastern part of Canajoharie. At the top of this quarry there appears a bed of mottled limestone six feet in thickness bounded above and below by thin layers of conglomeratic and slightly oölitic limestone which shows only incipient alteration of the matrix. Now the lower two feet of this mottled limestone member grades locally into a uniformly dolomitic rock through a transition zone only a few inches in extent. The gradation is accompanied by a gradual spreading out and enlargement of the dolomitic patches until they finally coalesce. Every stage, therefore, may be traced between a limestone with dolomitic fucoid markings to a uniform dolomite. There can be no escape from the conclusion that this mottled limestone represents an incipient stage in the process of dolomitization.

Precisely the same sort of mottling is developed in division D of the Beekmantown in the Lake Champlain region. A fine exposure of these mottled beds appears in the escarpment below the walls of old Fort Ticonderoga. The succession here from above downwards is approximately as follows:

	Feet	Inches
6. Dolomite, dark gray, faint traces of fucoid markings showing on weathered surfaces; upper portion bearing seams and reticulations of chert	12	
5. Concealed	7	
4. Limestone with pipes and reticulations of dolomite which stand out in relief on weathered surfaces	4	4
3. Dolomite, dark gray, with thin siliceous seams	2	8
2. Limestone, gray, fine-grained, with dolomitic fucoid markings	2	6
1. Dolomite, dark gray, showing fucoid markings on weathered surfaces; some layers cherty, the chert following fracture lines, stratification lines, and to some extent the fucoid markings. Exposed	20	

The limestone beds here, in addition to bearing dolomitized fucoids, also bear numerous dolomitized tests of Ophileta and Orthoceras, although the limestone matrix immediately adjacent is little if at all affected. Dolomite bed No. 1, which exhibits traces of fucoid markings, doubtless itself passed through a mottled stage during its formation comparable to that now exhibited by beds No. 2 and No. 4, but for some unknown reason it was altered more completely and more uniformly.

Other occurrences of mottled limestone, mainly of the fucoidal type, in association with dolomite, appear in divisions A and B of the Beekmantown at Shoreham, Vermont; in the Coplay limestone of Beekmantown age near Catasauqua, Pennsylvania; and in the Beekmantown at Staufferstown and at Harrisburg, Pennsylvania.

The Chazy Limestone.—Mottling of both the organic and the inorganic types appears in the Chazy limestone in the Lake Champlain region. The fucoidal mottling is well developed in the limestone exposed near Shoreham, Vermont. An outcrop in a small hillock on the east side of the road about one-half mile north of Shoreham shows dolomitic fucoid-markings at several horizons, and in the higher beds the tests of Maclurea also are dolomitized. The matrix of the dolomite areas seems to be but little affected, and the original outlines of the fucoid markings are well preserved. At one horizon in the lower beds dolomitization of the fucoids has been very imperfect and many of the markings are still preserved in an unaltered condition. These are of a darker tint than the limestone and can be distinguished from it with little difficulty. In order to determine if possible the cause of the selective dolomitization of such fucoid markings, samples of the darker areas and of the limestone matrix were submitted to Mr. H. F. Gardner of Columbia University for analysis. After the moisture and carbonaceous material were eliminated by heating, the following results were obtained.

	LIGHT COLORED PER CENT	DARK COLORED PER CENT
SiO_2	0.52	0.56
$Al_2O_3+Fe_2O_3$	1.04	0.52
$CaCO_3$	97.50	97.36
$MgCO_3$	0.98	1.18
Total	100.04	99.62

It will be noted that the $MgCO_3$ content of the fucoids is not appreciably greater than that of the limestone, and this constituent could not have exerted much selective influence. Nor do the analyses afford any other clue to the problem.

Microscopic examination of the darker material in thin section failed to reveal the presence of organic structures, but it is filled with dark inclusions which doubtless consist of organic matter. It seems probable that the selective dolomitization may be attributed largely to this, for reasons which will be considered later.

On Valcour Island also, in Lake Champlain, mottling is extensively developed in the Chazy, but here it is predominantly of the inorganic type. In all of the divisions of the formation exposed here the limestone is almost universally mottled on a small scale with areas of buff dolomite. Commonly the dolomite appears in the form of irregular streaks and patches along the stratification lines, but in many cases it forms small irregular areas scattered through the limestone layers. In most instances these dolomite areas are notably finer-grained than the limestone. Especially is this true of the areas in the coarse-grained fossiliferous limestones. This has resulted from the breaking down of the large calcite grains and fossil fragments into aggregates of fine dolomite grains during the alteration, a phenomenon which accompanies the alteration of all coarse-grained limestones. Moreover, the dolomite areas in the Chazy are in general softer and less resistant than the coarse-grained limestone and seldom stand out in relief as do the dolomite areas in the fine-grained limestones of the Beekmantown.

No beds of limestone within the Chazy, as developed here, were found to be uniformly dolomitized, but Brainard and Seeley[228] report that a dolomitic limestone member caps the formation at the north end of the island.

The Plattin Limestone.—Mottling is developed on a small scale, locally at least, in the basal portion of the Plattin limestone of the Ozark region. The mottled limestone constitutes a transition bed from the uniformly dolomitic Joachim limestone below to the unaltered compact limestones of the Plattin above. An unusually good opportunity for studying these relations is found in a small quarry opening about one and one-half

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[228] Bull. Am. Mus. Nat. Hist. Vol. 8, 1896, p. 306.

miles north of Perryville, Missouri, in a large sink-hole just west of the McBride road. The following section appears at this point:

	FEET	INCHES
PLATTIN:		
Shale, buff, calcareous, with thin layers of compact gray limestone	8	6
Limestone, dark gray, compact, with irregular seams and patches of lighter gray dolomite which weather yellowish	4	
Limestone, gray, imperfectly dolomitized, forming abrupt transition from dolomite below to mottled limestone above		1
JOACHIM:		
Dolomite, bluish when fresh but weathering yellowish, heavily bedded	5	6

The dolomite patches of the mottled limestone member are irregular in shape, and although for the most part they attain their greatest linear extent along the bedding planes of the rock, they are not confined to these, for a number of tongue-like extensions of the dolomite areas shoot out short distances into the limestone.

The Galena Limestone.—Mottling of the inorganic type is excellently developed in the Galena limestone at several localities in Clayton county, Iowa, as was first pointed out by Leonard,[229] who speaks of the mottled limestone as "partially dolomitized beds" and states that they constitute transition beds between the dolomitic and non-dolomitic portions of the formation. Incomplete analyses of the limestone and dolomite areas of the rock which were made for him showed them to contain 4.31 and 18.28 per cent of $MgCO_3$ respectively.

In rare instances the mottled limestone does not occur at the contact of the dolomite and limestone facies, but is developed farther down with several feet of limestone intervening. But typically the mottled rock forms a transition from the dolomite above to the limestone below. Therefore since the contact of the limestone and dolomite facies is not a definite plane but wanders up and down in the formation, the mottled limestone appears at no definite horizon.

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[229] Ia. Geol. Survey, Vol XVI, 1905, p. 250.

The mottled limestones of the Galena attain their greatest known development in the west bluff of the Mississippi river back of the town of Guttenberg, Iowa. The succession of beds in the Galena as measured and described by the writer is as follows:

	Feet
4. Dolomite, buff, vesicular, becoming pitted on weathered surfaces, grading abruptly into the bed below	65
3. Limestone, gray fine-grained, mottled with patches of buff dolomite which become smaller and more distant in the lower beds; in layers from 2 inches to 1 foot in thickness; with locally developed dolomite beds in middle portion	90
2. Shale, bluish, argillaceous	1
1. Limestone, gray, slightly argillaceous, no mottling noted. Exposed	35

Thirty-five feet above the base of No. 3 there appears a ledge of buff dolomite four to five feet thick. Above this comes five to six feet of mottled limestone, and then six to seven feet of dolomite again. When these layers of dolomite were traced laterally along the bluff for a distance of about ten rods, they were found to pass, in part, into mottled limestone, but never were the dolomite beds found to disappear entirely. Thus, at the north end of the section the upper bed is split into two almost equal parts by two feet of mottled limestone. The dolomite patches in No. 3 do not appear to increase notably in size either at the contact with No. 4 or in the vicinity of the dolomite layers within the member itself, but where the dolomite layers grade laterally into mottled limestone there is a gradual transition in the size of dolomite areas, from a dolomite with subordinate limestone areas to limestone with subordinate dolomite areas.

Attention should be called to the fact that no mottling appears below the shale layer No. 2 and that the number and size of the dolomite patches in the lower part of No. 3 decreases downwards. This would seem to indicate that the dolomitization here was a descending process and that the mottling was developed by imperfect alteration at the time the overlying limestones were uniformly altered.

As regards the details of the mottling of the Galena, it may be said that the dolomite areas possess no constant shape or size; that they are very irregular in outline; and that they possess no structure which would suggest the original presence of fucoids in the limestone. They are buff in color, coarser-grained than the gray limestone areas, and are essentially free from fossil remains, owing to the obliteration of structures which accompanied the dolomitization. Their boundaries appear to be fairly definite megascopically, but when examined under the microscope they are found to be gradational, dolomite rhombohedrons being disseminated in the limestone several millimeters beyond the main dolomite areas.

The Maquoketa Formation.—The Elgin limestone member of the Maquoketa formation shows a mottled structure locally in the neighborhood of Ft. Atkinson, Iowa. In a small exposure below the bridge over Turkey river one mile east of the town, the phenomenon is unusually well shown. About fifteen feet of the limestone is exposed here in the east bluff of the stream. The upper three or four feet is quite shaly, consisting of shale with nodular layers of limestone. The lower portion, however, consists of fairly pure calcareous layers. Originally this limestone was dense, gray and unaltered, but now it is mottled with patches and irregular seams of buff dolomitic limestone. Between layers of dolomitic limestone containing remnants of unaltered limestone on the one hand and layers of gray limestone containing seams and patches of dolomitic limestone on the other, every gradation is shown here.

The Hamilton Limestone.—Mottled limestone associated with dolomite appears in the Hamilton limestones in a bluff along the Toledo, Peoria and St. Louis railroad, about two miles above Chautauqua, Illinois. A bed of dolomite eight feet in thickness appears in the limestone at this place, and within this bed, one to two feet above its base, a zone of mottled limestone eight inches thick is locally developed. In the dolomite itself crinoid stems and brachiopods are still preserved as calcite. Many of the limestones interbedded with dolomite in the Middle Devonian of Iowa are also frequently blotched with dolomite. This relationship is well exhibited in the exposures at and near the town of Fairport, in Muscatine county.

The Louisiana Limestone.—Mottled beds have been observed in this limestone both at the type section at Louisiana, Missouri, and in equivalent beds of the Kinderhook group at Burlington, Iowa. At Louisiana the mottling appears in an irregular transition zone ten feet or more in thickness between a uniformly dolomitic limestone above and unaltered limestone below. The dolomitic areas of the mottled rock are medium-grained in texture and brownish in color, while the limestone areas consist of compact, gray, lithographic stone.

The relations at Louisiana are well shown in the bluff exposures at the foot of Tennessee Street and along Edison Avenue. The succession here from above downwards is as follows:

	FEET	INCHES
HANNIBAL:		
Shales, bluish, argillaceous	25±	
LOUISIANA:		
Limestone, buff to brownish, medium-grained, dolomitic, lower boundary indefinite	25±	
Limestone, mottled gray and brownish, gradually passing into the dolomite above by increase in size of brownish areas, and into the limestone below by increase in size of gray areas	10±	
Limestone, light gray, lithographic, breaking with conchoidal fracture	10±	
CHATTANOOGA:		
Shale, bluish, calcareous	1	
Shale, black, fissile	3–4	
Shale, bluish, argillaceous		3
Sandstone, yellowish, fine-grained, soft		3
Disconformity.		
ALEXANDRIAN:		
Limestone, brownish, dolomitic	3	
Limestone, gray, oölitic	7	
Disconformity.		
MAQUOKETA:		
Shale, bluish, calcareous, exposed	3	

It seems clear from the relations shown here that the dolomitization of the upper portion of the Louisiana and the formation of the mottled beds took place in the closing stages of Louisiana time prior to the deposition of the Hannibal shale and that the process of alteration proceeded from above downwards. This view is supported by the fact that the impervious nature of the Hannibal shale above would prevent sufficient ground-water circulation to accomplish dolomitization subsequent to its deposition and by the fact that the intensity of the transformation dies out downwards. Moreover, the dolomitization is in no way related to secondary structures, such as joints in the limestone.

In the Burlington section of the Kinderhook group a thin limestone member which retains all the characteristics of the typical Louisiana also exhibits mottling. This member ranges from eleven to eighteen feet in thickness and is both overlain and underlain by fine-grained, yellowish calcareous sandstone. It consists typically of light gray, thin-bedded, dense, lithographic limestone, but in places it is partly dolomitized and exhibits thin seams of yellowish coarser-grained dolomite along the bedding planes and irregular patches within the layers. At certain points the horizontal seams unite with the interior patches and the dolomite areas assume a reticulated appearance. Small remnants of limestone are in such cases entirely enveloped by dolomite.

In the Nagel quarries located in the bluff of the Mississippi river about two miles below Burlington the bed attains a thickness of eleven feet and consists of three feet of uniformly dolomitic limestone in its upper portion, with eight feet of mottled limestone below. Dolomite seams are greatly extended along the bedding planes of the mottled portion, and some of them are traceable for a distance of several feet.

The Saint Louis Limestone.—One of the best illustrations of mottling in the Saint Louis is found along Potter's Branch, a small creek which enters the Des Moines river from the northeast about one mile below Bonaparte, Iowa. About three-fourths of a mile back from the river badly fractured and very imperfectly dolomitized limestone appears along the bed of the branch. The fracture lines have been healed with calcite, and curiously enough the limestone in the immediate vicinity of the calcite veinlets is unaltered and where the fracture lines are closely spaced the limestone is either free from dolomite or only mottled with it, while the limestone surrounding the areas of local disturbance is everywhere dolomitic. The mottling developed here, then, represents imperfect dolomitization under unfavorable conditions.

The Main Limestone.—According to Dixon,[230] mottled limestones occur in the Main limestone member of the Carboniferous of South Wales, but their relation to the dolomite beds of the formation is not made clear. The mottling characterizes one horizon and has been observed at several localities. It is referred to as "pseudo-brecciated" structure by Dixon, who points out that the relations are original and not due to crushing. His analyses of the limestone and dolomite areas of the "pseudo-breccia" showed them to vary widely in their magnesia content. These are given below:

	LIGHT COLORED PER CENT	DARK COLORED PER CENT
SiO_2	5.85	2.22
H_2O at 105° C	.21	.06
Fe_2O_3, etc.	.63	.25
CaO	34.17	50.98
MgO	15.29	3.21
CO_2	43.60	43.62
Total	99.75	100.54

Remnants of Limestone in Dolomite.—The presence of local areas of unaltered limestone surrounded on all sides by dolomite in a given formation speaks unequivocally in favor of the view that the dolomite has resulted from the alteration of limestone. But remnants of limestone in dolomite seem to be the exception rather than the rule, and this criterion seldom can be applied in interpreting the history of dolomites.

Limestone remnants in dolomite have been observed by the writer in division B of the Beekmantown near Shoreham, Vermont. In the upper portion of this division there is a bed of

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[230] The Geology of the South Wales Coal-field, part 8; Mem. Geol. Survey, England and Wales, 1907, p. 10.

compact gray dolomite with an exposed thickness of ten feet which contains irregular areas of finer-grained, dark gray limestone several inches across. These have no definite shape or relations and many of them are penetrated by seams of dolomite.

In the Niagaran dolomite of Delaware and Buchanan counties, Iowa, limestone remnants are developed on a much larger scale, as pointed out by Calvin[231] and verified by the writer. With reference to the limestone remnants in Delaware county Calvin says:

> A very unusual phase of the Niagara limestone is seen at a few points in Union township. A fine-grained, bluish, compact limestone, not dolomitic, and resembling some portions of the Devonian, occurs in small patches a few yards in extent. These patches were supposed at first to be Devonian outliers, but their relations to the ordinary granular Niagara dolomite, into which they grade laterally and which sometimes overlies them, preclude their reference to the Devonian. One of the best examples of the phase described occurs a short distance west of the southeast corner of section 8 in the township named. Another patch of the same kind occurs near the northeast corner of the same section. More of the same stone is found one-fourth mile north of the center of section 19, and it is shown in an instructive exposure along the north line of section 29. Masses of the blue, fine-grained limestone lie in the midst of granular dolomite and are portions of continuous layers that, except in non-dolomitized spots, possess the characteristics of the ordinary Niagara. All the exposures named are purely local phenomena, small patches of Niagara that in some way escaped the process of dolomitization.
>
> More extensive non-dolomitized portions of Niagara limestone occur in Coffins Grove township. All the beds through a thickness of 20 or 30 feet and over an area some miles in extent, are non-dolomitic. Some of the beds are quite fossiliferous, the fossils being chiefly corals; and while the corals elsewhere at this horizon are usually silicified, they are here unchanged except by the interstitial deposition of calcite. Typical exposures of the beds under consideration are seen near the center of section 26 in the township named, and the same beds crop out

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[231] Ia. Geol. Survey, Vol. 8, 1897, pp. 154 and 218.

in the bluff along Prairie creek in section 28. The beds may be satisfactorily studied in the low bank of the creek at the point where the stream is crossed by the Masonville road, in the northwest quarter of section 28. . . .

The limestone remnant in the Niagaran in Buchanan county appears in section 2 of Hazelton township where coarse granular dolomite passes beneath fine-grained non-dolomitized limestone which may possibly represent the horizon of the evenly bedded quarry stone (dolomite) in the upper parts of the Delaware stage in Delaware and Jones counties.

Nests of Dolomite in Limestone.—As Bischof[232] has pointed out, the occurrence of nests of dolomite in limestone can be accounted for only on the basis of dolomitization. Several such occurrences are known. Klipstein[233] reported the presence of dolomite nests in the "transition" limestones of the Lahn district in 1843, and within recent years Salomon[234] has described nests and tongues of dolomite in the Ladinic limestones of the Alps. Again R. A. Smith[235] reports the presence of nests and large chimney-like masses of nearly pure dolomite in the coral limestone of the Traverse group at Alpena, Michigan.

The writer also has observed several instances where nests of dolomite appear in limestone. Thus, in the upper portion of the Saint Louis limestone at Alton, Illinois, bowlder-like masses and irregular lenses of dolomite are extensively developed. In the quarries which have been opened in the east bluff of the Mississippi river a short distance above the town there appears a thin-bedded, fine-grained, compact gray limestone three feet in thickness, which bears rounded masses of darker gray, coarser-grained dolomite ranging from a few inches up to six feet in greatest diameter (see figure 33). They normally lie with their longest diameter approximately parallel to the stratification and are in some places thickly set in the limestone, but elsewhere none appear within a horizontal interval of fifty feet or more. These dolomite masses at first glance might be taken

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[232] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 187.

[233] Quoted by Bischof, idem, p. 185.

[234] Abh. K.-k. geol. Reichsanstalt, Vol. 21, Part I, 1908, p. 408.

[235] Private communication.

FIG. 33. Bowlder-like masses of dolomite in Saint Louis limestone at Alton, Illinois.

for true bowlders, but careful study shows them to have been formed in place by the local dolomitization of the limestone. This is clearly indicated by the fact that the contact of the bowlders with the limestone matrix is in some instances gradational, and that the stratification lines of the limestone elsewhere may be traced directly through the bowlders. Analyses of a sample of the limestone and of one of the bowlders by Prof. A. W. Hixson yielded the following results:

	LIMESTONE PER CENT	DOLOMITE PER CENT
SiO_2	2.90	4.78
Fe_2O_3	1.14	1.93
Al_2O_3	.66	3.97
$CaCO_3$	91.88	57.41
$MgCO_3$	3.39	32.39
Total	99.97	100.48

In a bed of limestone a few feet above the bowlder bed irregular lenses and thin discontinuous layers of dolomite of the same physical character are developed (see figure 34).

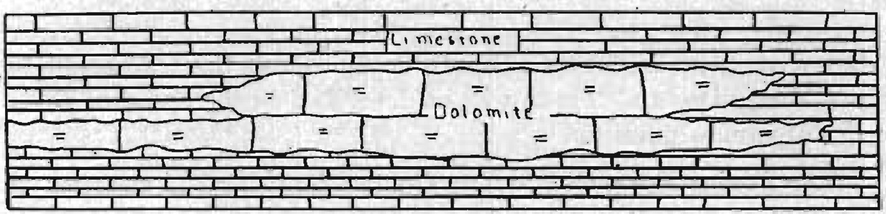

FIG. 34. Irregular lens of dolomite in Saint Louis limestone at Alton, Illinois. Scale, one inch=eight feet.

Similar lenses and bowlder-like masses of dolomite occur on a less extensive scale in the Saint Louis limestone along Indian creek near Farmington, Iowa, and in the Spergen limestone near Belfast, Iowa.

Lateral Gradation of Dolomite into Limestone.—Since it is not conceivable that dolomite could be deposited at one point and limestone at another only a short distance away, the lateral gradation of dolomite into limestone must be regarded as furnishing unimpeachable proof of the secondary origin of all dolomites showing these relations. Such a gradation was described long ago by Daubeny,[236] who stated that at Lake Lugano, in northern Italy, a limestone at one point is destitute of magnesium, farther along the lake it is traversed by small veins of dolomite, and still farther on it contains crystals of the same in small cavities, and finally it passes into dolomite with the disappearance of all traces of stratification.

Hardman[237] also has described instances of the lateral gradation of dolomite into limestone in the Carboniferous limestones of Ireland. Thus:

> It is frequent also in the county Kilkenny in many places within a circle extending from Gowran to near Ballyrogget, and I have hand specimens showing the gradual alteration, the fossils being completely obliterated, and the blue limestone at one side becoming perfectly crystalline dolomite on the other. Large masses of dolomite are seen which when traced out abut against and merge into limestone, and in some places, as at Ballyfayle, there will be as many as twenty or more alternations of limestone and dolomite in a distance of less than half a mile, the limestone always full of marine fossils, by no means dwarfed in appearance.

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[236] A Description of Active and Extinct Volcanoes, 2d ed., 1848, p. 150.

[237] Proc. Roy. Irish Acad., 2d ser., Vol 2 (Science), 1875-77, p. 728.

Many examples of lateral gradation have been observed by the writer, in limestone ranging in age from the Cambrian to the Mississippian. These will be described in the order of their stratigraphic position.

The Elvins Formation.—The Central bowlder bed member of the Elvins formation exhibits such relations repeatedly in a cut of the Illinois Southern Railroad between Flat River and Elvins, Missouri. This bed, although it is overlain by shaly beds and underlain by impure mottled limestone, consists typically of very pure light gray, fine-grained, compact limestone in the form of large bowlders imbedded in a shaly matrix, but locally it forms a continuous bed for several yards, and there it is apt to be imperfectly dolomitized. Large irregular patches of dark gray dolomite several feet across commonly appear in it, and at one point the bed is altered completely from top to bottom for a distance of several yards. A comparison of the analyses of the pure limestone facies of this bed as given by Buckley[238] with the analysis of the dolomitic facies made by Prof. A. W. Hixson for the writer will show the marked difference in the magnesia content of the two varieties.

	Limestone Facies		Dolomitic Facies
	1	2	
SiO_2	2.43	5.31	6.42
Fe_2O_3			3.35
Al_2O_3	0.80	0.69	7.81
$CaCO_3$	94.00	93.00	64.87
$MgCO_3$	2.94	0.23	16.18
Moisture	0.10	0.05	....
Total	100.27	99.28	98.63

The porosity of the limestone facies is .20 per cent while that of the dolomitic facies amounts to .97 per cent.[239]

The Platteville Limestone.—Lateral gradation of dolomite into limestone is also illustrated by the "Lower Blue Beds," a limestone member of the Platteville formation as developed in

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[238] Mo. Bur. Geol. and Mines. Vol. 9, Part I, 1908, p. 43.
[239] Determinations by Prof. A. W. Hixson.

the Upper Mississippi Valley lead region. At Dubuque, and at all other localities in Iowa, where this member is exposed, it consists of bluish, fine-grained, thin-bedded limestone about twenty feet in thickness, and is followed above by the Decorah shale member and below by the dolomitic limestones of the Lower Buff Beds. But at Darlington, Wisconsin, very different conditions are met. Here the member is uniformly dolomitized, as mentioned by Bain[240] and verified by the writer, and is followed directly by the dolomitic limestones of the Galena. On fresh surfaces the dolomite assumes a massive appearance very unlike the thin-bedded, non-dolomitic facies in Iowa.

The Fayette Breccia.—This phenomenon is exhibited to a lesser degree by the Fayette breccia in Linn county, Iowa, and this, together with other features, has given rise to some misapprehension as to the true nature of the Siluro-Devonian contact in Iowa.

In his report on the geology of Linn county, Norton[241] recognizes the following succession of formations:

Devonian (Wapsipinicon)	Upper Davenport	=Fayette breccia
	Lower Davenport	
	Kenwood	
	Otis	
Silurian	Coggan	
	Bertram	
	Anamosa	
	LeClaire	
	Delaware	

In a later report on the geology of Cedar county, the same writer[242] concluded that the Coggan should be referred to the Wapsipinicon, but no further reference to the Bertram was made.

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[240] Bull. U. S. Geol. Survey No. 294, 1906, p. 24.
[241] Ia. Geol. Survey, Vol. IV, 1894, p. 127.
[242] Ia. Geol. Survey, Vol. XI, 1900, p. 320.

The Bertram formation has its typical development "along Big creek and its tributaries from Springville and Paralta to Bertram." It is described as medium to light drab in color, as compact in texture, as sub-conchoidal in fracture, as magnesian in composition, and as locally exhibiting brecciation. At one point an exposure shows it resting directly on the Anamosa and this fact, together with its lithologic character, seems to be the sole basis for referring it to a horizon below the Coggan.

The preliminary studies of the writer lead him to suggest that the Bertram beds really represent a local dolomitic facies of the Fayette breccia let down on the Anamosa by disconformity, due to the Kenwood and Otis beds being cut out here. This interpretation is borne out by the facts that the so-called Bertram is locally non-dolomitic along Big creek, and that it then resembles the Fayette breccia in every particular. Moreover, evidence of a disconformity below the Fayette breccia has been observed in the cut of the Chicago, Milwaukee and St. Paul Railroad a short distance west of the station at Fayette, Iowa, where the breccia rests very irregularly on the surface of the Otis.

The Spergen Limestone.—Similar occurrences of dolomite grading laterally into limestone are found in the Spergen limestone in southeastern Iowa. This formation has been very imperfectly dolomitized, and some beds which are dolomitic at one point are represented by limestone only a few rods, or at the most, only a few miles, away. This feature is remarkably well shown in certain outcrops of the formation near Belfast, Iowa. The limestone has a most confusing way of grading laterally into dolomite, utterly different lithologically, within short distances and to one not familiar with true conditions the relations are very baffling to say the least. The unaltered facies consists of light gray, thin-bedded, coarse-grained crinoidal limestone, while the dolomitic facies is buff, fine-grained, massive and vesicular. The relations are still further complicated by the tendency of the limestone not only to pass into dolomite lithologically different, but also to grade abruptly into fine-grained, bluish, calcareous sandstone.

One of the best illustrations known to the writer of the lateral gradation of dolomite into limestone in the Spergen at this locality is found in an old quarry face along the Chicago, Rock Island and Pacific railway three-fourths mile south of Belfast. The relations here are exhibited by the accompanying sketch (figure 35).

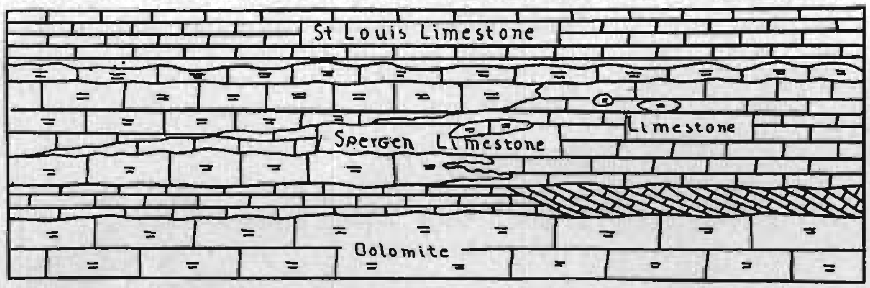

FIG. 35. Showing relations of dolomite to limestone at one point in quarry face, three-fourths mile south of Belfast, Iowa. Scale, one inch=twelve feet.

The Saint Louis Limestone.—Lateral gradation is exhibited along with other phenomena of imperfect dolomitization in the Saint Louis limestone of southeastern Iowa. This formation is dolomitic throughout in some sections, while in others nearby only certain layers are dolomitic. This has been clearly demonstrated by detailed study of the formation as developed along the Des Moines river in Lee and Van Buren counties. The faunal zones were worked out carefully here, and were traced from section to section. A great variation in the nature and degree of dolomitization was demonstrated. For instance, at one locality the formation was dolomitic from top to bottom, at another it was predominantly dolomitic, although a few layers of limestone still persisted, while at still another point the dolomite was subordinate and limited to thin zones. Thus, the dolomite is confined to no definite horizon, and the relations are very irregular and inconstant.

Frequently the dolomitization of the Saint Louis has been influenced somewhat by its structure. Thus many of the reef-like masses of disturbed and broken limestone which are common in this formation are but little if at all altered, while in many cases the undisturbed limestones on their flanks are uniformly dolomitic. This must be interpreted as meaning that dolomitization took place after the reef-like masses were formed. An instructive illustration of the influence of such structures on the dolomitization of the Saint Louis is found in the face of an abandoned quarry in the northeast bluff of the Des Moines river a short distance above the mouth of Reed creek, two miles southeast of Bonaparte, Iowa (see figure 36).

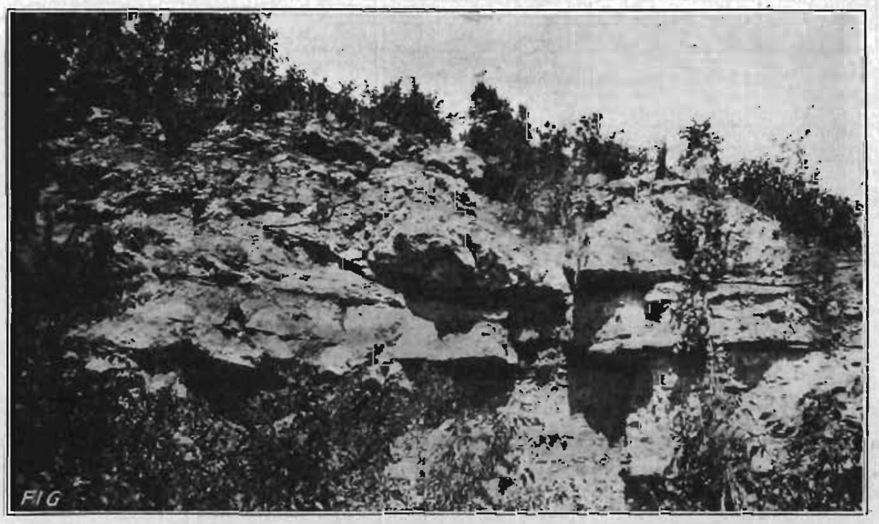

FIG. 36. Reef of unaltered, brecciated limestone bounded below and on the flank with undisturbed dolomitized limestone. Abandoned quarry above mouth of Reed creek, two miles southeast of Bonaparte, Iowa.

Irregular Boundaries.—Examples are known where limestone formations are dolomitic either in their upper or lower portions only and in these the boundary between the two divisions is sometimes very irregular and wavy. Such relations can have resulted only from the partial dolomitization of a formation originally represented entirely by limestone.

Examples of Irregular Boundaries.

The Galena Limestone.—Probably the most striking boundary relations known in any dolomite are shown by the dolomitic facies of the Galena formation in northeastern Iowa. In the region about Dubuque the Galena is dolomitic from top to bottom, and is represented by massive beds of buff, sparsely fossiliferous dolomitic limestone. To the northward, however, the lower portion of the dolomite tends to pass into limestone to a variable degree, thus giving rise to a very irregular lower boundary for the dolomite. At Specht's Ferry, nine miles north of Dubuque, twenty-five feet of limestone, with intercalated shaly layers in the upper portion, intervenes between the Decorah shales and the dolomite, while at Guttenberg, in Clayton county, twenty-five miles northwest of Dubuque, 125 feet of limestone, the upper 90 feet of which is mottled with dolomite, occupies the same position.

At Clayton, on the other hand, which lies only eight miles north of Guttenberg, only fifteen feet of limestone capped by a shale bed two feet in thickness, separates the dolomite from the Decorah shales. Still more striking relations are exhibited at other localities in Clayton county, as was pointed out by Leonard.[243]

In section 14 of Wagner township, non-magnesian strata have an exposed thickness of seventy-five feet and are seen to be overlain by the Maquoketa shales. Between six and seven miles to the south and at the same horizon the dolomitic beds are found at Elkader, with a thickness of at least 120 feet. At Volga the strata lying immediately beneath the Maquoketa are non-dolomitic, and along the Turkey river in Marion township similar beds are exposed at many points in the same position. At Osborne, only a little over four miles east of Volga, eighty feet of heavily bedded dolomite are exposed just below the shales of the Maquoketa.

Thus it is seen that the boundary relations between the limestone and dolomite facies of the Galena are very irregular and what is thin-bedded fossiliferous limestone at one locality is represented by massive dolomite at another only a few miles away. This confusing relationship was formerly the cause of much misapprehension regarding the true nature of the Galena. In the early geological reports on the region the dolomite and limestone facies were referred to two distinct formations, and the dolomite was called Galena while the unaltered limestones, locally present in the lower part of the formation, were included

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[243] Ia. Geol. Survey, Vol. XVI, 1905, pp. 248 and 249.

in the formation now designated the Platteville, and were called Trenton. N. H. Winchell,[244] however, basing his argument on paleontological evidence, concluded that the two facies were formationally identical and Calvin[245] soon after verified this conclusion by field study. Calvin's views on the subject are presented below.

> As above stated, the unchanged beds have been called Trenton, the dolomitic beds Galena; and the apparently irreconcilable statements concerning the thickness of the respective assumed formations have been due to the preconception that the whole of the Galena overlies the whole of the Trenton, with a definite formational or stratigraphic plane of separation between them. Instead, a large part of the Galena near Dubuque is the exact equivalent, bed for bed, of a correspondingly large part of the Trenton in northern Iowa. Bands characterized by distinct types of life run parallel and continuously through dolomite in one place and unaltered limestone in another. . . . The line of separation is not formational; it pays no regard to stratigraphic planes, except that in places it seems to be determined for some distance by beds of shale; it cuts across individual layers and life zones in the most erratic manner; and while, on the whole, it rises towards the north, it wanders up and down through many feet in very short space, as evidenced by the sections recorded by Hall near Elkader, Clayton City, and Guttenberg in Clayton county.
>
> It looks as if dolomitization had affected the limestone and produced the Galena type after the formation was complete; that the process began at the top and progressed downwards; and that the depth to which the change descended was in some instances and to some extent at least, determined by the presence or absence of impervious beds of shale.

With Professor Calvin's interpretation of the conditions existing here the writer is in complete accord. There seems to be no escape from the conclusion that the present relationship has resulted from a process of dolomitization which began at the top of the formation and proceeded downwards at the close of deposition, or at least in the closing stages. To the northward the alteration was less complete and more sporadic than to the southward where the transformation was more vigorous

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[244] American Geologist, Vol. 15, 1895, p. 33.
[245] Ia. Geol. Survey, Vol. X, 1899, p. 406 ff.

and doubtless more prolonged. The downward limit of change was controlled in part by exhaustion of the magnesium content of the waters and in part by the presence of locally developed impervious shale beds which protected the underlying limestone. The influence of thin shale seams in checking the descent of dolomitization at Specht's Ferry and at Clayton has been referred to. At these localities the alteration was halted before it reached the base of the Galena. At Dubuque, on the other hand, it extended down as far as the Decorah shale, and the whole of the Galena is dolomitic. Indeed, there is reason for believing that the alteration would have extended down still farther here and affected the Platteville if it were not for the presence of the shale bed. Such, in fact, is the state of affairs at Darlington, Wisconsin, thirty-five miles slightly north of east of Dubuque. At this place the Decorah shale member of the Dubuque region is absent, and we have a continuous section of dolomite from the base of the Platteville to the top of the Galena. There can be no doubt that the dolomitization of the Platteville was accomplished in this region at the same time as the dolomitization of the Galena and that the absence of the shale member at the top of the formation allowed the magnesian waters to descend farther here than in the Dubuque region.

The Saint Louis Limestone.—Irregular boundary relations are exhibited on a much smaller scale by the dolomitic and non-dolomitic portions of the Saint Louis limestone along the north bank of Indian creek two and one-half miles west of Farmington, Iowa (see figure 37). Here a bed of slightly disturbed, unaltered, gray, medium-grained limestone averaging about eight feet in thickness rests upon a bed of brecciated, yellowish, fine-grained, dolomitic limestone three to eight feet thick. The contact line is extremely irregular and fairly sharp. The marked difference in lithologic character of these beds and the irregular boundary between them suggests at once that they represent two distinct formations with disconformable relations, and in truth this was the interpretation first adopted by the writer. Further study, however, soon revealed the fact that these beds represent one continuous formation, and that the present relations resulted entirely from imperfect dolomitization of the limestone subsequent to its deposition. This interpretation is supported by the following facts: (1) If the beds are traced laterally a short distance it will be seen that the lower one has lost its dolomitic character and a perfectly continuous series of gray limestone is found; (2) the boundary, although fairly sharp, is not a stratigraphic plane of separation; (3) evidences of imperfect dolomitization, in the form of bowlder-like masses and lentils of dolomite, are found in the limestones of the upper member.

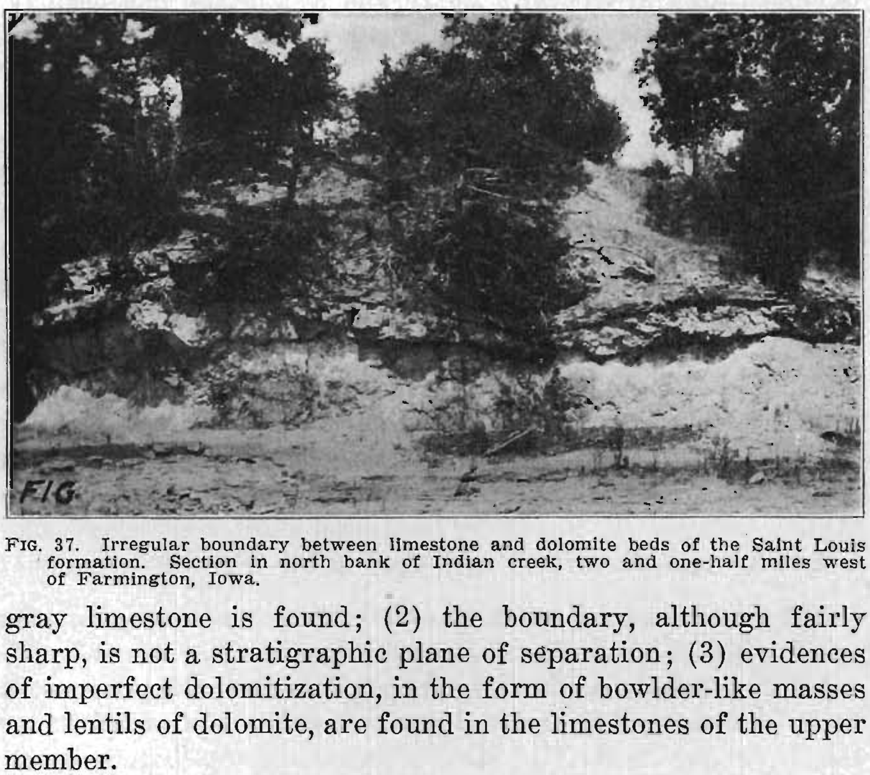

FIG. 37. Irregular boundary between limestone and dolomite beds of the Saint Louis formation. Section in north bank of Indian creek, two and one-half miles west of Farmington, Iowa.

That the alteration of the lower member took place subsequent to its brecciation is indicated by the fact that the brecciated structure now has been largely obliterated by welding, a process which normally accompanies dolomitization.

The Korallenoölith.—The dolomites of the Korallenoölith (Jura) also fail to be regularly marked off from the limestone, as was shown by Wichmann.[246] In the region about Selter and Ith the dolomite in this formation is not confined to a definite horizon, but encroaches upon the limestone both above and below within short distances.

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[246] Zeitschr. Deutsch. geol. Gesell., Vol. 61, 1909, p. 392.

The French Jura.—Relations such as these have been shown by F. Pfaff[247] to exist in the French Jura. In the Wisent Valley between Streitberg and Muggendorf, the boundary of the dolomite in the upper portion of the formation with the limestone below descends and rises rapidly, but a short distance above Muggendorf the formation is dolomitic from top to bottom. This can be interpreted only as meaning that an original limestone formation was transformed to dolomite by a descending process of alteration.

Pseudo-Interstratification Effects.—The interbedding of limestone and dolomite has been postulated by some as evidence in favor of the primary origin of dolomite, but it is believed that most examples of so-called interbedding have resulted from differential dolomitization and that this feature furnishes much stronger evidence in favor of the alteration theories. The following facts lend support to this view:

1. The contact lines, though frequently sharp, are often wavy and do not coincide with the bedding planes.
2. The dolomite layers sometimes grade laterally into limestone and the limestone layers into dolomite.
3. The limestone layers are frequently mottled and streaked with dolomite.
4. The dolomite layers sometimes bear small irregular remnants of limestone.

EXAMPLES OF PSEUDO-INTERSTRATIFICATION.

In the course of this investigation many examples of pseudo-interstratification of limestone and dolomite have been encountered.

The "Calciferous" Limestone.—The "interbedded" series of limestones and dolomites exposed in the old Walton quarry opposite Harrisburg, Pennsylvania, appears to be best accounted for upon the basis of differential dolomitization, although Lesley[248] has concluded that the dolomite beds represent primary mechanical deposits. This is borne out by the relations of the dolomite to the limestone at a number of points here.

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[247] Pogg. Annalen, 1851, p. 471.

[248] See ante p. 273.

Near the middle of the quarry face a bed of dolomite six feet in thickness and dipping about 30° to the south appears in the upper part of the opening. It is both overlain and underlain fairly regularly by limestone, but in the lower part of the opening its lower one-half passes abruptly into limestone and the bed continues to the quarry floor as two distinct layers each three feet in thickness (see figure 38). Samples of the dolomite and of the limestone were taken at the same level and only a few inches apart at the point where they grade into each other. These have been analyzed by Dr. W. S. Smith with the following results:

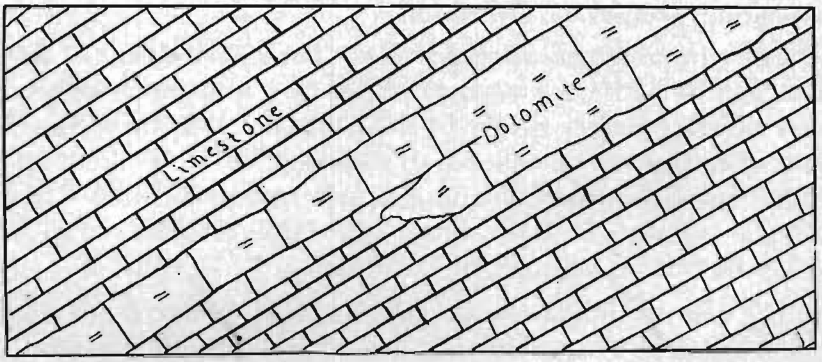

FIG. 38. Showing lateral gradation of a dolomite layer into limestone. Walton Quarry, opposite Harrisburg, Pennsylvania.

	DOLOMITE	LIMESTONE
SiO_2	4.7	0.9
$Al_2O_3+Fe_2O_3$	1.1	0.3
$CaCO_3$	76.1	97.97
$MgCO_3$	18.1	0.83
	100.00	100.00

Further data upon the relationship of limestone and dolomite are furnished by the following detailed section measured near the north end of the quarry. The succession is from above downwards.

	Feet	Inches
14. Limestone, gray, fine-grained, with solution hollows	4	3
13. Dolomite, grayish buff	2	6
12. Limestone, dark gray, compact	1	
11. Dolomite, light buff, seamed with crystalline calcite	1	8
10. Limestone, dark gray when fresh but weathering lighter, compact	2	
9. Limestone, gray, fine-grained, mottled with light buff patches of dolomite	3	
8. Limestone, gray, fine-grained	1	6
7. Limestone, gray, irregularly seamed with darker patches of dolomite		8
6. Dolomite, dark gray, fine-grained	5	
5. Limestone, gray, fine-grained, with seams of dolomite	2	
4. Dolomite, dark gray, fine-grained	1	7
3. Limestone, gray, fine-grained	1	
2. Limestone, gray, fine-grained, mottled with patches of dolomite	3	
1. Limestone, gray, fine-grained, upper six inches with irregular seams of dolomite	6	

Another instructive section is shown in a small pit near the middle of the quarry.

	Feet
5. Limestone, gray, fine-grained	
4. Limestone, gray, fine-grained, mottled with patches of dolomite	3
3. Limestone, gray, fine-grained	2
2. Limestone, gray, fine-grained, mottled with patches of dolomite	2
1. Dolomite, the upper one-half grading laterally into fine-grained limestone mottled with dolomite. Exposed	3

Near the south end of the quarry interesting relations again appear. At one point here a dolomite layer one and one-half feet thick bears irregular streaks and patches of unaltered limestone. Six feet higher up another layer shows similar relationships, while the limestone between is irregularly mottled with dolomite.

The Tribes Hill Limestone.—Relationships equally significant appear in the Tribes Hill limestone at Canajoharie, N. Y. The following section is exposed in the Allan quarry a short distance west of the village.

	Feet	Inches.
Utica:		
10. Shale, dark, laminated	20	
Trenton:		
9. Limestone, gray, subcrystalline, thinly bedded, with occasional shaly layers	19	
Disconformity.		
Tribes Hill:		
8. Dolomite, bluish-gray, compact, heavily bedded below	11	
7. Limestone, dark, compact, no dolomitic patches noted	2	
6. Dolomite, bluish, compact, upper portion blotched with patches of lighter colored limestone	5	6
5. Limestone, gray, subcrystalline, conglomeratic, with dolomitic matrix		10
4. Dolomite, dark gray, compact, with seams and irregular patches of gray limestone in the lower part	3	8
3. Limestone, gray, subcrystalline, with some oölitic grains, bearing occasional thin seams and irregular patches of brownish dolomite	4	6
2. Dolomite, dark gray to bluish gray, compact, upper 8 to 10 inches mottled with irregular patches of limestone	2	8
1. Limestone, dark gray, dense, upper and lower portions slightly mottled with dolomitic patches. Exposed	4	

The Chazy Limestone.—According to Hunt,[249] thin, irregular layers of ferruginous dolomite filled with crinoid stems consisting of pure $CaCO_3$ occur in the bluish, crystalline, fossiliferous Chazy limestones at Montreal. The matrix of the crinoid columns has the following composition:

	Per Cent
Sand	9.01
$FeCO_3$	27.03
$CaCO_3$	40.95
$MgCO_3$	24.19

A sample of the limestone taken one inch from the contact with the dolomitic layer yielded 18.4 per cent of insoluble matter and only .09 per cent of $MgCO_3$.

The Galena Limestone.—Leonard[250] has described a case of "interbedding" in the Galena limestone of Clayton county,

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[249] Am. Jour. Sci., 2d ser., Vol. 28, 1859, p. 371.

[250] Ia. Geol. Survey, Vol. XVI, 1905, p. 249.

Iowa, and this has been examined by the writer. The exposure in which this relationship is shown appears in the southwest quarter of section 9, Volga township. The succession here from above downwards is as given below.

		FEET
3.	Dolomite, buff, massive	4
2.	Limestone, gray, thin-bedded, with occasional small irregular patches of buff dolomite	8
1.	Dolomite, gray to buff, heavily bedded	6-7

The contact of the limestone with the dolomite above and below is fairly regular and sharp, but the line of contact is not a stratigraphic plane of separation.

The Niagaran Limestone.—Pseudo-interbedding of limestone and dolomite is exhibited by the Niagaran limestone about two miles southeast of West Union, Iowa, at the "Devil's Backbone." The succession here from above downwards is as follows:

		FEET
3.	Dolomite, gray to buff, massive, vesicular	25-30
2.	Limestone, gray, fine-grained, grading up into the bed above through 3 to 4 feet of mottled transition beds	20
1.	Dolomite, buff, massive. Exposed	12

The contact between beds 1 and 2 is not sharp, but the degree of dolomitization gradually decreases upwards through an interval of several inches. Similarly, the change from the limestone of bed 2 into the dolomite of bed 3 is not abrupt, but three to four feet of limestone in the upper part of bed 2 is blotched with small irregular patches and disseminated crystals of dolomite.

In the Williams and Davis quarry, located a few rods east of the "Devil's Backbone," beds 2 and 3 of the above section are again exposed. The contact of the beds at this point is abrupt and regular, and no well developed transition zone was noted. According to barometric measurements, the contact comes at the same level here as in the preceding section.

The Cedar Valley Limestone.—Instructive data on the relations of dolomite to limestone are furnished in an outcrop of Cedar Valley limestone at Portland, Iowa. The following section appears near the bridge over Lime creek, at this place:[251]

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[251] After Calvin, Ia. Geol. Survey, Vol. VII, 1896, p. 151.

		FEET
6.	Dolomitized bed with casts of thin laminar expansions of stromatoporoids, exposed between bridge and mill	5
5.	Coarse granular dolomite in thin layers...............	3
4.	White limestone with some stromatopores, the definitely bedded portion of the stromatopora reef............	2
3.	Stromatopora reef, with spheroidal corolla, but more perfectly stratified than at most exposures..........	4
2.	White limestone, evenly bedded......................	3
1.	Dolomitized limestone in heavy layers................	13

The contacts of beds 1 and 2, and of 4 and 5, are very abrupt, no transition of any sort being noted, but small irregular patches and seams of brownish, granular dolomite appear locally in beds 2, 3, and 4. In bed 4 an irregular network of thin dolomite streaks which tend to weather out in relief is developed. At the mill, a few rods above the bridge, bed 6 passes laterally from a uniformly dolomitized limestone through transition beds consisting of grayish, fine-grained limestone with streaks and patches of dolomite, to a nearly pure limestone, and all this within an interval of about four feet.

It is clear, then, that we are dealing here with pseudo-interbedding produced by the selective dolomitization of certain layers after the whole series was deposited.

A bluff section of Cedar Valley limestone and dolomite at Parker's Mill on Willow creek at Mason City, Iowa, also is of considerable interest in this connection. Calvin's description of this section is as follows.[252]

		FEET
6.	Stromatopora reef, equivalent of No. 5 of the Kuppinger quarry	4
5.	White limestone somewhat split up by weathering....	14
4.	Evenly bedded dolomite, in ledges varying from 3 to 30 inches in thickness	12
3.	Impure dolomite, breaking irregularly by exposure to weather, and containing many cavities lined by crystals of calcite	2½
2.	Crumbling, calcareous, granular bed, light gray in color, with many modular and branching stromatopores, some Favosites and beautiful corolla of *Pachyphyllum woodmani*	1
1.	Argillaceous limestone, dark drab in color, homogeneous, but breaks up on exposure to frost..........	2

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[252] Ia. Geol. Survey, Vol. VII, 1896, p. 149.

The contact of beds 2 and 3 is fairly regular and no boundary phenomena of importance were noted along it. But the boundary between beds 4 and 5 exhibits some interesting features. Thus numerous thin, discontinuous seams of fine-grained compact gray limestone are preserved in the upper portion of bed 4, and at some points the upper layer of this member is seen to pass laterally into unaltered limestone. Also, a transition from the dolomite of this member to the limestone above takes place locally through a thin zone of compact gray limestone with rather large crystals of dolomite disseminated through it. The upper boundary of this dolomite bed, therefore, is very indefinite, and is not an ordinary stratigraphic plane of separation.

"Interbedded" relations of limestone and dolomite are well developed in this formation at several localities in Mitchell county, Iowa. The discontinuous character of some of the dolomites in this region is well illustrated by a small exposure along the roadside two and one-half miles south of St. Ansgar. At the north end of the exposure a bed of unaltered gray limestone two feet eight inches thick, filled with colonies of stromatopores, is underlain by one foot of dense, white lithographic limestone. But as these layers extend southward a few yards they both pass abruptly into brownish dolomite at a point where they are intersected by a joint. In this dolomite the stromatopores are largely obliterated and the dolomitized lithographic stone is much coarser-grained than is the unaltered facies. The lower layer continues as dolomite as far as it may be traced in the exposure, but the upper layer which bears the stromatopores changes back within a few feet into imperfectly altered limestone which bears only thin seams and patches of dolomite.

The Chandler cliff section of the Cedar Valley limestone in the east bluff of the Cedar river one and one-half miles due west of Osage, Iowa, again furnishes some valuable data on the nature of the "interbedded" dolomites of this formation. The section here, modified after Calvin[253] in order to show the relations of dolomite to limestone in a more detailed manner, is given below.

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[253] Ia. Geol. Survey, Vol. XIII, 1902, p. 313.

		Feet	Inches
26.	Residual clay with thin weathered flakes of limestone	4	
25.	Dolomite, coarse-grained, weathered		6
24.	Limestone, lithographic, bearing imperfectly preserved stromatopores	1	
23.	Limestone, shaly	1	
22.	Limestone, light gray, lithographic	2	
21.	Shaly parting		1
20.	Limestone, lithographic, light gray, lower portion sometimes imperfectly dolomitized	2	6
19.	Shaly parting		2
18.	Limestone, light gray, lithographic, locally grading into dolomite in part	1	
17.	Dolomite, coarse-grained	1	
16.	Limestone, fine-grained, laminated	1	
15.	Dolomite, coarse-grained, brownish, in layers six inches to a foot in thickness, with casts of brachiopods in upper portion	4	
14.	Shaly parting		6
13.	Limestone, consisting of lithographic nodules in a granular matrix	1	2
12.	Limestone, light gray, lithographic, in one heavy layer, locally passing wholly or in part into coarser-grained, darker dolomite. In some parts only the upper and lower portions of the layer are altered. Again, in others the middle portion only is dolomitic. Where the layer is only slightly altered it bears small disseminated rhombs of dolomite which stand out in relief on weathered surfaces	1	2
11.	Shaly parting		6
10.	Dolomite, rather coarse-grained, dark gray, locally grading into compact gray limestone	1	6
9.	Shaly parting		2
8.	Limestone, lithographic above but granular below, in one heavy layer	1	6
7.	Limestone, light gray, lithographic	1	1
6.	Shaly decayed limestone	1	
5.	Limestone, light gray, crystalline	1	2
4.	Dolomite, yellowish, with occasional small remnants of limestone in basal portion; no fossils noted	9	
3.	Dolomite, yellowish, structureless, bearing casts of *Athyris vittata*, with a few remnants of dense gray unaltered limestone in which the shells of this fossil are preserved	12	
2.	Dolomite, in the form of two heavy, irregular beds which contain many shapeless cavities lined with calcite	5	
1.	Dolomite, in regular layers	15	

Pseudo-interbedding effects are typically shown also by the Cedar Valley limestones in the exposures at and near Fairport, Iowa. A section exposed in the north bank of the Mississippi river near the pottery works at this place is as follows:[254]

	FEET	INCHES
8. Dolomite, rather hard, massive......	3	
7. Limestone, fine-grained, hard, emitting a bituminous odor when struck with the hammer, imperfectly dolomitized locally	2	3
6. Limestone, compact, charged with ramifying growths of Idiostroma, in some parts partly changed to dolomite......................	1	6
5. Carbonaceous material in the form of a thin seam		1
4. Limestone, bearing large stromatopores, Amplexus and other fossils, imperfectly dolomitized locally	1	
3. Dolomite, dark, with unaltered corolla of Cyathophyllum and with occasional stromatopores, locally passing wholly or in part into unaltered gray' limestone	1	6
2. Dolomite, dark, filled with the nearly obliterated corolla of stromatopores and corals.........		8
1. Dolomite, soft, bluish, in rather heavy ledges, containing casts of brachiopods............	2	

Exactly the same relations are shown where this formation is exposed on Robinson creek, one-half mile west of Montpelier, Iowa. Here one bed of dolomite seven feet thick appears in the upper portion of the outcrop and another with an exposed thickness of five feet in the basal portion; and between these intervenes about four feet of limestone blotched with irregular patches of dolomite.

The Spergen Limestone.—The Spergen limestone frequently exhibits imperfect dolomitization phenomena and among these pseudo-interbedding is sometimes characteristically developed. Such relations are well shown in the old Fox quarry openings along the Chicago, Rock Island and Pacific railway track about one mile south of Belfast, Iowa. Near the mouth of a small ravine here the following section appears:

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[254] Revised after J. A. Udden, Ia. Geol. Survey, Vol. IX, 1898, p. 283.

	Feet	Inches
Saint Louis:		
7. Limestone, conglomeratic, imperfectly dolomitized, consisting of dolomitic and nondolomitic blocks indiscriminately mingled, marly towards the base	11	
Disconformity.		
Spergen:		
6. Limestone, gray, crinoidal, thin-bedded	4	
5. Dolomite, brownish, slightly arenaceous	4	4
4. Shale, calcareous and arenaceous	2	
3. Dolomite, bluish, arenaceous	1–2	
2. Limestone, gray, crinoidal, with a thin irregular seam of buff dolomite in middle portion	4	
1. Dolomite, brownish, arenaceous, in one massive ledge. Exposed	10	

Bed 2 has very wavy upper and lower boundaries due to the encroachment of the dolomite of the beds above and below upon it and at one point it passes entirely into dolomite for a short distance. In another exposure along the railway sixty rods farther south, the selfsame beds of the Spergen are dolomitic from top to bottom. The coarse-grained crinoidal limestone members of the preceding section are represented here entirely by fine-grained, brownish dolomite.

The Saint Louis Limestone.—Several occurrences of pseudo-interbedding have been noted in the Saint Louis limestone. In southeastern Iowa this feature is exhibited along with other phenomena of imperfect dolomitization. The formation is dolomitic from top to bottom at one locality while at another only a few miles away only a few layers are dolomitic. For example, in a bluff on Mud creek one mile east of Lowell, the Lower Saint Louis is represented by a massive buff dolomite thirty to forty feet in thickness, while in another section three miles northwest of Denmark and only about five miles away the selfsame formation is represented entirely, with the exception of a single dolomitic layer about three feet thick, by fine-grained, compact, gray limestone.

In the government quarries at Little Rock, Missouri, the Saint Louis shows similar relations on a smaller scale. At the south end of the northernmost opening there appears a bed of buff dolomitic limestone five feet in thickness, lying between beds of unaltered, compact, fine-grained limestone. Northward in the quarry face, however, the upper and lower portions of the dolomite grade gradually into limestone. At 100 yards its thickness has decreased to 3½ feet and at 150 yards the dolomite has so nearly disappeared that only thin seams and stringers remain. A few yards farther north no trace of dolomite is to be seen, but the bed has changed completely into a medium-grained, slightly oölitic limestone.

Another remarkably good exhibition of "interbedding" of limestone and dolomite doubtless due to differential dolomitization is found in the Saint Louis limestone in the vicinity of St. Louis. The following table, comprising a description of each individual bed and its composition, compiled from the report of G. E. Ladd,[235] will show the relations existing in the Martin Lorenz quarry, which is situated along the Iron Mountain and Southern railway track near Cahokia Street. The high siliceous content of some of the dolomitic layers of this section is worthy of notice.

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[235] Mo. Geol. Survey, Bull. 3, 1890, pp. 54, 55, and 76.

TABLE VII.

Description
Limestone, light gray, darker towards top, fine-grained
Limestone, as above
Limestone, light yellow and gray, soft
Limestone, light and dark gray, varying texture, compact, brittle, hard
Limestone, gray, fine-grained, jointed
Limestone, light gray, fine-grained, color and texture variable
Limestone, dull gray to yellowish, harder towards base
Limestone, brownish and gray, coarse-grained, shaly near top
Limestone, as in bed above
Limestone, dull gray, very fine-grained
Limestone, drab, hard, brittle, lithographic, shale seam 1 in. thick at base
Limestone, gray, hard
Limestone, light drab, with dark bands
Limestone, dark gray, carries layer of chert
Limestone, light drab, fine-grained, layer of chert 3 feet from base
Limestone, dark gray, bearing geodes lined with calcite crystals
Limestone, light gray, soft, chert concretions near top
Limestone, gray, coarse-grained
Limestone, as above
Limestone, dark gray to brownish, lower sixteen inches cherty
Limestone, brown, otherwise like bed above
Limestone, drab, hard, brittle, fine-grained, lithographic
Limestone, dark gray, coarse-grained, hard, in three ledges
Total Thickness

The Upper Jurassic Limestone.—Nahnsen[256] has mentioned a case of pseudo-interbedding in the Upper Jurassic of North Germany. Here a horizontal seam of dolomite with wavy boundaries appears in a limestone member which rests on a bed of dolomite. Near its borders the seam shows a pseudo-brecciated effect due to the presence of irregular remnants of limestone in the dolomite.

III. Evidence Bearing on the Leaching Theories.

THE SURFACE LEACHING THEORY.

Of the points which may be advanced in support of the surface leaching theory, the following are perhaps the most important:

1. The development of dolomite along lines of weakness, such as fractures, in limestone.

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[256] Neues Jahrb., Beil. Bd. 35, 1913, p. 277.

THICKNESS		COMPOSITION			
FT.	IN.	Insoluble	$Al_2O_3+Fe_2O_3$	$CaCO_3$	$MgCO_3$
1	6	6.53	0.83	83.85	8.16
1	10	8.02	1.01	79.40	10.81
0	8	9.97	1.07	70.80	10.86
2	10	3.44	.37	92.05	3.67
2	6	4.61	.34	93.85	.99
2	6	6.08	.61	78.15	15.81
4	2	11.63	3.10	52.85	29.25
3	0	2.83	.19	94.75	.97
2	4	6.79	.55	90.55	1.06
0	5	8.77	1.35	56.45	31.95
1	0	7.64	.80	84.75	5.27
0	9	11.02	2.50	57.80	26.33
1	10	6.29	.95	84.95	5.98
3	11	1.97	.35	87.60	8.66
8	2	10.40	11.75	68.30	17.22
0	8	3.20	.40	93.20	1.44
2	0	19.96	4.80	51.60	19.22
1	10	2.32	.26	94.35	1.70
0	10	1.64	.25	95.70	1.10
4	0	5.77	.43	89.95	2.23
3	9	2.84	.25	93.60	2.23
1	6	2.72	.35	93.75	2.38
3	4	2.77	.40	92.40	3.22
56	4				

2. The apparent tendency of dolomite to be developed in limestone at those points where CO_2 and humus acids are most abundant.
3. The vesicular character of some dolomites.
4. The existence of stalactite and stalagmite deposits of nearly pure $CaCO_3$ in caverns in dolomitic limestone.
5. The increase in the magnesium content of weakly dolomitic limestone as an accompaniment of weathering.

The Development of Dolomite along Fractures.—The occurrence of dolomite along fractures in limestone has been taken by some to mean that dolomite so related has been formed by the leaching out of the excess of lime from a weakly dolomitic limestone by solutions which circulated along these lines of weakness. This would seem to apply especially well to certain dolomites of the Lahn district, as pointed out by Grandjean. Bischof,[257] in summarizing the data furnished by this district, says:

> Wherever the fissures and cracks of the slightly inclined limestone strata have facilitated the penetration of water, there the production of dolomite appears to have taken place to the greatest extent. The strata which, by their exposed situation, were most subject to this penetration, present the most advanced state of alteration. But in the lower beds of limestone there has been but little, if any, production of dolomite. The dolomite, and the partially altered beds of limestone adjoining it, are traversed by numerous cracks, fissures, and cavities; and where the alteration is more advanced, the iron and manganese compounds, to which the colour is due, have been separated . . . Since the alteration of limestone, in consequence of the production of dolomite, may often be traced, even in a hand specimen, from the first stage, to the total conversion into an argillaceous mass, Grandjean infers that where the level character of the surface facilitates the continuous action of water, the limestone may be ultimately converted into clay.

An analysis by Bischof of a sample of limestone from Tiefenbach in this district showed it to have the following composition:

	PER CENT
$CaCO_3$	69.90
$MgCO_3$	2.34
$FeCO_3+MnCO_3$	8.18
Clay	20.43

As to the relative importance of leaching as compared to ground water dolomitization in the production of the Lahn dolomites, there may be some difference of opinion. If the analysis given above is representative of the limestones of the district, it is difficult to understand how leaching alone could give rise to the dolomite, since the proportion of clay and of iron and manganese in the rock would tend to increase so much more rapidly than the magnesia that the latter would be largely obscured. But that the magnesia liberated by the complete breaking down of the limestone into clay on the surface may have aided in the formation of dolomite along fractures in the lime-

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[257] Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 193.

stone below must be regarded as possible, since deposits of residual clay bearing iron and manganese ores are common in the district.

Local Development of Dolomite where CO_2 and Humus Acids are Generated.—If it could be shown positively that local occurrences of dolomite in limestone are in some way related to the amount of CO_2 and humus acids permeating the rocks, more tangible evidence of the production of these dolomites by leaching would be available. Phillipi[258] has obtained some data bearing on this point, but the evidence cannot yet be regarded as conclusive. Thus, the Conchodon limestone, which is only locally and imperfectly dolomitized, seems to be most strongly altered where it is permeated by water rich in CO_2 and humus acids. In the heights, on the other hand, where waters poor in CO_2 penetrate the rock, it is either not at all, or but little altered. The area examined by Phillipi, however, was not sufficient to prove that these relations were constant and pending further study too much emphasis should not be placed upon this apparent relationship.

The Vesicular Character of Some Dolomites.—Dolomites formed by surface leaching should be expected to be very porous and vesicular as a result of the removal of large quantities of $CaCO_3$, but not all vesicular dolomites have resulted from leaching, since it is well known that shrinkage effects characterize many dolomites which have resulted from the replacement of limestone. This criterion, therefore, must be applied judiciously. When, however, a dolomite possesses a porosity exceeding 12 per cent, the balance of evidence is in favor of the theory that leaching operated to some extent at least.

Certain dolomites of the Carboniferous of Ireland exhibit considerable solution effects according to Hardman.[259] For instance, at Drumreagh near Coal Island beds of dolomite interstratified with ordinary blue fossiliferous limestone are very cavernous, as fully half of the rock has been removed and has left numerous spar-coated cavities. But dolomites exhibiting so-

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[258] Neues Jahrb., 1899, Vol. I, p. 44.
[259] Proc. Roy. Irish. Acad., 2d ser., Vol. 2 (Science), 1875-77, p. 723.

lution effects are rare and unless we assume that the gradual settling and re-accommodation of the limestone has accompanied leaching it is difficult to conceive of dolomite having been formed extensively in this manner. Hall and Sardeson,[260] to be sure, have advocated that a great reduction in volume by means of leaching has accompanied the formation of the Lower Magnesian series of the Upper Mississippi Valley, but the field evidence of such a volume reduction is wanting. Some of the obstacles encountered by the leaching theory in this respect have been demonstrated by Skeats,[261] who showed that an original rock containing 1 per cent of $MgCO_3$ would have to be removed by solution to the extent of 80 per cent before the $MgCO_3$ of the remainder reached 5 per cent, and to the extent of 90 per cent before the $MgCO_3$ content attained the proportion of 10 per cent.

On the whole, therefore, the shrinkage phenomena of dolomites are not favorable to the idea of their having been formed extensively by surface leaching alone. But there can be no doubt that leaching has given rise to considerable enrichment of the magnesium content of limestones already dolomitic. For example, the unaltered calcareous skeletons of fossils have been leached out of most fossiliferous dolomites and when large numbers of these were present originally, their removal must have given rise to a notable increase in the proportion of the magnesium in the rock. The coral reef facies of the Niagaran dolomite of the Upper Mississippi Valley must have been considerably enriched in magnesia in this way.

Stalactite and Stalagmite Deposits in Dolomitic Limestones.—The occurrence of stalactite and stalagmite deposits of nearly pure $CaCO_3$ in the caverns of dolomitic limestones has been cited as positive proof of the possible operation of leaching on a large scale. Several such occurrences are known. Hardman,[262] upon analyzing both a stalagmite and a sample of the dolomitic limestone from the Dunmore Cave of Kilkenny county, Ireland, found a marked contrast in the magnesia content of the two specimens. The analyses are reproduced below.

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[260] Bull. Geol. Soc. America, Vol. 6, 1895, p. 167.
[261] Quart. Jour. Geol. Soc. London, Vol. 61, 1905, p. 132.
[262] Proc. Roy. Irish Acad., 2d ser., Vol. 2 (Science), 1875-77, p. 718.

	LIMESTONE PER CENT	STALAGMITE PER CENT
SiO_2	1.92	....
$Fe_2O_3 + Al_2O_3$	4.32	.23
$CaCO_3$	68.21	97.12
$MgCO_3$	24.00	.79
$FeCO_3$	.90	1.86
Total	99.35	100.00

Similarly, Högbom,[263] upon analyzing the stalactite from caves in the Bermuda reef stone, found only .18 and .68 per cent of $MgCO_3$ respectively, while the reef stone itself contains about five times this amount.

The presence of veins and druses of calcite in dolomitic limestone also must be taken as indicating that some removal of $CaCO_3$ from these limestones has taken place. Veinlets of calcite commonly traverse the deformed Cambro-Ordovician dolomitic limestones of the Appalachian region.

The operation of surface leaching, on a small scale at least, then, must be regarded as certain. But there is little evidence that enrichment of limestones in magnesium in this manner has gone far.

Increase in Magnesium Content with Weathering.—The progressive increase in the magnesia content of limestones low in $MgCO_3$ with weathering must be regarded as lending strong support to the surface leaching theory. Hiltermann[264] found such a rise in the proportion of $MgCO_3$ in the weathered limestones of the German Trias. Thus, a fresh sample of the Grenz limestone contained 54.69 per cent of $CaCO_3$ and 3.69 of $MgCO_3$, while the weathered rock yielded 11.96 of the former and 5.83 of the latter. Although considerable importance has been attached to these results by some, it is difficult to understand how this process could operate to produce other than very impure, argillaceous dolomites, because of the marked increase in the proportion of the insoluble matter of the rock as an accompaniment of the leaching. Unless it be assumed, therefore, that the original limestone is almost ideally pure, a type of limestone which is rare in nature, the leaching theory meets with grave difficulties.

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[263] Neues Jahrb., 1894, Vol. 1, 271.

[264] Quoted by Phillipi, Neues Jahrb., 1899, Vol. I, p. 34.

THE MARINE LEACHING THEORY.

That sea water has the power to remove the $CaCO_3$ more rapidly than the $MgCO_3$ from limestone and calcareous ooze low in the latter constituent must be admitted by all. Some of the facts which indicate this are:

1. The testimony of recent and near-recent marine calcareous deposits.
2. Actual demonstration of marine leaching on a small scale.
3. Obliteration effects and porous structures in recent dolomitic coral reefs.

Testimony of Recent and Near-Recent Marine Calcareous Deposits. — Högbom[265] has sought to show that certain marine Quaternary marls of Sweden exhibit a progressive increase in the $MgCO_3$: $CaCO_3$ ratio the further they lie from their original source, a Silurian argillaceous rock. (See Table VI, p. 293.) Thus, a sample nearest the source yielded 32 parts of $CaCO_3$ and 1.2 of $MgCO_3$, while the sample farthest away gave only 3.3 parts of $CaCO_3$ and 1.2 of $MgCO_3$. This is interpreted by him as meaning that the longer the sediment was in suspension and the farther it was carried from the source the more the $CaCO_3$ was removed and the proportion of $MgCO_3$ increased. The analyses of deep sea deposits furnished by the Challenger Report also are regarded by Högbom as significant in this connection (see Table V, p. 293), but the $MgCO_3$ content of these is low, as in the case of the above mentioned marls, since it does not exceed 2.1 per cent, while the $CaCO_3$ content also is low for the most part, and the insoluble matter is very high. It is difficult to understand, therefore, how these data can be applied in predicting the conditions of the formation of extensive dolomites nearly free from insoluble matter yet rich in $MgCO_3$.

Actual Demonstration of Marine Leaching.—That marine leaching is capable of enriching the magnesia content of calcareous deposits, on a small scale at least, has been proven both by Murray and Irvine and by Högbom. For instance, Murray

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[265] See ante, p. 293.

and Irvine[266] found a much higher per cent of $MgCO_3$ in the outer portions of the umboes of the giant clam, *Tridacna gigas,* than in the internal and more newly formed shell layers, and Högbom[267] has demonstrated the operation of leaching in the Bermuda coral reefs. Thus analyses by A. R. Manzelius of the reefstone and of the fine lagoon mud derived from it showed a greater proportion of $MgCO_3$ in the latter than in the former.

	$CaCO_3$	$MgCO_3$
Coarse reefstone	95.43	1.64
Reefstone with gastropod fragments	96.11	2.13
Coarse white lagoon mud	97.47	1.79
Fine terra-cotta colored lagoon mud	92.93	4.04

Upon the strength of these data the conclusion is reached by Högbom that if the fine mud were suspended long enough its enrichment in magnesia might proceed to such an extent that a dolomitic sediment might in the end result, but definite proof of this is wanting.

Obliteration Effects and Porous Structures in Recent Dolomitic Coral Reefs.—Shrinkage and obliteration effects are not necessary accompaniments of marine leaching, since the removal of $CaCO_3$ may sometimes go on in the fine calcareous sediment as it is being deposited, as in the lagoons of the Bermuda reefs. Where, however, the leaching is supposed to have taken place in coral reefs, a porous structure should be shown by these. The more dolomitic portions of the Funafuti reef are said to be cavernous and Judd[268] states that much of the mineral substance of the skeletons of calcareous algæ appears to have been removed. But Skeats[269] points out that the dolomites of the upraised coral islands of the southern Pacific, which exhibit all stages of replacement by dolomite, also are cavernous. Shrinkage and related phenomena of dolomites cannot, therefore, be regarded as indicative of their having been formed by marine leaching.

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[266] Cited by Judd, The Atoll of Funafuti, p. 378.
[267] Neues Jahrb., 1894, Vol. 1, p. 279.
[268] The Atoll of Funafuti, p. 384.
[269] Bull. Mus. Comp. Zool., Vol. 42, 1903, p. 115.

PETROGRAPHIC EVIDENCE.

In many instances dolomite can be distinguished from calcite in thin section by its tendency to take on a characteristic yellowish tint and by its more perfect rhombohedrons, which are almost invariably larger than the associated calcite grains and are much clearer. For careful differentiation of the two carbonates, however, microchemical tests must be resorted to. In the present investigation Lemberg's solution[270] yielded very satisfactory results. Upon applying this solution to the section the calcite is colored pink, while the dolomite remains unaffected, and in this way the most intimate relations of the two minerals are made clear. It should be stated, however, that this test furnishes no reliable guide to the exact amount of magnesia in the rock, for homogeneous crystals containing not more than 23 per cent of $MgCO_3$ react in the same way as normal dolomite. But this in truth must be regarded as a distinct advantage, for alterations of only a slight degree are indicated as well as the more marked ones.

I. Evidence Bearing on the Primary Deposition Theories.

A. *The Chemical Theory.*—Some compact dolomites possess an extremely fine and uniform grain, and this feature has led some to believe that such dolomites represent chemical deposits. For instance, Daly[271] has described a pre-Cambrian dolomite of the Rocky Mountains region which consists of roughly rhombohedral and anhedral grains, the former of which range from .01 to .03 millimeter and the latter .005 to .03 millimeter in diameter. By him the fine and monotonous grain of this rock is regarded as strong evidence of its primary character. In order to test the validity of this argument the finest grained dolomites of unknown origin encountered by the writer in these studies were compared with the finest grained dolomite of known secondary origin. Thus the Jefferson City dolomite of the Ozark region, whose origin is not known from the field evidence, contains unusually dense and compact layers which are seen

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[270] For the composition of this solution and method of preparing it see W. F. Hillebrand, Bull. U. S. Geol. Survey No. 422, 1910, p. 211.

[271] Bull. Geol. Soc. America, Vol. 20, 1909, p. 153.

under the microscope to be made up of minute granules ranging from .001 to .045 millimeter in diameter, although the majority of the grains are below .003. The size of grain of this rock then, according to Daly's argument, suggests that it is a chemical precipitate. But the strength of this interpretation is greatly weakened by the fact that an equally fine-grained dolomite, which is known from the field evidence to be an alteration product, has been found in the Fayette limestone near Bertram, Iowa. The latter dolomite has resulted from the dolomitization of a dense, lithographic-like limestone with the approximate retention of the original texture.

B. *The Clastic Theory.*—As regards the possibility that some dolomites are of clastic origin, none has been found which exhibits any signs of clastic structure. But that the original structure in rocks of this type might have been obliterated during recrystallization is easily conceivable. Some of the dolomites of supposed clastic origin do, however, show other features which suggest a primary origin. For example, fragments of calcareous fossils showing no trace of corrosion are common in the impure siliceous dolomites of the Keokuk formation at Keokuk, Iowa. The experience of the writer has been that such fossils as occur in secondary dolomites are at least partly obliterated by the invasion of dolomite. The fact that certain impure, siliceous dolomitic limestones are seen in thin section to be clouded with dark inclusions also might be regarded as possible evidence of their clastic origin, since no known secondary dolomites have been observed to exhibit this to the same degree.

II. Evidence Bearing on the Alteration Theories.

Turning now to the petrographic evidence bearing on the alteration theories, we have much more definite data. Indeed, by virtue of the fact that the transformation in many instances has been halted before it proceeded to completion, we are often able to trace all stages of dolomitization from a limestone showing only incipient alteration to a good dolomite. Thus, it is possible to describe the steps normally passed through during the transformation of a limestone to dolomite.

The Alteration of Fine-Grained Limestones.—So far as the testimony of the microscope goes, the fine-grained limestones are more susceptible to alteration than the coarse-grained ones, a fact which is in keeping with the laws of chemistry. The evidence also points to the fact that the alteration does not proceed in exactly the same manner in the two types of limestone.

The alteration of fine-grained, compact limestone appears to be accompanied normally by a notable increase in size of grain. Frequently the average diameter of the dolomite crystals formed is many times greater than that of the original calcite grains. But in rare cases, such as that of the dense dolomite of the Fayette formation referred to above, the original structure and texture are approximately retained. In the dolomitization of such fine-grained limestones the replacement in some cases proceeds uniformly over a large front, but in most instances it begins at many centers throughout the rock and spreads outwards from these; or if the rock possesses fine stratification the replacement may follow closely these original lines of weakness in the early stages. In those cases where the alteration began at certain favorable centers and spread out from these, fucoid markings in a few instances have served as the nuclei, as in case of the Tribes Hill limestone. The exact nature of these fucoids is not revealed in thin section. When they have been changed to dolomite their original structure is of course mainly lost, but where they are still partly or wholly preserved in the unaltered condition they are differentiated from the adjacent limestone only by the fact that the calcite grains are clouded with dark inclusions suggesting carbonaceous material. None of them has been found to possess any signs of organic structure.

Again, there are cases in which the dolomitization in its early stages is known to have attacked calcareous algæ. This is particularly true in the Chazy limestone of the Lake Champlain region, where it exhibits evidences of incipient alteration. There are several specimens from this region in the writer's collection which show algæ of the Girvanella type in an advanced stage of alteration while the adjacent limestone areas are but little if at all affected. Still other fossils are known to have been selectively replaced in the early stages of dolomitization. Thus, dolomitized tests of the gastropod Ophileta have been observed in unaltered Beekmantown limestones at Ft. Ticonderoga, New York, and the tests of Maclurea are similarly affected in the Chazy near Shoreham, Vermont. Similarly the tissues of Stromatopores have been selectively replaced during the imperfect dolomitization of the Cedar Valley limestone at Fairport, Iowa. There can be no doubt that fossils frequently have served as the starting point in the early stages of dolomitization. But there is convincing evidence that this has not always been the case, for many instances are known where the alteration has proceeded independently of the organisms imbedded in the rock. In the Galena limestone of northeastern Iowa and in the Elvins formation of southeastern Missouri the transformation is inaugurated by the appearance of minute patches or isolated crystals in the fine-grained limestone and the gradual enlargement of these areas at the expense of the limestone. But whatever the nature of the early stages of dolomitization, whether they were influenced by organisms or not, the later stages are always the same, and uniformly dolomitized limestone is the ultimate product in each case.

As the dolomitization spreads from the original centers the limestone typically is not completely replaced, and although the dolomitic patches may appear to be made up entirely of dolomite crystals, they may not bear more than 23 per cent of $MgCO_3$, nor is the limestone in all cases uniformly replaced. Small irregular remnants and streaks of limestone are passed over and become incorporated in the dolomite area. The boundary between the limestone and the spreading dolomite may or may not be abrupt. In a few examples in which it is abrupt, veinlets of dolomite shoot out into the limestone in advance of the main dolomite areas, and on the whole the tendency is to produce a ''pseudo-brecciated'' effect. So far as the experience of the writer goes, these abrupt contacts are most characteristically developed in the early stages of the alteration of limestones which have undergone recrystallization prior to dolomitization. To illustrate, the Saint Louis limestone, which exhibits this phenomenon at several localities in southeastern Iowa, is known to have experienced mashing and brecciation previous to the time it was altered, a fact which indicates unquestionably that it had already recrystallized.

Where the boundary is gradational, on the other hand, as is usually the case, rhombohedrons of dolomite, variable in size but usually nearly perfect in their development, are disseminated through the limestone a short distance in advance of the dolomite area. The regular rhombohedral outline of these disseminated crystals is in strong contrast to that of the crystals of the dolomite area, which have interfered with one another in their development, thus giving rise to an interlocking structure. The usual large size of the isolated dolomite crystals as compared to that of the associated calcite grains also is a striking feature. This is especially true in the case of a Devonian lithographic limestone near Osage, Iowa, which shows incipient dolomitization. The calcite grains of the rock do not exceed .003 millimeter in average diameter, yet the dolomite metacrysts attain a maximum diameter of .75 millimeter. A similar relationship is exhibited, but to a lesser degree, by the Joachim limestone of southeastern Missouri. A sample of the limestone streaked with dolomite shows a range in diameter of the calcite grains from .001 to .015 millimeter, while the associated dolomite crystals range from .005 to .145 millimeter in diameter. Many other examples exhibiting a similar relationship could be cited. The great increase in size of grain which normally results from the dolomitization of fine-grained limestone is in this way accounted for. It should be stated, however, that many of the above mentioned metacrysts of the Devonian lithographic stone are not perfectly developed. Many of them are filled with minute unoriented inclusions, which evidently represent small calcite grains enveloped in the crystals as they grew. Furthermore, some of the dolomite metacrysts show evidences of zonal growth where they are in contact with the unaltered limestone, and a single thin band of calcite appears within their borders. It is a singular fact that these inclusions and zonal growths are never seen in the more completely dolomitized areas, a fact which suggests that in these the calcite grains and bands, if they once existed, have been changed over to dolomite.

The Alteration of Coarse-grained Limestones.—In considering next the alteration of the coarse-grained limestones, we meet with somewhat different phenomena, although the ultimate effect is the same. In these mottling does not seem to be the rule, and the effect on the size of grain is quite the reverse of that exhibited by the fine-grained limestones. In these the dolomitization is accompanied by a decrease in size of grain which becomes the more marked as the original calcite grains are larger. Here, then, we have a great equalizing process tending to produce coarser-grained rocks from fine-grained ones and finer-grained rocks from coarse-grained ones.

Typically the alteration of coarse-grained limestone proceeds by an attack on the matrix in the early stages, with the formation of small scattered dolomite rhombs, and then by invasion of the large calcite grains, whether they be fossil fragments or ordinary crystals, both by corrosion of their borders and by the breaking down of their interiors. In this process the large calcite grains are broken down into aggregates of smaller dolomite grains, and in the end the original structures and textures are obliterated.

This is the method of dolomitization of the coarse-grained crinoidal limestones of the Burlington and Keokuk formations of the Central Mississippi Valley. In the alteration of certain coarse-grained limestone layers of the Beekmantown at Plattsburg, New York, however, the above described order of replacement seems to have been reversed. This limestone is uniformly medium-grained to coarse-grained and is dotted with the tests of foraminifera and with other areas of a variety of shapes and of a dark tint which are doubtless also organic, although they are structureless and indeterminate. Strangely enough many of the interiors of the foraminifera and of the associated dark areas are either partly or wholly changed to dolomite, while the surrounding matrix is practically unaffected. Where the alteration is incomplete, numerous perfect isolated rhombs of dolomite are developed, but where it is more advanced the crystals interfere and are irregular in outline. By this method of dolomitization mottling on a microscopic scale is produced.

The coarse-grained Chazy limestones of Valcour Island exhibit mottling on a much larger scale, but organic factors seem to have played no part in the production of this phenomenon. The dolomite areas of this rock are fine-grained, although they have resulted from the alteration of coarse-grained limestone, as shown by the presence of corroded remnants of large calcite crystals and fossil fragments surrounded on all sides by minute crystals of dolomite. Some of the crystals preserved are more than 200 times as large as the dolomite grains about them.

The Alteration of Oölitic Limestones.—In the dolomitization of oölitic limestones the alteration of the oölite grains appears to proceed, in most cases at least, independently of the matrix and probably more often in advance of the alteration of the matrix than contemporaneously with it. Several examples of dolomitized oölites are known.

A sample of oölite from the Elbrook limestone in a quarry at West Waynesboro, Pennsylvania, has the appearance of a good oölite megascopically, but under the microscope the oölite grains are represented only by structureless, rounded, darker areas scattered here and there throughout the field. These are for the most part replaced by dolomite, while the matrix, except for a few small, irregular patches of this mineral, is unaltered. Precisely the same relations are exhibited by an oölite from the imperfectly dolomitized limestones of the Elvins formation near Elvins, Missouri; by the Lucas oölite as developed near Sylvania, Ohio; and by the Tribes Hill oölite at Canajoharie, New York.

In a dolomitic oölite from the Allentown limestone near South Bethlehem, Pennsylvania, somewhat different relations are shown. In thin section the characteristic radial and concentric structure of oölite is not exhibited, but the original outline of the grains is retained in every case. In a few examples the grains are completely altered to dolomite, but even there a faint, dark line marks their borders. But most of the grains are only partly altered, and still consist of an inner nucleus of cloudy dolomite with an outer rim of transparent calcite. The matrix is everywhere dolomitic except for occasional minute irregular areas of calcite. The unaltered calcite rims of the oölite grains have a perfectly regular, rounded outer border which shows no corrosion effects even though they are completely surrounded by dolomite. Their inner borders, however, are much less regular, indicating that the nuclei of dolomite were formed by a process of dolomitization which began at the center of the grains and spread outwards. The alteration of the oölite grains then proceeded independently of the alteration of the matrix. The oölite which occurs at the basal portion of the Oneota dolomite at McGregor, Iowa, exhibits almost identically the same features as the Allentown oölite, but in this rock the original calcite remnants have been replaced by silica since dolomitization took place. Every step may be traced in the transformation of the oölites from wholly unchanged grains to completely altered ones.

Only one uniformly dolomitized oölite has been found in these studies. This is from the Hoyt limestone near Saratoga Springs, New York. It consists of rather large and distantly placed rounded to sub-ovate dolomitized oölite grains in a dolomite matrix. Quartz grains, of which the larger have rounded but the smaller very irregular outlines, are disseminated throughout the rock, appearing both in the oölite grains and in the matrix. The dolomite crystals within the areas of the original oölite grains do not extend beyond the borders of these and behave independently of those of the matrix under crossed nicols, a fact which indicates that even in this rock the dolomitization of the two areas proceeded separately.

CONCLUSIONS.

Considering all the evidence, there seems to be no escape from the conclusion that the great majority of the stratified dolomites have had their inception in the alteration of limestones. It will not be denied, however, that some dolomitic formations of minor importance have had a different origin. The possibility of direct chemical precipitation of dolomite from the sea, on a small scale at least, has not been wholly disproven, and there is evidence that some impure dolomitic limestones of minor importance may represent original clastic deposits. That such a method of dolomite building is possible is suggested by the resistant character of dolomite rocks and the tendency of the coarser-grained varieties to weather to a dolomite sand. If such a dolomite sand should be carried to the sea and incorporated in a sedimentary series, an impure dolomitic rock might result.

As regards the possibility that organizms have ever given rise to more than very weakly magnesian limestones, this seems doubtful, as has been shown. But that limestones which are originally weakly magnesian may become enriched in magnesium more easily and more rapidly than those nearly free from this constituent is not only conceivable but very probable.

The importance of marine and surface leaching in the production of a dolomite is believed to have been overemphasized. There can be no doubt that this process has enriched in magnesium the more vesicular dolomitic limestones. But these must have been rich in this constituent before leaching began. The leaching theory, therefore, does not explain the ultimate source of the magnesium. It merely shows how the magnesia content of a rock originally magnesian can be enriched.

Time and Place of Dolomitization.—To return now to the dolomites which have resulted from the alteration of limestone: there are many reasons for believing that the more extensive of these have all been formed beneath the sea, and that dolomitization effected by ground water is only local and very imperfect. Some of the features which lend weight to this view are as follows: (1) The dolomite areas of mottled limestones are believed to have undergone recrystallization at the same time as the associated limestone areas, as suggested by the occasional development of zonal growths of calcite and dolomite. (2) In imperfectly altered limestones the dolomite is seen to follow original lines of weakness rather than secondary structures such as joints or fractures. (3) In most cases of mottling the dolomitization appears to have spread out in every direction and to have progressed uniformly, as we should expect it to in an unrecrystallized rock, rather than to have proceeded by forming veinlets and stringers in the early stages. (4) The existence of perfect rhombs of dolomite in many imperfectly altered limestones suggests that the latter had not yet solidified when dolomitization took place. (5) The widespread extent and nearly uniform composition of many dolomites indicates that they must have been formed by an agent capable of operating uniformly over wide areas. (6) An adequate source of magnesium for transforming extensive limestone formations into dolomite is found only in the sea, which contains many times as much of this constituent as ordinary ground water. (7) Many dolomites are directly and regularly overlain by pure limestone formations or by thick shale beds, proving that they must have been formed before these overlying beds were deposited.

Some dolomites of minor importance, such as those associated with ore deposits, and probably most if not all of those related to fractures, must have been formed through the agency of ground water. But in general ground water is incapable of carrying dolomitization far. Study of analyses of ground water and of river water shows these to be uniformly low in magnesium, while this constituent normally is greatly exceeded in amount by lime. How, then, could such waters dolomitize limestone when they already contain $CaCO_3$ far in excess of the $MgCO_3$? The law of mass action speaks strongly against ordinary waters being able to accomplish extensive dolomitization. In the case of mineral springs and the mineralizing solutions which are related to ore deposition, however, it is conceivable that magnesia might be present in sufficient proportions to accomplish local dolomitization, and doubtless most vein dolomites have been so formed.

With reference to the possibility of dolomite ever having been formed extensively through the action of pneumatolytic agencies on limestone: this also is improbable. Both Fournet[273] and Wissman[274] have pointed out that the dolomites of the Tyrol, which formerly were regarded by Von Buch and others as having been formed in this manner, are in no way related to the melaphyr which there penetrates the limestone. It must be regarded as possible, however, that small amounts of dolomite might be formed locally when limestone is permeated by volcanic gases bearing magnesia. But this has little bearing on the problem at hand.

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[273] Bull. Soc. Geol. France, 2d ser., Vol. 6, 1849, p. 502.

[274] Cited by Bischof. Elements of Chemical and Physical Geology, English translation, Vol. 3, 1859, p. 200.

Details of the Replacement Beneath the Sea.—Sea water contains in solution on the average 3.5 per cent of solids. The salts present and their proportions, as averaged by Dittmar, are indicated in the following table:[275]

	PER CENT
$NaCl$	77.758
$MgCl_2$	10.878
$MgSO_4$	4.737
$CaSO_4$	3.600
K_2SO_4	2.465
$CaCO_3$[276]	.345
$MgBr_2$	.217

One is at once impressed by the high proportion of salts of magnesium in sea water, and it is to the action of these that dolomitization beneath the sea must be attributed. As to which of the two more abundant magnesium salts, $MgCl_2$ and $MgSO_4$, has been the most influential in the production of dolomite, nothing is definitely known, but there is some reason for believing that $MgSO_4$ is the most active agent of dolomitization. The effect of the relatively large amount of $NaCl$ present in sea water would appear to be to repress the ionization of $MgCl_2$ and thereby to lower its efficiency greatly. In fact, experiment shows that the chloride of magnesium reacts much more feebly with $CaCO_3$ in the presence of $NaCl$ than does the sulphate. The effect of the common sulphate ion in reducing the efficiency of $MgSO_4$ would not be nearly so great since the additional salts which possess this, $CaSO_4$ and K_2SO_4, are present in much smaller proportions.

As to the details of the reaction by which dolomite is ultimately produced by the action of the magnesium salts of the sea, it cannot be stated positively whether the double carbonate is formed directly or whether hydrous $MgCO_3$ is first formed and this subsequently combines with the $CaCO_3$ with loss of water of crystallization to form dolomite. In ordinary temperature and pressure experiments the hydrous carbonate of magnesium appears to be the normal product. It has been suggested that in time this might become dehydrated and unite with $CaCO_3$ to form dolomite. But this seems doubtful. If this were the method of replacement it does not seem probable that the re-

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[275] Quoted by Grabau; Principles of Stratigraphy, 1913, p. 147.

[276] Including all traces of other salts.

action could proceed far, since the solution would become so rapidly enriched in this easily soluble constituent that equilibrium would soon be reached. If, on the other hand, we assume that the double carbonate is produced contemporaneously with replacement, the richly dolomitic limestones are easily accounted for, since under these conditions the equilibrium would not be so easily reached and the reaction might proceed until all the free $CaCO_3$ was exhausted. In short, the $MgCO_3$ produced, by combining with $CaCO_3$ as rapidly as it was formed, would be taken directly out of solution before it accumulated sufficiently to halt the forward reaction. The equilibrium would be shifted constantly towards the dolomite end of the equation. At the instant replacement takes place the $CaCO_3$ must exist in solution. It seems probable that at the time of the reaction each molecule of $MgCO_3$ formed unites with one molecule of $CaCO_3$ in solution to form the double molecule of dolomite, and that deposition then takes place. Assuming that the reaction proceeds in this manner, the equation may be written as follows:

$$1.\ \left\{\begin{array}{l} MgSO_4+CaCO_3=MgCO_3+CaSO_4. \\ MgCl_2+CaCO_3=MgCO_3+CaCl_2. \end{array}\right.$$

$$2.\ MgCO_3+CaCO_3=CaMg(CO_3)_2.$$

Conditions Influencing Replacement Beneath the Sea.—The more important of the factors influencing the reaction resulting in the dolomitization of limestones beneath the sea are: (1) mineral composition, (2) original content of $MgCO_3$, (3) fineness of grain, (4) porosity, (5) amount of CO_2 present, (6) temperature, (7) pressure, (8) concentration, and (9) time.

The mineral composition of the limestone is very important from the standpoint of dolomitization. It is well known that aragonite and other metastable forms of $CaCO_3$ react much more readily with chemicals than does calcite. If then a newly formed limestone consisted mainly of metastable $CaCO_3$ it would be in a very favorable condition to be dolomitized.

The presence of a small amount of $MgCO_3$ in a limestone likewise will render it more liable to dolomitization under favorable conditions.

Fineness of grain and porosity also are important. Other things being equal the more porous a limestone and the finer its grain, the more susceptible it is to dolomitization.

To consider the influence of CO_2 on the reaction: anything which tends to render the limestone more soluble will hasten the replacement. It seems probable that the CO_2 generated by the decay of organic matter in the limestone must frequently aid considerably in taking $CaCO_3$ into solution. Limestones rich in organic remains should, therefore, be more liable to alteration than limestones poor in these, and if in a given limestone the organic matter should be more concentrated in certain local areas, we should expect these to be more easily dolomitized than the surrounding rock. This must be regarded as a possible explanation of the selective dolomitization of fucoid markings in some limestones.

Experiment shows that dolomitization proceeds most favorably at elevated temperatures, but high temperatures have never obtained over wide areas beneath the sea. The temperature of the sea, however, is not absolutely uniform, and it must be assumed that dolomitization goes on most favorably in those regions where the waters are warmest, if other conditions are the same.

Regarding the influence of pressure induced by depth on dolomitization beneath the sea, there has been some disagreement. Thus F. W. Pfaff,[277] upon finding as the result of experiment that the reaction takes place most rapidly at pressures ranging from forty to sixty atmospheres, concluded that dolomitic formations were formed at great depths corresponding to these pressures. But both Skeats and Phillipi[278] have shown this view to be untenable. There is every evidence that the dolomitization of the Paleozoic limestones has taken place at relatively shallow depths. Schuchert has estimated that these limestones were deposited at depths not exceeding 300 feet. The presence of ripple marks in dolomites such as those in the Allentown in the quarries near Allentown, Pennsylvania, and the presence of intercalated sandy layers such as those which

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[277] See ante p. 311.
[278] See ante p. 281 and p. 278.

appear in the Kittatinny, Little Falls and Oneota dolomites and in many others, speaks for their shallow water origin. On the whole it does not seem probable that the replacement has taken place under pressures exceeding ten to fifteen atmospheres.

As to whether dolomitization takes place in concentrated seas or not, there has been considerable disagreement. Until recently the tendency has been to follow Dana, who intimated that the ancient dolomites were formed under conditions analogous to those which obtain when recent limestone is dolomitized in the concentrated lagoons of coral reefs. But Skeats pointed out in 1905[279] that there are cases in which the outer parts of fringing reefs facing the open ocean are dolomitized and that the dolomitization of coral reefs is not confined to the lagoons; and Phillipi soon after[280] presented evidence of recent dolomitization in the open sea. Still more recently Blackwelder[281] has given it as his opinion that the Bighorn dolomite has resulted from the progressive alteration of limestone during deposition, and that the concentration of the magnesia was not more than two or three times as great as in the present ocean, since more than this amount would have been unfavorable to the life processes of the time. There are many commendable points to this theory of progressive dolomitization at low concentrations. But if dolomitization can go on under these conditions, why are not all of our limestones dolomitic? In answer to this it might be said that the alteration takes place under unusual circumstances, possibly through the agency of certain bacteria which are not always present when limestone is deposited. But even then it is difficult to understand how magnesia could be precipitated under these conditions, since all low concentration experiments have failed to produce a precipitate of $MgCO_3$ except Leitmeier's, whose results must be regarded as questionable. Much of the field evidence also speaks against progressive dolomitization. Irregular boundaries, lateral gradations, dolomitized oölites, mottling, pseudo-interstratification effects and many other features can be accounted for only by assuming that dolomitization took place after all the beds involved were depos-

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[279] See ante p. 282.
[280] See ante p. 278.
[281] See ante p. 284.

ited. When, however, a pure limestone member comformably succeeds a dolomite member known to be an alteration product and the contact line is regular and continuous over wide areas, it cannot be assumed that this relationship has resulted from the alteration of the lower bed after both beds were deposited. The "Lower Buff Beds" of northeastern Iowa, which consist of dolomite with occasional minute limestone remnants, are abruptly followed by the pure limestone of the "Lower Blue Beds" over hundreds of square miles, and the transition from one into the other takes place through only a few inches of imperfectly dolomitized limestone.

Moreover, the tendency of some limestones to be most highly dolomitic in their lower portions and to become progressively less dolomitic upwards, also must be regarded as lending support to the theory of progressive dolomitization. Orton and Peppel[282] state that the Delaware and Columbus limestones of Ohio are more dolomitic in their lower than in their upper portions.

But even if it should be positively shown that dolomitization can go on at low concentrations, all must agree that it would proceed not only much more rapidly but also more completely at higher concentrations. As to whether the ancient seas which accomplished such extensive dolomitization were more concentrated than the modern ones or not, little can yet be said. On this point we must rely solely upon inference. Steidtmann[283] has presented strong evidence to show that the ancient seas were more highly magnesian than those of today. From independent lines of reasoning based upon paleogeographic evidence the writer is also led to believe that the magnesia content of the ancient seas may have been at least temporarily greater than at present. Let us consider the conditions obtaining in a restricted interior sea from which limestone is being deposited on a great scale. Fresh quantities of lime and magnesia and other salts are being introduced into this interior sea both by influx from the open ocean and from the streams draining the land. Now lime is constantly being depleted from this inland sea by

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[282] Ohio Geol. Survey, 4th ser., Bull. 4, p. 165.

[283] Jour. Geology, Vol. 19, 1911, pp. 323 and 392.

lime-secreting organisms, while the magnesia and other salts tend to accumulate. It seems possible, then, that during a long period of limestone formation under these conditions magnesia might accumulate in considerable excess and that ere long extensive dolomitization might set in and continue until equilibrium was once more established.

Applying this theory now to the stratigraphic column, we actually find that many periods of extensive limestone formation in interior seas may be correlated with periods of extensive dolomitization. Witness the great dolomite masses of the Cambrian of the Appalachian province and of the early Ordovician and the Niagaran.

As further evidence that the early seas which accomplished extensive dolomitization may have been temporarily concentrated, attention may be called to the fact that these seas in many instances were retreating and contracting towards the last, and that unless they were freely connected with the open ocean, evaporation under arid or semi-arid conditions might give rise to a considerable increase in salinity. Such a condition would seem to apply especially well to the Niagaran Sea. Paleogeographic studies have shown that this sea became very much contracted towards the close of this epoch, and Clarke and Rudemann[284] have concluded that the Guelph fauna must have inhabited a sea of abnormally high salinity. The latter fact considered in connection with the evidence of widespread dolomitization in the later stages of the Niagaran seems significant.

The influence of the time element in dolomitization beneath the sea must be great, for we cannot escape the conviction that long periods of time must be involved in the transformation of thick beds of limestone into dolomite. Replacement beneath the sea must proceed under very stagnant conditions and the transfer of fresh magnesium salts to the scene of the reaction as well as the removal of the soluble reaction products from it must be accomplished by a process of diffusion which operates very slowly. That this diffusion must have been fairly complete, although extremely slow, is suggested by the complete-

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[284] Mem. N. Y. State Museum, No. 5, p. 117.

ness to which the reaction has in many cases proceeded, and by the general absence of reaction products such as gypsum or anhydrite in the secondary dolomites.

As to the cause of pseudo-interbedding, inorganic mottling and other imperfect dolomitization effects, little definite data are available. It must be conceived that the solutions which produced these selective dolomitization phenomena permeated the rocks uniformly, but that certain layers or areas were more readily altered than others. In the case of pseudo-interbedding, several factors may have operated, viz.: variable amount of original $MgCO_3$ content, variable amount of organic matter and variable texture. The last two of these might possibly apply to inorganic mottling also. But such mottling should be regarded as a normal incipient dolomitization effect rather than a selective one. As regards the influence of textural differences in the production of pseudo-interbedding, it is believed that this has played an important part in some instances. For example, none of the coarse-grained layers of the Tribes Hill limestones at Canajoharie, New York, are more than very imperfectly altered, while many of the limestones above and below are completely changed. Textural differences, however, are far from being the whole story.

Acknowledgments.

For early inspiration and encouragement in the prosecution of this investigation the writer wishes to express his indebtedness first of all to the late Professor Samuel Calvin and to Professor George F. Kay, of the geological department of the State University of Iowa. Thanks are also due to Professor J. Newton Pearce of the chemical department of the same university, who supervised the experimental studies and who has read and criticised certain sections of the report. Last but not least, the writer is under great obligations to the members of the staff of the geological department of Columbia University, who have from the first manifested great interest in the development of the problem and who are responsible in a large measure for its successful completion.

PLATE XX.

Surface of slab of mottled Tribes Hill limestone from Palatine Bridge, New York, two-thirds natural size. Note the rounded, sinuous pipes of dolomite weathering in relief. Some organism of unknown affinities appears to have exerted a selective influence upon the dolomitization.

PLATE XXI.

Figure 1.—Face of layer of mottled Tribes Hill limestone, Palatine Bridge, New York. About ⅛ natural size. The dark areas represent dolomite; the light ones limestone. This is interpreted as representing an incipient stage in the dolomitization.

Figure 2.—Mottled limestone from the same locality showing more advanced stage of dolomitization. Note that the dolomite areas are larger and of more irregular outline than in the preceding figure.


FIG. 1


FIG 2

PLATE XXII.

Figure 1.—Later stage of alteration of Tribes Hill limestone. The dolomite areas are larger and have begun to coalesce.

Figure 2.—The alteration nearly completed. Only very small isolated areas of limestone remain.

FIG 1

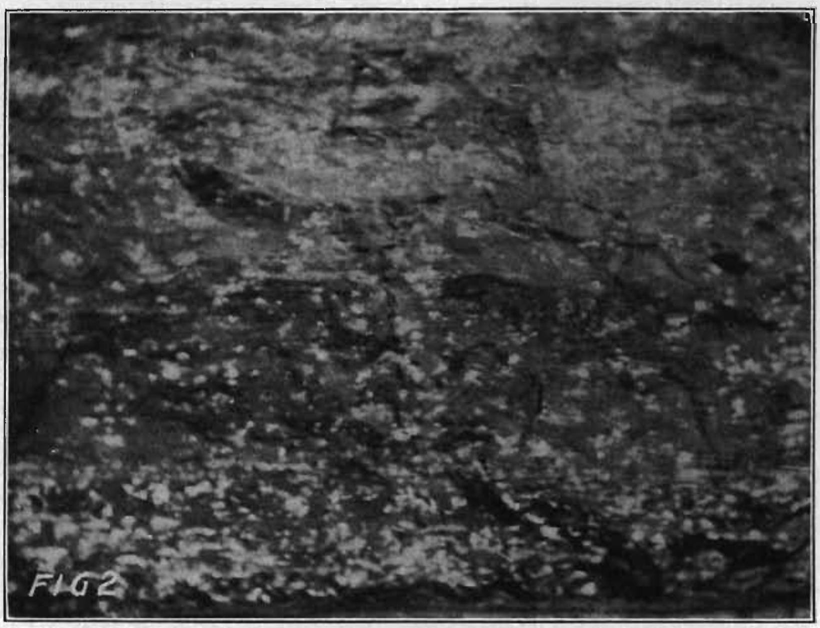


FIG 2

Plate XXIII.

Polished slab of mottled Galena limestone from Elkader, Iowa, ¾ natural size. The irregular areas of darker tint are of dolomite. The dolomitization of this limestone does not appear to have been influenced by organic factors.

PLATE XXIV.

Figure 1.—Microphotograph of imperfectly altered fine-grained Devonian limestone from Portland, Iowa. X 22. The relation of calcite to dolomite was clearly brought out by staining the former, which shows dark, with Lemberg's solution. Note the tendency toward the development of zonal bands of calcite in the large dolomite crystals.

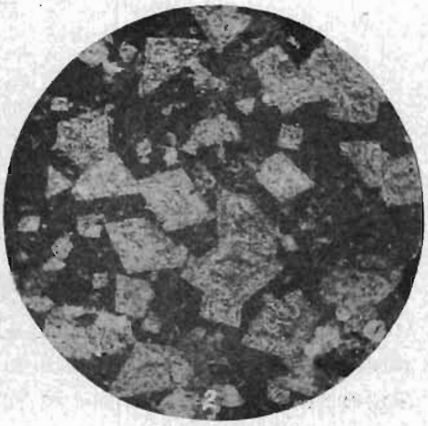
Figure 2.—Section of Cedar Valley limestone from Osage, Iowa. X 22. This shows large metacrysts of dolomite with a fine-grained groundmass of calcite. The imperfect character of the dolomite crystals is due to the presence of many minute inclusions of calcite.

Figure 3.—Section of Stonehenge limestone from Bellefonte, Pennsylvania, X 55, showing zonal growths of siderite and dolomite in a matrix of fine-grained calcite.

Figure 4. — Extremely fine-grained dolomite of unknown origin from the Jefferson City formation near Perryville, Missouri. X 41.

Figure 5.—Fine-grained dolomite known to be of secondary origin from the Fayette breccia near Bertram, Iowa. X 41. Compare with Fig. 4.

Figure 6.—Imperfectly dolomitized brecciated Saint Louis limestone from Belfast, Iowa. X 22. Some of the angular fragments of limestone have resisted alteration although the matrix is uniformly altered.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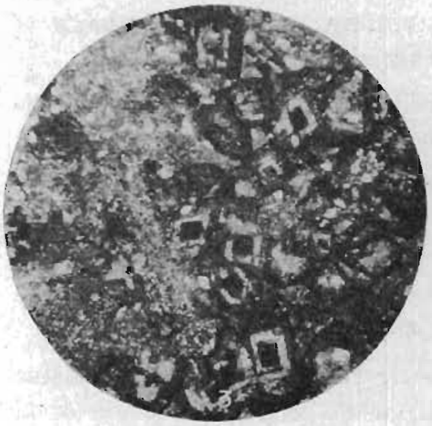
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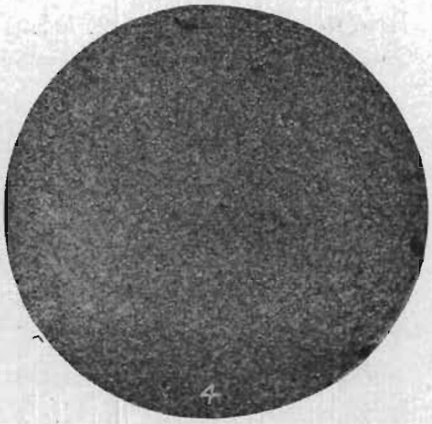
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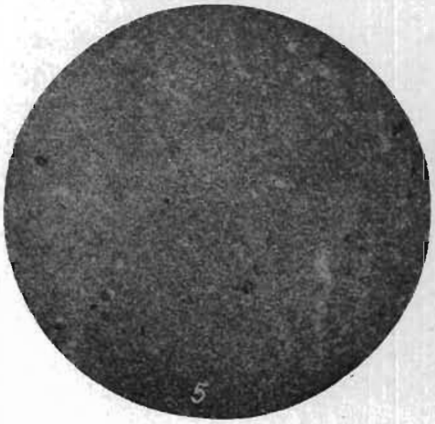
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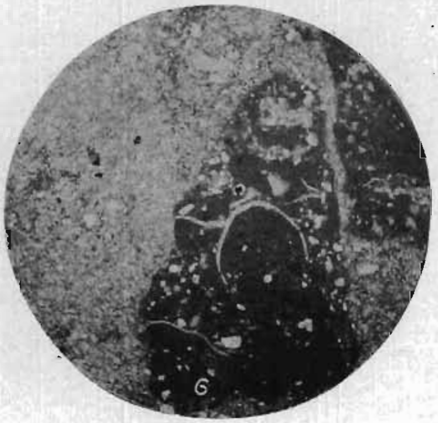
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Plate XXV.

Figure 1.—Section of mottled Tribes Hill limestone from Canajoharie, New York. X 41. Showing small limestone area partly surrounded with dolomite. A small veinlet of dolomite appears in the limestone in the upper part of the figure.

Figure 2.—Mottled Tribes Hill limestone from Palatine Bridge, New York. X 41. A minute irregular remnant of fine-grained calcite in coarser-grained dolomite.

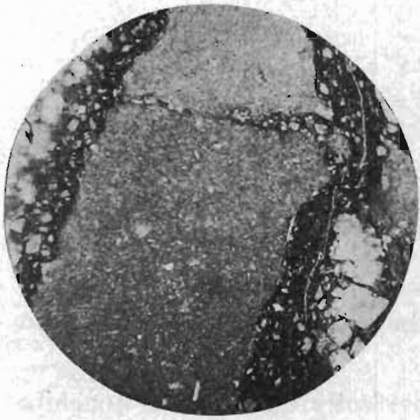
Figure 3.—From the same section as figure 2. Observe the tongue-like extension of dolomite invading the limestone.

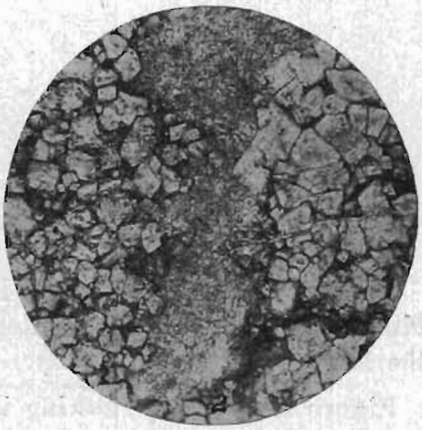
Figure 4.—Another area from the same sample as figure 1 showing gradational contact between limestone and dolomite areas. The dolomite crystals in the limestone area are, for the most part, very perfect but those of the dolomite area are more irregular, due to growth interference.

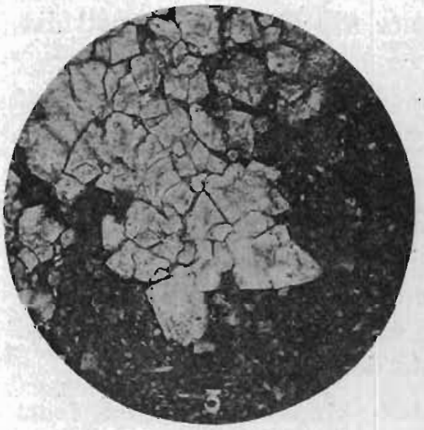
Figure 5.—Mottled Tribes Hill limestone from Palatine Bridge, New York. X 41. Small areas of dolomite developed in the limestone early in the progress of dolomitization.

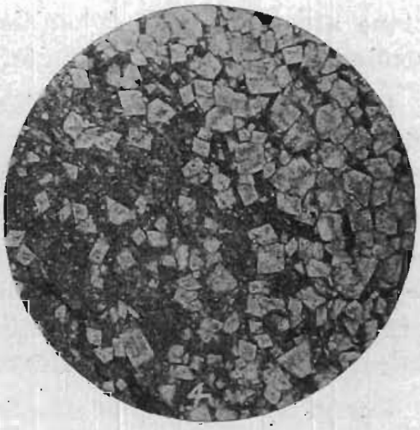
Figure 6.—Dolomite from the Tribes Hill formation at Palatine Bridge, New York. X 41. This shows the nature of the product of more complete transformation of the limestone. No calcite remnants remain in this rock.

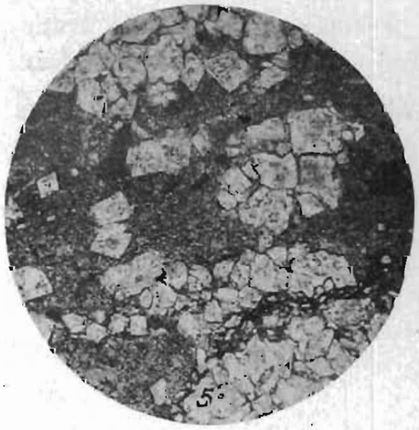
PLATE XXV.











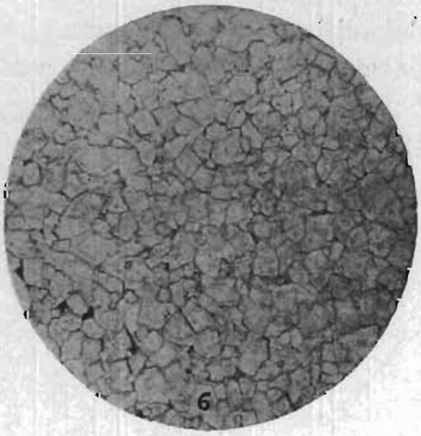


Plate XXVI.

Figure 1.—Mottled Plattin limestone from near Perryville, Missouri. X 22. In this section the dolomite areas grade into the limestone very gradually.

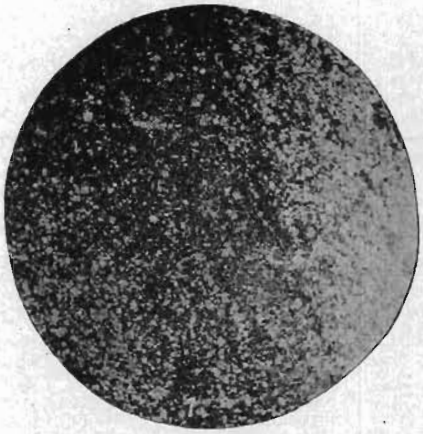
Figure 2.—Section showing imperfectly dolomitized Joachim limestone from near Bloomsdale, Missouri. X 22. The limestone areas near the dolomitic ones are filled with small disseminated crystals of dolomite.

Figure 3.—Imperfectly altered coarse-grained Chazy limestone from Chazy, New York. X 22. The small transparent rhombohedrons scattered through the section are of dolomite.

Figure 4.—Organism with calcareous tissues altered to dolomite. Cedar Valley limestone, Fairport, Iowa. X 22. The large white areas consist of calcite filling original cavities. This coarse-grained calcite resisted alteration at the time the finer-grained calcareous tissues were changed to dolomite.

Figure 5.—Section of Burlington crinoidal limestone from Chautauqua, Illinois. X 22. The rock has undergone incipient dolomitization, as is shown by the presence of the minute, transparent rhombs of dolomite scattered about through the matrix.

Figure 6.—Imperfectly altered Cedar Valley limestone from the same sample as figure 4.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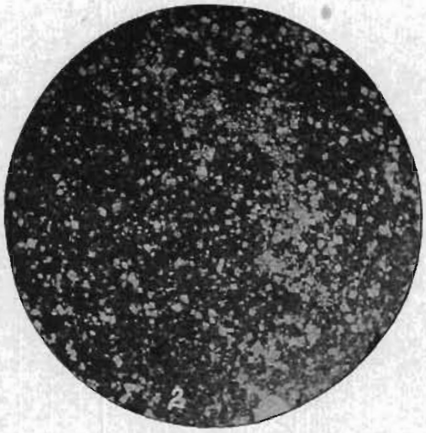
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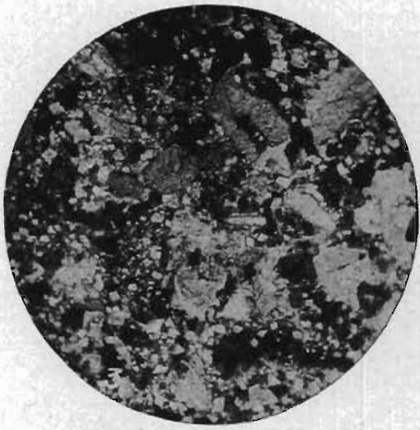
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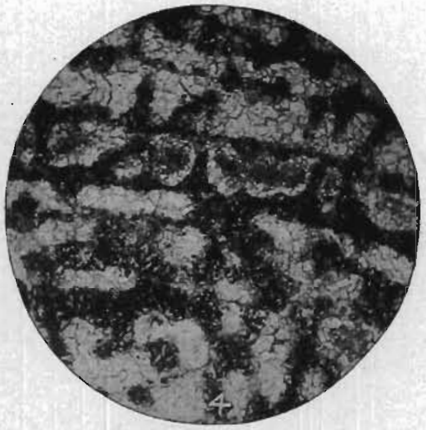
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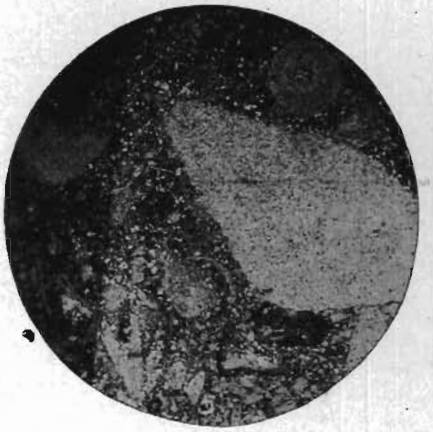
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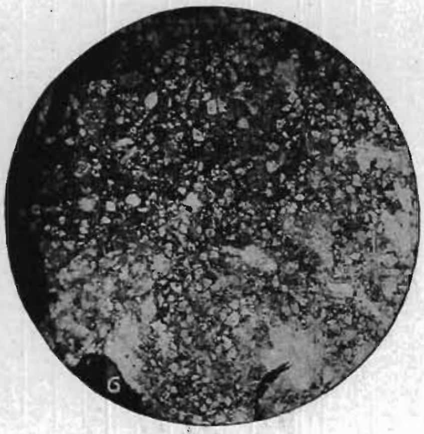
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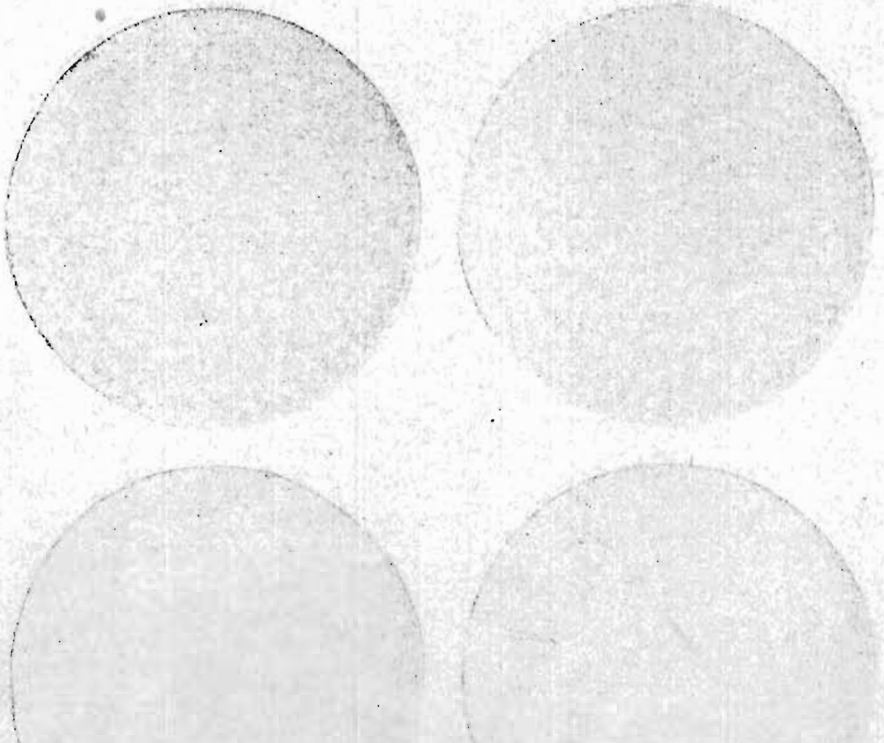
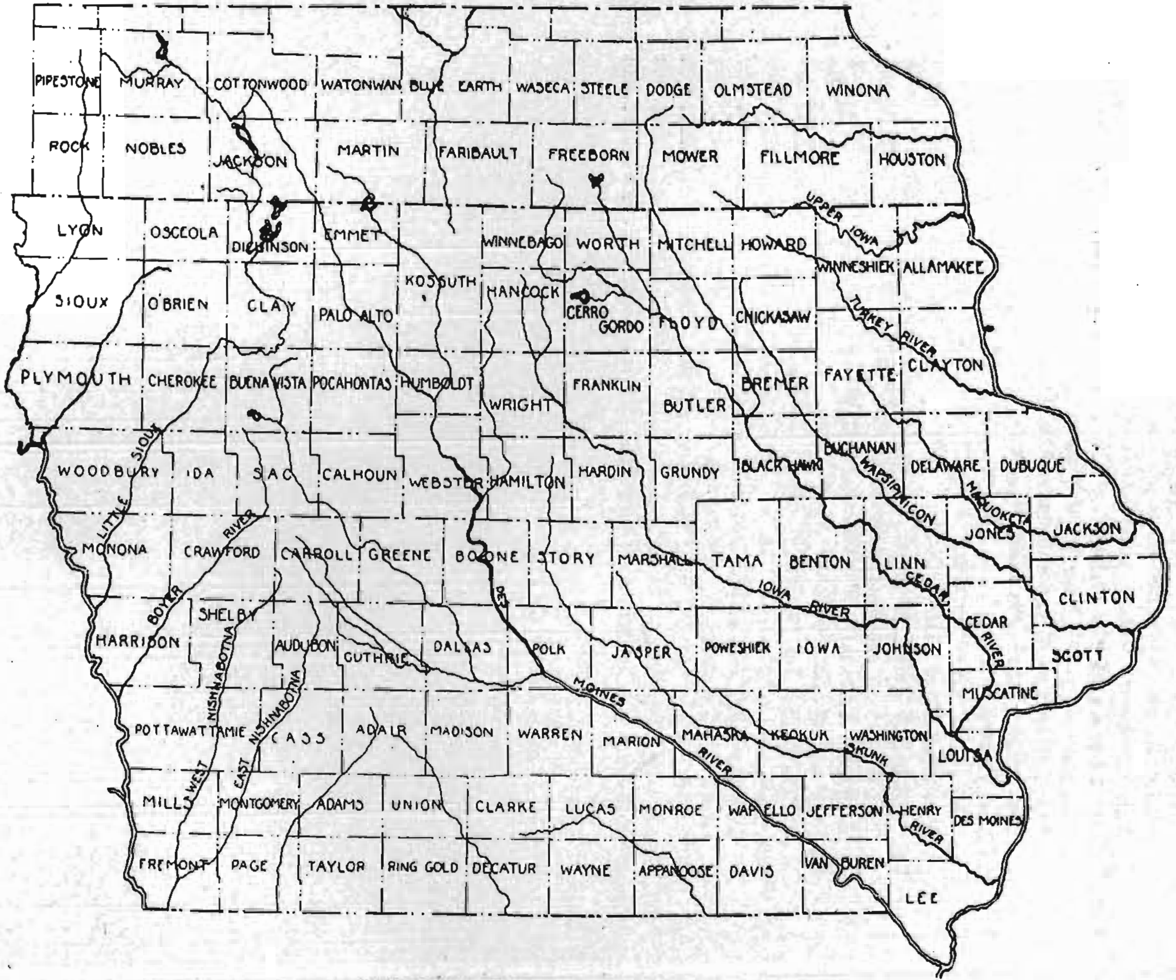


PHYSICAL FEATURES AND GEOLOGIC HISTORY OF DES MOINES VALLEY

BY

JAMES H. LEES

CONTENTS



Outline map of southern Minnesota and Iowa.

PHYSICAL FEATURES AND GEOLOGIC HISTORY OF DES MOINES VALLEY

CHAPTER I.

Introductory.

Purpose of this Report.—The aim of this report is to describe the important features of the valley of Des Moines river and to discuss as well the geologic history and structure of the region in which the valley is situated.

The motive in undertaking this work has been to make available for study and general use a simple and yet comprehensive outline of the characteristics of a typical Iowa river and its valley. A study of this kind should be of value and interest in widening and intensifying the knowledge of Iowa geography and geology, especially among Iowa people.

Area Included.—This study is not intended to be carried far beyond the immediate valley of the river, nor is it the intent to include the entire drainage basin, but rather the valley in its more restricted sense. Only the lower courses of tributary streams are considered. The broader view is left for a later, more inclusive survey. Plate XXVII will show the general relations of Des Moines valley and the region which it crosses.

Des Moines river aids in the drainage of three states. Its two forks, the East and the West, rise in the lakes and prairies of southwestern Minnesota and unite their waters below the town of Humboldt, Iowa. In the last few miles of its course it divides Iowa from Missouri and the irregular triangle included between the Des Moines and the Mississippi is the southernmost land of Iowa.

The Des Moines river system drains an area of 12,500 square miles in Iowa together with about 1,525 square miles in Minnesota and about 75 in Missouri. This gives to the entire basin an area of about 14,100 square miles. The basin is nowhere very wide and below the mouth of the Boone the divide between Des Moines and Skunk rivers is scarcely over ten to fifteen miles from the former stream.

History of Des Moines Valley.—The early settlers of Iowa sought the river valleys, both as lines of travel and in locating their homes. Railroads were unknown or so few as to be but slightly available and the river courses offered easy and certain lines of communication. The valleys furnished shelter for the homesteads and their supplies of timber yielded material for building as well as for fuel. The difficulty of winning the farm lands from the forest was supposed to be more than counterbalanced by the superiority of the valley soils over those of the prairie. These hardy pioneers had not come to realize that instead of marking the richest soils the forest indicated the poorer ones; that the barren open uplands carried a soil which would far surpass in its yield of crops the tree-covered soils of the valley sides. Many of the flat bottom-lands, it is true, bear a rich alluvial soil of great fertility. But the wider areas of forest-covered slopes can not hold rank with the prairies, as is shown abundantly by comparison of present day farms in the two regions. Nevertheless the forest-filled valleys served their purpose in offering indispensible timber and water for the standard bearers of civilization, and, leading as they did into the heart of the unknown, they were a perpetual incitement to further effort toward the solution of the mystery of the lands beyond.

For an early view of the prairies the following clipping from the Saint Louis Enquirer, written in 1819, is interesting. "After you get forty or fifty miles west of the Mississippi the arid plains set in. The country is uninhabitable except upon the borders of the rivers and creeks."

Apparently, the first white men to visit the Des Moines valley were Pere Jacques Marquette and Sieur Louis Joliet, who came westward from the Great Lakes country down the Wisconsin to its confluence with the Mississippi, which they reached on June 17, 1673. They descended the Father of Waters as far as the mouth of the Arkansas river and on their journey spent a few days on Des Moines river with a band of Illinois Indians. They reached the river on the 25th of June and were welcomed most hospitably by the Indians living on its banks. These natives called their village Mon-in-go-na, (meaning "at the road"), which name was shortened to Moingona by the map makers. Nicolet states that the French abbreviated the name still more, and, applying it to the river, called it "la riviere des Moins," whence the modern name. It was not until a later day that this name was associated with that of the Trappist monks (Moines de la Trappe), who lived with the Indians.

Other Indian tribes lived in the Des Moines valley, among them the Iowas, of whom Ma-has-kah was one of the noted chiefs. His home was near the present site of Eldon. The famous Black Hawk, chief of the Sacs and Foxes, spent his last years on the banks of the Des Moines near Iowaville, a village in Van Buren county near Selma, and he was buried near the northeast corner of Davis county, not far from his home. Keokuk, Appanoose and Wapello, chiefs of the Sacs and Foxes, lived near Agency and Ottumwa.

By treaties made in 1832 and 1842 the Sacs and Foxes ceded their lands, including the Des Moines valley below the junction of the two forks, to the United States. This was the Black Hawk Purchase. The upper stretches of the valley were owned by the Sioux and other tribes of the Dakota group, who ceded their lands to the Federal Government by various treaties between 1825 and 1846.

White men were pressing westward, government troops were stationed at army posts to preserve peace and order and it was not long until settlements were springing up all along the river, as well as elsewhere over the state. In 1820, Dr. Samuel Muir, an army surgeon stationed at Warsaw, Illinois, crossed the river and built a cabin and located a farm where Keokuk now stands. He and his Indian wife lived here until his death in 1832. A station of the American Fur Company was afterwards established here. The organization of a city was undertaken in September, 1834, and it was agreed to name the town for the Sac chief, Keokuk.

The Appanoose Rapids Company laid out a town site in May, 1843, and named it Ottumwa, an Indian word signifying "rapids" or "tumbling water," and in the same year J. P. Eddy, a trader, plotted a town at the location of his store and named it Eddyville. In 1859 the Burlington and Missouri River Railroad, now the Chicago, Burlington and Quincy Railroad, extended its line to Ottumwa and the next year the Des Moines Valley Railroad, since acquired by the Chicago, Rock Island and Pacific Railway, was built through Eddyville and Ottumwa and soon was extended through Oskaloosa to Des Moines.

In order to prevent disturbances among hostile Indian tribes and also to check the activities of a band of outlaws in the vicinity the Federal Government issued orders in 1842 for the establishment of a fort at the junction of the Des Moines and Raccoon. Captain James Allen ascended the river in November of this year to select a site and in March of the next year he returned and built the post, which General Scott named "Fort Des Moines." It was built on the west bank of the river near the present line of Second Street. The Government maintained the post until 1846, a year after the Indian reservation had been opened to settlers. The town was platted in 1846, and the Capitol of the State was located here in 1857. The first railroad to reach the town was the Des Moines Valley, in 1866. The Rock Island was built in a year later.

In 1835 Captain Nathan Boone was sent out in charge of a party of United States cavalry from a temporary post at the Raccoon forks. He explored the Des Moines and Boone river valleys and a few years later some of his party made settlements along the river. When these settlements were organized into a county, in 1849, it was named in honor of its first explorer, Boone.

Another of the outposts of the early days was located on the upper Des Moines by the Federal Government in 1850 and named Fort Dodge. This post was occupied by the army for three years and upon its abandonment the land was sold and a town site was platted and given the name of the army post. The town thrived and was soon made the county seat. It was not until 1869 that the Iowa Falls and Sioux City Railroad reached Fort Dodge and in this same year the town attained notoriety in another way—through the Cardiff Giant. This was a gigantic statue unearthed near the village of Cardiff, near Syracuse, New York. After being heralded far and wide as a "petrified giant" and a "Phœnecian idol" this statue was proven to have been carried from the gypsum beds of Fort Dodge, carved into its existent form in Chicago and taken to Cardiff and buried, soon to be dug up and exhibited as a marvel of antiquity. Even at the Pan-American Exposition in Buffalo in 1901 this statue was the center of such interest that many visitors paid admission to witness the great Cardiff Giant.

For many years gypsum had been used as a building material and in 1871 plans were perfected for making stucco and plaster from it. One of the first public buildings in which Iowa stucco was used was the new State House at Des Moines. Since then the industry has grown until Iowa ranks first among the states in the manufacture of gypsum products.

Coal mining began in Iowa in the year 1840 near Farmington. Some of the product of these early mines was hauled to Keokuk by team and some was used by the steamboats which came up the Des Moines. Coal retailed at $4.50 to $5.00 per ton. By 1843 the blacksmiths were using Mahaska county coal and within ten years several mines were opened in the county. During the fifties the village of Coalport in Marion county was the most important coaling station for river steamers between Eddyville and Des Moines. Today Coalport is wiped off the maps. In 1843 Captain Allen dug coal from the vein still exposed near the dam at Des Moines, but wood was so plentiful that coal could not compete very successfully. Its chief use was in the army blacksmiths' forges. After 1865 the industry grew rapidly and Polk county always has held a leading position as a coal producer. It was about the same time that mining in Boone county received great impetus by the advent of the Chicago and North Western Railroad. In 1870 the first shipping mine of Webster county was opened and since then coal has been mined continuously on a large scale. The fact that the Des Moines traverses the entire length of the Coal Measures in Iowa has made exploitation of the coal deposits relatively easy and has directed the growth of the industry along the valley. Here also is seen the influence of the river valley in the development of the state. Previous to the advent of railroads the river furnished a waterway leading to the heart of the state. One of the first railroads to be built in Iowa was pushed up the valley as far as Eddyville. At the present time two other railroads follow the valley more or less closely from Des Moines to Harvey.

The importance of the rivers for navigation was early realized by the people of Iowa and in 1846 Congress was persuaded to cede to the state upon its admission into the Union a grant of land for the improvement of the Des Moines. This grant included every alternate section on each side the river and within five miles of its banks. It was estimated in 1848 to amount to nearly 1,000,000 acres. Work was at once undertaken by the state for improving the channel of the river by the building of canals, dams and locks and the Legislature lent every aid in its power. The land was sold to settlers for $1.25 per acre. But the work proceeded slowly and by 1854 it was seen that river navigation could not be so successful as had been hoped and that railroads must be depended on very largely for transportation. By 1857 nearly $800,000 had been spent and but three dams completed. In this year the legislature authorized the payment of claims against the work and the sale of lands, tolls and water rents to any company who would give good security for the completion of the work. In 1858 a portion of the original land grant was given to the Keokuk, Des Moines and Minnesota Railroad Company for the purpose of helping the construction of a road up the valley of Des Moines river, and final settlement with the Des Moines Navigation Company, which had assumed the work, was provided for by granting to it another part of the land. This company claimed all the land included in the grant north of the Raccoon forks and from this claim arose one of the most expensive and disgraceful series of litigation in the history of the United States. There is not space here for recounting this episode but a full review will be found in Hon.

B. F. Gue's History of Iowa, from which the facts here given are gathered. Much of the land included in the grant still lies idle and useless as a result of the avarice of the eastern speculators who obtained title, however falsely, to the property.

General Character of the Valley. A. Geologic.—Throughout its entire course Des Moines river, including both its east and west forks, flows across a region which in past ages was covered by continental glaciers. The mantle-rock in this region therefore, is composed of loose material—clay, sand, gravel, bowlders—carried by these glaciers and left as sheets of glacial drift when the glaciers melted away. Overlying the drift sheet found south of Des Moines is a very fine-textured, yellow or gray, siltlike material known as loess. Beneath these superficial glacial deposits there is universally present the bedrock, which consists of layers of various classes of stone—limestone, sandstone or shale—and is for the most part in nearly horizontal position. In the upper stretches of the valley these rocks are concealed entirely by the mantle-rock and it is only near Humboldt that any outcrops of bedrock are to be seen on either branch. Below here to the Mississippi they are common features. The bottom of the valley is covered throughout most of its extent in Iowa with a layer of alluvium, which consists of black soil mingled with more or less coarser matter. In places great bodies of sand and gravel cover the valley floor or form terraces on its sides.

B. Topographic.—The topography of the region bordering the valley is determined chiefly by the glacial deposits, but in part by the bedrock. It is to be understood, of course, that the effects of these factors have been more or less modified by erosion. Below Des Moines the changes due to this agent are of large importance but they become less important in the upper portions of the valley. For this reason the valley itself below Des Moines is wide and mature, while most of the portion above the capital city is narrower and has the appearance of youth. It is true that in Kossuth, Palo Alto and Emmet counties, as well as in Minnesota, some parts of the valley are very wide, but at the same time they are very shallow and do not show evidences of much erosion. Their topographic features are of glacial origin, practically unmodified by the work of the modern stream.

It may be remarked that the statements regarding the topography of the valley hold true for the entire region drained by the Des Moines. Below the junction with the Raccoon, streams are abundant and have done much to modify the ancient land forms. North of the Raccoon the surface is much more level and streams and valleys are relatively rare while the prairies are dotted with sloughs and lakes, direct evidences of topographic immaturity.

CHAPTER II.

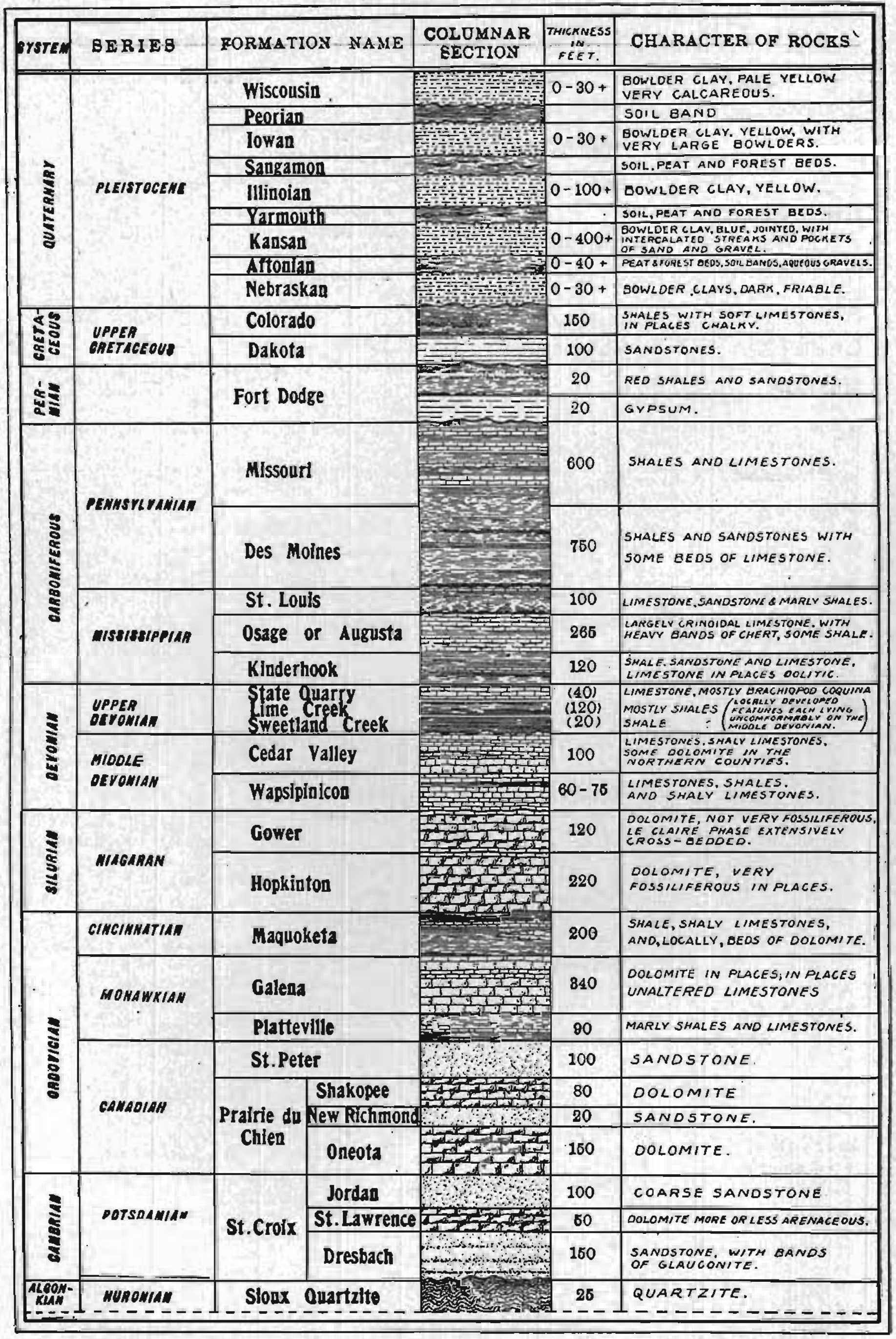
THE GEOLOGY OF THE REGION.

THE BEDROCK.

Rock Deposition and Erosion.—The geologic history of the Des Moines valley begins long before the formation of the oldest rocks exposed therein, but it will be understood that a knowledge of the underlying rocks and the history of their formation is necessary to a thorough comprehension of the later stages of the development of this region as revealed in the strata in which the valley itself is cut. The rocks which lie below the floor of the valley are similar in many respects to most of those which are exposed along its walls and from the very fact that they do underlie the valley we need to know something of their original character. Because of these facts and because there are several breaks in the record as found in the valley we must go outside our immediate region if we would learn the complete sequence of events.

Geologic time has been separated, for convenience, into divisions known in descending rank as eras, periods, epochs and ages. The rocks deposited during these time divisions are classed as groups, systems, series and stages (formations). In general the same names are applied to time divisions and to the corresponding rock strata. In order that the succession of these divisions may be clear the following table is inserted.

ERA	PERIOD	EPOCH
Cenozoic	Quaternary	Recent Pleistocene
	Tertiary	Pliocene Miocene Oligocene Eocene
Mesozoic	Cretaceous	Upper Lower
	Jurassic	
	Triassic	
Paleozoic	Permian	
	Carboniferous	Pennsylvanian Mississippian
	Devonian	Upper Middle Lower
	Silurian	Cayugan Niagaran
	Ordovician	Cincinnatian Mohawkian Canadian
	Cambrian	Potsdamian Acadian Georgian
Proterozoic (Algonkian)	Keweenawan	
	Huronian	Upper (Animikee) Middle Lower
Archeozoic (Archean)	Great Schist Series	
	Great Granite Series	(granite intruded into Great Schist Series)



SYSTEM	SERIES	FORMATION NAME		COLUMNAR SECTION	THICKNESS IN FEET.	CHARACTER OF ROCKS
QUATERNARY	PLEISTOCENE	Wisconsin			0-30+	BOWLDER CLAY, PALE YELLOW VERY CALCAREOUS.
		Peorian				SOIL BAND
		Iowan			0-30+	BOWLDER CLAY, YELLOW, WITH VERY LARGE BOWLDERS.
		Sangamon				SOIL, PEAT AND FOREST BEDS.
		Illinoian			0-100+	BOWLDER CLAY, YELLOW.
		Yarmouth				SOIL, PEAT AND FOREST BEDS.
		Kansan			0-400+	BOWLDER CLAY, BLUE, JOINTED, WITH INTERCALATED STREAKS AND POCKETS OF SAND AND GRAVEL.
		Aftonian			0-40+	PEAT & FOREST BEDS, SOIL BANDS, AQUEOUS GRAVELS.
		Nebraskan			0-30+	BOWLDER CLAYS, DARK, FRIABLE.
CRETACEOUS	UPPER CRETACEOUS	Colorado			150	SHALES WITH SOFT LIMESTONES, IN PLACES CHALKY.
		Dakota			100	SANDSTONES.
PERMIAN		Fort Dodge			20	RED SHALES AND SANDSTONES.
					20	GYPSUM.
CARBONIFEROUS	PENNSYLVANIAN	Missouri			600	SHALES AND LIMESTONES.
		Des Moines			750	SHALES AND SANDSTONES WITH SOME BEDS OF LIMESTONE.
	MISSISSIPPIAN	St. Louis			100	LIMESTONE, SANDSTONE & MARLY SHALES.
		Osage or Augusta			265	LARGELY CRINOIDAL LIMESTONE, WITH HEAVY BANDS OF CHERT, SOME SHALE.
		Kinderhook			120	SHALE, SANDSTONE AND LIMESTONE, LIMESTONE IN PLACES OOLITIC.
DEVONIAN	UPPER DEVONIAN	State Quarry			(40)	LIMESTONE, MOSTLY BRACHIOPOD COQUINA
		Lime Creek			(120)	MOSTLY SHALES (LOCALLY DEVELOPED FEATURES EACH LYING UNCOMFORMABLY ON THE MIDDLE DEVONIAN.)
		Sweetland Creek			(20)	SHALE
	MIDDLE DEVONIAN	Cedar Valley			100	LIMESTONES, SHALY LIMESTONES, SOME DOLOMITE IN THE NORTHERN COUNTIES.
		Wapsipinicon			60-75	LIMESTONES, SHALES, AND SHALY LIMESTONES.
SILURIAN	NIAGARAN	Gower			120	DOLOMITE, NOT VERY FOSSILIFEROUS, LE CLAIRE PHASE EXTENSIVELY CROSS-BEDDED.
		Hopkinton			220	DOLOMITE, VERY FOSSILIFEROUS IN PLACES.
ORDOVICIAN	CINCINNATIAN	Maquoketa			200	SHALE, SHALY LIMESTONES, AND, LOCALLY, BEDS OF DOLOMITE.
	MOHAWKIAN	Galena			340	DOLOMITE IN PLACES; IN PLACES UNALTERED LIMESTONES
		Platteville			90	MARLY SHALES AND LIMESTONES.
	CANADIAN	St. Peter			100	SANDSTONE.
		Prairie du Chien	Shakopee		80	DOLOMITE
			New Richmond		20	SANDSTONE.
			Oneota		150	DOLOMITE.
CAMBRIAN	POTSDAMIAN	St. Croix	Jordan		100	COARSE SANDSTONE
			St. Lawrence		50	DOLOMITE MORE OR LESS ARENACEOUS.
			Dresbach		150	SANDSTONE, WITH BANDS OF GLAUCONITE.
ALGONKIAN	HURONIAN	Sioux Quartzite			25	QUARTZITE.

General Geological Section of Iowa.

If this table be compared with the general section of the rocks of Iowa, as shown in Plate XXVIII, or with figure 39, their relationships will become evident. It will be seen that the oldest rock exposed anywhere in the state, the Sioux quartzite, (compare also Plate XXIX) is evidence of the effectiveness in those early days of the processes of rock weathering, transportation and deposition—the processes by which sedimentation always has been carried on. For unknown ages the agencies of weathering had been attacking the rocks, and immense quantities of sand grains were accumulating as the residue of rock wastage and were being carried into the sea or piled upon the land. In time these grains were cemented and recemented until they became an extremely hard rock—the Sioux quartzite. While not over twenty-five feet of this quartzite are exposed in Iowa the total thickness is known to be many hundreds of feet. The rock outcrops in Iowa only in the northwest corner of the state but it underlies the entire state, probably, and reappears at the surface in south-central Wisconsin.

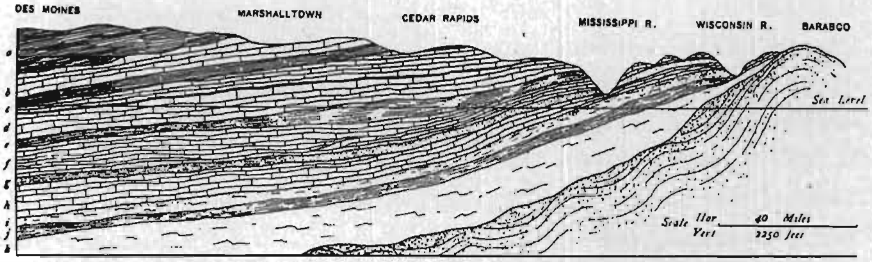


FIG. 39—Geological section from Baraboo, Wisconsin, to Des Moines, Iowa, showing the general stratigraphy of the region. The drift is not shown. The line of juncture of the Dresbach sandstone and the Huronian is hypothetical. *a* Des Moines; *b* Mississippian; *c* Devonian; *d* Niagaran; *e* Maquoketa; *f* Galena-Platteville; *g* Saint Peter; *h* Prairie du Chien; *i* Jordan sandstone; *j* Saint Lawrence; *k* Dresbach.

Immediately beyond the margins of the Des Moines basin in southwestern Minnesota the Sioux quartzite outcrops in widely separated areas around Pipestone and a few miles north of Windom. This formation also immediately underlies the drift in a somewhat limited area between those just mentioned, and within the confines of the valley; but the rock nowhere rises nearer the surface than 100 feet, and it has not been reached by post-Pleistocene erosion. It is not at all probable that it exerts any influence on the position or character of the present valley.

We have been accustomed to think, perhaps, that during the formation of the continents they have changed places many times with the oceans as we now know them, that there have been going on during geologic times great oscillations between these two grand divisions of the crust. But it seems probable, indeed, it is almost certain, that the oceans have occupied substantially their present basins from the beginning of their existence; likewise, that the continental masses always have retained about the shapes and positions they now occupy. They have been often more or less covered with water, it is true, but the same condition exists today along the continental borders, and the presence of waters over the continents in times past was due merely to the action of the same forces which today are elevating or depressing parts of the land masses. These continental oceans or epicontinental seas always were relatively shallow, and the deposits formed in them wherever they are known, are all characteristic of shallow seas; none of them are at all like those found in the deep ocean basins. Thus near the shores, where rivers brought down their loads and dropped them, or where waves and currents carried them about, were formed the beds of sand which we know as the sandstones of the geologic section. The ocean waters carried a little farther out, the finer sands and the muds and silts but these soon were dropped and accumulated on the bottom, to be consolidated into beds of shale. Still farther from the shores and below the disturbing effects of the waves were formed banks of limy ooze, mingled with shells of marine animals, and out here would grow up coral reefs and banks. All of these united in forming the beds of limestone which are so common over the state. Some of the limestones were altered by the partial replacement of the lime by magnesia and became dolomites. In many cases the different classes of deposits grade into each other and we have sandy or limy shales, sandy or shaly limestones, limy or clayey sandstones. These beds have hardened into rock by cementation, by pressure of overlying rocks and by removal of the water contained therein.

It was under such conditions as these, then, that the sands which now form the Sioux quartzite were accumulated and that ages afterward the sands of the next member of the geologic column of Iowa—the Saint Croix—piled up on the sea bottom. This sea bottom must have been subsiding slowly through a long period to allow the building up of such an immense thickness—1500 feet— of fine material as the Saint Croix sandstones. Only about one-fifth of this total is exposed in Iowa.

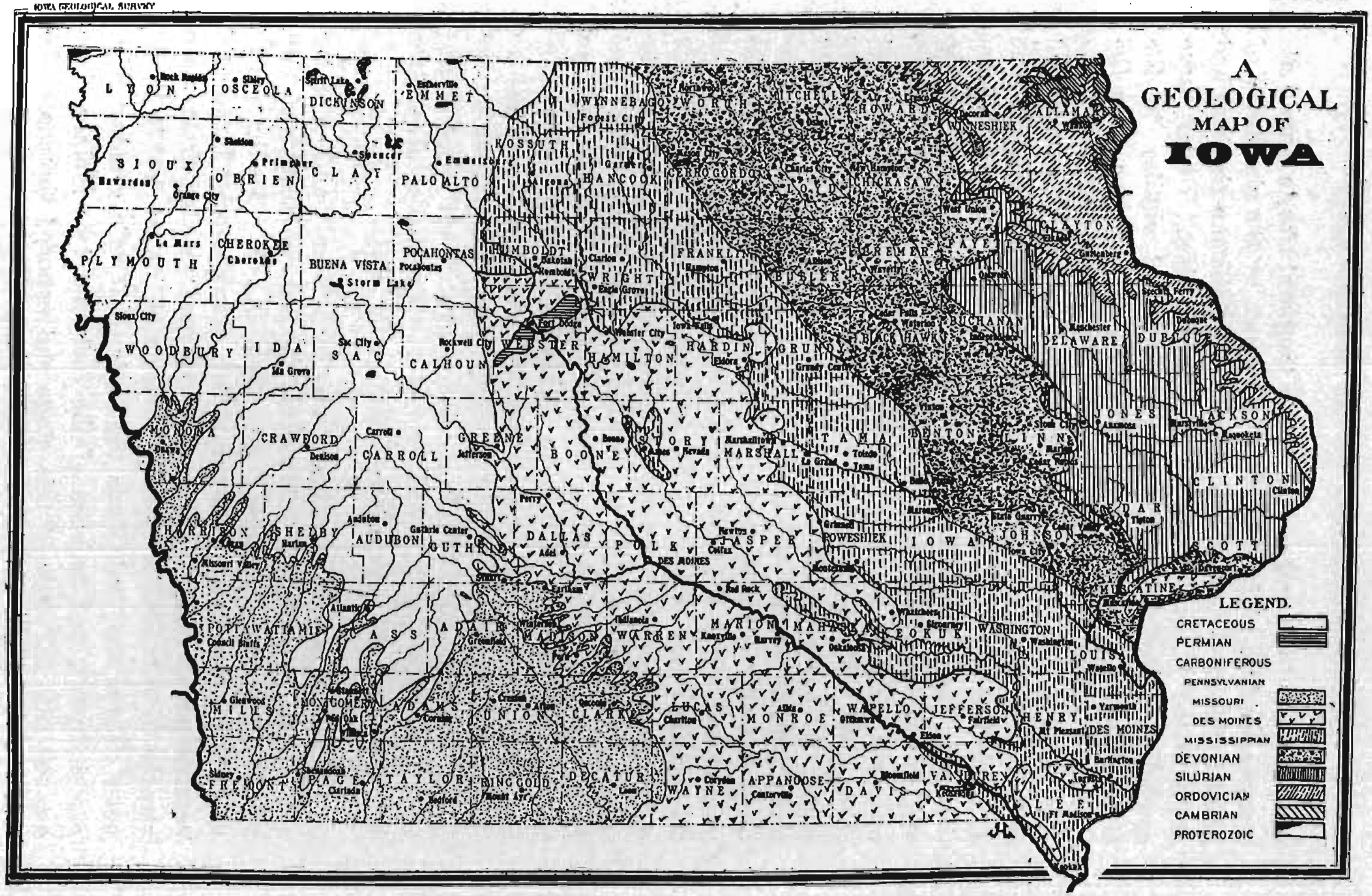
Above the sandstones of the Saint Croix were laid the varied types of rock of the Ordovician, Silurian and Devonian series, whose characters as indicated in the section (Plate XXVIII) bespeak the changing conditions attending their deposition. As these rocks are exposed nowhere within the area of our study we may pass them with this word. Since northeastern Iowa was being elevated slowly, though with many oscillations, during these epochs, the rocks now outcrop in parallel bands to the southwest of the ancient land mass, as may be seen by inspection of the geologic map, Plate XXIX.

The oldest rocks which are found at the surface in the Des Moines valley are those of Mississippian age and so it is with the beginning of the Mississippian epoch that the immediate history of the valley may be said to begin. Lest there be any misunderstanding it should be explained that the valley did not originate until long after this time, not until the epicontinental seas had left Iowa for the last time as will be described farther on. But the history of the Mississippian and later rocks becomes a part of the history of the Des Moines valley because it is through these rocks that the valley has been sunk. Therefore the course of events from this time forward acquires a special significance in our study.

A study of the geological map, Plate XXIX, will show that Mississippian strata form the country rock under a considerable area in north-central Iowa, as well as under a wide band southeast to the Mississippi. North of the latitude of Des Moines these country rocks belong chiefly to the Kinderhook stage (Plate XXVIII). In the valley of the Des Moines these strata outcrop only as very small patches along the river in central Humboldt county along the West Fork. The strata of the Osage stage (Plate XXVIII) are found in the valley of the Mississippi below Fort Madison and appear along the Des Moines as a narrow belt extending up to the Keosauqua oxbow. Above this point the Saint Louis limestones outcrop (Plate XXVIII) as long narrow patches extending up the valley into central Marion county, and again appearing as isolated areas in the bottom of the valley, or more rarely out on the prairies in Webster and Humboldt counties. The most northerly outcrops of this rock to be found along the West Fork are small exposures east of Bradgate. Similar outcrops are found at Dakota on the East Fork, but north of these points the indurated rocks are covered deeply with glacial drift.

Following the deposition of the Saint Louis strata the sea receded from Iowa and there followed a period of prolonged erosion, including the Kaskaskia (uppermost Mississippian) and the early part of the succeeding stage, during which valleys scores and hundreds of feet in depth were carved in the once level surface of the limestones. How irregular this surface became is shown by the fact that in the Greenwood Park well at Des Moines the top of the St. Louis limestone is 373 feet above sea level, at Commerce, a few miles to the west, it is 300 feet, at Valley Junction, intermediate in position, it is about 600 feet, at Carbondale, a village at the southeast margin of Des Moines, the surface of the rock is about 600 feet above sea level, and at Mitchellville, about twelve miles to the northeast, it rises to 760 feet above sea.

This period of erosion had brought much of the country to the condition of a low plain and as another periodic incursion of the sea began at the opening of Des Moines times (Plate XXVIII) great areas were reduced nearly to sea level. Climatic conditions now favored the development of a vegetation exceeding in luxuriance anything the earth had yet seen. These con-


A
GEOLOGICAL
MAP OF
IOWA
LEGEND.
CRETACEOUS
PERMIAN
CARBONIFEROUS
PENNSYLVANIAN
MISSOURI
DES MOINES
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PROTEROZOIC
LYON
OSCEOLA
DICKINSON
EMMET
WINNEBAGO
WORTH
MITCHELL
HOWARD
WINNESHIEK
ALLAMAKEE
SIOUX
O'BRIEN
CLAY
PALO ALTO
KOSSUTH
HANCOCK
CERRO GORDO
FLOYD
CHICKASAW
FAYETTE
CLAYTON
PLYMOUTH
CHEROKEE
BUENA VISTA
POCAHONTAS
HUMBOLDT
WRIGHT
FRANKLIN
BUTLER
BREMER
BUCHANAN
DELAWARE
DUBUQUE
WOODBURY
IDA
SAC
CALHOUN
WEBSTER
HAMILTON
HARDIN
GRUNDY
BLACK HAWK
MONONA
CRAWFORD
CARROLL
GREENE
BOONE
STORY
MARSHALL
TAMA
BENTON
LINN
JONES
JACKSON
CLINTON
HARRISON
SHELBY
AUDUBON
GUTHRIE
DALLAS
POLK
JASPER
POWESHIEK
IOWA
JOHNSON
CEDAR
SCOTT
MUSCATINE
POTTAWATTAMIE
CASS
ADAIR
MADISON
WARREN
MARION
MAHASKA
KEOKUK
WASHINGTON
LOUISA
MILLS
MONTGOMERY
ADAMS
UNION
CLARKE
LUCAS
MONROE
WAPELLO
JEFFERSON
HENRY
DES MOINES
FREMONT
PAGE
TAYLOR
RINGGOLD
DECATUR
WAYNE
APPANOOSE
DAVIS
VAN BUREN
LEE
DES MOINES

ditions seem to have been moderate temperatures, a humid atmosphere and a uniform climate, as shown by the similarity of plant life from Greenland to Brazil. In addition a rich soil had accumulated through ages of rock weathering. Under these conditions great coastal swamps developed similar to the Great Dismal Swamp of Virginia. In these swamps grew the moisture-loving plants of the times, such as great tree ferns and clubmosses. These flourished, died and fell, were buried in the water and succeeding generations followed them. In time a thick bed of vegetal matter accumulated, preserved from decay by the water. A slight change of level brought in the sea, or enabled the streams to carry in detritus from the lands, and this bed was covered by sediments, usually mud, in some cases sand. When this layer approached the surface or another slight earth movement occurred, vegetation would take hold again and the process would be repeated. Meanwhile the underlying bed of vegetal matter was being compressed, some of the gases were driven off, and a bed of coal was being evolved. If the swamps had continued for a long time the coal bed was correspondingly thick, or on the other hand, it might be a mere film between layers of mud. In this way bed above bed of coal formed in the coal swamps until in places in the Des Moines valley there were ten or twelve. Meanwhile the sea was creeping northward until it had covered the Saint Louis limestone in Webster county, and had overspread the older beds as far as Linn and Jackson counties. Later it retreated to the southwest and, following the deposition of the Missouri strata (Plate XXVIII), passed beyond the limits of the state.

The Des Moines beds extend today in a broad band on either side of the Des Moines valley from the eastern border of Van Buren county to Humboldt. See Plate XXIX. To the southwest they pass under younger rocks. They consist largely of sandstones and shales, with seams of coal varying from mere streaks to beds four or five and rarely eight or ten feet in thickness. These coal beds form the basis of Iowa's greatest mineral industry, and because of the fact that Des Moines river has cut into the beds of this stage and exposed the coals, the mining industry of the state has always centered along the valley. The value at the mines of the coal produced in Iowa in 1915 amounted to $13,577,600. The shales of the Des Moines beds, or Lower Coal Measures, make high grade brick, drain tile, sewer pipe and other ware.

It is very difficult to determine the relations of different beds in the Coal Measures because of the lack of continuity between them. The coal swamps seem to have been limited in extent and the same is true of most of the other beds. However, those in southeastern Iowa doubtless are the oldest of those exposed at the surface, while those seen between Des Moines and Fort Dodge probably belong about in the middle of the stage. These may correspond to the Cherokee shales of Kansas. The younger layers occur in the counties west of the river from Appanoose to Guthrie. Some of these latter are quite constant over wide areas. Probably they are to be classed with the Henrietta and Pleasanton formations.

In Webster county there is a series of rocks of Permian age, laid down in a basin cut in the beds of the Des Moines and Saint Louis stages (Plates XXVIII and XXIX). The basin extends across the county from northeast to southwest, and in it are found the bed of pure gray gypsum for which Webster county is noted, and about twenty feet of overlying red shales and sandstones. The gypsum is extensively mined and quarried for manufacture into wall plaster, plaster of Paris and other products. In 1915 the output of these articles was valued at $1,278,128. The river has cut its valley right across the old basin and through the gypsum, through the Coal Measures in many places, down into the Saint Louis limestone. Whether there are elsewhere in the state other beds of Permian age now covered by later deposits is not certainly known. Probably there were such at one time but doubtless they were removed by erosion during the long interval preceding Upper Cretaceous times, and doubtless the wastage was continued in some localities until the indurated rocks were covered by the deposits of the Pleistocene.

The Permian ocean came from the southwest and on its floor were formed the salt beds of Kansas and the gypsum of Iowa, Kansas, Texas and Oklahoma. These gypsum and salt beds are indicative of an arid climate and they tell us that during the Permian the interior sea was more or less cut off from communication with the oceanic waters. In this restricted sea evaporation proceeded until gypsum was precipitated, and in some cases the process went on until salt was deposited. In Webster county the bed of gypsum thus formed has a maximum thickness of thirty feet. A few thin interstratified clay bands speak of the admission of new supplies of ocean waters from which again precipitation took place. Then there came a more extensive inundation attended, probably, by uplift of the lands, and the red shales and sandstones overlying the gypsum were brought in. They were the terrestrial remnants of erosion under arid conditions as the gypsum was the marine representative of these conditions. In places the shales are interbedded with thin layers of gypsum. No fossils have been found in these beds.

There had been similar periods of aridity in past times, for the record of the deep well at Des Moines shows layers of gypsum in the Silurian, and during 1911 a bed of pure gypsum eighteen feet thick was found in the upper part of the Saint Louis limestone at Centerville in Appanoose county. These facts emphasize the recurrence of similar conditions during geologic history and they also show conclusively that the earth could not have been swathed in a dense blanket of hot vapors and heavy gases during Paleozoic times, as was long supposed. The presence of glacial deposits in the Permian of India, South Africa and South America also points to the same conclusions.

All through the Triassic and Jurassic and Comanchean (Lower Cretaceous) periods the Des Moines valley, in common with all the upper Mississippi valley, was land, and was subjected to all the degradational processes of Nature. Just how much was accomplished by these processes is difficult of reckoning. If we could gain an estimate of the differential erosion in areas not covered by Upper Cretaceous sediments over those which have been so protected, we might have a fair basis for judging of this pre-Dakota erosion. But the entire country affected is overlain by drift and the region covered by Cretaceous deposits (Plate XXIX) is especially deeply buried, so that it is almost impossible to judge of what was done during this long period.

With the opening of the Upper Cretaceous (Plate XXVIII) there was ushered in the formation, as a lake and river deposit, of the Dakota sandstone, a very widespread stratum whose eastern fringe is found in western Iowa. Following this there occurred one of the greatest incursions of the sea known in geologic history and in this sea were deposited the chalks and other beds of the Colorado stage (Plate XXIX). While Cretaceous strata probably underlie the valley of the upper Des Moines they are exposed nowhere in this region and are of no practical consequence as a topographic factor.

A series of great crustal and mountain-making movements marked the close of the Mesozoic and the beginning of the Cenozoic eras. See the table on page 437. Throughout most of the Cenozoic the Des Moines valley was affected almost entirely by the degradational forces of Nature. The rocks have been weathered and carried away by the waters, the topography has advanced through the different stages of development and in addition there have been progressing certain diastrophic movements which eventually have raised northwestern Iowa from a position below (Cretaceous) sea level to one which gives it the highest altitudes within the state. The culmination of these movements probably came after the close of the Pleistocene. By the close of the Mesozoic, too, northeastern Iowa had been cut down to a low, level plain and subsequently shared in the elevating movements mentioned above. These various uplifts while very slow, gave the drainage systems new energy and enabled them to cut deep valleys into the surface. Some of the rivers of eastern Iowa probably owe their origin to this quickening and the same doubtless is true of the two great rivers bordering the state. The Des Moines basin probably owes its location to these different warpings of the surface, although the present valley differs widely from the original.

It will be seen that the geologic range of the bedrock exposed in the Des Moines valley is quite limited. From the Kinderhook of Humboldt county, and the Osage, as seen near Keokuk, through the Saint Louis, the Des Moines and the Fort Dodge stages (Plate XXVIII) is only a small portion of the geologic section of the entire state. Not over twenty feet of Kinderhook limestone are exposed near Humboldt and Rutland, but nearly the entire thickness of the Osage and all of the Saint Louis and Coal Measure beds are cut through by the river in its lower course. Within this limited span are compassed some of the most characteristic and vital elements of the geologic record.

Structure.—A number of years ago a well was drilled in Des Moines to a depth of 3000 feet. The section of this well, when compared with the geologic map, shows the important fact that all of the strata which appear at the surface in eastern Iowa as roughly parallel belts are present beneath the site of Des Moines. Now the Saint Croix sandstone at Lansing, Allamakee county, rises 300 feet above Mississippi river or 930 feet above sea level. But this sandstone is reached in the well at Des Moines 1547 feet below sea level. In other words it has descended about 2475 feet in the 175 miles between the two towns. The same condition holds true for the strata above the Saint Croix, and this is the dominant factor in the structure of the strata underlying the Des Moines valley. These rocks are not warped or twisted or folded to any great extent but all have an inclination to the southwest of a few feet to the mile. This does not apply, of course, to the deposits of Pleistocene age, as these were laid down indiscriminately upon the beveled edges of the older formations. It is true also that there are a few warpings of the strata, such as one, an upbending or anticline, in the Saint Louis strata of Story county, just beyond the limits of our present study. But these are only minor exceptions to the general rule.

In northwestern Iowa, conditions are reversed. Here the Sioux quartzite formed an island in the ancient seas, just as did the Cambrian sandstones in northeastern Iowa, and so the strata rise to the north and northwest, so that at Sioux City the top of the Saint Croix sandstone lies about 300 feet above sea level.

Thus it happens that, in northern Iowa at least, and probably as far south as Des Moines, the river valley lies near the axis of a great trough, or syncline, which embraces the whole state and extends beyond its borders. It is scarcely likely, however, that this trough determines the position of the river, as the depression had been filled up before the river began to cut the valley.

A feature which cannot fail to interest the student is the apparent discontinuity of the beds as they are exposed along the walls of the river valley. Thus at several points north of Fort Dodge the river has cut into beds of sandstone, shale and coal belonging to the Des Moines stage, while between these exposures there are outcrops of limestone of Saint Louis age. The same is true below Fort Dodge, where gypsum of Permian age, shales or sandstone of the Coal Measures and limestone of the Saint Louis stage alternate in the valley walls. This phenomenon is not due to breaking up or displacement of the strata, as might be suspected, but to the fact that the younger strata are in each case laid down in channels or basins cut into the older rocks. Small bendings of the strata also may cause similar appearances, though these probably are not so common as are the features due to erosion.

THE PLEISTOCENE SERIES.

General.—Some scattered beds of sand assigned with some uncertainty to the Pliocene are the only known representatives of the Tertiary system in Iowa. The climate of the Tertiary period was mild and pleasant, with gradual development of temperature zones. But by the end of the Pliocene the climate of North America had become much cooler and with the opening of the Pleistocene (Plate XXVIII) there was initiated the most remarkable series of glacial invasions of which present day science has knowledge. What the ultimate causes are which lead to the formation of a continental ice-sheet is not positively known, but whatever the causes were they resulted in the formation in Canada of several great snow-fields from the excess of snowfall over summer melting. It will be seen that this condition would tend to be self-perpetuating and so the snow-fields increased and the snow became ice. Then under the pressure of its own weight the ice began to move away from the center of accumulation and became a glacier. The glaciers from the different centers spread until at their maximum they covered Canada and extended into the United States as far as Long Island and Ohio and Missouri rivers. About 4,000,000 square miles of North America were buried under this frigid mantle. Following a period of glaciation came one of more genial climate when the ice was melted partly or wholly away. This succession took place several times and so the Pleistocene consists of a series of glacial ages alternating with a similar series of interglacial ages.

The Work and Movement of an Ice Sheet.—The progress of a glacier is accomplished by the forward movement of the ice, caused by the pressure at the center of the ice-field, aided more or less by the slope of the ground. But when the front of the glacier retreats there is no backward motion. The ice either continues to advance or remains stationary. The recession is caused by the excess of wastage through melting or evaporation over advance by forward push of the ice. There also will be times when the ice front will remain stationary, when the two factors of forward push and wastage balance more or less exactly.

In its advance the glacier tended to plow up the superficial covering of the rocks and because of its own weight and force and with the aid of the loose material it had thus accumulated it scored and scraped the rock surface and plucked off such masses as it could move. In this way the glacier gathered a great load of rock-flour, clay, sand, gravel and bowlders, which was carried or pushed toward the margin. At the ice-front where melting was in progress, the material brought down was dumped in great heaps and ridges or was carried away by the streams flowing from the ice. When the front retreated the glacier's load was spread blanket-like over the ground. If the margin remained stationary for an interval during its retreat another series of heaps and mounds would be piled up. The ridges thus formed at the limit of the ice-sheet are known as a terminal moraine, those marking stages of rest in the retreat form recessional moraines and the great sheet of detritus spread over the ground is the ground moraine, the glacial drift, the till. The content of the moraines naturally will depend upon the character of the rocks over which the glacier passed. Thus the Kansan drift of western Iowa contains large numbers of Sioux quartzite bowlders, gathered from the ledges of quartzite outcropping in the area centering about Sioux Falls. The Iowan drift of eastern Iowa carries many immense granite bowlders picked up or plucked from the parent beds in Minnesota or Canada. While most of the material of the till is local in origin, some has been transported for scores and hundreds of miles.

Types of Deposits.—The deposits of the Pleistocene series belong to two classes—first, bowldery clays, with associated sands and gravels and in some areas numerous surface bowlders; and second, soil bands, peat beds, forest remains, and silts, sands and gravels. The deposits of the first class owe their origin and position to the work of glaciers and glacial waters while the beds of the second class in part are the remnants of the vegetable life of the interglacial ages and in part represent the work of the interglacial streams.

In addition to these two classes mention must be made of a peculiar type known as the loess, which is intermediate in its relations to the other two groups. It may be stated that the bed rock series are largely of submarine origin. They were laid down under the sea. On the other hand, the Pleistocene deposits were all made after the lands had been raised above the sea. They are subaerial or subglacial according as they were formed in the air or under the glaciers.

History of Glacial Invasions in Des Moines Valley.—When the first continental glacier of the Pleistocene, the Nebraskan (Plate XXVIII), entered Iowa it found a deep layer of residual material, which it plowed up and again spread out, together with some foreign material, as the Nebraskan drift sheet. This sheet is covered commonly by later beds and so is known chiefly by exposures along river banks and in artificial excavations.

It has been found at different localities in the valley and over the state, for example, in Fayette, Polk, Union and Harrison counties, but its exact extent is not known. Where it is unweathered it is a very dark gray, almost black clay, containing some pebbles. When dry it breaks into small blocks like starch but when wet it is very gummy and sticky. How long this glacier covered the state is not known but its occupancy probably is to be reckoned in thousands of years.

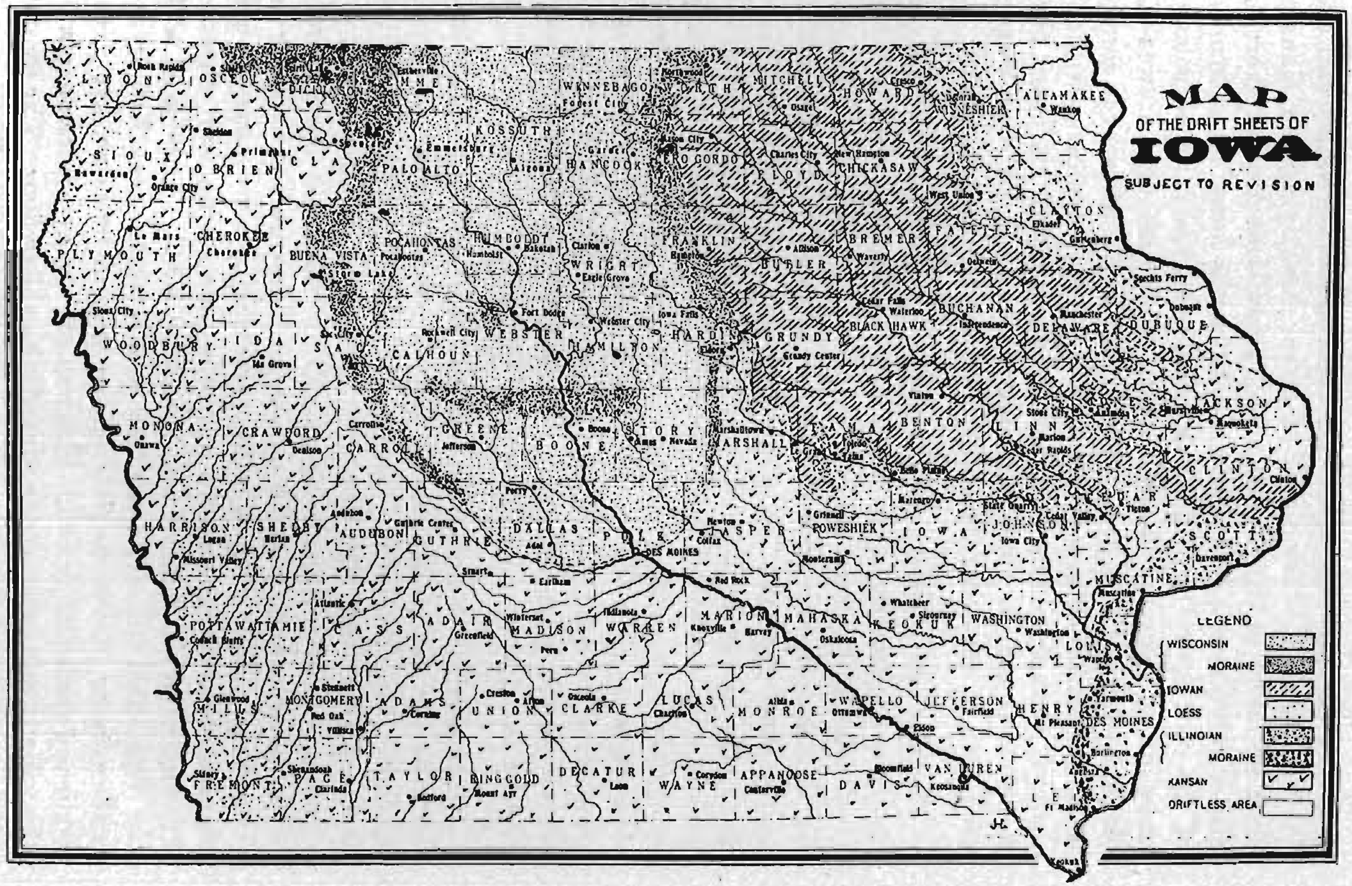
During the Aftonian interglacial age the climate became so mild that such animals as the horse, camel, elephant, deer, bear, sloth and many others flourished on the plains and in the forests. During this time, too, great floods carried down immense quantities of sand and gravel, which filled many of the stream valleys.

The Aftonian is thought to have been the longest of the interglacial ages, and there seems to have been a progressive shortening of these from the earliest and longest to the latest and shortest.

After many years, however, the conditions favoring the formation of the continental ice-sheet recurred and again the glacier crept down from the north and spread over Iowa and as far south as Missouri river. This is known as the Kansan glacier and its work was similar to that of the Nebraskan except that some of the material which it found and worked over was drift from the older sheet which had escaped erosion during the long Aftonian interval. The Kansan is the surface drift of the Des Moines valley south of the city of Des Moines and over probably half the state (Plate XXX). It is typically a bluish pebbly clay becoming yellow and even reddish on exposure. Many outcrops may be seen on the valley sides bordering the Des Moines and at some localities Aftonian and Nebraskan materials are found between the bedrock and the Kansan drift. However, for the most part the latter rests directly on the bedrock, and the same condition holds true in the case of the later drift sheets.

Associated with the Kansan drift sheet in different parts of Iowa are large bodies of gravel, some of them rusty and weathered, known as the Buchanan gravels and belonging to the Yarmouth interglacial stage (Plate XXVIII). These are ex-

PLATE XXX


MAP
OF THE DRIFT SHEETS OF
IOWA
SUBJECT TO REVISION
LEGEND
WISCONSIN
MORAINE
IOWAN
LOESS
ILLINOIAN
MORAINE
KANSAN
DRIFTLESS AREA

posed at several localities along the Des Moines valley and are very common in other parts of Iowa. Overlying the Kansan drift at many points in the valley below Des Moines there is also a fine blue-gray or yellow silt known as loess. It is formed of the rock-flour from the glacial mill and seems to be related in origin of material to the Kansan drift, although it owes its present position to deposition by winds which brought it chiefly from the valley flats near by. The loess is typically without pebbles, though locally it is sandy, especially in its basal portions. It is usually more or less calcareous, except when weathered, and is noted for its ability to maintain vertical walls.

The third or Illinoian glacier failed to affect Des Moines valley except indirectly, since at its closest approach—in Lee county—it was still several miles from the river, and the upper valley is much farther distant, as will be seen from examination of the map opposite. It seems probable that these conditions were true of the Iowan ice-sheet also, although the general direction of the southwestern margin of the Iowan drift-sheet is such that if it were continued to the northwest it would bring that margain near, if not into, Des Moines valley. Further discussion of the effect of a possible invasion of the valley by the Iowan ice can be given best in connection with the detailed outline of the history of the valley. See page 548.

Stretching as a broad lobe southward from Minnesota into Iowa as far as Des Moines, is the drift sheet of the Wisconsin glacier. This, the most recent of the glacial drift sheets of the state, differs from the others in presenting along parts of its eastern and western margins ranges of knobs and mounds scattered promiscuously about or grouped compactly together in long series. This is the Altamont moraine, and a similar, though smaller, recessional series within the area of the drift sheet is known as the Gary moraine. See Plate XXX. Associated with the Wisconsin till, as in the Des Moines valley near Estherville and in many of the mounds on the ground moraine, are great bodies of sand and gravel. Those of the valley are remnants of the valley train, which once covered the valley floor. The mound gravels are *kame* deposits.

The valley of the Des Moines crosses two of these drift sheets—leaving the buried tills out of consideration—namely the Wisconsin and the Kansan. The upper valley, down to Des Moines, is parallel with the axis of the Wisconsin lobe and in northern Boone county cuts directly through the Gary moraine. Below Des Moines the river turns a little more to the east and flows across the Kansan plain to the Mississippi.

The glacial forces seem to have exerted their greatest efforts in the early invasions, for the last two failed by many miles to reach the limits of the earlier ones. In Iowa the Iowan and Wisconsin glaciers are represented merely by lobes covering a few counties each.

Physiographic History.—There are now no well-defined terminal or recessional moraines belonging to the Kansan drift. Such as may have been left by the ice long since ceased to exert any visible effect on the topography. On the contrary, streams have been long at work upon and have cut deep trenches into the Kansan till. While the skyline is almost everywhere level, the surface is deeply scarred and gashed by rivers, creeks and ravines. The Kansan ice-sheet, without doubt, left the surface with a topography not far from even and very similar to that of the Wisconsin drift sheet today. The amount of erosion which has taken place and the amount of time required for the work will be realized by anyone who travels over these two areas or compares topographic maps of the different sheets. The character of the topography of the younger and older drift sheets is an accurate index of their relative ages. The Wisconsin still has a typical glacial topography. It has been but little modified by erosion, comparatively few streams cross its surface and the terminal and recessional moraines doubtless are nearly as distinct as when first formed, while the ground moraine still retains its original features. Wide expanses of prairie stretch to the horizon, broken only by a shallow slough or deeper lake, or perhaps by a rare sag through which flows more or less intermittently a small stream carrying off the surplus rainfall.

Length of Time Involved.—Geologists have estimated the length of time since the climax of Late Wisconsin glaciation at 20,000 to 60,000 years. The interval since the final retreat of the ice would, of course, be many years less. Doctor Calvin, a number of years since, suggested 6,000 to 10,000 years for this period. The smaller figure, especially, seems low in view of the advanced civilizations flourishing on the earth at that time. If we adopt as unity the period which has elapsed since the Late Wisconsin drift-sheet began to suffer erosion, the ages of similar stages in the history of the Early Wisconsin, Iowan, Illinoian and Kansan are thought to be roughly represented by the series 2, 4, 8, 16. (The Late Wisconsin is the sheet found in Iowa; the Early Wisconsin occurs east of the Mississippi.) To these estimates we must add the time while the Kansan ice covered Iowa, the length of the Aftonian interval and that of the Nebraskan age in order to get the full sweep of the Pleistocene epoch. For the duration or antiquity of this first invasion, especially, we have no adequate data upon which to base any estimate. Although not too much confidence must be placed on the figures given they will serve to indicate the order of magnitude in which Pleistocene time must be computed.

It has seemed probable that the Pleistocene is one of the shorter geologic time divisions. If this is the case we may begin to gain some conception of the immensity of the periods of earth life. There are no means for a close measure of the duration of the geologic periods, but since an intelligible record was first made, with the beginning of Cambrian deposition, 100,000 feet of strata, at least, have been laid down by the extremely slow methods of erosion and reaccumulation. The length of time required for this has been computed variously at 50,000,000 to 100,000,000 years, with both higher and lower figures. Before the Cambrian lie the uncounted ages of the Proterozoic, which probably exceeded in length the duration of all Paleozoic and post-Paleozoic time. Again the Proterozoic was preceded by the illimitable eons of the Archeozoic, which is considered to have been longer than all succeeding time and preceding which were incalculable years of development and growth. Since life had attained probably three-fourths of its present development at the beginning of Cambrian time we may see how long must have been the antecedent ages of the earth.

POST-PLEISTOCENE EVENTS.

Down the full length of the Wisconsin drift lobe in Iowa extends the valley of Des Moines river (Plate XXX). In their upper reaches the two forks occupy shallow trenches in wide sags in the plain. As the junction point is approached, the sags grade into definite valleys and in Webster and Boone counties the river flows through a deep though not wide gorge. The sags show no evidence of being erosional but rather are constructional, in their present form at least; but where the river occupies a well defined gorge, as mentioned above, it has been very active and the gorge shows the large amount of post-Wisconsin cutting which has been accomplished within its limits. For it will be understood that whatever the development of a valley preceding any glacial age, the advancing glacier would fill the valley with drift as much as it was able and so would put an end to the life of the river. Many large streams have thus been blotted out. But others have been able to resurrect their valleys, as it were, and this is the case, in part, with the Des Moines, which has resurrected the lower part of that portion of its valley which was buried by the Wisconsin ice-sheet. But all the energies of the river have been devoted to the excavation or reëxcavation of its valley, and very little has been done toward carving any relief forms in the level prairies.

Below its exit from the Wisconsin plain at Des Moines the river has been long at work and in contrast to the very slight influence which it has exerted on the younger topography, its effect on the vastly more mature landscape of the Kansan is very noticeable. It has not only widened its valley but side wash has assisted it in smoothing down the valley slopes and its many tributaries have penetrated nearly all the surrounding prairies, which have been transformed into more or less flat-topped ridges and divides separating wide valleys.

During the glacial occupations those parts of the state not covered by ice were still subject to arctic conditions and plant and animal life must have been modified accordingly. With the passing of the glaciers, vegetation again spread its mantle of green over the desolate landscape and forests resumed their footing along the valleys. When the white man settled in these valleys they were covered with timber, which served as a protection against the wash of the slopes and bottom lands. The settlers' needs and their successors' greed and thoughtlessness have transformed many of these beautiful and useful timber tracts into barren wastes gashed by rains and trenched by ravines. In contrast with these tracts are those spots where judicious cutting and proper care have resulted not only in immediate financial returns, but also in assurances for the future by way of increase in economic and esthetic value.

With the clearing and cultivation of the hills and slopes there has come inevitably an increased wastage of the soil. Many of the hillslopes bordering the Des Moines in southern Iowa now show, instead of that covering of rich black loam which had accumulated during ages of plant growth, yellow patches which show where the top soil has been washed away, leaving exposed the unmodified and therefore less fertile loess or drift, which in turn is following the overlying loam into the valley.

Parallel with the erosive, down-cutting work of the rivers there is going on a process of up-building. The smaller streams may deliver to their mains the loads they have received, but in the case of the Des Moines, as with other large streams, deposition is taking place in the valley. Since the finer materials on the valley floor represent surface wash from fields and hillsides they are often rich in plant food. Hence when the bottom lands, covered with their veneer of fine black alluvial silts, are brought under cultivation, they yield bountiful returns for the labor expended on them.

The terraces of sand or gravel found along the river are not to be classed as postglacial, but are remnants of glacial valley trains and old flood plains which covered the valley floor, and the deposition of this material was associated with the closing stages of the ice-sheet. This is true also of the great bed of gravel filling the valley between Estherville and Emmetsburg. The sands of Van Buren and Lee counties also are to be assigned to a glacial age.

Upon the generally level surface of the Wisconsin drift are numerous depressions, some of which are filled with water and form lakes and ponds. Others have been partly filled, during the years, with the remains of water-loving plants and now contain beds of peat of varying thickness. Some of these lakelets or peat swamps may be found almost at the margin of the Des Moines valley and testify to the slight extent to which the river, as yet, has affected the topography left by the last ice-sheet.

It is probable that the elevation of western Iowa mentioned on page 447 has been in progress since the close of the Pleistocene. The east and west margins of the Wisconsin drift differ in height by several hundred feet and this seems best accounted for by the theory that in Wisconsin time western Iowa was lower than now by the larger part of this difference and has been elevated as a part of the general uplift of the continent closing the Pleistocene epoch. This tilting of the surface must have influenced the location of the Des Moines valley, whose position was being determined also by several other factors, among them the broad sags in the Wisconsin plain, the pre-Wisconsin valley—more or less drift filled, and the activities of that part of the antecedent river which had not been destroyed by Wisconsin glaciation.

CHAPTER III.

THE WORK OF RUNNING WATER.

THE GROWTH OF VALLEYS.

The Beginnings of a Valley.—Whenever a land area emerges from the sea or is uncovered by the retreat of a continental glacier its surface is somewhat irregular. Elevations alternate with depressions. If the depressions are without outlets—are basin-shaped—water from rainfall will fill the basins and they become lakes. If, however, the depressions have outlets the waters which fall upon their slopes are gathered into the lowest part—the axes—of the troughs and run off as streams. Even clear water running over loose material has some cutting power and so the water running down the slopes will cut for itself a channel in the axis of the hollow. The material which thus is cut away will assist in further cutting and so *gullies—infant valleys*—are made. Each succeeding rainfall aids in deepening and widening and lengthening the gullies until they develop into ravines and with further growth into valleys.

Why do some gullies remain small and insignificant while others grow into valleys hundreds of miles long and carry the waters of great rivers? Several factors influence the problem. Assuming an equal rainfall the size of the basin supplying the gully with water (the catchment basin) will affect the rate of growth of the gully. A gully carrying the run-off from a large basin will increase faster than one serving a smaller basin, since the greater the supply of water the greater the erosive power. Thus a gully may grow into a ravine and gradually rob its neighbors of their gathering grounds. The slope of the depressions acts in a similar manner. That stream which has a greater slope, or gradient, than its neighbor flows more swiftly, cuts more energetically and enlarges its channel in every direction more rapidly than do its weaker competitors. The law of the struggle for existence and the survival of the fittest is inexorable.

Stages in the Development of a Valley.—During the early part of its growth a valley is enlarged chiefly by cutting at the bottom because erosion is most active along this line. The valley is steep-sided and V-shaped. If it is being cut in unconsolidated material the walls will be no steeper than the angle at which such material can lie (the angle of rest). This usually is not much more than 30°. If the walls are of solid rock they may be precipitous or vertical. The valley is now in its youthful stage of development. It is well to call to mind here that the development of topographies follows that of valleys and hence the area which is affected by a series of young gullies or valleys is itself youthful.

With progress of time the valley lengthens by head erosion and at the same time, while deepening is still in progress above, the valley begins to widen in its lower part. The rains wash down the loose soil and stones from the sides and the stream may undercut its banks. The material thus thrown into the water is carried off and so the valley grows broader and at the same time the areas separating it from its neighbors on either hand (the divides) grow narrower. During the growth of the valley tributaries develop on either side just as the main valley grew on the original surface. These aid and indeed are the principal agents in cutting up the divides and also in wearing down their surfaces, which is one part of the development of topography. When the valley has acquired gentle slopes and a broad bottom it has reached the stage of maturity. The divides, by this time, have been reduced to rounded ridges with few or no flat tops.

By the time a valley has reached the point when flats have been developed to a notable extent the most active down-cutting has ceased. In other words it has, for the area where flats exist, practically reached its base-level.

This base-level always is reached first at the mouth and is here the level of the main valley, or of the sea if the valley opens into the sea. Back from the mouth of the valley the base-level rises somewhat, since a stream can not cut its channel down to a horizontal line, but always the channel assumes the form of a concave curve.

From this time on, then, the activities of the stream are devoted to side-cutting, and the valley grows wider and flatter while the divides become narrower and lower. The stream meanders across its valley from side to side, undercutting its banks and building up flats from the material thus gained as well as from that brought in by tributaries. In this way the valley passes through the later stages of maturity and arrives at old age. It will be seen that the different parts of a valley may show several or even all of these stages at the same time. Thus at the headwaters of the Des Moines the valley is still in its infancy and farther down the stages of youth and maturity are reached. In the last few miles of its course the valley has arrived at late maturity and long ago reached base-level—the level of the Mississippi bottom-lands.

It will be understood also that a given stage will travel up the valley from its mouth as development proceeds and that a given locality will pass through the stages from infancy to old age and possibly death, provided there is no interference. When erosion has reduced a surface to old age, when the divides are low and narrow, the land is said to be a peneplain (an "almost-plain"). If erosion proceeds further and the whole land becomes practically level it is called a base-leveled plain. None of our Iowa topography is at present in so advanced a state as a peneplain. The oldest part of the state, topographically as well as geologically, the Driftless Area (Plate XXX), is in its maturity.

The progression which has been outlined is known as a cycle of erosion, and every normal valley and normal topography passes through this cycle in greater or less degree. If the region remains stationary long enough the entire cycle will be enacted. But we have seen that in Iowa there have been many depressions and elevations and tiltings of great areas, and these have interfered with the histories of the streams. The lowering of the surface through crustal movements has drowned the lower reaches of the valleys and lessened or terminated the work of the upper parts and it is easy to see how the mature portion of a valley in this way may have had premature old age or death forced upon it. On the other hand, when the land has been elevated, the drainage systems have been quickened, their fall has been increased and the mature part of a valley, for instance, may have been rejuvenated by the increased erosive power of the stream, which has cut deeper into its bed and caused greater activity among its tributaries. If an area is tilted unequally the streams of the elevated portion will increase their activity and will deepen and enlarge their valleys, hastening the cycle along, while the streams and parts of streams in the unaffected land may not receive any quickening, or on the contrary may be unable to care for the increased loads of detritus brought down by the upper waters. In such a case their lower valleys will be filled up, will be aggraded, by this excess of sediments. There is no doubt that all of these accidents have affected the successive drainage systems of our state.

In our special region, the valley of Des Moines river, there is another complication. This lies in the fact that the upper part of the valley has been obliterated, or practically so, by the Wisconsin glacier, as discussed in Chapter II. Because of this we have the unique phenomenon of a young valley being attached to a mature valley. Of course the valley advanced northward from Des Moines as the ice melted back, keeping pace with the retreat of the margin, and so the lower part of this newer section is a little older in years as well as in development, than the stretches farther north. But in spite of this the statement as to the inequality of development of the two parts is essentially true.

THE WORK OF STREAMS.

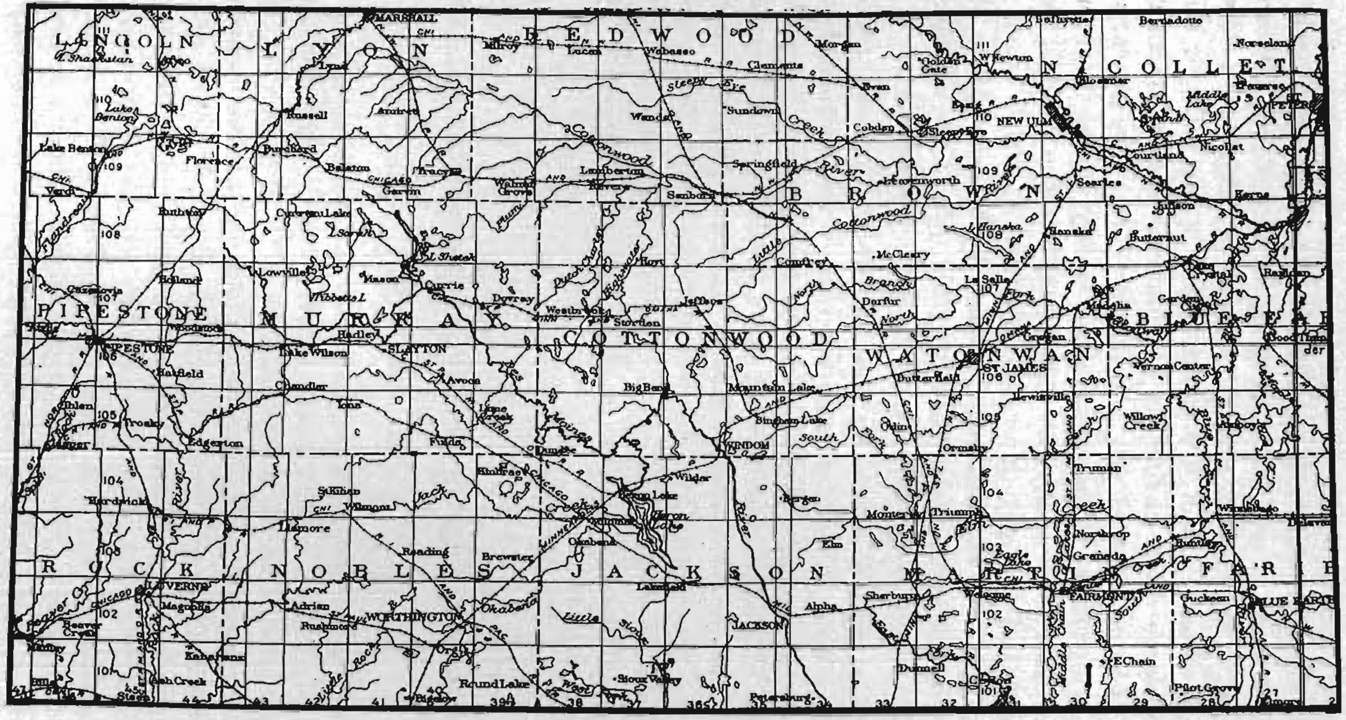
Growth of the Stream.—In the preceding paragraphs attention has been devoted chiefly to valleys, but it has been made plain that these owe their origin and development to running water, or streams. Normally valleys begin by the work of wet weather torrents and are dry between rains or rainy periods. But by and by, as these torrents cut deeper valleys, water stands in these valleys or flows through them during a greater portion of the year, and with the continued growth of the valleys they come to have permanent streams. How is this brought about?

We know that if we dig a well water will fill it to a certain level. If other wells be sunk near by through similar material water will rise in them to a similar level. This level is known as the ground-water level or water table. The surface of the water table partakes somewhat of the irregularities of the topography, rising under the uplands and sinking beneath the valleys. But it is not so near to the surface under the hills and may rise to the surface of depressions, creating swamps and lakes, or if the depressions have outlets, allowing the ground waters to flow away as streams. The ground-water level rises in wet weather and sinks in dry seasons as is known to anyone who has had experience with wells. Now when a valley is cut down to the ground-water level the valley will have a stream which is permanent so long as the water table maintains its level. If during the summer months the water level sinks below the valley the stream dries up until the water level rises again.

Below the water-table the rocks are saturated to unknown depths. It has been estimated that the ground water in the upper 100 feet of the earth's crust in the humid regions is equal to one-fourth of the volume of the subsoil and rock and that it represents six or seven years' rainfall. It is equivalent, therefore, to a reservoir twenty-five feet deep and having an area equal to that of the humid regions. Since the annual rainfall in Iowa is about thirty-one inches, this reservoir represents ten years' rainfall. The ground water is supplied by rains and represents that portion of the rainfall which soaks into the soil. Another part is evaporated while a third portion flows away at once into the streams as the run-off.

The different parts of a large valley will show various stages in the development of the stream. Des Moines river, for instance, is permanent in the driest seasons from its mouth to the forks at Humboldt and both branches flow continually many miles above here. So at Algona on the East Fork the valley contains a permanent stream but at Armstrong during the dry summer of 1911 only disconnected pools occupied the lowest hollows of the channel. Similarly, on the West Fork there is a never failing stream at Estherville but at Windom, Minnesota, the channel was dry except for isolated pools during the dry season mentioned, while in the extreme upper reaches of the valley above Lake Wilson, in Murray county, there were scarcely any pools and the tiny channels of the river's feeders are occupied only by wet weather rivulets.

Work of the Stream.—The great work of streams is the cutting down of the land and carrying it to the sea. The manner in which streams work during the stages of their development has been indicated in the discussion of Valleys. The ability of flowing water to push or carry solid material is shown by every stream. This ability varies with the slope or gradient of the bed and with the volume of water, both of which factors affect the velocity. Hence the working power of the stream's tools—the materials it is carrying in suspension—is enormously increased with added velocity. In addition to carrying matter in suspension the stream also carries much in solution. Des



Map of southwestern Minnesota.

Moines river is estimated to carry to the Mississippi each year 5,130,000 tons of solids in suspension and 2,480,000 tons in solution. This indicates that its basin is being worn down at the rate of one inch in 370 years. This is much faster than is true of some other basins, as for instance that of Iowa river, which is being lowered one inch in 980 years. The average rate for the lowering of the Mississippi valley is one inch in 510 years. Of course much the larger part of the river's load is gathered and brought in by the tributaries, which reach back into all parts of the drainage basin. While some parts of the basin are being cut down rather rapidly others are affected but slightly; hence the general level is altered but little.

Weathering.—Weathering aids the direct work of streams in several ways. Freezing and thawing of the contained water expand and loosen soil and rock and this process is aided also by roots of plants. Rains wash down the loosened material into the streams and it is carried away. Rain and ground water also dissolve out a portion of the rock through which they pass and this finds its way to the sea. All these agencies, and others, help in cutting valleys and in reducing the whole land surface towards base level.

CHAPTER IV.

PHYSIOGRAPHIC FEATURES OF DES MOINES VALLEY

The East Fork.

The Upper Valley.—The East Fork of Des Moines river rises in the prairies of southwestern Martin county, Minnesota, at an altitude about 1350 feet above sea level (Plate XXXI). It is a typical prairie stream of the Wisconsin drift area, meandering across a flat sag, five or ten feet below the prairie level and one-fourth mile wide near its mouth. The gradient of the stream is so gentle that it has been necessary to straighten the channel to increase its capacity. After a course of about fifteen miles the valley opens into Alton lake, a picturesque sheet one and one-half miles long. Alton lake is connected by a short stream with Tuttle lake which is crossed by the state line. It covers about

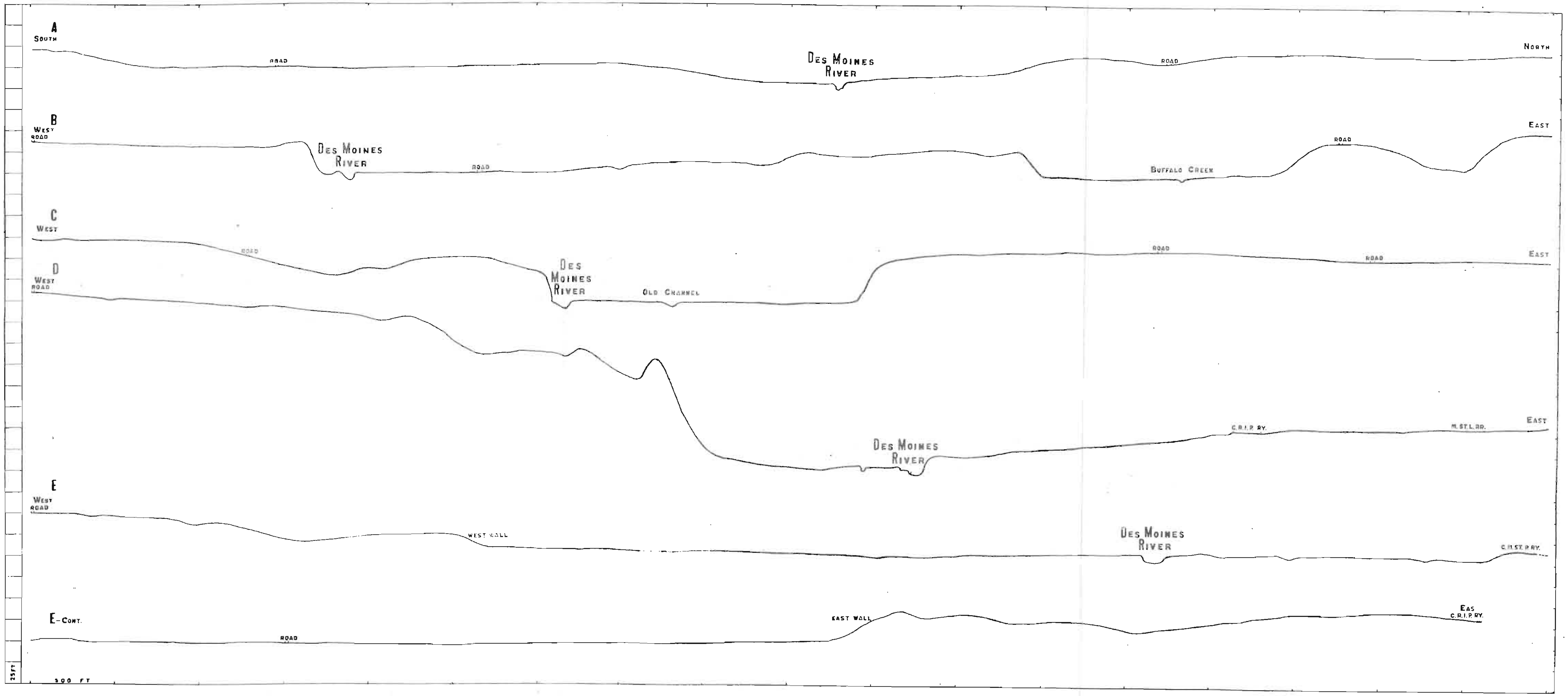
Map of Des Moines valley from Minnesota line to Fort Dodge, Iowa.

four square miles and like Alton lake is bounded here by gentle slopes; there by steep though not high bluffs. The shores are wooded and form attractive spots for summer camp-grounds. See Plate XXXIV, A.

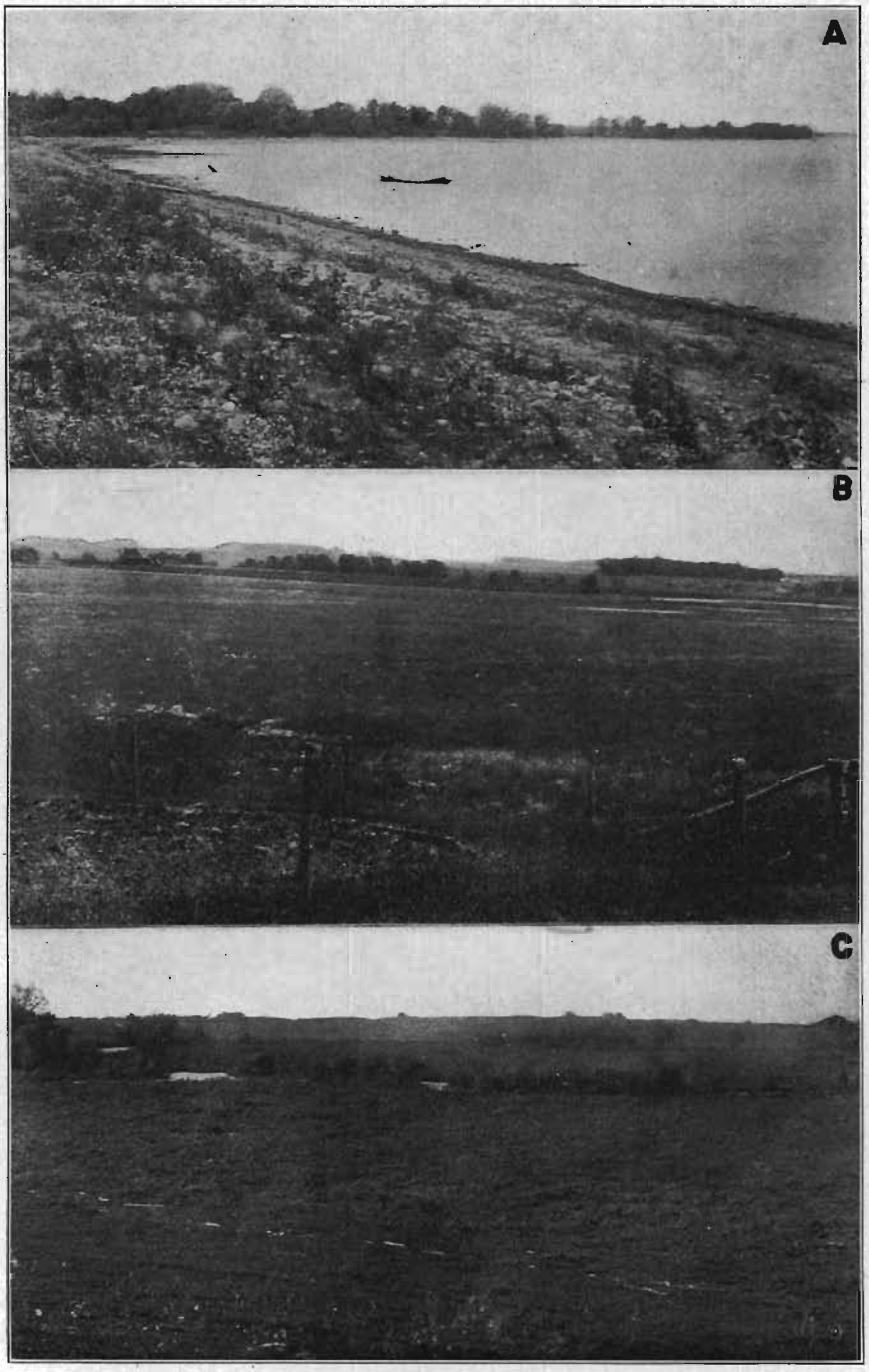
The outlet of Tuttle lake has been cut in the bottom of a broad sag which stretches southward from the southeast corner of the lake. During the very dry weather of the summer of 1911, however, the lake level was two feet below the bottom of the channel. The sag confining the stream—when there is a stream—is one-fourth mile wide and in wet weather is swampy, although the shallow channel is well defined. Where the valley cuts through a range of morainic hills, in southeastern Lincoln township, Emmet county, it is deeper, twenty to forty feet below the hilltops, and shows fairly steep walls. It is everywhere quite wide and flat-bottomed, much too large and well-developed to have been made by the present stream. Soldier creek, which drains Tremont lake in northwest Lincoln township, shows similar features—an insignificant stream in a broad flat sag, except where a morainic knob juts into the valley and forms a steep slope ten or fifteen feet high.

It seems to be a characteristic feature of the upper course of the East Fork that on one side the valley is bounded by a rather steep bluff which faces a long gentle slope reaching back half a mile, a mile, or even two miles to the prairie level. For instance, just southwest of Armstrong the north bluff is fifty feet high and very precipitous, while the south wall slopes back a mile before it reaches this level. Where the road leading south from Armstrong crosses the river the flood plain is forty feet below the station. In many places, however, the bluff is absent and there are present merely the two long gentle slopes, so that the stream occupies a depression a mile or two miles wide.

In several places, notably in the central and southeastern parts of township 99, range 31 (see Plate XXXII), the morainic knobs flank the stream on both sides and so form a rather steep-walled valley. The stream here makes several wide detours as if it were forced to wind about among the hills to find an outlet for its waters. After the stream emerges from these morainic



A. Profile of the valley of East Fork of Des Moines river about two miles south of Bancroft, Kossuth county. B. Profile of the valley of East Fork of Des Moines river and of Buffalo creek just above their union, east of Burt, Kossuth county. C. Profile of the valley of East Fork below the mouth of Buffalo creek, one mile south of B. From the east end of the profile the surface drops 5 feet in 1000 feet, then rises 10 feet in 3000 feet. From the west end of the profile the surface drops ten feet in one-half mile, then rises five feet in one-half mile, thence is level to Burt, one-half mile. D. Profile of the valley of West Fork at Estherville. East of the profile the surface rises 27.5 feet in 6950 feet, then sinks to Brown creek. E. Profile of the valley of West Fork at Emmetsburg.



A. Tuttle lake, on the state line. B. Des Moines valley two miles south of Bancroft. The railroad bridge at the left crosses the river. C. Buffalo creek valley opposite the junction with Des Moines river.

hills its valley shows, in western Kossuth county, features similar to those seen in the more level portions of Emmet county, namely, very long gentle slopes, with here and there a steep bluff caused by the inroads of the stream upon a morainic ridge or knoll. These latter features, however, are less conspicuous than farther west and are rarely more than twenty or thirty feet high. The cross section profile of the valley just south of Bancroft, Plate XXXIII, A, and the view shown in Plate XXXIV, B, will show how exceedingly gentle the slopes are. South of Bancroft as far as the mouth of Buffalo creek similar conditions prevail, although the valley becomes somewhat deeper, as the profiles taken east of Burt indicate (Plate XXXIII, B and C).

Gravel beds.—Gravel deposits of large extent are quite common in the wide valley, such as the bed opposite Armstrong, one filling the long plain in the eastern part of township 98, range 30, Kossuth county, and an especially noticeable bed two miles southwest of Bancroft. This extends south for one-fourth mile from the river and its probable limit is marked by a slight rise to the prairie level. At the west line of township 98, range 29, a recent straightening of the channel has revealed gravel above yellowish Wisconsin till, and one-fourth mile up stream a pit shows the same succession of materials. Again, a gully close to the railroad bridge crossing the river west of Armstrong shows gravel overlying till, which in turn rests upon rusty gravel which perhaps is to be correlated with the Buchanan gravels (page 452, Plate XXVIII), although it may be interbedded Wisconsin gravel. These exposures indicate that after the Wisconsin glacier had spread out its sheet of till and had melted back until its edge stood a little north of our immediate region, floods from the melting ice brought down great quantities of gravel and dropped them on top of the drift in this sag, which served as an outlet for these glacial waters.

Origin of the Valley.—It seems evident that the upper portion of the East Fork, and its tributaries also, (1) have done much more erosive work in the past than they seem capable of doing now, or (2) the valleys in which they flow are constructional in origin, or else (3) the streams have sought out courses or parts of courses of pre-Wisconsin streams which were not entirely obliterated by the till of the last ice-sheet, and are utilizing these for their present valleys.

With regard to the first of these hypotheses, it will be seen that whatever erosion might be accomplished in late Wisconsin time by flood-waters from the melting ice-sheet would be more than counteracted by gradation through deposition of the vast loads of silt, sand and gravel carried by these waters. We might attribute to this gradational process, perhaps, in some cases, the excessive width and very gentle side slopes which these valleys present today, but this leaves no room for the effective erosion of young valleys which must have preceded gradation.

As to the second theory, it will be understood that the ground moraine had a more or less irregular topography. Drift was heaped up here, while depressions were left there. The drainage waters from the Wisconsin glacier during the retreat of the ice margin naturally sought out the easiest path and so made use of depressions. Thus in the morainic region of Emmet and Kossuth counties the new-born Des Moines wandered about among the hills, and the path thus originated has been slightly better defined and more accentuated during subsequent time. Elsewhere, in the more level regions, the escaping waters found the broad shallow sags which lie between the low swells of the prairie, and put them to use. The question may be raised as to the sufficiency of such sags, in number and arrangement, to form a continuous valley. It is not necessary to suppose that they were entirely continuous. The early streams as they sought their way from one swale to another may be assumed to have cut away some obstacles to a clear channel.

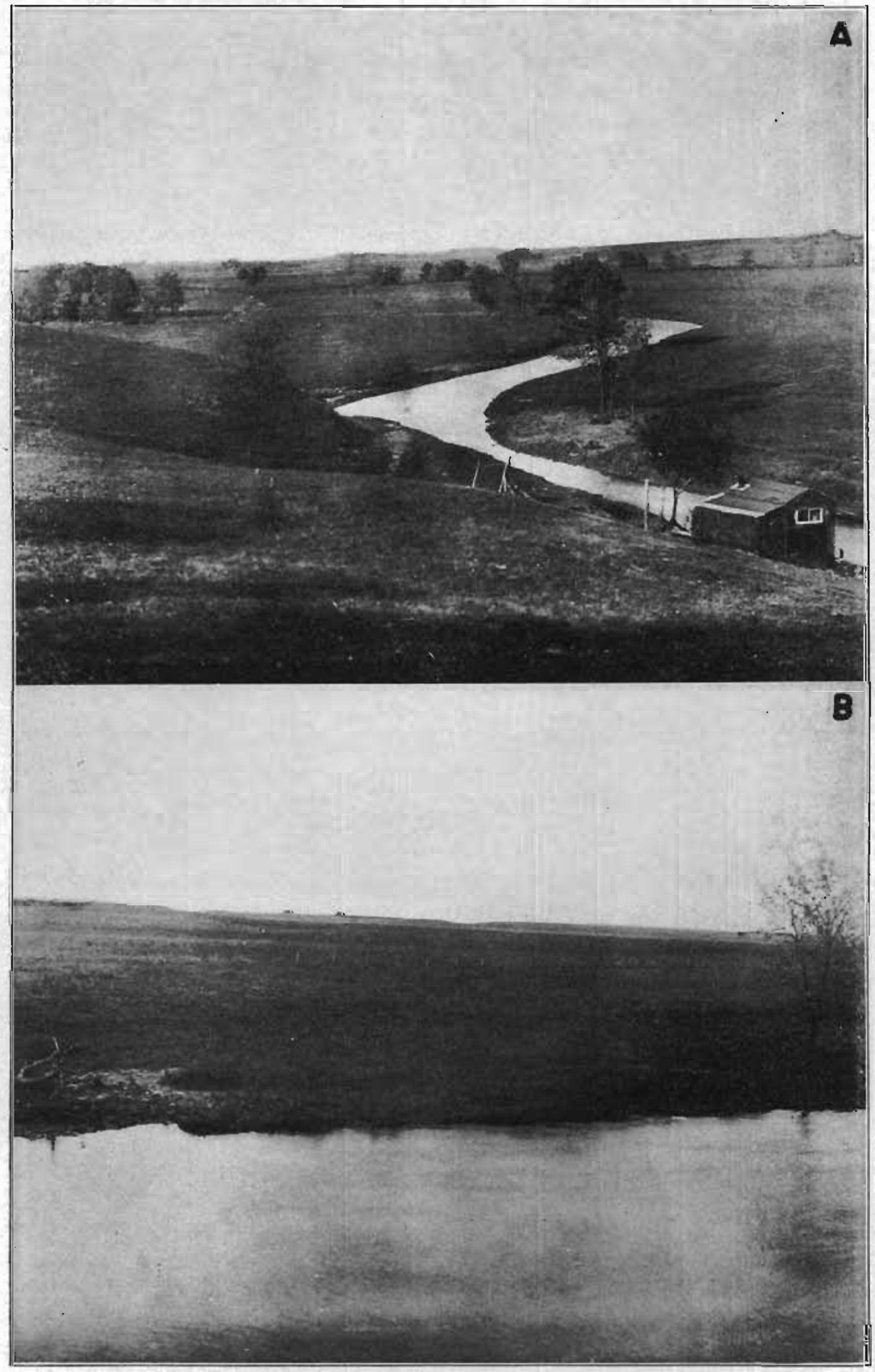
It is quite possible that the condition to be outlined in the third hypothesis may have aided in the formation of valleys; that is, some of the older stream courses were again made serviceable through their incomplete filling with drift and also to a less extent, perhaps, through the greater settling of drift in the valleys than over the upland owing to its greater thickness in the valleys. How important these factors have been can not, of course, be told without a thorough knowledge of the relations of the different drift-sheets and the underlying rock. For reasons which will be explained later (see page 477) it does not seem likely that these conditions held to any great extent.

Considering all the evidence available it seems probable that by far the most important factor in the initiation and development of the upper valley of the river and the valleys of its tributaries has been the use of constructional valleys. The streams from the ice-front took advantage of depressions in the drift-sheet, scoured these out to some extent and then in many cases filled them up again, as shown by the bodies of gravel bordering the streams. Macbride repeatedly has emphasized the fact that in this part of Iowa drainage—or the lack of it—is determined by topography, rather than the opposite, and this is nowhere better shown than in the valley of the East Fork. The streams have not formed the topography but have been imposed upon one that had been created before they came into being. Hence the valleys are variable, they change in character from point to point and are not definite, fixed features of the landscape as is true lower down the course of the Des Moines.

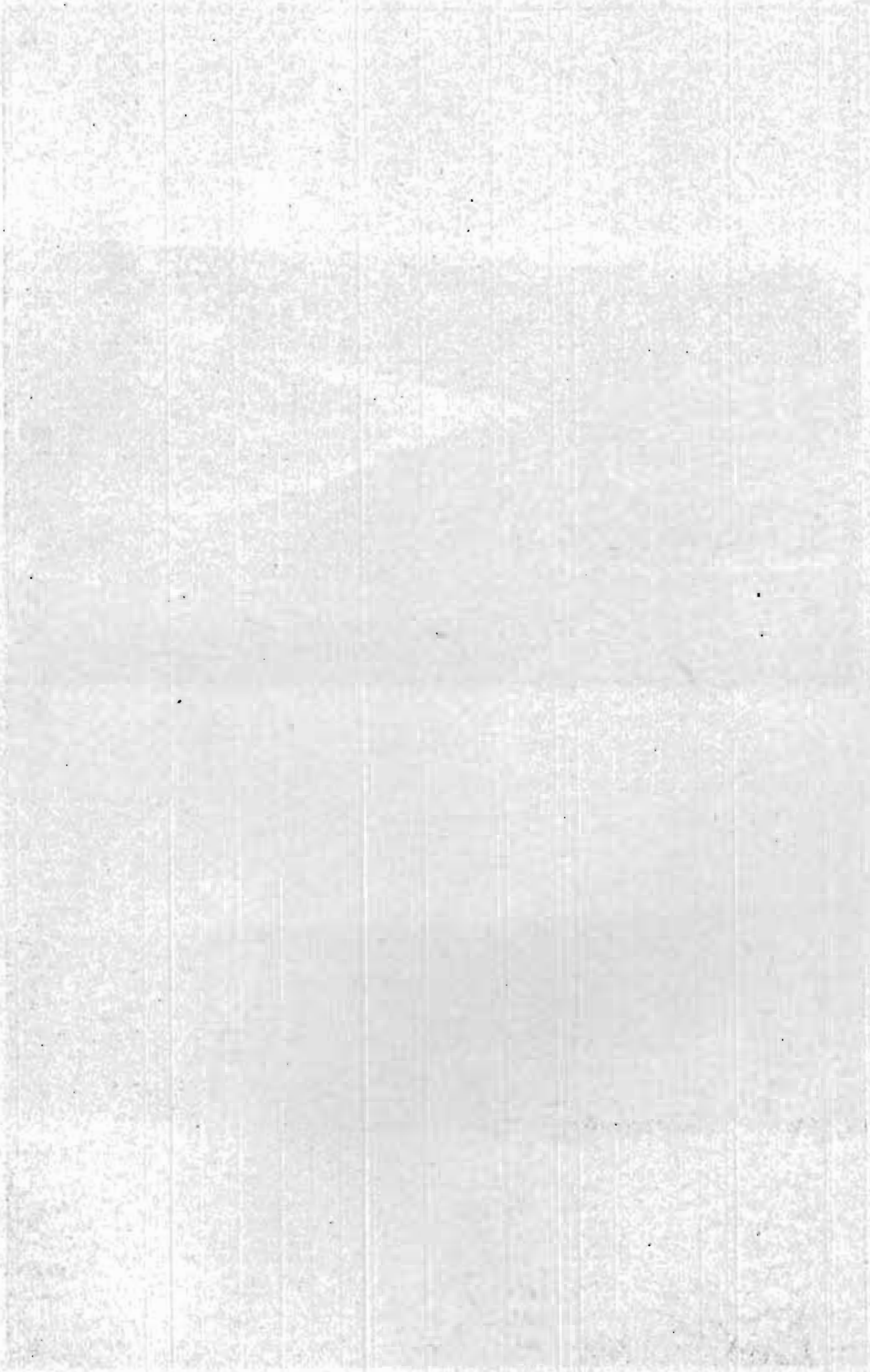
But below the mouth of Buffalo creek (Plate XXXII) there is a marked change in the character of the valley. The broad shallow sags give way to a wide, flat-bottomed valley bounded by fairly steep, well-defined slopes rising at angles as high as 20° or more. See the profile of the valley east of Burt, Plate XXXIII, C. These slopes are not merely the result of the undercutting of morainic hills, but they represent the actual depth of the valley below the general upland level. This is now a normal mature valley, albeit incised in a plain still in its early youth, and as such it continues as far as Algona.

Buffalo Creek and Union Slough.—In order to understand this very significant change in the valley we must examine the lower course of Buffalo creek. The profile taken across Des Moines and Buffalo valleys above their union, Plate XXXIII, B, and the views shown in C of Plate XXXIV, page 469, and A and B of Plate XXXV show that the valley of the creek is as wide as that of the master stream, and much better defined. The stream itself, while not large, is nearly as important as the East Fork before the two unite. This condition remains true as far as a point two miles above the mouth of the creek, where it makes an abrupt turn from the east to the south. See Plate XXXII. At this point there opens into the creek valley a long flat depression one-eighth to one-fourth mile wide, and limited laterally by clearly defined, rather gentle to fairly steep walls twenty to thirty feet high. See Plate XXXV, A. In fact it is an almost exact duplication of the lower valley of Buffalo creek, except that here it contains no stream channel. This is Union slough, and in its northern stretches rise the headwaters of one of the forks of Blue Earth river, which drains into Minnesota river. The slough retains similar characters as far as the state line except that here the walls are somewhat lower and the floor is better drained by Blue Earth river. The width is fully as great at the state line as at the junction with Des Moines river and the bottom is practically as level.

Above the mouth of the slough the valley of Buffalo creek is narrower and it rises until within a few miles it is not over ten to fifteen feet below the general level of the plain. It is a typical prairie stream, like the upper reaches of the other creeks of the region. Union slough on the other hand, is not a typical prairie slough. It is far too deep and too well defined. It is very evident that Union slough, Buffalo creek below the mouth of the slough, and Des Moines river below the mouth of the creek are occupying an ancient valley, one which they found ready to hand when their careers began, after the region was uncovered by the melting of the Wisconsin ice. But this valley differed from those now used by the Des Moines and its feeders above the mouth of Buffalo creek in being an erosional valley rather than constructional. The fact that no stream at all has yet formed in the southern part of the slough, coupled with the great discrepancy between Buffalo creek valley below the slough and the insignificant streamlet which now occupies it, shows that post-Wisconsin drainage can not be held responsible for the



A. Looking up Union slough from its mouth. Buffalo creek crosses along the line of trees. B. The long gentle wall of Des Moines valley a mile above its union with Buffalo valley.



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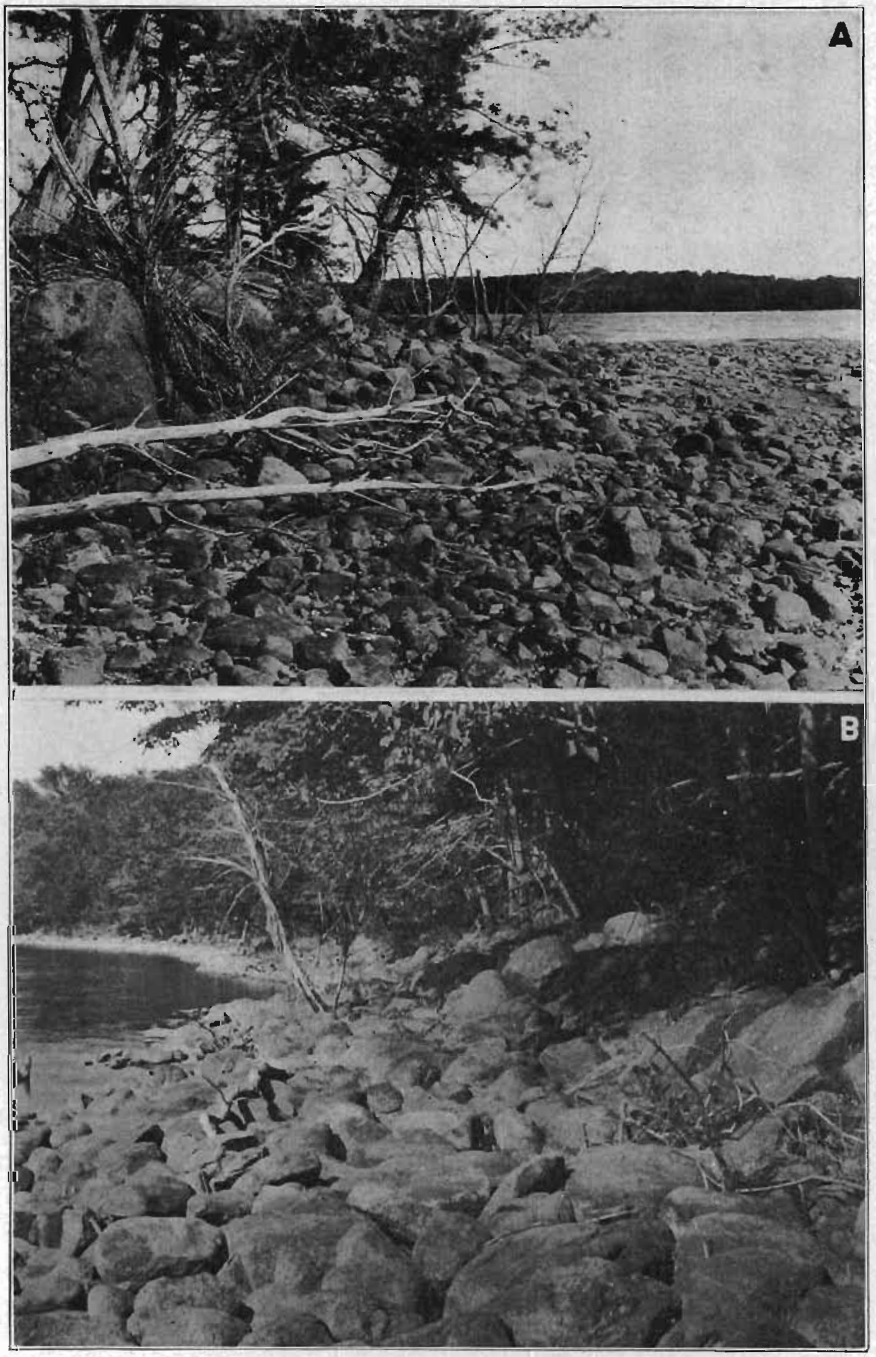
very mature features of the valley, and the same is true in practically the same degree of the Des Moines and its valley below the junction.

It was stated above that the use of old valleys probably was not responsible to any extent for the features characterizing the Des Moines and its tributaries above the union with Buffalo creek. If we assume that such use does account for the really remarkable features of Union slough, Buffalo creek south of the slough, and the East Fork below the junction, and we are seemingly driven to that assumption, it is easy to see why the same condition could not have held good for the upper part of the main valley. Post-Wisconsin stream erosion, sidewash and weathering have not been sufficient to develop an erosion topography on the Wisconsin plain and could not have produced either type of valley we have before us—the broad sag or the well-defined flat-bottomed valley. Furthermore, the differences between the two types are so great that they can not be the result of the same forces acting during a similar period of time, and we can not think that two regions so close together were subjected to different conditions. The one agent to whose work we can assign such a valley as Union slough is erosion during the long post-Kansan or possibly post-Iowan epochs, preceding the Wisconsin invasion. When the last ice-sheet covered north-central Iowa, it was unable to fill all of the valleys and this one, then as now one of the largest, was left with only a veneer of Wisconsin till over its slopes and upon its bottom-lands, to be alternately filled and scoured by the rushing waters from the melting ice.

After studying the Wisconsin moraines and till sheet in Iowa and Minnesota, Mr. Warren Upham decided that Union slough marks the outlet of a glacial lake which covered parts of Faribault and adjacent counties in Minnesota during the retreat of the Wisconsin ice, and which later found a lower outlet to the northeast by way of Cannon and Minnesota rivers.

The Chain Lakes.—A similar case, but one in which Wisconsin filling proceeded somewhat further, is found in the Chain lakes of Martin county, Minnesota (Plate XXXI). Three diverging series of lakes extend from the Iowa line in Emmet county northward and northwestward across Martin county. The East and Center Chains are well connected for the most part and drain into creeks flowing east or northeast into Blue Earth river. The West Chain, of which Tuttle lake is the southernmost and largest, is not so well connected. The Center Chain is the most remarkable. See Plate XXXVI. It extends in an almost perfectly straight line for more than twenty miles and includes twenty lakes. These lakes are bordered by undulating expanses of till which rise thirty to fifty feet above their shores, and while the depression in which they lie has not a uniformly level floor its valley-like shape is too prominent to escape even casual observation. Mr. Upham concluded that these three converging chains, the western one with a branch on either side, occupy the valleys of interglacial rivers whose waters flowed southward into the East Fork of Des Moines river. The convergence of the chains southward seems to indicate that the interglacial streams flowed in that direction. One of the strange results of glaciation is shown in the fact that the present drainage of Martin county is to the north and east, except for that part which drains into the East Fork, and southward through Tuttle lake. Possibly, however, the uplift of northwestern Iowa referred to on page 459 is partly responsible for this change. In any event the traces of this pre-Wisconsin drainage in Iowa have been wiped out entirely, unless it be for the present system of the Des Moines. For reasons before given it is not thought that the upper part of this system dates back of the last ice invasion. Hence the pre-Wisconsin drainage course extending southward from the Chain lakes could not have followed the same lines as those now followed by the East Fork. There is a possibility that the West Fork of Des Moines river, in some part of its extent, is utilizing a fragment of this pre-Wisconsin water-course. With this hypothesis in mind the most attractive point at which to locate the union of the post-Wisconsin Des Moines valley with the pre-Wisconsin Chain lakes valley is near the northeastern corner of Pocahontas county. The discussion of the evidence can be given best in connection with the description of the West Fork. See page 509.



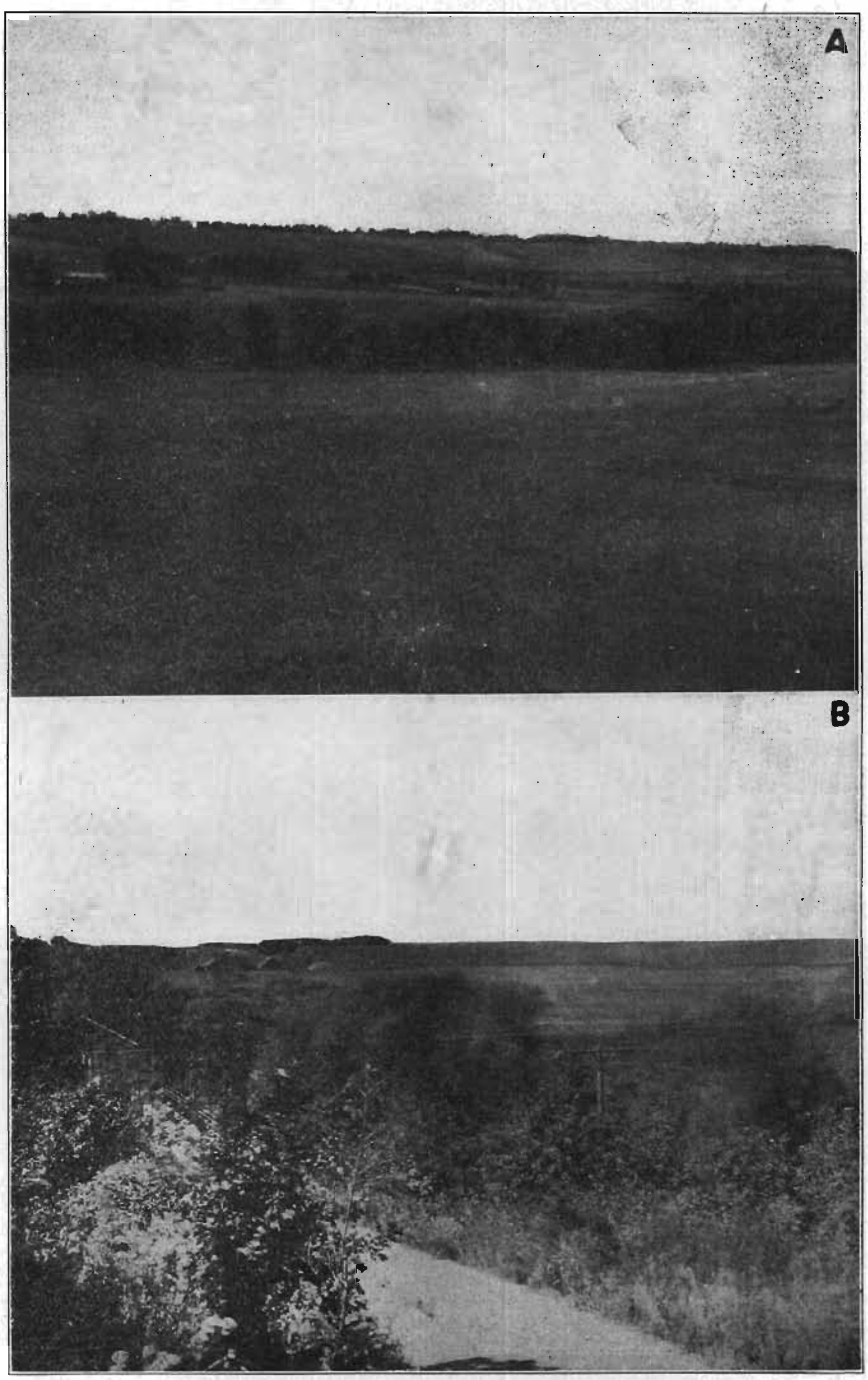
A. The natural riprap on Silver lake, one of the Middle Chain, a mile north of the Iowa line. B. The "wall" of Silver lake. The views show the effect of ice-push and erosion of the banks.

While we may accept Upham's statements regarding the mode of origin of the Chain lakes and the Wisconsin history of Union slough, there seems no sufficient reason for regarding them to be of different age and development, as is held by Mr. Upham. Their characteristics and similarities of form are so striking as to point to the conclusion that they are both of pre-Wisconsin age, but that during Wisconsin time Union slough was kept open by serving as the outlet of a glacial lake while those valleys which now are occupied by the Chain lakes, being in a region of greater deposition, were so far choked with drift as to render them useless as waterways, at least so far as southward drainage was concerned.

The Valley Below Buffalo Creek.—The valley of the East Fork presents some rather peculiar features between the mouth of Buffalo creek and the Kossuth-Humboldt county line. Below the mouth of the creek the river swings to the southwest as far as Algona, where it suddenly turns upon itself and pursues a southeastward course to Irvington. At this village there is a sharp bend to the west, followed by an equally abrupt one to the south two miles farther west, whence the course is direct to the county line. Above Algona the valley is wide, with much alluvium covering its flood plain. In places the walls are rather steep, elsewhere they are fairly gentle. In the vicinity of Algona the east wall especially is cut by ravines into a series of ridges and is choppy and rough. The valley is still quite wide, however, nearly one-half mile, but narrows somewhat toward Irvington. All along here the sides are rather steep and the flood plain is well defined. At Irvington the bluff where the river impinges upon it is fifty or sixty feet high. Embraced in the bend of the stream opposite the village is a long, gently sloping plain built up of sand and gravel, and facing the river from the east after it turns southward a long, rather high terrace of the same material separates the valley wall from the present channel. The wall is very distinctly outlined, by a bluff-face along much of its extent, and the terrace is lower near this face than near its free edge. Several large oxbow lakes fill remnants of old channels in the wide valley.

Here, then, are several features which require explanation. Doctor Macbride, in his study of this region, assumed, as is done here, that the valley above Algona is pre-Wisconsin. But he states that "at Algona the channel seems to have been pushed west by the drift," and cites as evidence the fact that the valley, on the east side, "is flanked by narrow choppy ravines." However, the ice-movements were from the north as shown by Macbride's map of Kossuth county, and hence would have affected the valley uniformly rather than have tended to push it to one side locally. If the pre-Wisconsin valley swung westward here there might have been some increase in the deflection, though this should be manifested in the immature character of the west wall, a condition which does not exist. The long smooth slopes of this wall are shown in Plate XXXVII. The fact that the river here flows near the east wall probably has influenced the formation of ravines along that side. The statement that "the valley is here new and narrow" does not seem to the writer exactly to fit the facts, since his own repeated observations led him to conclude that the appearance of the valley here is as mature as those parts above or below the city, and the width of the flood plain—nearly one-half mile—is as great as that above the town and greater than that above Irvington. The profile of the Chicago, Milwaukee and Saint Paul railroad gives a width of three miles for the depression west of Algona, though this exaggerates the actual width of the valley a little on account of the oblique direction in which the railroad crosses it.

On his map of Kossuth county Macbride has drawn a line from Saint Benedict through Irvington to Whittemore, which marks the "border of a glacial advance not characterized by conspicuous morainic deposits." This border is shown in the field by a low terrace forming the edge of the *coteau,* which faces the south and crosses the river just above Irvington. When the edge of the ice-field lay here, the valley must have been taxed to its utmost to contain the floods which issued from the glacier and we may readily ascribe to these floods the great amounts of sand which fill the elbow in the valley at Irvington.



A. The valley of the East Fork three miles north of Algona. B. The valley of the East Fork at Algona. These show the wide valley with fairly gentle walls.

The great terrace occupying the eastern edge of the valley southwest of Irvington doubtless had the same origin. These floods with their loads were not able to obliterate the old valley but they did make some important changes. The bend of the river at Irvington was pushed to the southeast by partial filling of the valley, or other obstruction, so that the stream now impinges on its east wall, while the bend to the west was forced farther westward and the stream which had flowed in an almost straight direction between the site of Algona and the county line, was forced to adopt a sinuous course to escape being overwhelmed altogether.

Very possibly the narrowness of the valley for some distance above Irvington is to be attributed to the effect of this minor glacial advance. There are no deposits of sand or gravel above the line of the coteau, the valley is cut in drift, and even if it was not drift-filled by the secondary advance it may have been narrowed materially.

At the county line the flood plain is one-half mile wide, but below here it narrows somewhat though it is still one-fourth mile wide at Livermore, and maintains this as its normal width along the remainder of its course. The river meanders across its flood plain, and here and there it undercuts and forms steep banks, such as those just northeast of Livermore and those southeast of Dakota, but elsewhere it leaves the valley walls rather long and gently sloping. For the most part these lie at angles not higher than 10°. All along its course the valley sides are covered by patches of timber which alternate with bare, grass-covered stretches of prairie. In places along the lower course of the river the flood plain bears upon its surface ponds which probably are remnants of old channels abandoned through the swinging of the river from side to side. Very abundant in the lower course also are bowlders, some of which are four to six feet in diameter, and which locally are so numerous as to form reefs across the channel.

Tributaries.—There are very few tributaries entering the East Fork, not only in its upper course, but along its entire extent. See Plate XXXII. Mud creek is one of the few, and it is typical of those which join the main valley above Buffalo creek. It enters the larger valley south of Bancroft and presents phenomena common among these tributaries—a minor stream in a widely expanded shallow sag-valley; an infant in adult dress, as it were.

The few important creeks which enter the valley below the mouth of Buffalo creek—Lindner and Plum creeks from the east and Black Cat, Fourmile and Lotts creeks from the west—share in the change of character which the valley of the East Fork has undergone. The lower courses of their valleys possess wide bottom lands bounded by mature side slopes, although farther back they are typical shallow prairie water-courses. The lower courses of even the minor tributaries have mature valleys showing flat bottoms and very broadly arcuate cross sections. It will be clear that no matter how small a tributary stream may be the tendency is for it to keep pace in the development of its valley with that of its master stream, so long as the latter passes through only the normal stages in valley-making. Therefore we would expect the valleys of these creeks to present mature features in their lower parts, though they are but very young prairie swales in their upper parts. If, however, an accident happens to a master stream, such as the passage of a glacier down its valley, this may be cut down so rapidly that the tributaries can not keep pace with it and are left as "hanging valleys." This is what has happened to the Yosemite Valley and what has given it such charming grandeur and picturesqueness.

During dry summers the smaller streams disappear, except for the underflow as revealed by the waterholes, and even the larger valleys are dry except near their mouths. Where the walls of the East Fork are steep they are cut by numerous ravines which generally are short and steep-sided, with very high gradients, and which carry no water except in time of rain. Many of these ravines are wooded and all of the tributary valleys have more or less forest filling for some distance above their mouths.

Like their master stream, those tributaries which join the main valley below its union with Buffalo creek, seem to have found remnants of pre-Wisconsin drainage courses, at least so far as their lower reaches are concerned. Their valleys are far too mature to belong to the same erosion cycle as the undrained Wisconsin plain surrounding them. It is not uncommon upon ascending a road leading out of one of these valleys and before one is fairly upon the plain to see an undrained kettle hole or marsh by the roadside. If these valleys had arrived at such a degree of maturity by post-Wisconsin erosion alone they should have developed also a well-defined system of lateral drainage—the dendritic form should have been assumed by this time. But this is far from being the case. The upland immediately adjacent to the river shows all the characters of the unmodified Wisconsin plain and is practically as high as that farther back from the valley's edge. Hence it is possible to look across the valley from a short distance and see no signs of its presence. The hills and plain along the horizon seem continuous with those in the nearer distance. The long gentle slopes reaching back from the stream a mile or two miles or even three miles which characterize some parts of Kansan drift areas, are here conspicuously absent. Evidently the Wisconsin ice, while failing to fill the major valley, succeeded in obliterating the minor drainage lines except the lower portions of a favored few. Therefore, when stream work began anew the main valley already was well developed, but lateral drainage had to start from the beginning, or nearly so. Hence its present immaturity.

Rock Outcrops.—South of Humboldt and Dakota the East and West Forks run nearly parallel, separated by a high tableland about a mile wide, as completely uneroded as if the rivers were miles away. In several places along the river's edge near Dakota there are outcrops of limestone, identified by Macbride as Saint Louis, and lower down, notably at the Minneapolis and St. Louis railroad bridge, there are shales and sandstones of Des Moines age. These are considered by Macbride as filling a valley eroded in Saint Louis limestone. No outcrops of rock *in situ* are known along the East Fork north of Dakota. Three miles south of Dakota the valleys unite, and the two forks mingle their waters in the common flood. The nose of the tableland slopes down to the valley and a great bed of sand and gravel fills the flood plain between the two streams.

The West Fork

The Upper Valley.—The West Fork of Des Moines river rises in upland meadows among the morainic knobs of the crest of the *Coteau des Prairies* on the border between Pipestone and Murray counties, Minnesota (Plate XXXI). The *Coteau des Prairies,* so called by the early French explorers, is the high rough land representing the outer terminal (Altamont) moraine which marks the western edge of the Wisconsin glacial lobe in South Dakota, Minnesota and to a less extent in Iowa. Several small creeks which rise in springs and tiny lakelets unite in northwestern Murray county to form the headwaters of the river. The meadows in which these take their origin lie at altitudes of 1800 to 1850 feet above sea while the crests of the hills and ridges about them rise 50 to 100 feet higher.

After winding about among the hills for three or four miles the branches emerge from the moraine and enter a broad sag which extends along its inner edge. On the east this sag rises very gently to the fairly level upland plain, but on the west it is bordered by the knobby region of the moraine.

In its southward extent the sag widens until in the vicinity of Lake Wilson it has a breadth of three to four miles from crest to crest. This swale, and also a continuation of it which stretches north to Redwood river, is similar except for its larger size to those described in connection with the East Fork, and like them doubtless is to be attributed to the irregular deposition of Wisconsin drift, aided in some measure, perhaps, by drainage from the ice. The drainage of this region is still immature as is shown by the presence of the headwaters of three drainage systems—Des Moines river flowing to the Mississippi, Redwood river to the Minnesota and Rock river to the Missouri—all within a small area upon the crest of the Coteau des Prairies, while there is undrained territory between and around them. In fact the topography of all the region east of the moraine is quite youthful. Very little drainage has been developed. On the west of the Des Moines sag-valley is the moraine with its constructional knobs and undrained marshes, while to the east stretches the great plain of Wisconsin drift with very few streams and with very little erosion yet accomplished. An instance of this immaturity is given by Lake Wilson, near the town of the same name. This lake is on the very margin of the great swale in which lies Des Moines river, it lies at a similar level and is separated from it by a ridge less than ten feet high. Nevertheless it is drained to the south into Chanarambi creek and thence into Rock river.

A short distance east of Lake Wilson the valley, if such it may be called, is diverted by a curve in the moraine from its southeasterly course into a northeasterly one. It extends in this general direction past Hadley and Slayton until near Currie it approaches the inner (Gary) moraine of the Wisconsin drift, by which it is deflected southeast again. It retains its width and shallowness between Lake Wilson and Slayton, north of which town it makes a minor loop to the southeast. While above Slayton the valley is several miles wide, where it again turns northeast it narrows suddenly until it is not much over one-fourth mile from crest to crest. It also becomes quite deep and steep-sided. Beyond the crests the river is of very little force topographically. There are almost no secondary valleys, only a few short steep ravines which run up into the prairies 200 to 300 yards and there terminate.

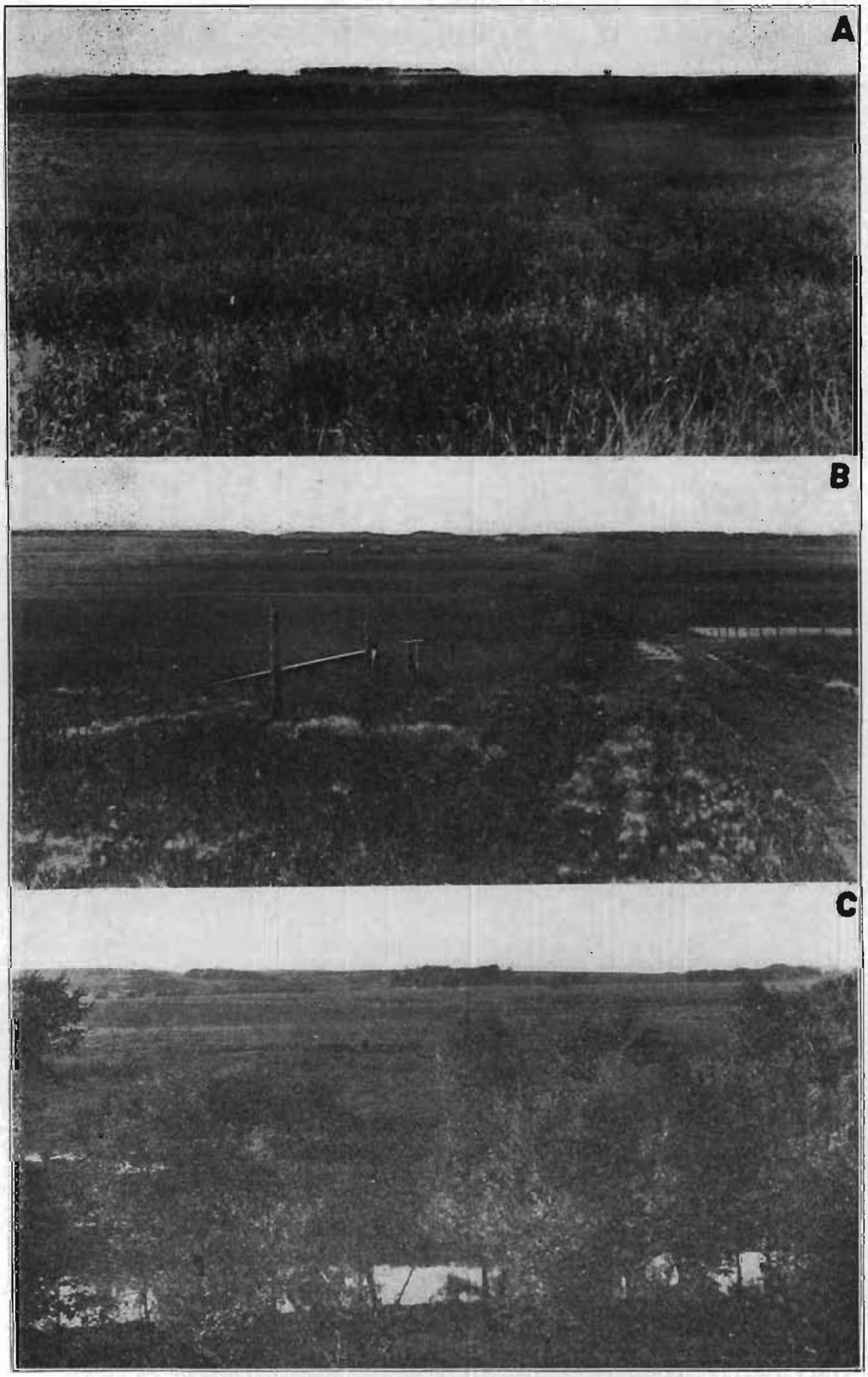
What the cause of this change in the character of the valley may be is not clear. It may be due to topographic causes as there is, near Mason (see Plate XXXI), three or four miles north of the valley, quite a prominent elevation due to drift accumulation. This may be represented southeasterly by a less conspicuous swell which has been cut through by the river. Evidently this part of the valley owes its present condition to erosional activity, in part, at least.

The narrow valley continues within two miles of Lake Shetek, where it begins to widen out, first by the flattening and lengthening of the north wall and then by the same change on the south side. Lake Shetek lies in the outer part of the Gary moraine and its lower end and outlet lie in a broad flat swale with very low, gently rising sides. The upper end of the lake is continued as a long narrow arm known as The Inlet. The lake seems to occupy a depression which is continued to the southeast as the valley of Des Moines river. It empties into the river, when the water level is high enough, by a short channel less than a mile long. Above this outlet the main stream is known as Oksida or Beaver creek; below, it is Des Moines river.

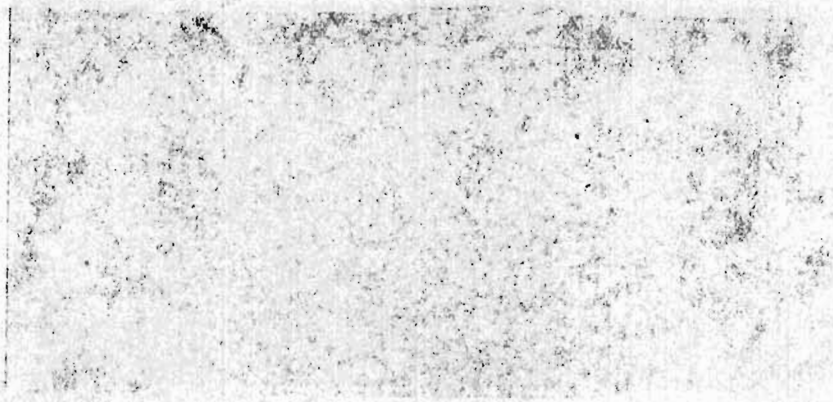
The wide, shallow depression continues past Currie (Plate XXXVIII, A) and across this valley the stream wanders aimlessly back and forth in a shallow channel. In southeastern Murray county the broad sag is so poorly defined along parts of its extent as to render the stream almost devoid of any true valley. This is well shown on Plate XXXVIII, B. In places it is two, three or four miles wide, although not over fifteen or twenty feet deep. Here and there are low, steep embankments, the result of side-cutting, but the sag is the predominating feature as far as the southern line of Cottonwood county. Its floor in places is over a mile wide and practically flat except for occasional low mounds which apparently are built of gravel. Wherever the road is cut into the valley floor, gravel is revealed. It is not very coarse, but is in immense quantities, sufficient for every conceivable purpose for years to come.

In the southwestern township of Cottonwood county several long flat swales open into the valley and some of these are occupied by shallow lakes. Such are Talcott lake, Oaks lake and Clear lake.

The Valley in the Moraine.—Beyond the point where the river turns northeast from the county line its valley changes character. On the north the wall is fairly steep and high, although the southern slopes still are rather gentle. The valley here is clearly marked and well confined, much more so than it is farther west. The stage of sag-valleys is past until the river passes Estherville. This change in character is due partly, at least, to the fact that the river is approaching, and near Big Bend cuts through, the Gary moraine.



A. The wide sag-valley of the West Fork below Currie, Minnesota. B. The wide valley of the West Fork in southeastern Murray county, Minnesota. C. The valley train at Estherville, showing how the wall is buried by gravel.



Immediately upon accomplishing this it turns southeast again, skirts the inner edge of the moraine, except where it cuts through a branch which strikes northward from Windom, and so continues past Jackson, into Iowa and beyond Estherville.

Where the moraine is bordered by the river, south of Big Bend, the ridge rises into great knolls, the Blue Mounds, which appear in profile to be piled upon the otherwise almost level surface. This is especially well shown from the top of the valley wall at the head of the bend, where the Mounds seem to stand out from the plain like western buttes. The valley is about fifty feet below the prairie, and these morainic knobs rise fifty to one hundred feet higher than the upland.

Control of Tributaries.—The control of the character of secondary valleys by the major stream is well illustrated in this general region. Thus Lime creek in southeastern Murray county (where the Des Moines valley is of the wide sag type), lies in a narrow, rather shallow valley even to its debouchure. On the other hand the South Branch of Des Moines river—the outlet of Heron lake—enters the Des Moines (which now is constricted and deepened as it approaches the moraine) by a deep, rather narrow, forest-filled trench. The upper part of the valley is merely a typical broad, very shallow flat swale, opening out of the greater though otherwise similar depression which contains Heron lake. The fact that Little Sioux river rises in a swamp only a mile or two south of the lake shows how imperfect has been the drainage of the Wisconsin plain.

Characterizing the morainic belt where the river crosses it are several rather deep, flat-bottomed swales whose floors are more or less covered with water in wet weather. One of these swales is almost closed near its mouth by the hills, through which it breaks by a mere gap, and beyond which it again widens toward the river. Somewhat resembling these swales, although larger and of different origin, is a great depression which opens into the river valley at Big Bend. It is fully half a mile wide at its mouth and extends northwestwardly about six miles to Lake Augusta, whose surplus waters it carries away by means of a channel known as Honey creek. The valley is well de-limited, its side walls slope up at angles of 10° to 20°, and it is much better defined than is the river valley in southwestern Cottonwood county. Probably it was a pre-Wisconsin channel which served to carry the waters from the retreating glacier, as is evidenced by the filling of gravels in its mouth, and the well developed gravel terraces in the river valley just below the junction. No gravels were observed in the narrow main valley above Big Bend.

Relation to Interglacial Valleys.—The action of the Des Moines in turning abruptly northeast at the north line of Jackson county and cutting directly across the moraine seems, at first sight, quite inexplicable. It would have seemed so much more reasonable had the river continued its course southeast through Heron lake and so to the southward. Mr. Upham, of the Minnesota Geological Survey, formulated a theory by which to explain this anomalous situation. Briefly stated the theory is this: The basin of Lake Shetek, Des Moines valley from the lake to the south line of Cottonwood county, and the basins of Heron, Spirit and Okoboji lakes form parts of a river valley excavated during post-Kansan times and extending along the present valley of the Little Sioux as far south as Spencer and thence eastward to Emmetsburg, where it entered the present valley. This ancient valley was partly filled by Wisconsin drift and the drainage of Spirit and Okoboji lakes and Little Sioux river was diverted to the Missouri. The waters of the more northerly part of this system found an outlet through the newly formed Gary moraine, and being there held in check by the ice front they flowed southward along the inner margin of the moraine.

While it is quite probable that the valley of the Des Moines in Minnesota originated in a manner similar to that suggested in the preceding sentence, it does not seem to the writer that there is sufficient evidence for postulating such a pre-Wisconsin valley as that outlined by Mr. Upham. Every existing element of this hypothetically reconstructed valley, with the exception of West Okoboji lake, is merely a shallow depression in the Wisconsin plain or among the mounds of the moraine. For reasons outlined in connection with the discussion of the East

Fork (pages 471 to 473), these depressions are not thought to antedate the Wisconsin ice invasion. Certainly, there seems to be no basis for tying an ancient river to the Des Moines at Emmetsburg, as there is no change in the character of the valley above and below the city except that due to the divergence of the moraine and the valley as they proceed southward from Estherville. Indeed there does not appear to be any necessity for supposing that the Little Sioux must have joined the Des Moines in pre-Wisconsin times, as is done by several authors. From such study as the writer has given to the valley of the Little Sioux in northern Iowa, he is disposed to assign it a history entirely independent of that of Des Moines river. Professor Macbride has suggested that Beaver creek valley in northeastern Pocahontas county may represent a pre-Wisconsin valley which at one time connected with the Little Sioux in Clay county. It is true that in this general region the Des Moines assumes features which seem to be of pre-Wisconsin age, and this fact apparently lends strength to the hypothesis regarding the age of the creek valley. But the present character of this valley offers no support to the idea that it once connected with the Little Sioux. In its lower part it is simply a fairly wide, flat-bottomed trench cut in drift, and in its upper part it becomes a shallow prairie sag.

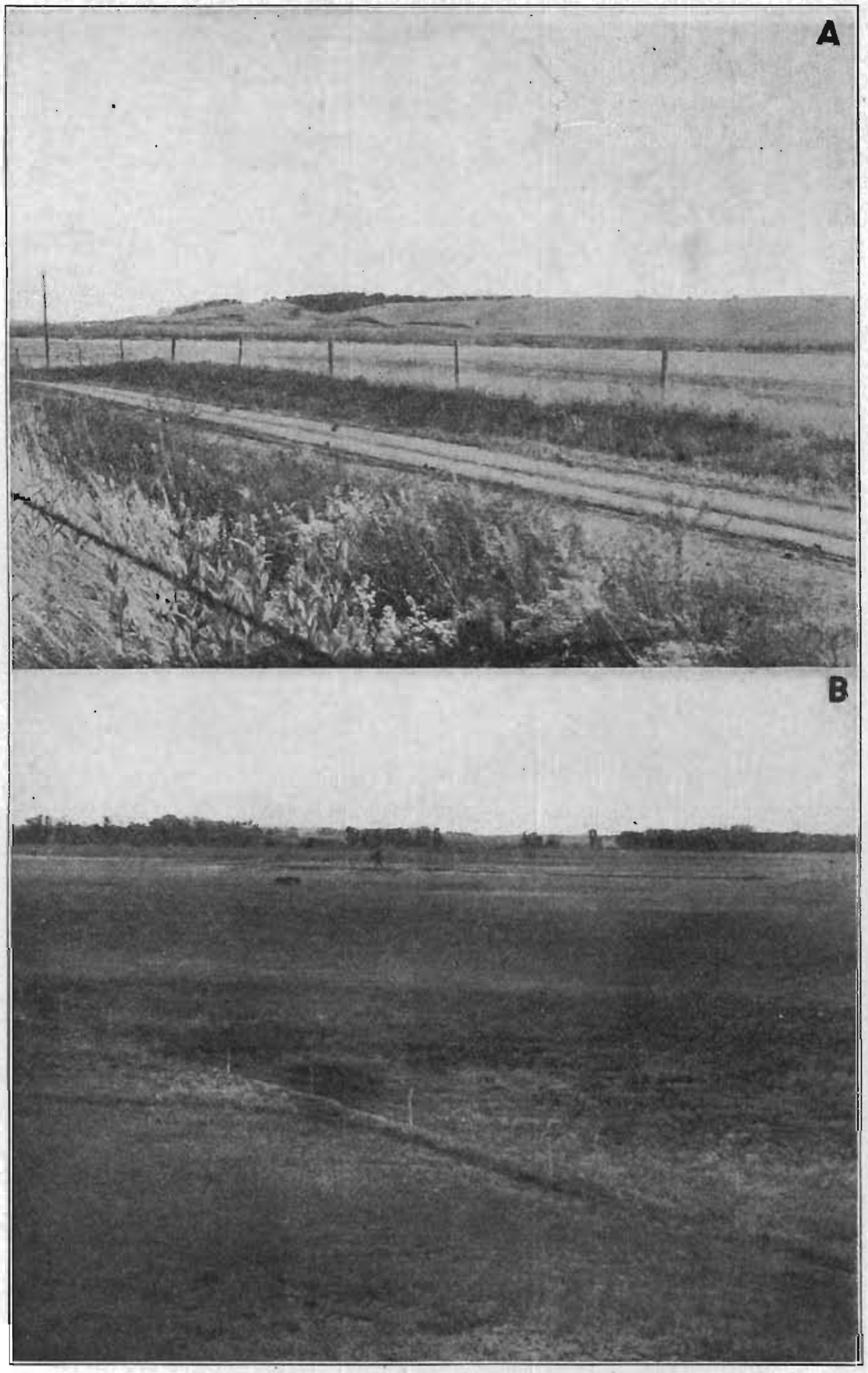
Before leaving this point it may be suggested that very possibly the passage of the river through the moraine north of Windom was helped by the use of one of those deep swales which are still so common here and some of which are low enough and capacious enough to carry the waters of the Des Moines very easily. Once the obstruction was passed the flood waters found the wide sag described on page 493, and utilized it as far as Windom at least. Possibly, too, the slow post-Pleistocene elevation of this region later made it possible for the stream to deepen its channel and to hold its course and avoid ponding. This would account for the depth and narrowness of the valley in the vicinity of Jackson.

Where the valley crosses an arm of the moraine near Windom it is steep sided and narrow. Here lakes are abundant and the topography is quite rough. In this region, too, the valley becomes quite heavily timbered. About six miles above Jackson some ravines on the east side of the river show steep sides and flat bottoms in the lower mile or two of their extent although they are shallow and much less steep-walled above. It is probable that they acquired their size and depth while the Wisconsin ice lay in their upper courses and the waters from the ice passed down them to the river. They may have been partly filled later, when the floods had less carrying force.

Near Jackson the valley has a depth of 100 feet or more and is quite steep-sided. Its floor is less than one-fourth mile wide and the town is built on a series of gravel terraces which reach back to the west for another quarter of a mile. Above the town, similar gravels bank the east wall for fifty feet above the valley floor. The ravines which enter the valley here are deep and narrow and have steep grades but within short distances they become shallow and of low gradient—mere prairie stream-courses. While much of the west wall of the main valley is wooded the east side is for the most part bare, due in part at least to its exposure to the afternoon sun.

Five miles below Jackson the walls begin to diverge and to flatten so that the valley becomes a mile or so in width from crest to crest and at the same time is much shallower. It is only fifty or sixty feet deep instead of one hundred as at Jackson. This condition persists as far as the state line. Between this point and Estherville the country bordering the valley, and especially that on the western side, is morainic, and consequently the river is walled in by a deep valley whose western slopes in particular are rather steep. Just above Estherville the valley contains some prominent gravel terraces, which rise forty feet or so above the stream and have buried the walls to that extent (Plate XXXVIII, C, page 491).

The Valley Below Estherville.—The Des Moines breaks through the morainic belt a little north of Estherville and thenceforward flows along its eastern margin. On this account it is bordered to the Palo Alto county line and beyond by a bold steep wall which is constructional rather than erosional, built of piled-up mounds of drift, knobby and rolling as far as



A. The high morainic west wall a mile below Estherville. B. The wide sag-valley near Ottosen.

the eye can reach (Plate XXXIX, A). The east side of the valley, however, is a long gentle slope, reaching back for a mile or even two miles, and on this slope the town of Estherville is built. The cross section profile, Plate XXXIII, D, will show this feature clearly.

Below Graettinger the hills to the west of the valley become lower and the topography is less knobby and rolling, although a clearly marked moraine, the Ruthven moraine, is present in western Palo Alto county. See the map, Plate XXXII, page 467. On the east side also the rise to the upland is less and in places there is no demarcation between valley and upland, so gentle is the rise. Near Emmetsburg the valley widens to such an extent that its floor is a mile and a half to two miles wide. See the profile of the valley at Emmetsburg, Plate XXXIII, E. See also Plate XL, A, page 502, for the narrow flood plain in the vicinity of Graettinger.

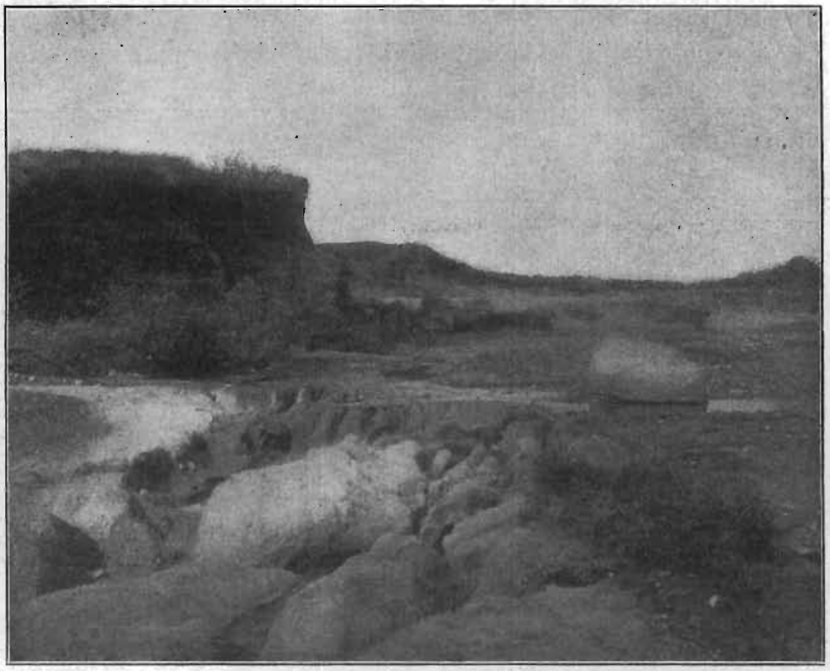


FIG. 40—Kansan blue clay beneath the gravels at Estherville. Pit of Minneapolis and St. Louis Railroad Company.

Beginning with the terraces above Estherville and continuing to Emmetsburg and beyond is an immense gravel train which covers, or once did cover, the entire valley floor and whose constituents grow progressively finer from the bowlder besprinkled coarse gravel of the Estherville pits to the fine sands and alluvium which border the river in central Palo Alto county. The Minneapolis and Saint Louis Railroad Company formerly operated a great pit in these gravels on the south edge of Estherville and the drainage streams from the pit have uncovered the Kansan blue clay which underlies these Wisconsin gravels. See figure 40. At Graettinger also a large pit is opened in the gravels, which have been penetrated for twenty-two feet, until water forbade further digging. They show all the characteristics of water-laid materials, such as cross-bedding, contemporaneous erosion and those irregularities of deposition which one might expect from shifting, hurrying floods. See figure 41.

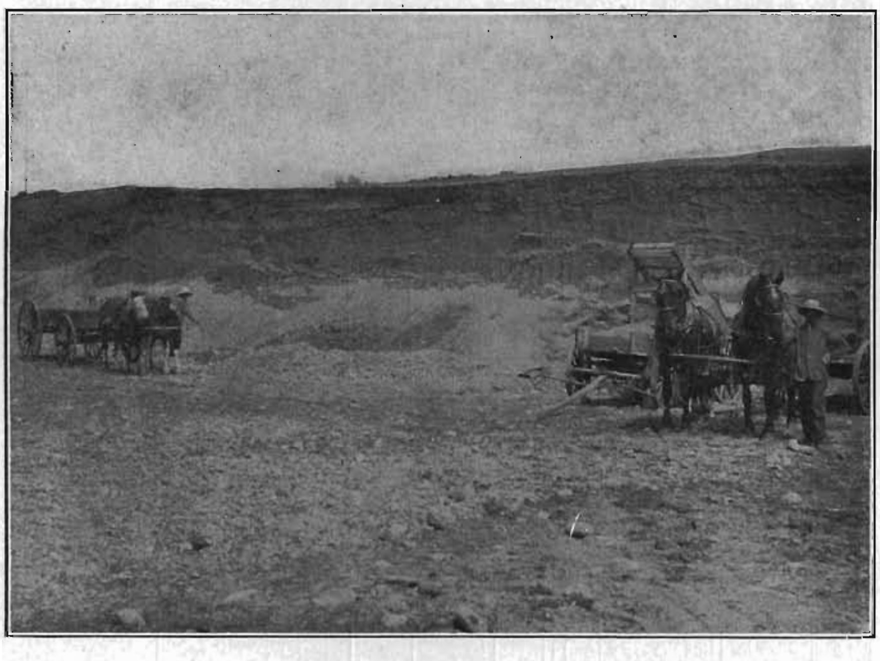


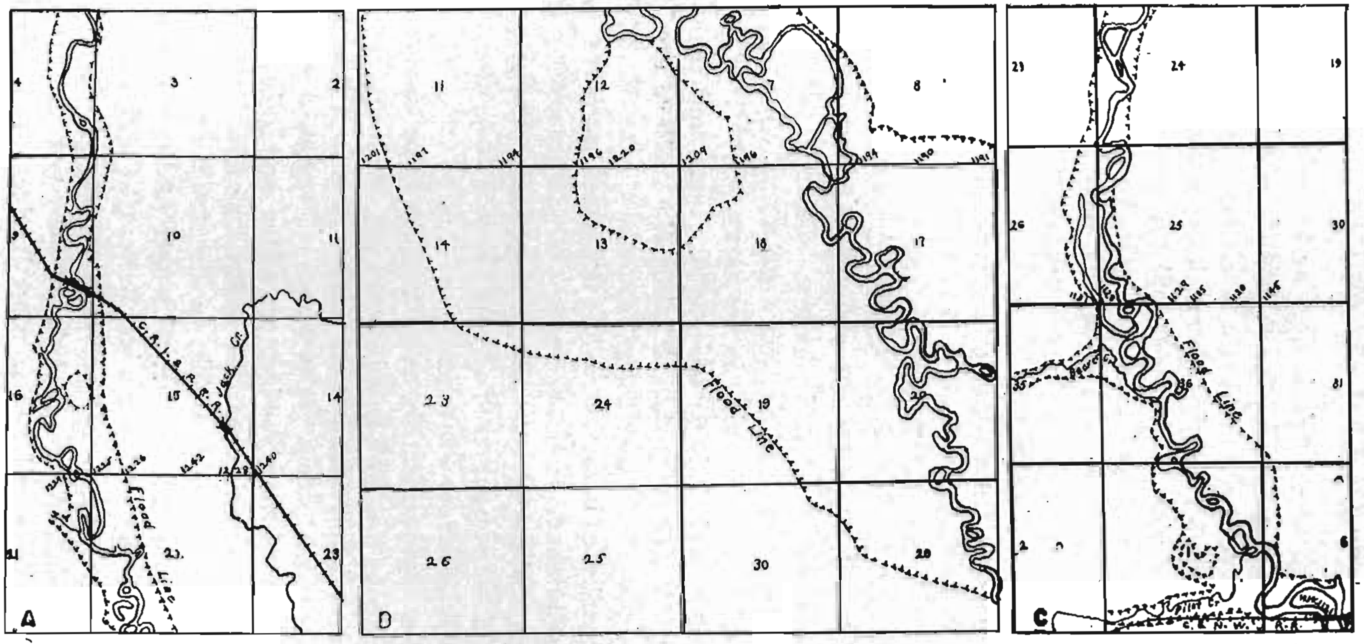
FIG. 41—View of the gravel pit in the valley train at Graettinger, Palo Alto county.

The origin of these gravels is not far to seek. We may picture to ourselves the edge of the Wisconsin glacier as lying at one time just above the present site of Estherville, for example, with torrents of water passing down the great hollow between the high rolling region to the west and the more level plain to the east. All the mud and sand and gravel and bowlders that the stream could carry or push were brought down this channel and when the water could no longer transport them they were dropped over the valley bottom.

The Valley from Emmetsburg to Humboldt.—Between Emmetsburg and Rodman the valley is remarkably wide and flat. For distances of two to three miles one may look across the bottom-lands and see scarcely a change in level, excepting here a low mound and there an old abandoned channel. Most of these channels are short and shallow, although one south of Emmetsburg is several miles long. Another remarkable feature of the valley in this region is the extreme gentleness of the bounding slopes and their great length. Here and there is a rather steep though low rise defining the valley, especially where, as south of Emmetsburg, the valley is bordered by a group of morainic knobs. But for the most part the valley margins are ill-defined or not defined at all. They merely grade back through a slope of one mile to three miles to the ground moraine. This is equally true of both sides of the valley; there seems to be little or no difference.

The maps accompanying the report of the Iowa Conservation Commission show how widely separated the floodlines are below Emmetsburg and how shallow the valley is. See Plate XL, B, which is reproduced from these maps. They also show how exceedingly crooked the river is in its minor wanderings. There are a few great swings across the valley, but more conspicuous are the smaller meanders which, in the southern part of the county especially, double the actual length of the stream. The low gradient of the valley across Palo Alto and Pocahontas counties—less than three feet per mile—renders a deflection of the stream by relatively small obstacles very easy and hence its course is bent hither and yon in most intricate and marvelous fashion.

PLATE XL



A. Map showing narrow flood plain of Des Moines valley at Graettinger, Palo Alto county. B. The wide flood plain just south of Emmetsburg. C. The narrow flood plain west of Bradgate, in Palo Alto county. Reproduced from maps of Iowa State Drainage Waterways and Conservation Commission, 1910. Altitudes above sea level.

The valley train fades out in this latitude and only the finer materials were carried beyond. These finer materials are covered by several feet of alluvium—rich black silt mingled with more or less sand—a gift which is renewed by each recurring flood. The valley gravels no longer form a conspicuous feature of the landscape.

The only tributaries in this region worthy of note are Jack creek, which drains Swan lake in central Emmet county, Willow creek, the outlet of Silver lake, which reaches the main stream west of Emmetsburg, and Cylinder creek, which winds its tortuous way across the prairie from Medium lake near Emmetsburg to yield its contribution to its master southwest of Rodman. Jack and Cylinder creeks in their lower reaches occupy valleys of some width but of slight depth and probably largely constructional. Willow creek finds its way among the low knobs of the Ruthven moraine until it leaves these to enter the broad sag which contains Des Moines river. Beaver creek, in northeastern Pocahontas county, has been mentioned on page 495, and Pilot creek is practically identical with it, except for its somewhat smaller dimensions.

Below Rodman the valley begins to narrow somewhat, although many of the slopes still are long and gradual, stretching away a mile or even two miles, such as those shown in Plate XXXIX, B, page 497, west of Ottosen. However, in places the bounding walls are well defined, and locally are steep. Here and there groups of low knobs at the valley's margin accentuate the division between lowland and upland. Such are a group south of Rodman and another three miles east of Bradgate, which latter sends the stream off to the south. Much of the valley between Bradgate and Rutland, however, is bounded by rather gentle slopes which rise thirty to forty feet to the prairie levels. See Plate XL, C, for the narrow flood plain above Bradgate.

The valley near Bradgate is underlain by alluvium and sand to a depth of fifteen to twenty feet. Below this yellow Wisconsin till fifteen to twenty-five feet thick is reported and beneath this a layer of very fine sand ten to twenty feet in thickness often causes serious trouble in wells. This sand may be of Buchanan age, although more probably it is Wisconsin outwash material. Beneath it Kansan blue clay is reported, and this has been penetrated sixty feet.

Rock Outcrops.—Professor Macbride maps a small exposure of Saint Louis limestone opposite Bradgate but this could not be found by the writer, even with careful search. However, there were seen near river level two small outcrops of the bright colored, variegated, finely sandy clay shales which are characteristic of both the Des Moines and the Fort Dodge beds, and which are readily distinguished from Pleistocene clays by the vividness of their coloration. These clays apparently form the first outcropping of the preglacial rocks along the West Fork. In the vicinity of Rutland Kinderhook limestone underlies the valley plain and at the village it outcrops abundantly. A vertical scarp of the limestone twelve feet high forms the south wall of the channel at the Rutland bridge. A view of this escarpment is shown in figure 42.

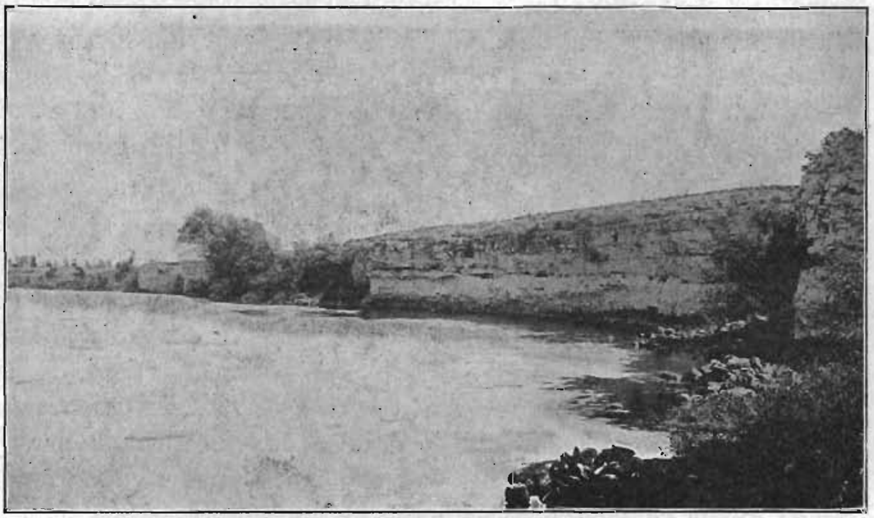
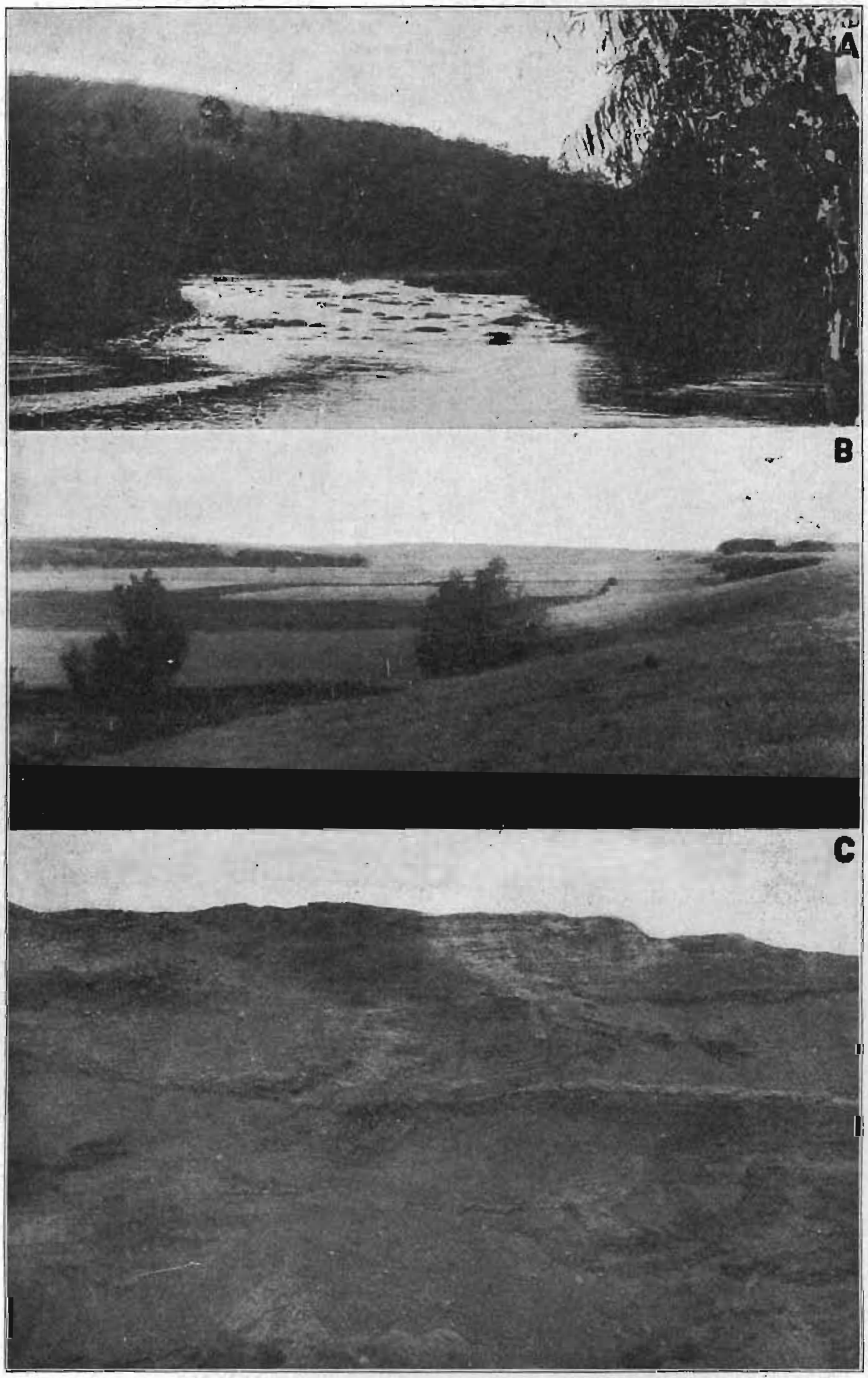


FIG. 42—The escarpment of Kinderhook limestone at the Rutland bridge, Humboldt county.

Below Rutland the valley becomes quite narrow, so that the flood plain is not over one-fourth mile in width and in some



A. The bowlder sprinkled channel at Humboldt. B. The wide valley of the West Fork just below Humboldt. C. Crossbedded gravels near Humboldt.

places even less. The valley also becomes deeper and where the river cuts against the banks, as is the case above Humboldt, the bluff is high and steep, and heavily wooded. The narrowing no doubt is due to the presence of the limestone, which, being so much more resistant than the unconsolidated drift, has confined the activity of the stream to a narrower zone. The channel from Bradgate eastward is strewn with bowlders, which in places are so abundant, to use Macbride's phrase, as to suggest some New England mountain channel, rather than the quiet, creeping river of the level prairie. This is especially true at Bradgate and at Humboldt as Plate XLI, A, shows. Below the exposures of Kinderhook limestone the chips and blocks of this stone litter the floor and banks of the valley.

Humboldt is built upon a rock platform which stands twenty feet or more above the narrow flood plain and has been swept almost clear of drift for a width of a mile. It is covered with a thin veneer of soil through which in numerous places the rock projects as small mounds rising about six feet above the surrounding level. This plain seems to be a remnant of the post-Kansan valley which was not filled with Wisconsin detritus to the same extent as adjacent portions. Its width is about the same as that of the valley just above Bradgate and probably represents fairly well the size of the older watercourse.

At Humboldt the steep, timber covered slopes of the west wall rise sixty to eighty feet above the water's edge and are indented by numerous short, steep ravines and gullies which cut into the upland for a short distance but fail to effect much in the way of drainage. The east wall also is quite steep for two miles below Humboldt. South of the town the walls approach each other within one-half mile or less and retain this relation for many miles below the union with the East Fork. See Plate XLI, B.

Three miles below Humboldt the West Fork swings to the east, bounded by the rather steep, wooded slopes of its west wall, and passing the nose of the dividing ridge, meets its fellow, the East Fork, at a right angle, two miles north of the county line.

Age of the Valley.—There seems to be no evidence to prove that the valley of the Des Moines in Minnesota and across Emmet and Palo Alto counties is older than the retreat of the Wisconsin glacier, if we make a possible exception of the stretch between Big Bend and Windom, Minnesota. If the depression above Big Bend is pre-Wisconsin, it would seem probable that a portion of the main valley below would be of the same age. For the most part, however, the valley is simply a great, broad sag, chiefly constructional, partly erosional, although the present river is entirely inadequate to determine the form of its valley except to a very minor extent.

Because of the outcrops of limestone in the valley below Bradgate Professor Macbride has suggested that in this locality the modern stream enters a rock-walled channel of Pre-Wisconsin age. In northeastern Pocahontas county as well as near Bradgate the valley floor is a mile wide, the walls are perfectly defined and their slopes are fairly steep, in places precipitous. At the bridge crossing the river a mile south of Bradgate, undercutting and road grading have exposed twenty feet of yellow, very pebbly Wisconsin till, five feet of rather fine, fresh gravel and twenty feet of drab, sparsely pebbly Kansan drift to water level. It was here also that the exposures of pre-Pleistocene clay shales were observed. The succession below river level already has been described. On the other hand wells on the uplands are reported as reaching rock at depths varying from a few feet to twenty, forty or sixty feet or occasionally at even greater depths. These facts are cited to show that above the mouth of Beaver creek as well as below, the river evidently is occupying a valley cut wide and deep before the Wisconsin glacier brought down its load of clays and sands. There is no such abrupt change in character here as one might expect to find, did Beaver creek represent a pre-Wisconsin watercourse. It was stated above that beyond Rutland the valley floor is not more than one-fourth of a mile wide. But this narrowing is the natural result of the gradual sinking of the valley into the resistant limestone of the Mississippian, rather than of a sudden change in the age of the valley. It is evident that somewhere in this region there occurs the passage from the wide, immature, constructional, modern sag to the narrower, better defined, erosional, interglacial valley. But Beaver valley does not bear the evidence of being at the critical point or of marking the continuation of the older channel. But wherever the change in age may occur, the assumption of an interglacial valley seems necessary to account for the depth and definiteness of the present course across Humboldt county, as well as for the rock cuts at Rutland and Humboldt.

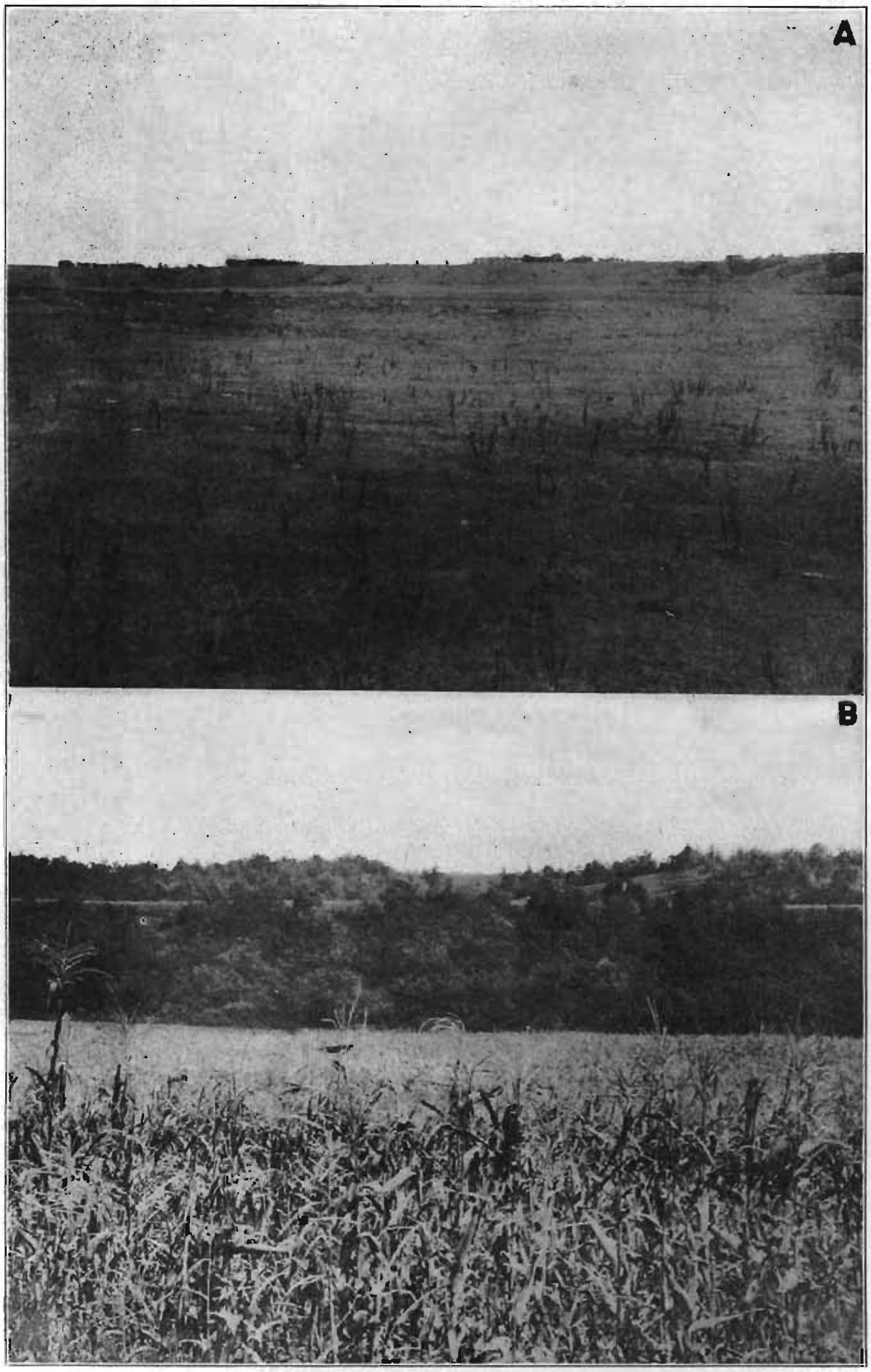
Outlet of the Chain Lakes.—In connection with the discussion of the origin of the valley of the East Fork the possibility was suggested (page 478) that the pre-Wisconsin drainage line now represented by the Chain lakes in Martin county, Minnesota, might be continued southward by the lower part of the West Fork valley and that a possible point of juncture was near the northeastern corner of Pocahontas county. Since here the younger valley seems to join the older, this locality affords the logical point for the attachment of the buried Chain lakes river to the pre-Wisconsin Des Moines. At least this theory has the advantage of accounting for the pre-Wisconsin valley in Pocahontas and Humboldt counties and of suggesting as well the outlet of the ancient river which once occupied the Chain lakes valley.

Age of the Gravels near Humboldt.—There are large amounts of gravel in a low terrace along the West Fork below Humboldt. Plate XLI, C, shows their character well. Where the long upland ridge between the two forks slopes down to the south its face is banked by a broad terrace of sand and gravel which also fills the entire valley and forces the West Fork against its south wall. Professor Macbride assigned this latter deposit to the Buchanan and the same is done by Beyer and Wright in a recent publication. The bed near Humboldt is assigned by these writers to the Wisconsin, as are also beds on the East Fork. The materials banked on the nose of the ridge are slightly rusted, the sands are stained a little yellow, the gravels a little red, but they are far less weathered than typical Buchanan gravels of eastern Iowa. Furthermore they contain a strikingly large proportion of fresh limestone pebbles of all sizes up to several inches in diameter. Those beds which lie down in the valley bottoms are very similar in composition and in showing streaks of iron rust and stain, especially in their coarser parts. The same is true of the terrace materials near Humboldt; while they are essentially fresh they show streaks of iron and manganese stain. There seems to be no sufficient basis for separating these various deposits as to their age. Between the low terrace near the city and the bank at the foot of the ridge dividing the forks there is no distinguishing criterion, and as between these latter and the materials somewhat higher up the slopes there can be no doubt of their equivalency and continuity. It seems scarcely reasonable to consider the valley as pre-Pleistocene or even pre-Kansan in age, but the gravels can not be Buchanan if the valley is post-Kansan. Considering then the character and age of the valley and the character and physical condition of the gravels it seems necessary to assign them to a period later than the Kansan, in other words to the close of the Wisconsin. There is, of course, the alternative of an Iowan age for the gravels, but judging from conditions where the Iowan is better known, this does not seem an attractive hypothesis. The Iowan does not seem to have been a period of extensive gravel deposition.

Des Moines Valley Below the Forks.

Within a few miles below the junction of the forks the valley becomes much deeper. Near the mouth of Deer creek, the bluff is ninety feet high and at Fort Dodge the river is 160 feet below the upland level. This notable deepening is continued into Boone county and is due not merely to the natural processes of erosion but chiefly to the ridges of drift material which are piled across its course in ever increasing height, from northern Webster county to their culmination as the Gary moraine of Boone county.

Near the county line Saint Louis limestone comes into view in the bed of the river and continues intermittently as far as



A. The wide flat valley above Fort Dodge, near Deer creek. B. A high bench a mile below Kalo.

Fort Dodge. A mile south of the line a terrace rises fifty feet above the flood plain and has a width of one-fourth mile. It is seen clearly to be a rock platform and upon it lie great numbers of Wisconsin bowlders, and probably there is Wisconsin till beneath the soil. It is evident that the erosion of the valley in the limestone was pre-Wisconsin as the slope to the flood plain is covered with Wisconsin bowlders. In places the rock has been cut out for a width of a quarter of a mile, and, as is the case opposite this terrace, through a thickness of fifty feet, too great a task for the present stream to have accomplished during its brief history. The high platform, like the inner gorge, may be the result of interglacial erosion.

Three miles north of Fort Dodge a broad expansion of the valley covers about a square mile. For the most part it lies above the reach of modern floods and evidently is an ancient flood plain. The surface, where the road traverses it, is covered with sand which may have been swept in by Wisconsin floods. Opposite this plain the river is cutting into Coal Measures clays and coal, although above and below here the Saint Louis limestone is exposed. The presence of the softer Coal Measures doubtless accounts for the expansion of the valley at this place. Plate XLII, A, shows well the character of the valley between Humboldt and Deer creek in northern Webster county.

Tributaries.—The tributaries of the Des Moines in Humboldt county are of little consequence. In Webster several laterals enter the master stream but these are typical prairie creeks, with the exception of the Lizard Forks, until within a mile or two of the main valley. In their lower courses they have been obliged to cut deep trenches into the rock to keep in topographic accord with the great valley. North Lizard is the most important creek of the county (Plate XXXII, page 467). Where it opens into the Des Moines valley it has cut a deep gorge in which it has developed a moderately wide flood plain. For some distance above the mouth the north wall is lower than the south wall, owing to the presence of a prominent range of morainic knobs which extends across this township and which here bounds the valley closely. The south wall is accordingly rugged and well timbered while the north slope is less rough and rather bare. Above the junction of the forks the North Lizard has a rather wide valley, but this shallows rapidly. Followed back a few miles it is only a few feet below the prairie level, and is quite a typical valley of the drift plain.

Where the South Lizard cuts through or abuts against the knobby drift region it develops steep bluffs but elsewhere its valley is shallow until within two or three miles of the junction with the North Fork. In the lower stretches several remnants of old levels appear as terraces on the steep walls and some low hills of circumdenudation are seen in the narrow valley. Apparently the stream occupied a somewhat different course when it flowed at a higher level but the process of adjustment to changing conditions in the Des Moines valley caused it to seek new channels as it deepened its valley.

The secondary streams exert practically no influence on the topography of the region aside from their immediate valleys, and the same is true to a large degree of the master stream itself. One no sooner ascends from the deep gorge than the unchanged Wisconsin plain stretches away before him, mile after mile. Swamps and sloughs remain undrained on the very border of the valley and bear witness to the immaturity of the drainage.

A small creek valley in southern Webster county, west of Stratford, down which the Chicago and North Western railroad runs for a short distance, is typical of the secondary drainage of the Des Moines system in this region. It begins as an insignificant swale or shallow sag in the drift plain about two miles from the river but deepens rapidly and within a mile has attained a depth of ninety feet. It is narrow, however, down to its junction with the main valley, for, although its depth at the mouth is 180 feet, even here there is a space of only thirty to forty feet between the bases of the bluffs.

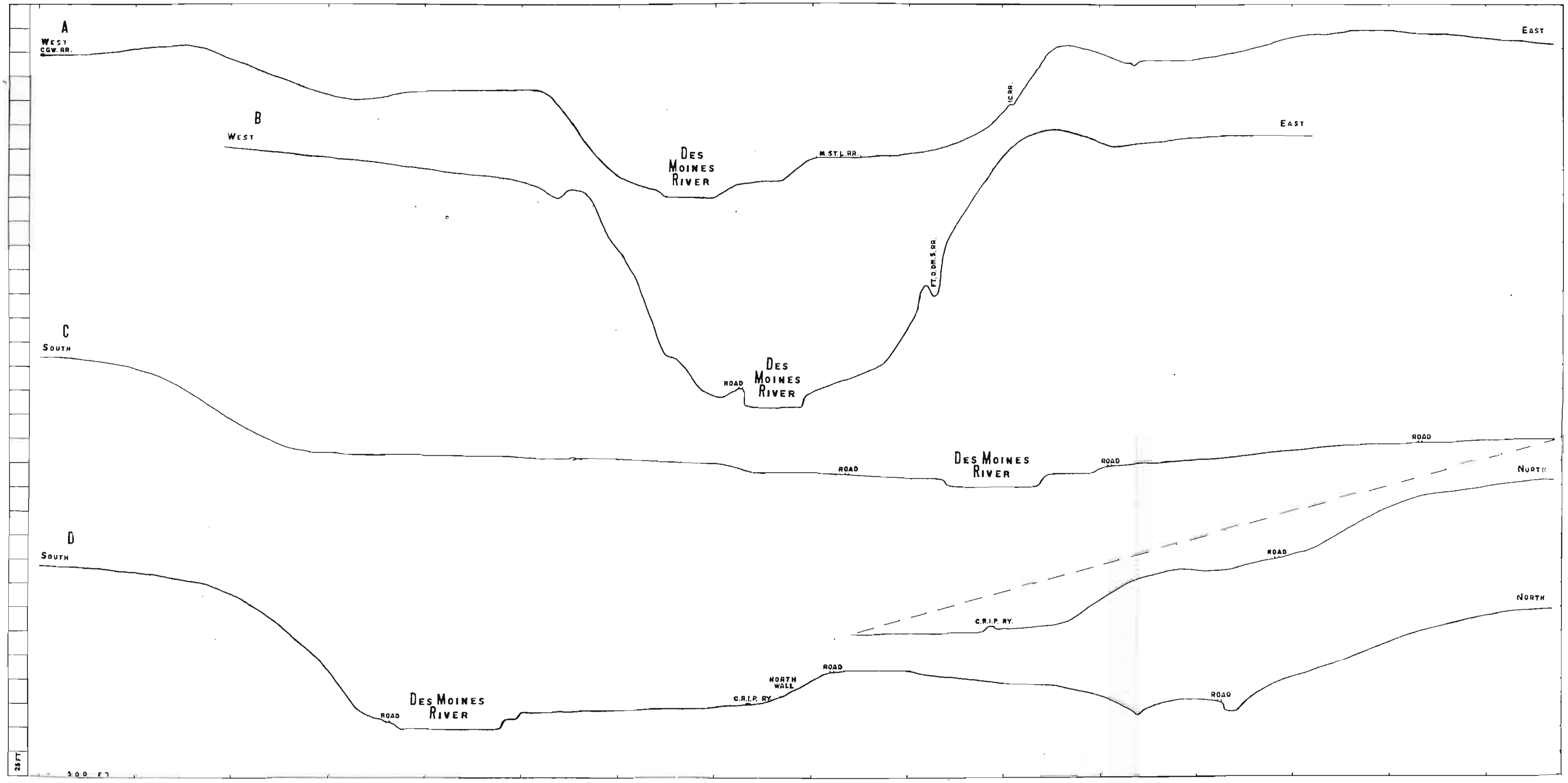
The Valley Below Fort Dodge.—Below Fort Dodge for many miles the high walls of the valley are relatively steep for the

Map showing Des Moines valley between Fort Dodge and Des Moines.

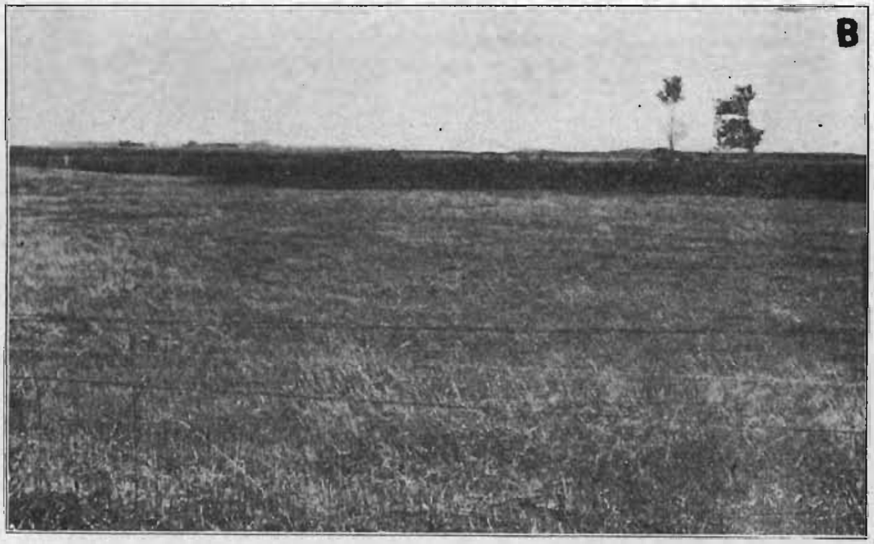
most part even where not affected by recent erosion. Both the main valley and its short, steep tributaries are heavily wooded up to the prairie level and form most picturesque features of the landscape. In most of the valley's extent across Webster and Boone counties (Plate XLIII) the flood plain is narrow, rarely more than 200 yards wide, and in places less, as at Fort Dodge and above Boone (Plates XLIV, A and B; XLVI; XLVII, A, page 521) and at Fraser where a mere strip of lowland 100 yards wide lies between river and bluff. South of the Gary moraine, however, from which the river emerges within the last few miles of its course in Boone county (see Plates XLVI and XLIX), the valley widens until at the county line it is a full mile from rim to rim.

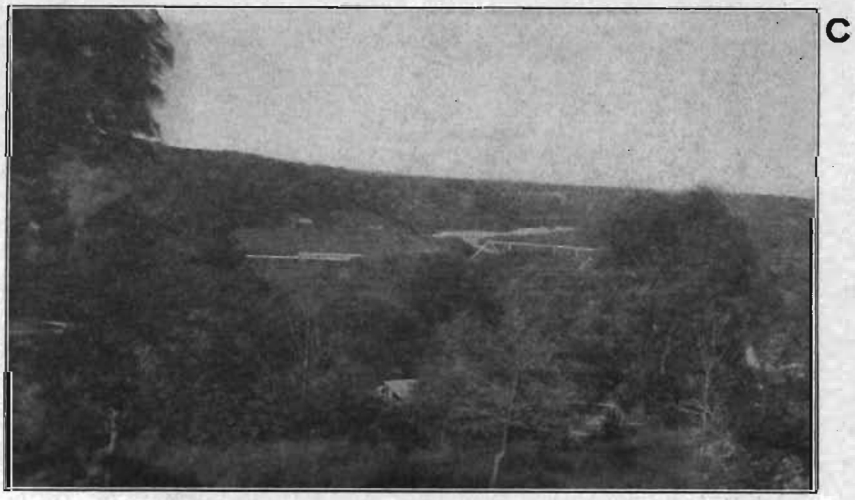
Below Fort Dodge exposures of shales are very frequent along the banks as far south as Kalo. In the vicinity of Fort Dodge gypsum also may be seen outcropping along the main valley and in its tributaries. Below Kalo massive, yellow, cross-bedded sandstone forms the walls as far as Lehigh, though covered along much of this distance with a veneer of drift. The bare rocky walls of the master gorge, presenting occasional vertical cliffs forty to fifty feet in height, are exceedingly picturesque and make delightfully attractive spots when framed in the verdant mantle which clothes much of the floor and slopes of the valley. With the increasing depth of the gorge the picture becomes more charming and where, as at Lehigh, the bluff rises at one sweep 190 feet from the water's edge to the upland levels it is one which will be excelled with difficulty in the landscape of central Iowa.

Boone River.—Boone river enters the valley of the Des Moines just within the limits of Webster county. The river has cut a gorge fully one-half mile from rim to rim and 180 feet deep in its lower reaches. This valley possesses all the characters of the master valley and in but slightly smaller degree. The rather insignificant stream meanders idly over its flood plain, which is flat and sandy. The side walls are quite steep, just as are those of the major valley. Angles of 12°, 15°, 20°, 22° and even 26°, were measured at various points. About a

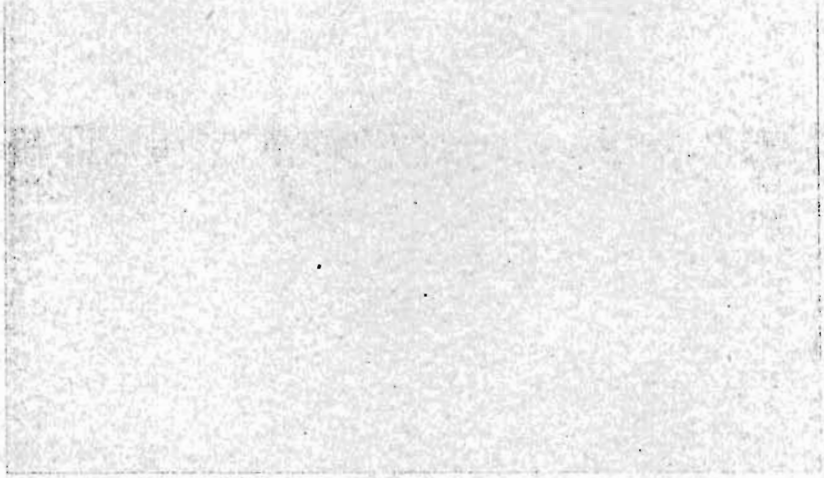


A. Profile of Des Moines river at Fort Dodge. Beyond the east end of the profile the surface is practically level. On the west are gently rolling uplands. B. Profile of Des Moines valley across middle of section 12, Yell township, and section 7, Des Moines township, Boone county, about two miles north of Boone. See Plate XLIX. Slightly rolling uplands west of profile; level land east of profile. C. Profile of Des Moines valley one mile west of Selma, Van Buren county, showing the wide valley. D. Profile of Des Moines valley one-half mile east of Selma, showing the narrow valley.





A. Boone valley about a mile above its mouth. B. The flat Wisconsin plain stretching away from the edge of the valley. Taken from the same point as A. C. Boone valley at the first bridge above Stratford, about two miles above its mouth.



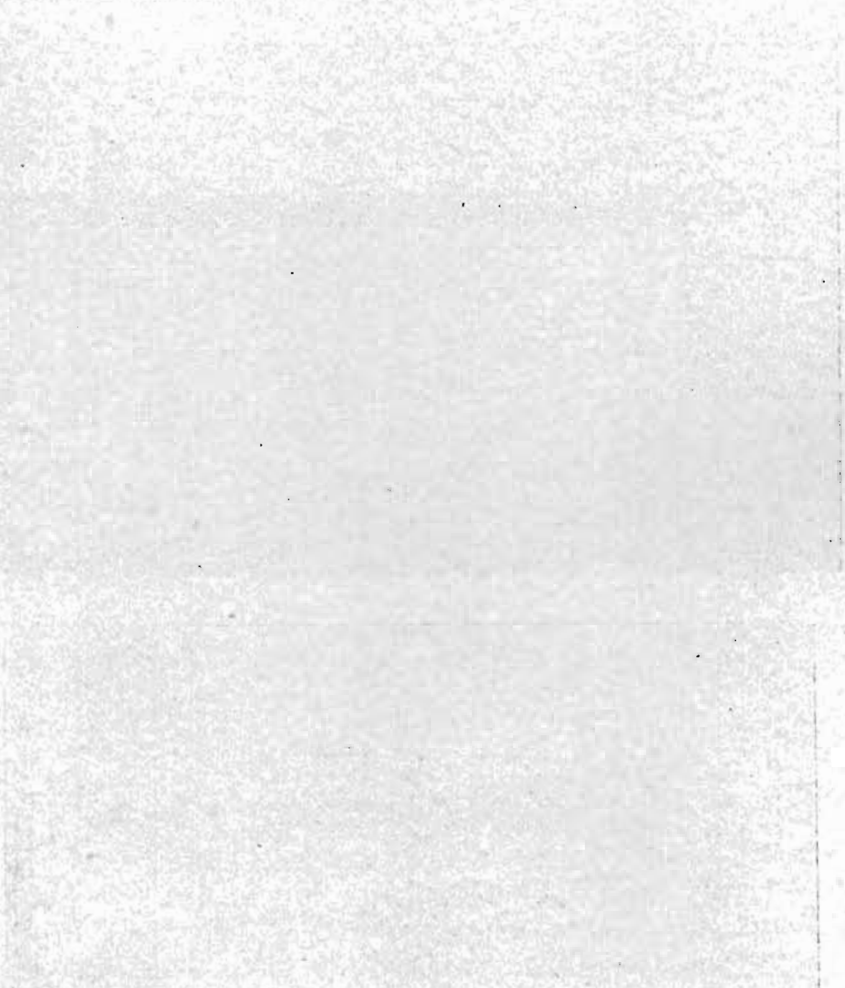


PLATE XLVI

Topographic map of northern part of Boone quadrangle, including parts of Webster, Hamilton and Boone counties.

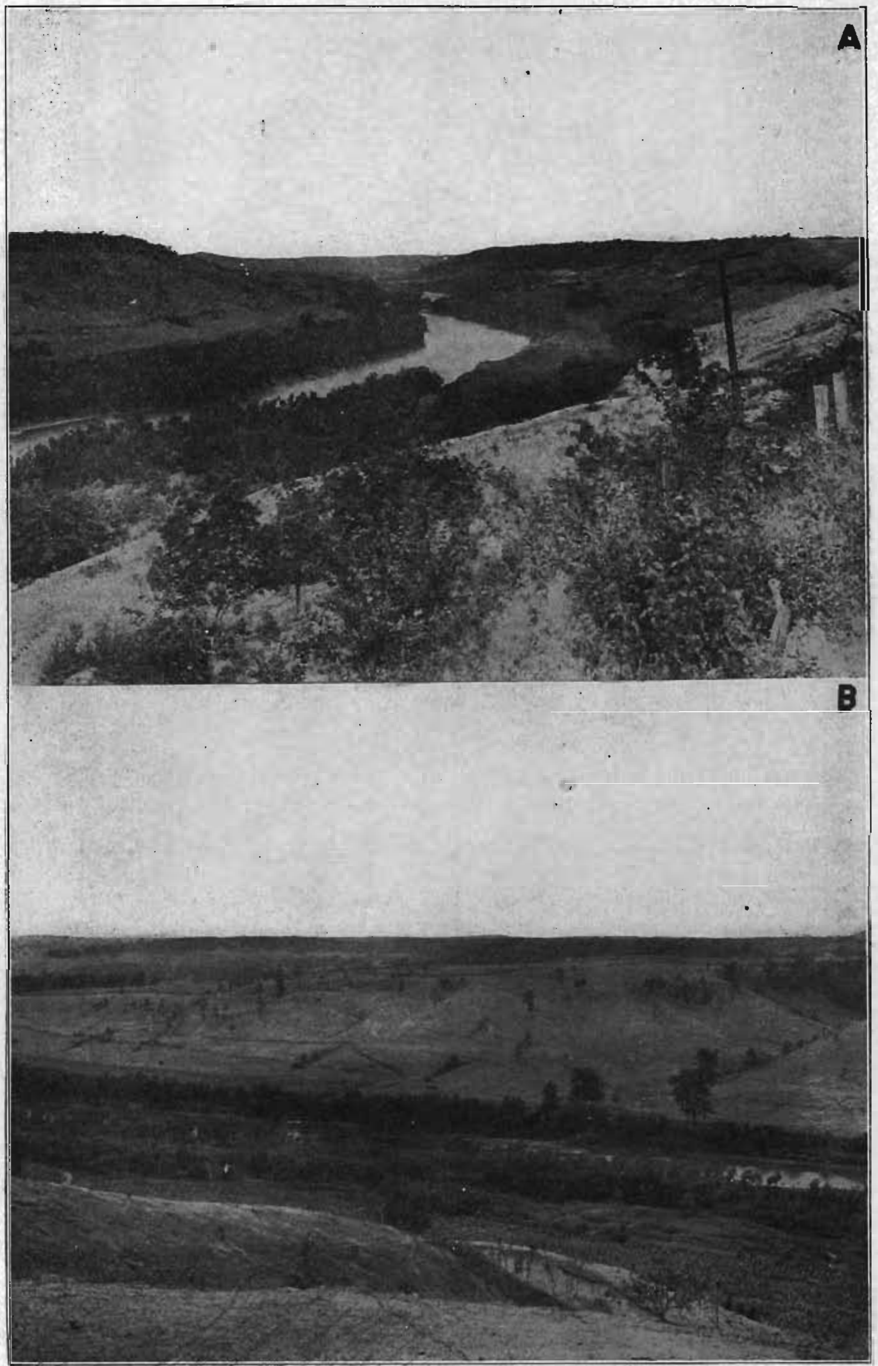
mile above the mouth of the stream is a bench ninety feet high which doubtless is related in origin to those in the major valley. See Plate XLV, A, B and C.

Terraces.—A mile below Kalo there is a high bench on the south side of the river, representing a former level of the valley. It is underlain by Des Moines shales and doubtless is to be correlated with the high benches noted in the north part of the county, both in age and in method of formation. See Plate XLII, B, page 511.

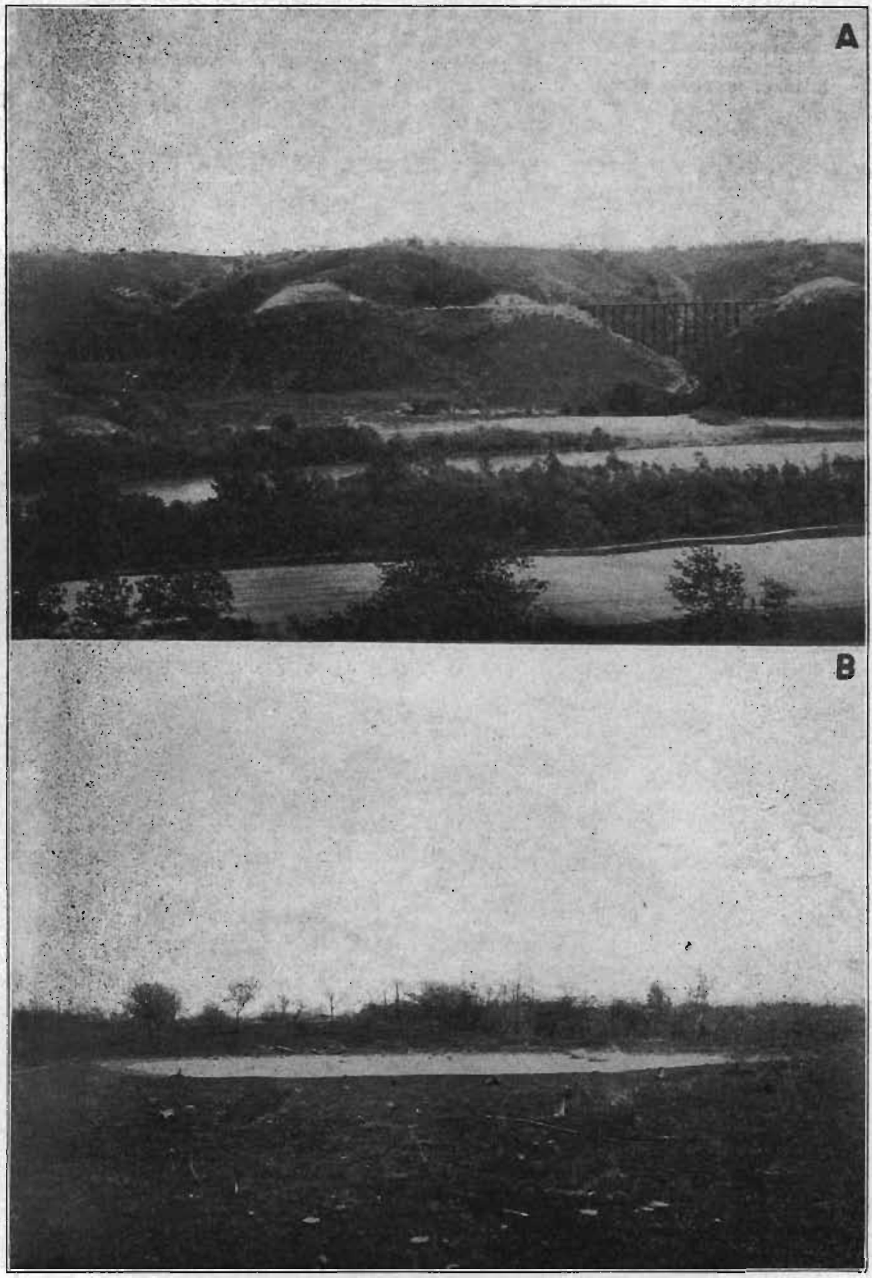
Opposite the mouth of Boone river is a bench which is nearly 100 feet high, and in its course across southern Webster, Boone and northern Polk counties the river is bordered almost continuously by benches and terraces. Just south of the Webster-Boone line, for example, a low terrace 300 yards wide rises ten feet above the flood plain, and a mile down the valley a high bench lies seventy feet above the stream. Its rough surface rises to meet the bluffs, at whose bases it is one hundred feet high. This bench covers one-fourth of a square mile and so far as can be seen in cuts it is built of waterlaid sand and gravel. It seems to fill a recess in the ancient valley. The village of Fraser is built upon another of these high benches and still another fills the hollow across the river from the village.

A similar bench fills the north part of the bend east of Fraser (Plate XLVI) and, in common with many others, consists of sand, gravel and cobblestones. To the south it slopes down to a lower terrace, built of detrital material, which fills the mile-wide recess between the river and the bluffs. The upper bench is perhaps sixty feet high and the lower one is about thirty feet above water level. The bayou in which these are built is one of the largest along the river. Plate XLVII, B, shows a similar group of terraces in sections 1 and 12, Yell township.

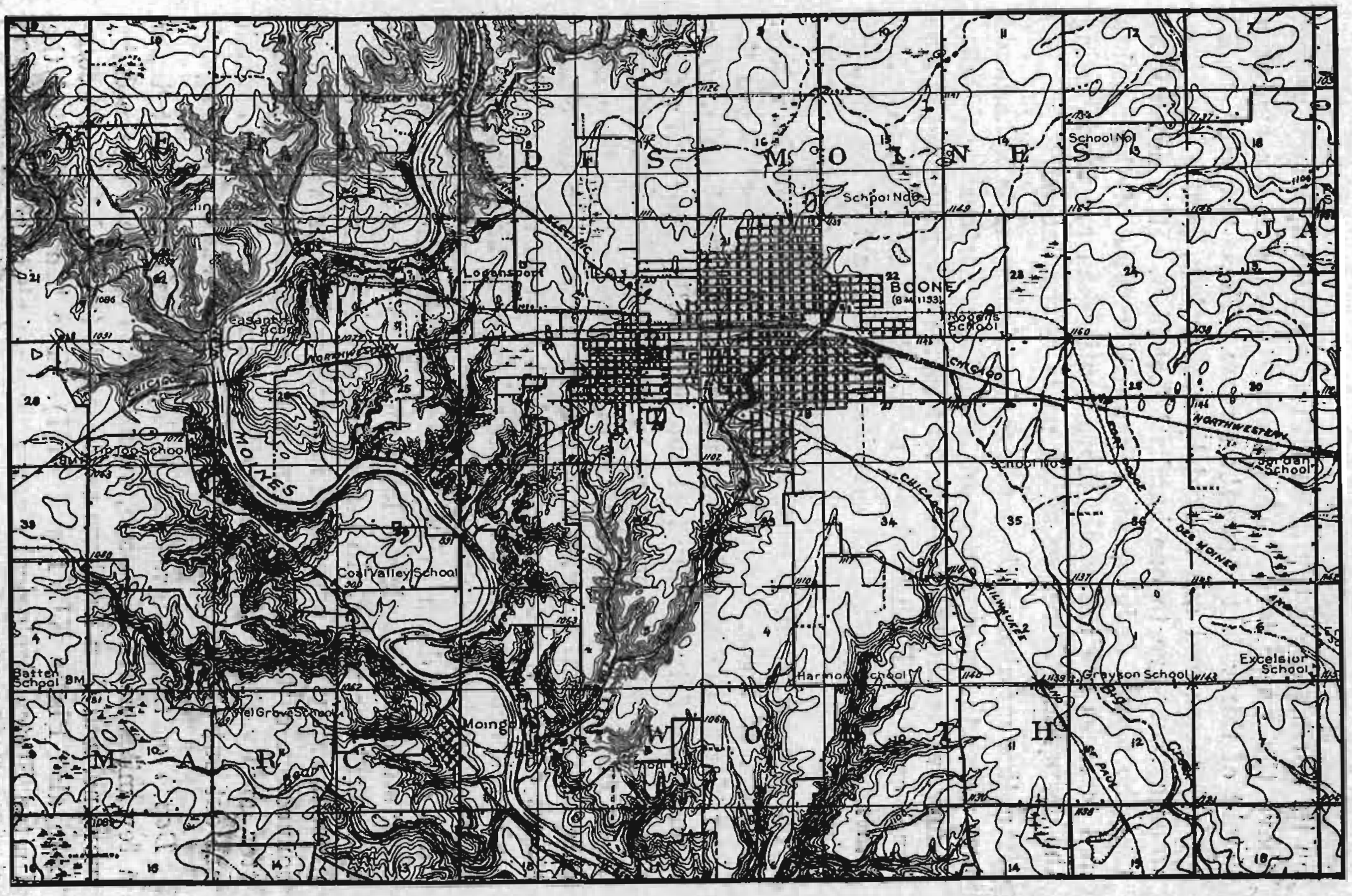
The series of terraces to which the upper one just mentioned may belong, is represented by that on which Moingona is built and other representatives of this series are to be seen near the north and south lines of Douglas township. See Plate LII, page 531. The former of these shows gravel and waterlaid sands



A. The narrow gorge of Des Moines river, midway between Boone and Fraser. B. High terraces on the west side of the valley above Boone. The upper edge of the higher terrace is shown in A at the left. Note the even skyline.



A. Short steep ravines in the east wall above Boone. They are only about two hundred yards long and are two hundred feet deep. B. A pond on the unaltered Wisconsin plain, between the ravines shown in A. The beginnings of a third ravine approaching from the rear may be seen to the right of the center background.



Topographic map of southern part of Boone quadrangle, in Boone county.

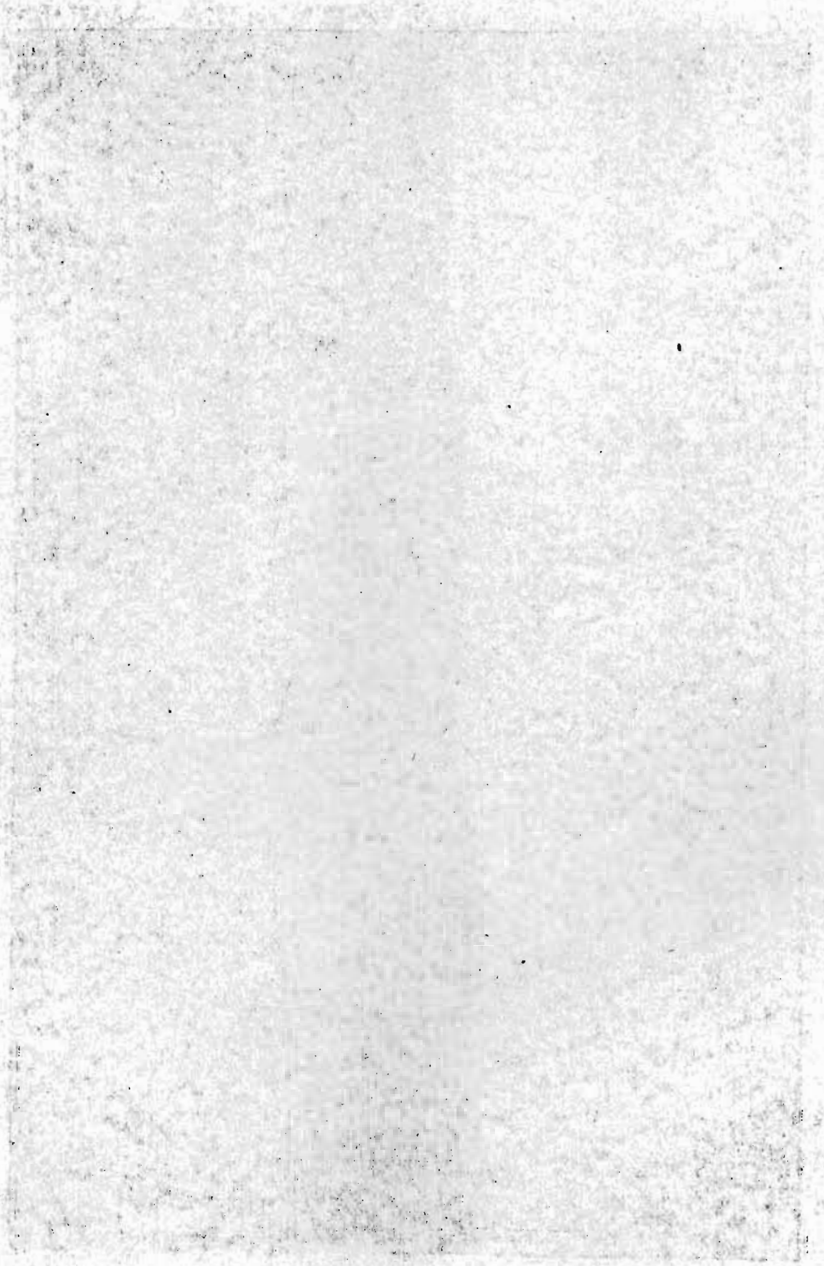
on its north side, but on the south side shales appear fifty feet above the water level. This terrace faces a lower one at a height of thirty feet above the stream. These two seem to fill an old recess and are backed by rather low, gentle bounding walls seventy-five to one hundred feet high. It is noteworthy that the slopes defining the rearward margins of the benches and terraces are uniformly more gentle than are those facing the deeper and therefore newer parts of the valley.

Another member of the lower series of terraces is to be found just above the mining camp of Scandia, in northeastern Dallas county, while the seventy-five foot series is represented by the bench on which High Bridge is built. See Plate LIII, page 533. Others of these series are plentiful in this part of the valley's extent.

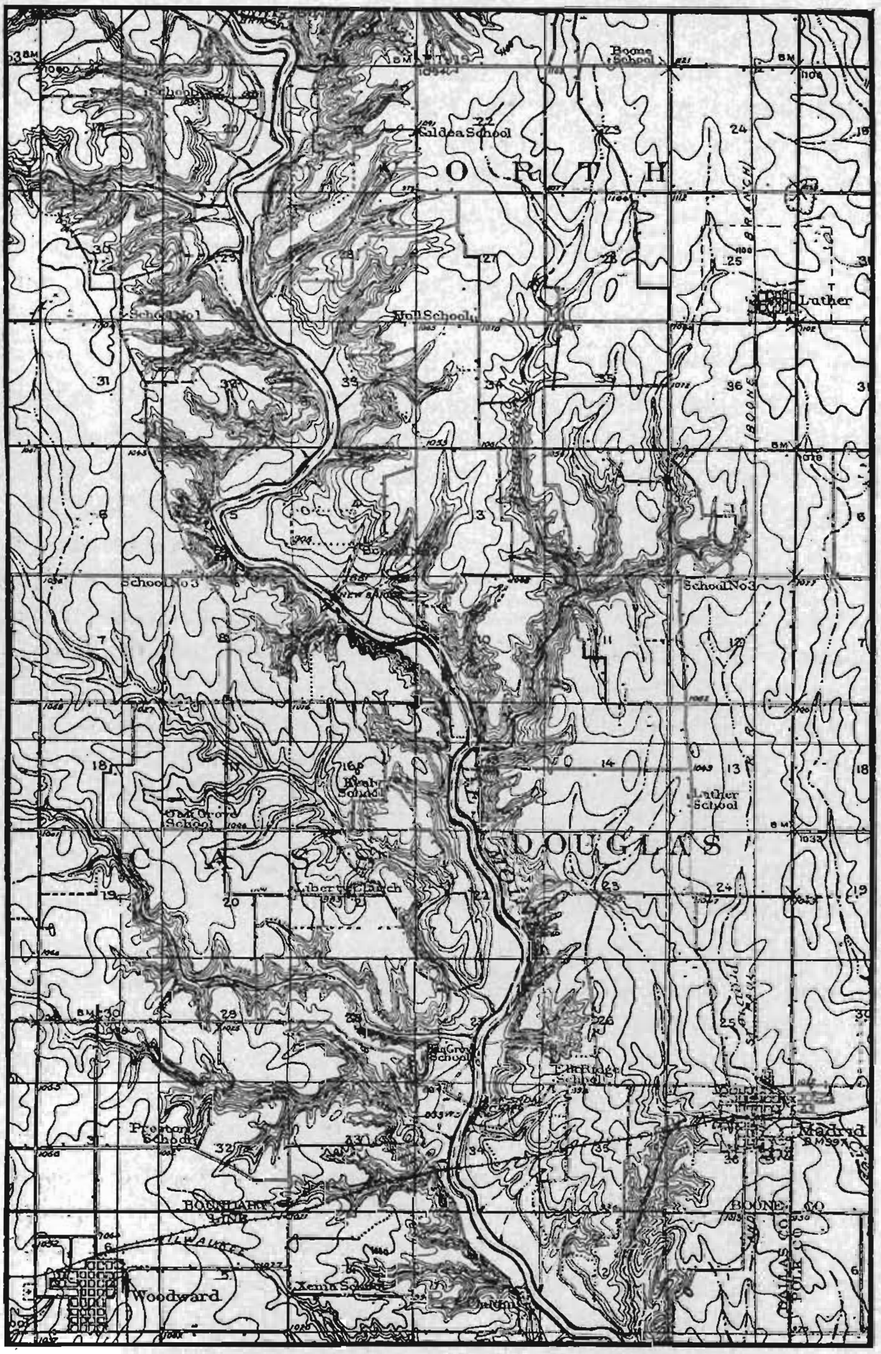
There seem, then, to be three series of benches in the valley. The first of these, ranging from ten to thirty feet above the river, forms the immediate boundary of the flood plain. The second rises fifty to sixty feet above the valley floor and a third series is seventy to one hundred feet from the bottom-lands. In so far as these terraces are of sand and gravel they indicate that the valley was at one time, probably in the closing stages of the Wisconsin age, filled at least to the level of the highest bench, and that the filling has been since largely cut away. The two lower series of gravel terraces, as well as terraces cut in or down to the indurated strata, indicate that the river stood at those levels long enough to widen out its valley by lateral corrasion. In other words the down-cutting of the present valley has proceeded intermittently. As was stated in connection with the rock terraces near the north line of Webster county those of Webster, Boone and Polk counties which are cut out of Coal Measures must be pre-Wisconsin in age.

Depth of the Valley.—The valley attains its greatest depth a few miles north of Boone, owing to the presence of the Gary moraine, and then shallows to the south (Plate XLIV, B; compare also Plates XLVI and LIII). The bench marks of the United States Geological Survey give an altitude of about 890 feet for the river two miles north of Fraser while the uplands

The Gary moraine in Boone county, and a Wisconsin bowlder.



The Ledges, Des Moines valley, Boone county.



Topographic map of northwestern part of Madrid quadrangle, including parts of Boone, Dallas and Polk counties.

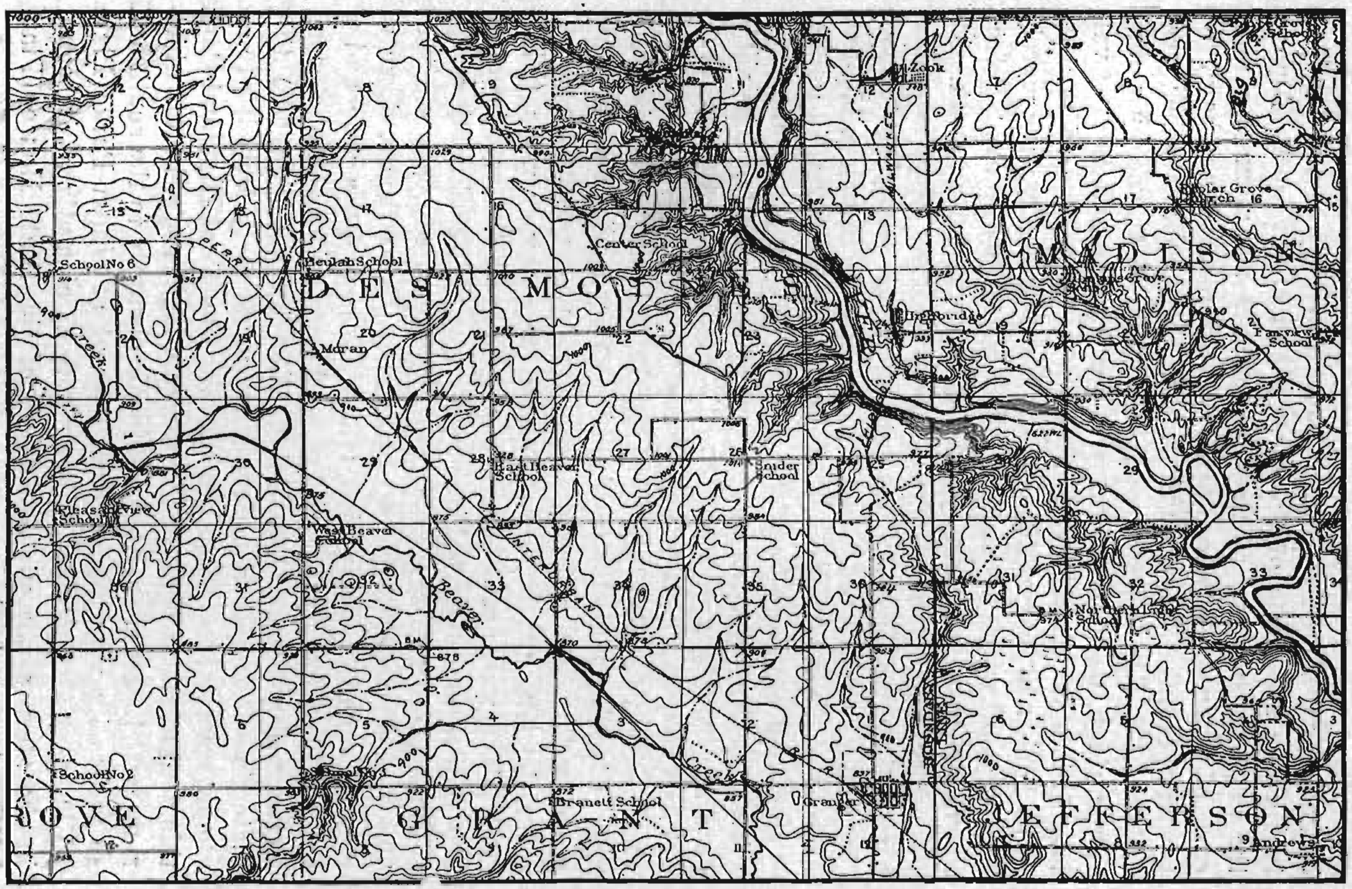
on either side rise to elevations of 1120 to 1160 feet, and Mineral Ridge, the crest of the Gary moraine, reaches a height of 1240 feet above sea level. See Plates XLVI and L. This means a maximum depth of over 260 feet, although the immediate rise to the crests of the bluffs is generally about fifty feet less. Where Mineral Ridge approaches the valley the bluffs rise fully 250 feet at a single sweep. However, where the valley is crossed by the Dallas-Polk county boundary its depth does not exceed 160 feet, and the prairies scarcely are 1000 feet above sea. See Plate LIII.

The Ledges.—There are numerous ravines along the valley walls but many of these extend back only a short distance and are very steep. So in many cases they are only 200 to 300 yards long but are 200 feet deep. The ravines shown in Plate XLVIII, A, are excellent examples, while B of the same plate shows how little they have affected the topography. The creeks which enter the valley also have deep timber-filled gorges. Bear creek is one of the best examples. One of the most picturesque scenes along any part of the valley is The Ledges, near the mouth of Pease creek in section 16, Worth township (Plates XLIX and LII). Massive sandstone forms high mural escarpments between which lies a charming valley with its little stream. See Plate LI. Trees and grass and rocks combine to form one of the most attractive spots of the region and one whose charm is greatly appreciated and utilized by visitors from far and near.

Doctor Beyer ascribes the formation of the Ledge sandstone to rapid sedimentation during Pennsylvanian times, apparently in a valley of limited area eroded in older Coal Measures. The present valley has been formed by erosion and differential weathering in this heavy bedded sandstone.

Moraines.—Below the Boone county line the valley shows on its western side a marked tendency toward long gentle slopes after the crest of the bluffs has been passed. On this account the highest land is not reached for a mile or more back from the first sharp rise. This feature is accentuated by a high morainic swell extending from northeastern Dallas county past Woodward and Granger into Polk county. This swell is capped

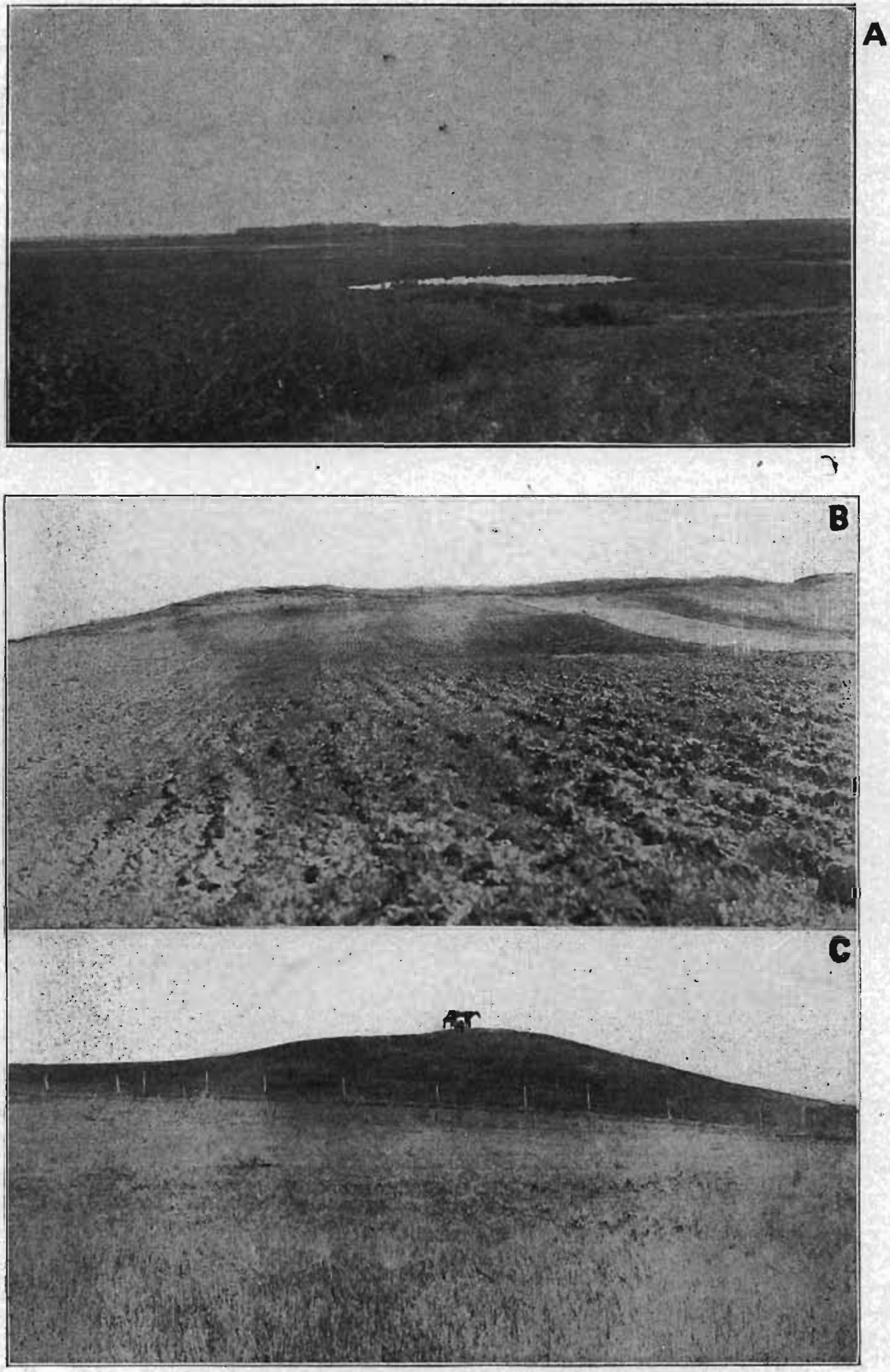
PLATE LIII



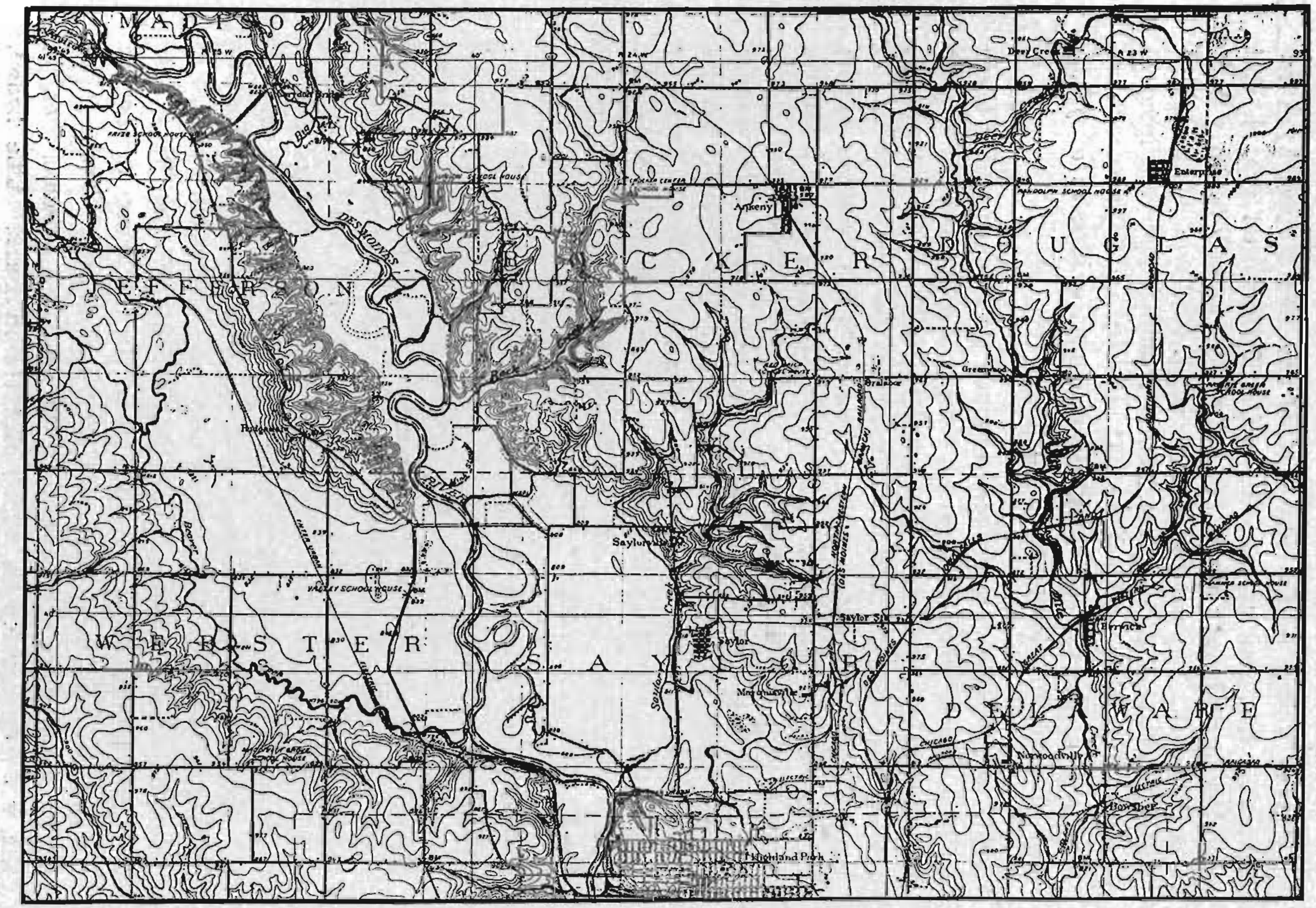
Topographic map of southern part of Madrid quadrangle, including parts of Dallas and Polk counties.

by knobs and kamelike ridges which rise eighty to one hundred feet above the crests of the river bluffs to the west. Among the most conspicuous of these ridges are the mounds a mile east of Granger (Plate LIII), one two miles northeast of Granger (Plate LIV, B) and another three miles further west (Plate LIV, C). Southward this swell is continued by a narrower ridge, which separates the Des Moines and Beaver valleys (Plate LV). This ridge is only a mile to two miles wide at its base, and its crest is in many places broad enough merely for the road which follows it. The highest points are 200 feet above the river and twenty feet less above Beaver creek. Although capped by aeolian sands it is built up of yellow Wisconsin till, blue, fossiliferous loess, perhaps overlying Kansan till, and a core of Coal Measures, which rises in places 100 feet above the river. Its eastern slope, facing the river, is almost everywhere steep and rugged and gashed by many short ravines, but the westward slope is much more gentle. The ridge descends by a long easy grade to the mouth of Beaver valley.

The Valley in Polk County.—From the Polk county line to the south line of Crocker township the Des Moines valley is gradually widening until the flood plain is fully a mile wide and the entire valley is practically three times that width if we consider the long gentle slopes back of the steeper walls (Plate LV). The wall overlooking the valley from the east becomes less rugged and dissected in Crocker township and south of the township line this transition suddenly becomes very marked. The gentle, mature slope swings off to the southeast, down to a point opposite Saylorville (Plate LV), where a mile and a half of level flood plain intervenes between it and the stream. Between Saylor and Des Moines city limits (Plate LV) this plain rises by a rather steep wall twenty to forty feet high to an almost equally level plain beyond. Just north of Highland Park this wall meets at right angles a steep, high, rugged bluff which runs west to the river. Here it bends abruptly to the south and so makes its way with a local descent at Union Park (Plate LVI), past Capitol Hill, to terminate as abruptly as it began, in the steep sandstone cliff south of the State House (Plate LVIII, A, page 553).



A. A pond near the kame shown in B. B. A kame in section 31, Madison township, Polk county. View from the west. C. A kame in section 34, Des Moines township, Dallas county. View from the east.

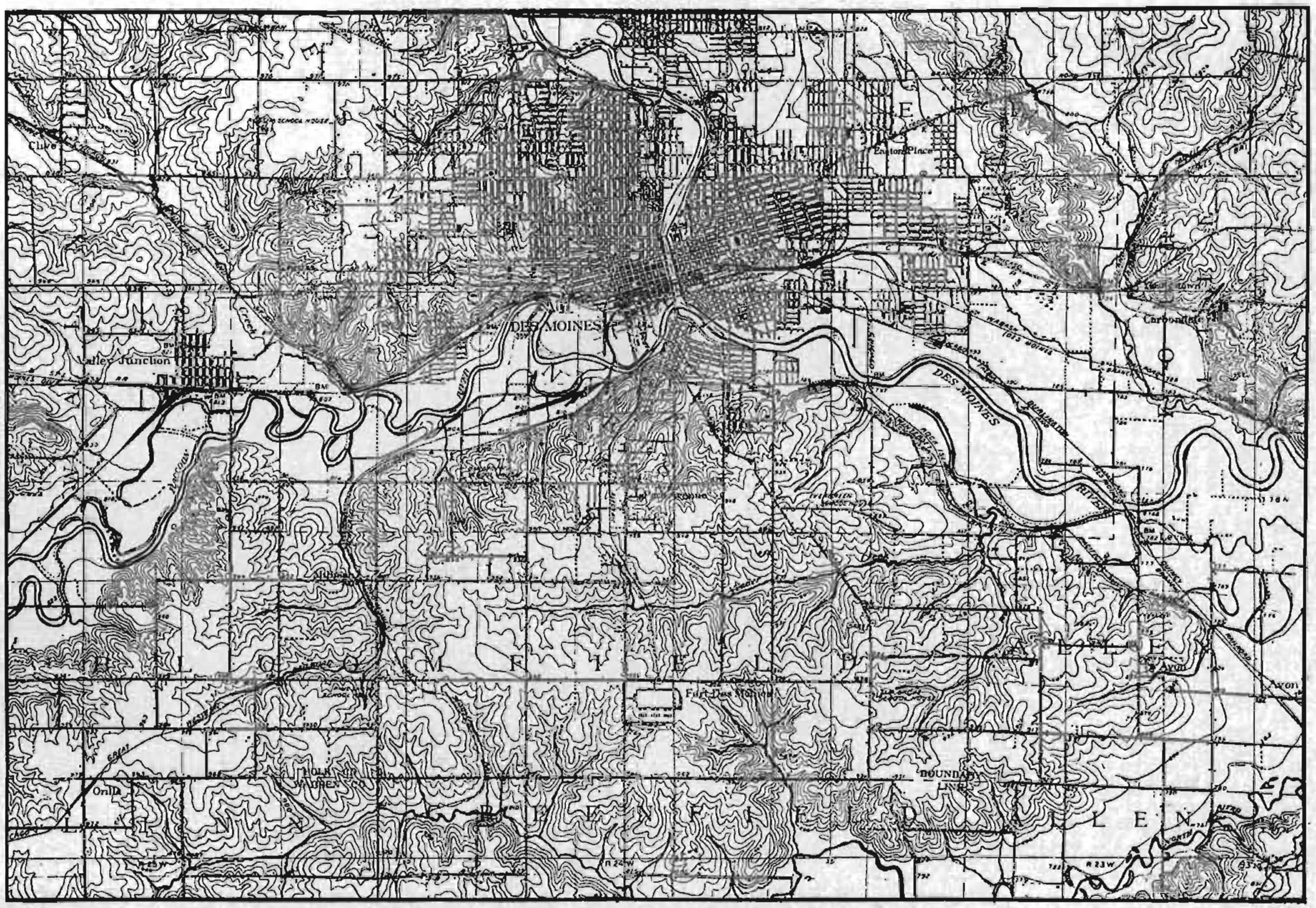


Topographic map of northern part of Des Moines quadrangle, in Polk county.

Beaver Valley opens into that of the Des Moines by a remarkable flat, two miles wide, built of sand and gravel, and varying in its height above the river from twenty to forty feet. See Plate LV. Beyond this flat the steep west wall of the major valley, as described on page 532, is resumed and continued to the junction with the Raccoon. It is trenched by numerous ravines, and, like the opposing slope, shows evidences of youth and immaturity along nearly all its extent.

The wide flat just mentioned extends up Beaver valley three to four miles. But far beyond, along all of its extent in Polk and Dallas counties, as well as across southern Boone county, the creek occupies a broad shallow sag, many, many times too large for the present stream. It reminds the observer of the great swales in Minnesota and in Palo Alto county, for instance, along which the sluggish stream winds its aimless way. The sag rises to the east to the range of morainic hills previously mentioned as extending past Granger and Woodward. To the southwest stand knobs and high ridges like sentinels guarding the broad and fertile plains beneath. The valley of the Beaver, like the Plain of the Jordan of the ancient writer, is "fair as the Garden of Jehovah." See Plates LIII and LV.

Now it is to be noted that immediately opposite the mouth of Beaver valley lies the wide plain which has been spoken of already as reaching from Saylorville almost to the limits of Des Moines and which occupies the west half of Saylor township—the plain popularly known as Saylor Bottoms. The relations of these are well shown on the map of the Des Moines quadrangle (Plate LV). Beyond the low wall south of Saylor there stretches southeast a wide plain limited on the east by the upland on which stand Saylor and Marquisville, and south of this by the more strongly rolling ridge known as Four Mile ridge, on whose slopes are Grandview Park and the State Fair Grounds (Plate LVI). On the west lie the lower eminences crowned by Highland Park and East Des Moines. From these latter, the slope is very gently to the east, and between them is the wide depression in which lies Union Park. The broad,



Topographic map of southern part of Des Moines quadrangle, including parts of Polk and Warren counties.

smooth slopes of these walls give an aspect of considerable maturity and offer a strong contrast to the choppy topography of the valley slopes to the west.

The sag or plain which lies between these walls is very level in general, except for scattered mounds which dot its surface, and which seem to be dunelike in origin and nature. It sinks to the south from elevations of 840 and locally 860 feet to an altitude of 800 feet or less where it opens into the great valley of the Des Moines between Capitol Hill and the Fair Grounds. Like the mouth of Beaver valley it is underlain very largely with sands, as has been learned to their cost by some of the coal mining companies which have run entries into it. It is obviously the continuation of the broad depression through which Beaver creek meanders, and must be connected with it in origin. The two are merely separated, or we may say united, by the now somewhat lower expansion of the Des Moines valley which lies between them.

DISCUSSION OF CONDITIONS.

We have now reached the point where Des Moines river emerges from the Wisconsin plain and passes into the much older topography of the Kansan drift area. Hence it is well to consider the reasons for some of the features that have been studied.

In Boone County.—Doctor Beyer, in his study of Boone county geology, indicated certain facts which he considered to point toward the youthfulness of Des Moines river in that county. These are: "(1) The extreme shortness of the tributaries, taken in conjunction with their high grades, is indicative of brief careers. (2) The river itself has done comparatively little lateral corrasion. Only in rare instances does it impinge on the limiting walls of the valley. (3) According to data derived from coal mines and well sections the position of the stream appears to be out of harmony with the topographic features of the older formations; i. e., the Des Moines is a superimposed stream, younger than the glacial deposits." The accompanying diagram, figure 43, adapted from Professor Beyer's report, shows the relations of the present and pre-Pleistocene surfaces.

In Webster County.—For Webster county, Doctor Wilder brings forward similar topographic evidence to show that the present valley is very young, but demonstrates from geologic facts that the river is "reworking a pre-Wisconsin, perhaps pre-Kansan valley."

Relations of the Valley.—It is very probable that the statements of these two writers, while seemingly contradictory, are entirely in harmony. It is true that the valley in both counties has every appearance of youthfulness and that the system appears to be out of harmony with the underlying topography. But the first of these conditions may be ascribed to the Wisconsin glaciation of a post-Kansan valley, while the second is accounted for by the probable fact that the post-Kansan river was imposed upon a drift sheet so thick that the underlying topography was entirely ineffective as a controlling agent. It is certain that the detritus of the Gary moraine in Boone and Webster counties would so conceal any pre-Wisconsin drainage lines that the survival of even the master valley is a marvel, and its immaturity and youthful appearance are quite to be expected. Nevertheless, it seems to be a fact that the modern valley holds its present position by inheritance, by virtue of necessity. The presence in the valley of terraces, in-so-far as these are built of glacial materials, indicates that when the Wisconsin ice covered central Iowa, the Des Moines valley had attained practically its present dimensions, that while the

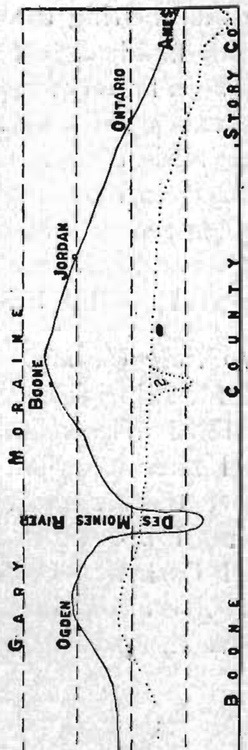


FIG. 43—Section across Boone and Greene counties, showing the relation of the present surface to the pre-Pleistocene surface. The latter is shown by dotted line. The relation of Des Moines river to the Gary moraine is well shown.

ice was melting the valley was filled to a depth of seventy-five to one hundred feet with waste from the glacier, and that this has been largely swept away since, leaving mere remnants along the valley sides as terraces and benches. If all that has been done since the end of Wisconsin time is the excavation, almost entirely in loose materials, of the inner, and narrower, valley, we can scarcely attribute the making of the great gorge in its entirety with its rock walls scores of feet in height, to the closing years of the briefest of the glacial ages.

In Polk County.—Within Polk county Doctor Bain learned the following facts: The bottom of Beaver valley is filled with modified Wisconsin drift to depths exceeding fifty feet. The Coal Measures rise in the side slopes to heights considerably above the stream, and undisturbed Kansan drift is found at points low down in the valley. In the low plain east of Highland Park and Capitol Hill, wells and mines go through seventy-five to one hundred feet of filling, although rock rises well above the present floor in the hills on both sides. The valley

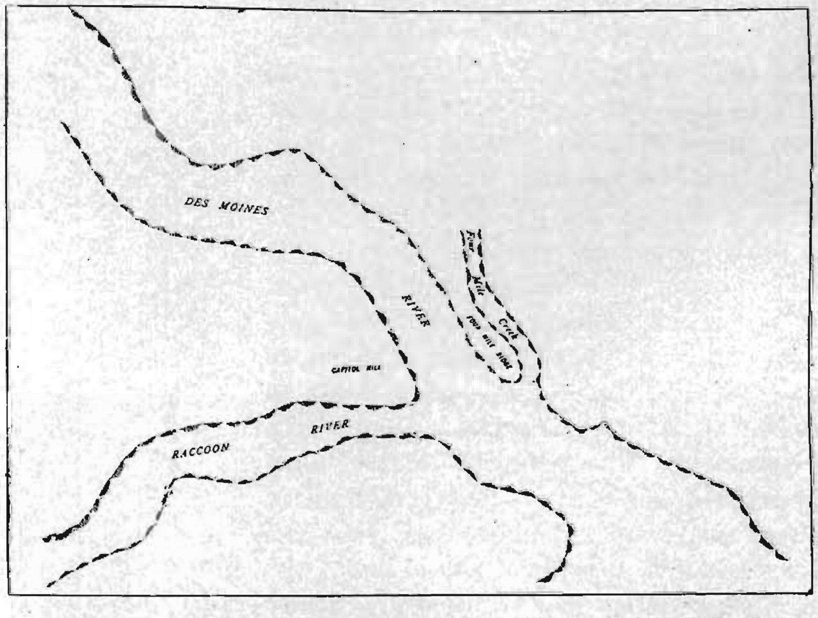


FIG. 44—Preglacial drainage at Des Moines. (After Bain.) The present site of Des Moines is indicated by Capitol Hill.

filling is in part Kansan drift. Below Des Moines the present river valley has been filled with many feet of drift—between fifty and one hundred.

Bain's hypothesis.—From these and similar facts Bain has constructed the following history for Des Moines river. The valley probably was excavated in the period immediately preceding the advent of the first ice sheet, as was that of the Raccoon, and their aspect near Des Moines was somewhat as represented in figure 44. The Kansan ice of course buried these valleys (the Nebraskan was not considered, as little was known of it when Bain made his studies), but did not fill them completely, and they were found by the post-Kansan streams—the valleys were resurrected. A system of drainage represented in figure 45 developed in the long post-Kansan interval, and among the minor streams those marked A and B played a most important role. The advance of the Wisconsin ice blocked the main valley opposite the stream B before the upper portion of the river was thrown entirely out of its valley. The swollen

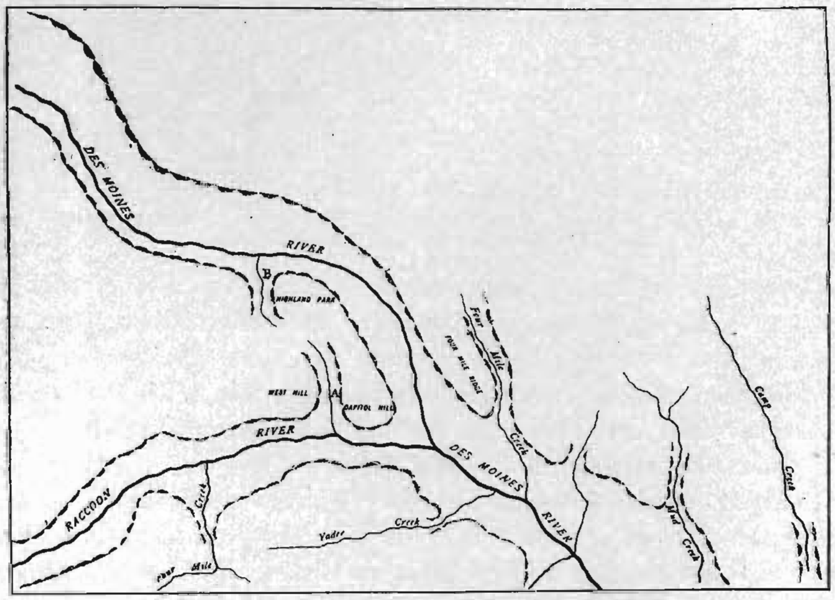


FIG. 45—Pre-Wisconsin drainage at Des Moines; illustrating Bain's theory of development of present drainage. The present site of Des Moines is indicated by Capitol and West Hills.

waters of the upper course flowed up the stream B, across the divide, and down A into the Raccoon. As the ice did not advance much farther the stream may have held its course under the ice. When the glacier melted back, the river held to the new course and abandoned the old one. It also abandoned the upper valley, now occupied by the Beaver, and cut the newer and narrower one in which it now flows. Present day conditions are shown in figure 46.

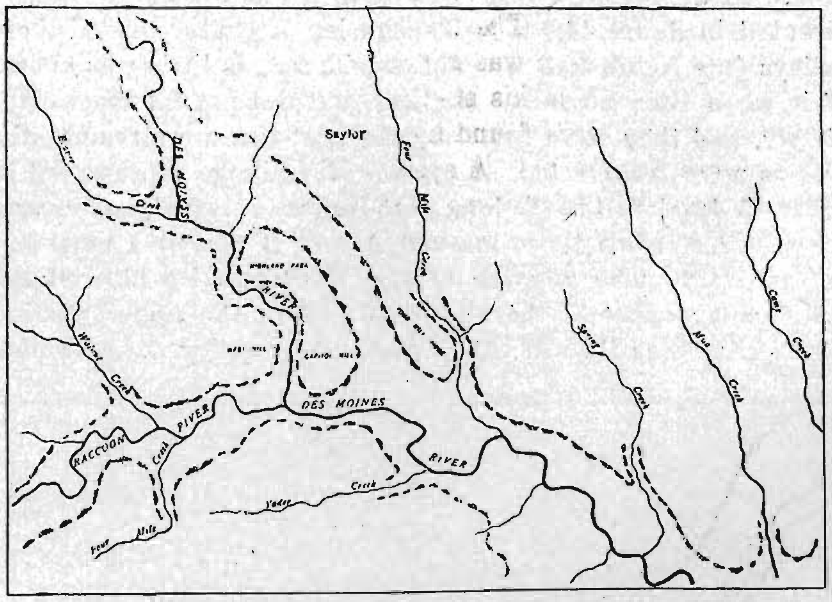


FIG. 46—Postglacial drainage at Des Moines. (From Bain.) Saylor Bottoms are located immediately north of Highland Park.

Objections to Bain's Hypothesis.—According to this theory the valley above Saylor Bottoms was excavated during the retreat of the Wisconsin ice. During the same period the portion between Beaver creek and the Raccoon was being deepened. Since terraces are found in the valley above Saylor Bottoms we must assume that the newly made valley was partly filled with sand, much of which has been carried away since. This sequence of events does not agree with the course outlined on page 541, but implies a very different history and necessitates a very much more rapid downcutting than is there postulated. Incidentally it may be questioned whether a glacier moving from west of north—which is also the general direction of the valley—would block the valley opposite B of figure 45 before the upper part of the river was overwhelmed or thrown out of its course.

That part of the valley within the city limits (see Plate LVI) is narrower than the upper reaches, although a somewhat greater age is assigned the former. And yet, rock outcrops are as common north of Beaver valley as in the city, the strata are similar, and rock rises fully as high above stream level, so there is no difference in this respect on which to rely for interpretation.

The assignment of the valley-cutting to the Wisconsin ice epoch might accord with Beyer's outline of conditions in Boone county but it fails to harmonize with the statements of Wilder as to the situation in Webster. If the Des Moines in Webster county is re-excavating a pre-Wisconsin valley while the Des Moines in Polk and Boone counties occupies a valley dating back only to the close of the Wisconsin epoch there should be topographic unconformity between the parts and there should be somewhere in the valley a topographic break which would record this fact. However, there is no such break and so the difference must be one of interpretation rather than of fact.

A NEW HYPOTHESIS REGARDING THE AGE OF THE VALLEY.

In order to harmonize these apparent discrepancies and to obviate certain difficulties which seem to be inherent in the theories heretofore presented, the following working hypothesis is offered.

Date of Origin.—It will be shown later from the relation of Des Moines river to the Mississippi, that the initiation of the Des Moines valley cannot antedate the beginning of the Pleistocene. The earliest date to which we can assign its formation is the close of Nebraskan glaciation. The post-Nebraskan Des Moines followed the course of the present river below Des Moines, but across the site of the city it occupied the wide depression described on page 540, and to the northwest, across Polk and Dallas and southwestern Boone counties at least, it cut out the wide sag through which Beaver creek now flows. The

Aftonian interval must have been of great duration to give time for the cutting of such a large valley even though it was sunk entirely in the soft strata of the Coal Measures for many miles above and below Des Moines. Raccoon river also probably originated at the same time, since its features are much more like those of the older than of the younger parts of the master valley.

Effect of Kansan Glaciation.—The oncoming Kansan ice filled the valleys, blotted out the drainage systems and so forced the waters, after its retreat, to seek new courses for themselves. Owing to their not being entirely filled with drift, as well as to the greater thickness of drift in them, the pre-Kansan valleys would be made manifest by the presence of sags over their former courses. In this way the old valley of the Des Moines was revealed and was used by the resurrected stream as far up as the junction with the Raccoon which also had been revived. But above this point the stream course suffered profound changes.

Width of the Valley.—North of Saylor Bottoms the present valley floor has a width varying from three-fourths of a mile to more than one mile. West and south of Highland Park the width is a little less, but is still from five-eights to three-quarters of a mile. At Union Park, which is opposite the bend in the valley, the rock wall is cut away below river level, as is shown by wells and drill holes in the vicinity, and the depression is filled with silts and sands. The sag here is on the same level as the pre-Kansan valley to the east, and the two are continuous.

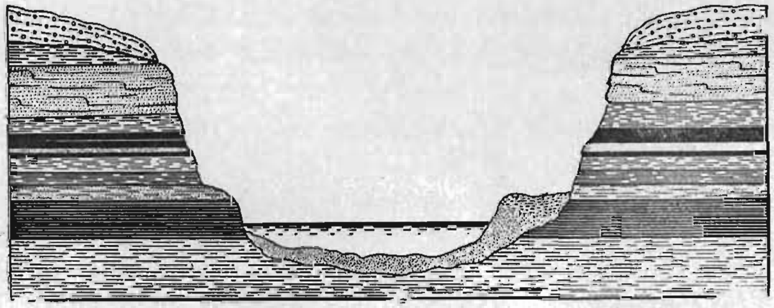


FIG. 47—Gorge of Des Moines river at Des Moines above the dam. (After Keyes.)

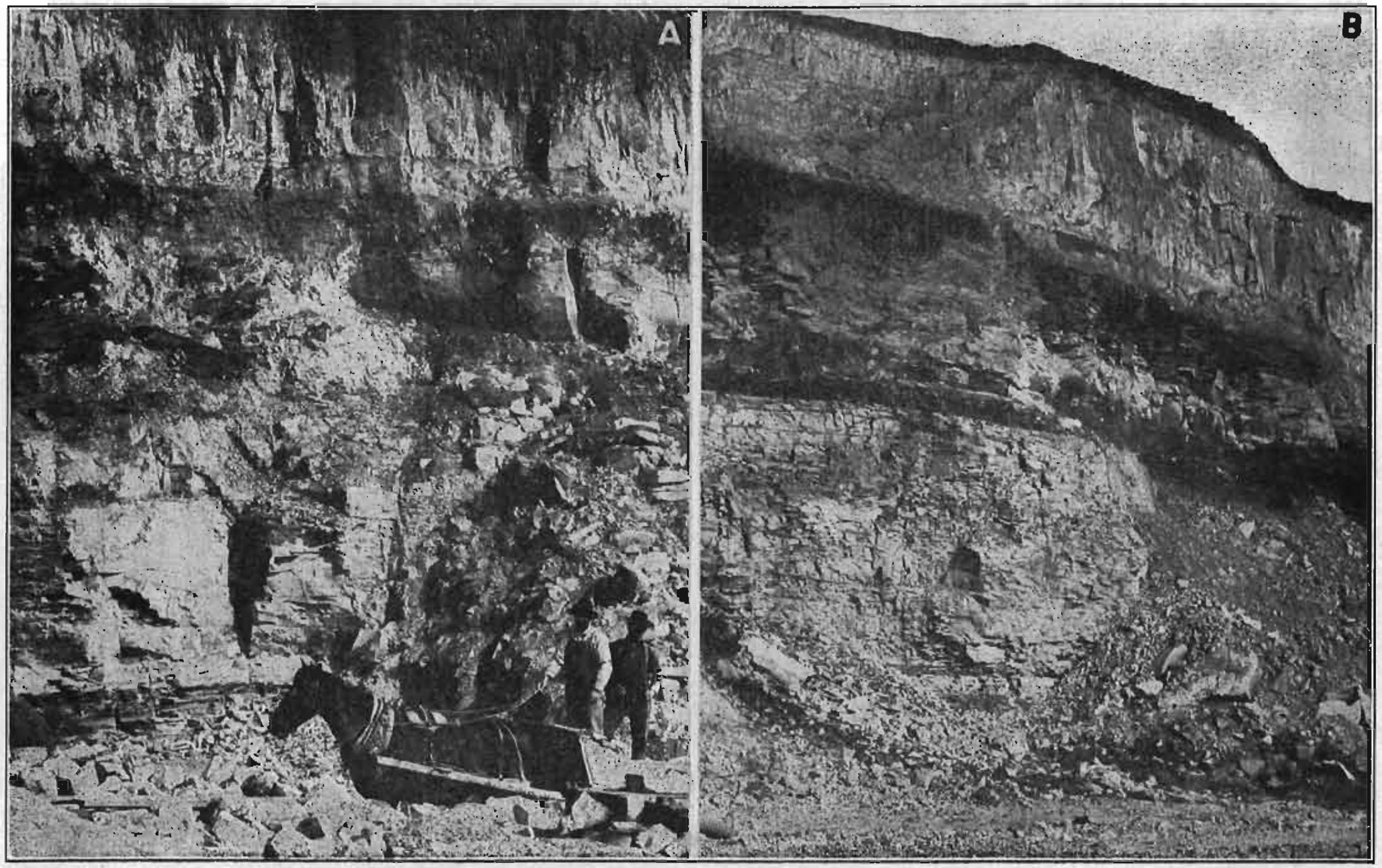
See Plate LVI. South of Union Park the valley again narrows until it is not more than one-fourth of a mile wide and the bottom is almost entirely covered by the river, as is shown in figure 47. This notable difference in the size of the valley immediately above and below Union Park seems to point definitely to a difference in age.

The Post-Kansan Valley.—Despite the difference in the width of the valley immediately above and below Saylor Bottoms both sections may be of the same age. From the evidence given on previous pages we may assume that the post-Kansan Des Moines established the course now followed by the river across Humboldt, Webster, Boone, Dallas and northern Polk counties (Plate XLIII), but instead of following the pre-Kansan course below the intersection at Saylor Bottoms it cut a new valley west of Highland Park as far south as the present site of Union Park. The absence of the rock wall at Union Park, and the extremely narrow gorge south of this locality seem to indicate that the post-Kansan stream, instead of making the abrupt southward bend which exists at present below Highland Park (Plate LVI), flowed across Union Park, down the pre-Kansan valley east of Capitol Hill and so into the valley at present occupied by the river below Des Moines. The fact that the old valley is wider between Capitol Hill and Four Mile ridge than east of Highland Park seems to lend additional support to this view.

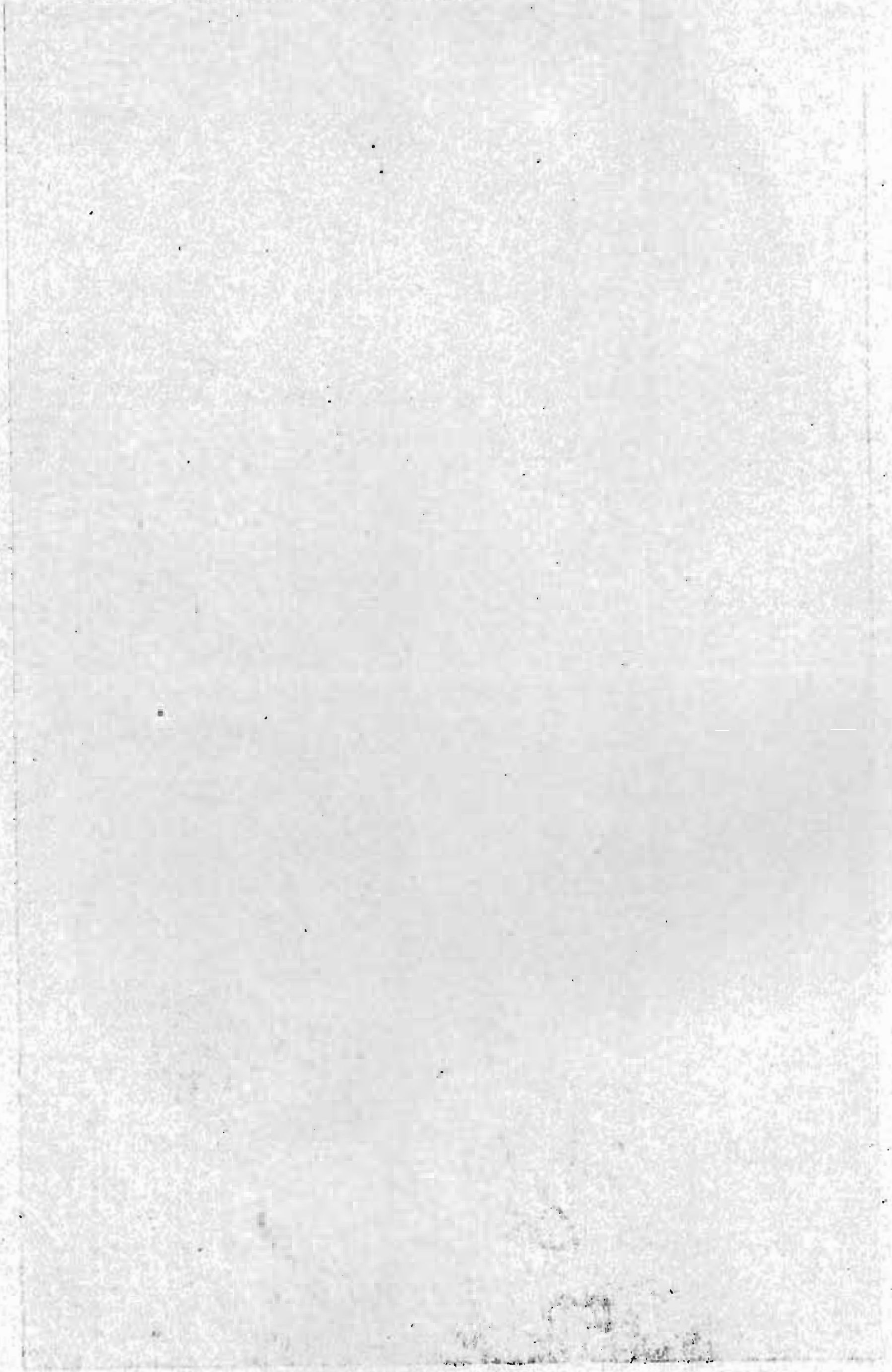
Just why the river chose the course it did after the retreat of the Kansan ice can not be told. Perhaps it was because the pre-Kansan valley was filled to a level higher than the course taken by the post-Kansan river. Perhaps it followed the valley of a tributary of the post-Nebraskan Des Moines, or it may have been guided by swales similar to those which today are so abundant on the Wisconsin drift plain of northern Iowa. Its action is paralleled by that of the Mississippi near Rock Island and Keokuk.

Effect of Iowan Glaciation.—During the long ages following the Kansan glaciation the river was cutting its valley through the drift and into the Coal Measures until interrupted by the advance of the Wisconsin glacier. The Illinoian glacier could affect this region only indirectly, of course. See the Pleistocene map of Iowa, Plate XXX. If the Iowan glacier entered the territory tributary to Des Moines river its effect would be twofold. The upper valley would be buried, while beyond the reach of the glacier the depositional work of the stream would be somewhat accelerated. It does not seem probable that any of the significant changes which the Des Moines has undergone are due to Iowan glaciation. The Iowan ice seems to have been so ineffective as a topographic agent that at many places within its borders in eastern Iowa the pre-Iowan topography was not much obscured, but was merely mantled. The slopes were toned down and the irregularities were smoothed out somewhat, but there still remain areas which retain the contours of pre-Iowan time. Then, too, the entire valley within the region which would have been crossed by the Iowan margin is a unit, and at present shows no evidences of having been subjected to influences which would affect one part more than another. The changes which are evident, those near Des Moines, are so far beyond the probable extent of the Iowan glacier that it is difficult to see how they could have been caused through its agency. If the Iowan ice had found Des Moines river occupying its post-Nebraskan course, the ice-free section of this great valley would have served as a channel for the outlet of glacial waters, and the blocking and abandonment of this channel must have been postponed until Wisconsin time, conditions which are directly contrary to what the evidence shown in the present valley above Des Moines seems to the writer to prove.

Origin of the Gorge below Union Park.—With the development of the Des Moines-Raccoon drainage system there may have been cut out two ravines, one heading south from the locality of Union Park (rather than from west of Highland Park, as Bain supposed, see figure 45) and another working north from near the present mouth of Raccoon river. These ravines grew and enlarged until their heads met and ultimately they formed a broad low sag where the river now flows through the city. The present form of the valley here seems to agree bet-



The clay pit of the Iowa Pipe and Tile Company, Des Moines, showing Coal Measures shales, overlain by loess, which extends within two feet of the surface and is capped by a thin layer of Wisconsin till which appears as the dark band in B. The dark upper part in A is the loess modified by vegetation.



ter with the theory of two ravines than with that of but one which cut across the point from one side. This sag was well developed when the loess was spread out over this region, since loess, in places covered by Wisconsin drift, is found as low as fifty feet above the present river level. See Plate LVII. The sag evidently was so broad and low at the time of loess deposition that later the waters from the Wisconsin ice did not need to scour away the veneering materials from the rock walls. The facts that the loess was spread over a well developed erosion topography and that the Kansan drift beneath it is locally much weathered and leached, or even absent, or present merely as a residual band of ferretto, are facts which point to a date for the loess formation much later than the close of the Kansan epoch and suggest that the buff and blue-gray loess of the Des Moines valley and adjacent regions may be the equivalent in age of the Iowan loess of the counties farther east, although it is of local derivation and not related genetically to the Iowan loess. Exposures recently made on Capitol Hill in connection with enlargement of the State House grounds give additional evidence of the same sort.

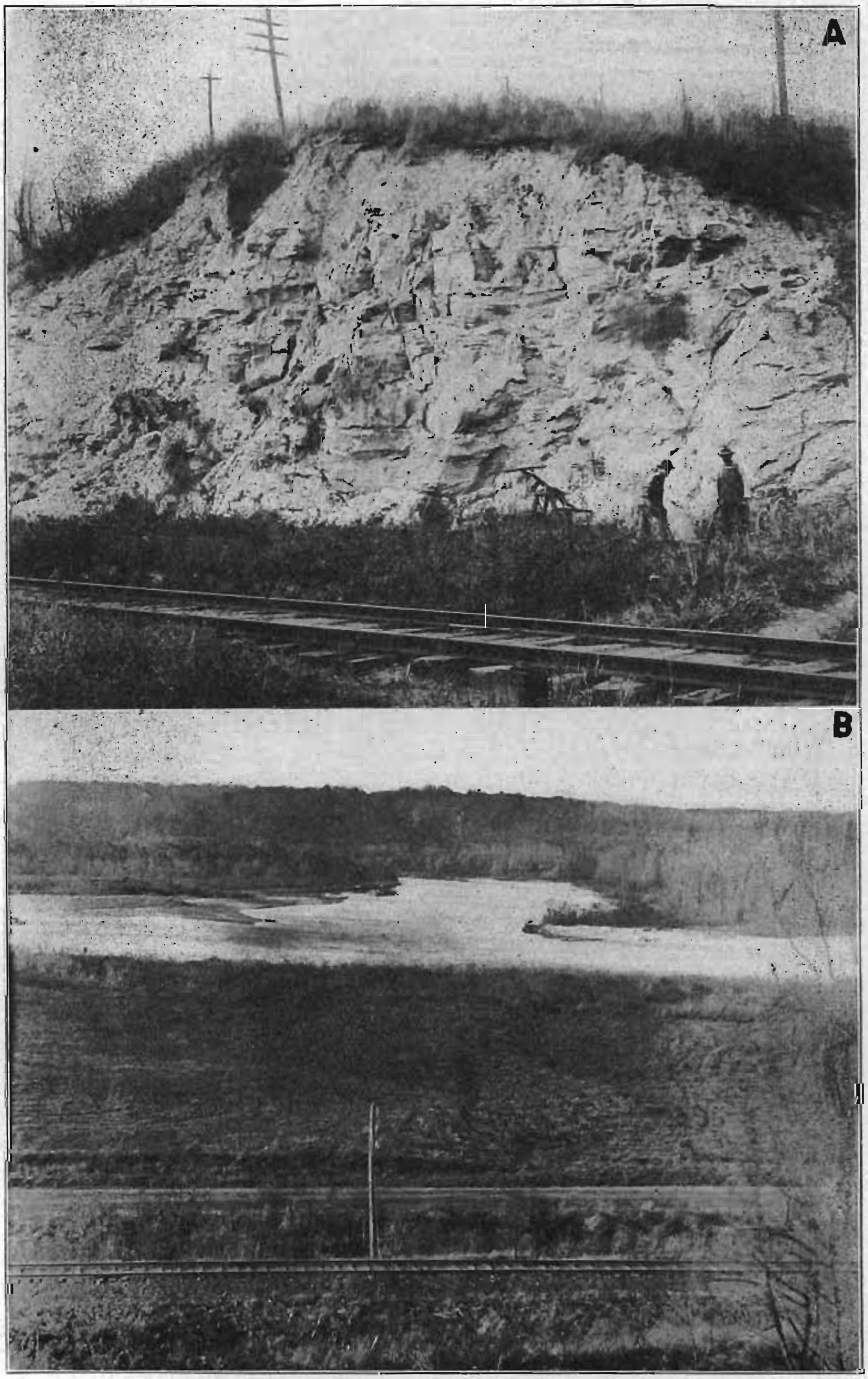
Effect of Wisconsin Glaciation.—While the Wisconsin glacier occupied the Des Moines drainage basin, the great valley east of Capitol Hill was filled with detrital material, the passage of the river by that channel was obstructed and so the younger and much narrower sag cut out west of Capitol Hill was utilized and deepened to gorgelike proportions, though possibly not until the later stages of Wisconsin occupation. That portion of the present Des Moines valley immediately south of Capitol Hill is so evidently related to the Raccoon valley in size and direction (see Plate LVI), rather than to the Des Moines valley below it, that it seems plain that here is a case of stream shifting. This fragment of the Raccoon valley was cut off and added to the valley of Des Moines river.

The Wisconsin glacier reached only as far as Des Moines and its attenuated border in this vicinity did not effect serious topographic changes by direct erosion or deposition. Its chief work was accomplished by means of the waters arising from the melting of the ice. Probably the lower Des Moines and Raccoon valleys were not modified to any notable extent, and the smaller drainage lines covered by the ice were not effaced, but resumed their functions after the retreat of the glacier. Above Saylor Bottoms the valley sides are covered with Wisconsin drift, in places to the bases of the bluffs, and are flanked here and there by terraces of Wisconsin gravels. Both of these demonstrate the pre-Wisconsin age of the valley, as has been emphasized before.

Relation of the Gary Moraine.—Another, though perhaps indirect, proof of the pre-Wisconsin age of the valley above Des Moines is the fact that it cuts directly across the Gary moraine, the area of highest altitudes and of deepest drift in this immediate region. Compare Plates XLVI and LVI. See also figure 43. It is, to say the least, more reasonable to assume that the valley was formed before such a barrier was thrown across its course, and that the river maintained or resumed its path through the moraine after this was formed than to suppose that the post-Wisconsin river cut a new channel along the most difficult course which it could have found.

An Alternative Hypothesis.—As an alternative hypothesis we may assume, as was done on page 547, that the valley above Des Moines is of immediate post-Kansan age but that originally it united with the pre-Kansan valley at Saylor Bottoms rather than at Union Park, as was assumed in the first hypothesis. The present valley through the city, by this hypothesis, originated somewhat as described by Bain—by the junction during pre-Wisconsin time of a series of ravines, probably four, which were cut practically to the present dimensions of the valley when the loess blanketed their slopes. This hypothesis, it will be seen, calls for only one episode of valley cutting to form the present course of Des Moines river across the city, but it is open to the objection of the difference in size of the valley above and below Union Park.

The smooth gentle slope of the west bank opposite Union Park bespeaks a mature stage of development, but this rather anomalous feature may be explained as follows. If the modern



A. The massive sandstone at the foot of Capitol Hill. B. The valley of Raccoon river three miles above its mouth. Note the sand spit at the left. The north wall, here shown, is the limit of the Wisconsin glacier.

valley from Saylor Bottoms to Raccoon river all dates from the same period, the sag at Union Park must have been an embayment of the old valley to the east, and the smooth slope just described probably formed its west bank. In this case it was necessary for only the sections of the valley west of the now isolated eminences of Highland Park and Capitol Hill to be cut out by ravines between the Kansan and the Wisconsin ice invasions. When the Wisconsin ice came down and filled the older valley of the Des Moines with glacial and fluvio-glacial material the waters found a way of escape through these ravines and abandoned the old channel in favor of the newer one to the west.

Character of the Strata.—The variations in the strata cut through by the river do not seem to be of such character as to account for the differences in the valley, or to help in solving the problems it offers. Above Beaver valley and west of Highland Park these strata are shales with two to three intercalated bands of hard limestone six to ten inches thick. These limestones rise toward the north from at or near river level, to eighty feet above that datum at Corydon bridge. On the south bank of the river opposite Highland Park a soft sandstone fifteen feet thick replaces the shales below the limestone beds and west of Capitol Hill ten feet of this sandstone are exposed. On the south front of Capitol Hill the bed of sandstone attains a thickness of twenty-five feet. See Plate LVIII, A. Another bit of evidence is the fact that the valley here, which, as explained above, originally belonged to Raccoon river, is as wide as the valley of that stream above its present mouth, where the sandstone lens is absent or thins down to a few feet. It seems then that the Des Moines cut its valley through sandstone or through shale with no apparent difference in the result.

Summary.—According to the hypotheses here proposed the Des Moines valley originated after the Nebraskan glaciation. Below Des Moines the river still occupies its post-Nebraskan valley, but north of the city it found a new course after the retreat of the Kansan glacier. The first hypothesis considered gives reason for believing that the present valley between Saylor Bottoms and Union Park also is of immediate post-Kansan age, but that the gorge between Union Park and the Raccoon was not occupied by the river until Wisconsin time. By the second hypothesis the modern valley from Saylor Bottoms to the mouth of Raccoon river is all of the same age and was used first by the river when the Wisconsin glacier covered the region. Aside from assigning the date of origin of the valley to post-Nebraskan rather than to pre-Pleistocene time these hypotheses differ from that of Bain chiefly in calling for a post-Kansan instead of a post-Wisconsin age for the valley north of Des Moines. The first hypothesis, in addition, differs in postulating diverse ages for the two parts of the valley west of Highland Park and of Capitol Hill respectively, while the second hypothesis demands more than two ravines to form the valley within the city. As Bain did not take into consideration the sag at Union Park he assumed only two ravines to mark out the future course. The first hypothesis is preferred to the second because it accounts better for the difference in the size of the valley opposite Highland Park and opposite Capitol Hill (see Plate LVI), since the evidence seems to strengthen the theory of diverse times of origin for the valley within the city rather than that of a single date.

The foregoing interpretation of conditions in Polk county will allow us to tie the valley in the northern part of this county to the parts in Boone and Webster counties without a break in topographic continuity. In its essentials the valley is similar in all these counties, and there seems to be every reason to think that the different portions have had a similar history. Naturally the valley, if of pre-Wisconsin age, would be at least partly filled with Wisconsin drift and valley train, and the river has not yet had time to clear out this material completely. Hence it presents an appearance of youth and immaturity very commonly above Des Moines. In contrast with this appearance, however, the size of the valley and its evident maturity in some parts of its course in central Iowa are more consistent with the view of its post-Kansan age adopted here than with that of its extreme youthfulness advocated by Beyer and by Bain.

TODD'S PREGLACIAL NIOBRARA RIVER.

In his vice-presidential address, "The Pleistocene History of the Missouri," delivered before Section E of the American Association for the Advancement of Science, at the Atlanta meeting, Professor Todd suggested that Niobrara river of northern Nebraska, during pre-Pleistocene time joined James river northeast of Yankton, thence "turned south and followed the courses of the James and Missouri to the vicinity of Onawa, Iowa, thence east and northeast through Ida and Sac counties past Wall Lake and thence southeast along the Raccoon river." The map accompanying the paper seems to locate this preglacial channel along the course of Beaver creek, just north of Des Moines.

This hypothesis is attractive as proposing a solution for the question regarding the continuation northward of the old valley of the Des Moines. It might also serve to explain the enormous width of the Missouri valley between Sioux City and Onawa—fifteen to eighteen miles on the Iowa side. It is based admittedly on rather slender evidence—"a few apparently reliable reports from wells which show that the pre-glacial surface indicates a valley whose bottom is less than 900 A. T., in some cases less than 850"; past and present supposed drainage conditions of Wall lake; the anomalous course of Boyer river. The two last named features clearly are due to post-Kansan causes, while Professor Todd is discussing preglacial conditions, and the first is not supported by any evidence available to the writer. At present it seems best not to place too much confidence in this hypothesis so far as it concerns Des Moines river.

RACCOON RIVER.

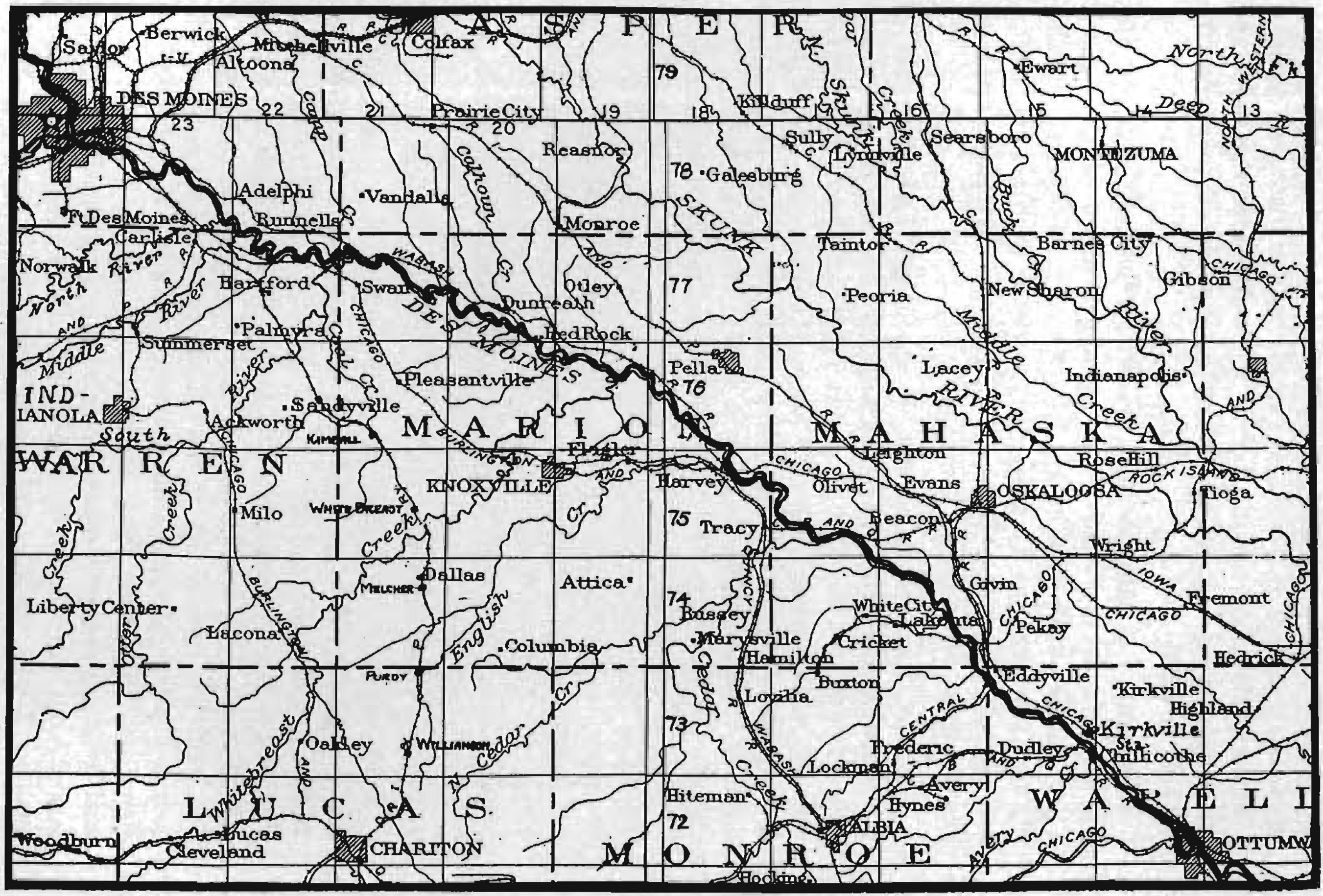
As previously mentioned, Raccoon river is utilizing a post-Nebraskan valley. The valley is wide and flat—its floor is at least a mile across—and it contains immense quantities of sand (Plate LVIII, B, page 553). The walls below Valley Junction are very different in character. The north wall is high and rugged. Short, steep ravines cut up this wall and the neighboring upland and give them a rough and rolling aspect. The opposite wall, on the contrary, is for the most part rather gentle, the ravines are not so steep, the bluffs are less bold. The last mile or so above the junction with the Des Moines is quite abrupt as here the river has been undercutting within recent times. The valley of the Raccoon marks the limit of advance of the Wisconsin ice and probably this accounts for the difference in the valley slopes. The north wall was covered with ice and a mantle of drift was left upon it, while the south bank still retains its pre-Wisconsin features unaffected by the glacier's work. See Plate LVI.

Walnut creek has a broad saglike valley, which may represent an interglacial line of drainage and which served also to carry the waters from the ice front.

The Valley Below the Raccoon Forks.

Direction.—Below its union with the Raccoon, the valley of the Des Moines changes abruptly and markedly in both character and direction. Compare Plates XLIII and LIX. The river has now left the narrow, steep-sided valley in which it flowed through the city of Des Moines and, after traversing the short fragment once attached to the Raccoon, it enters a broad plain two to three miles across (Plate LVI). Instead of running a few degrees east of south, its general direction from the Minnesota line, the valley now follows a course a few degrees south of east to the Mississippi. The abandoned preglacial valley opens into its modern continuation with a two mile mouth stretching between Capitol Hill and the Fair Grounds and lying about twenty feet above the river. The nose of Four Mile ridge is high and steep and beyond it is the narrow mouth of Four Mile valley. This valley has been restricted here by the piling up of Wisconsin drift, no doubt, for above the mouth it widens out, and the restraining slopes become less steep.

General Character.—In general, the broad valley of the river shows all the phenomena of maturity. The excessively flat, broad flood plain across which the river winds is bordered by slopes which for the most part rise gently to the uplands, although the line between flood plain and slope is well marked.



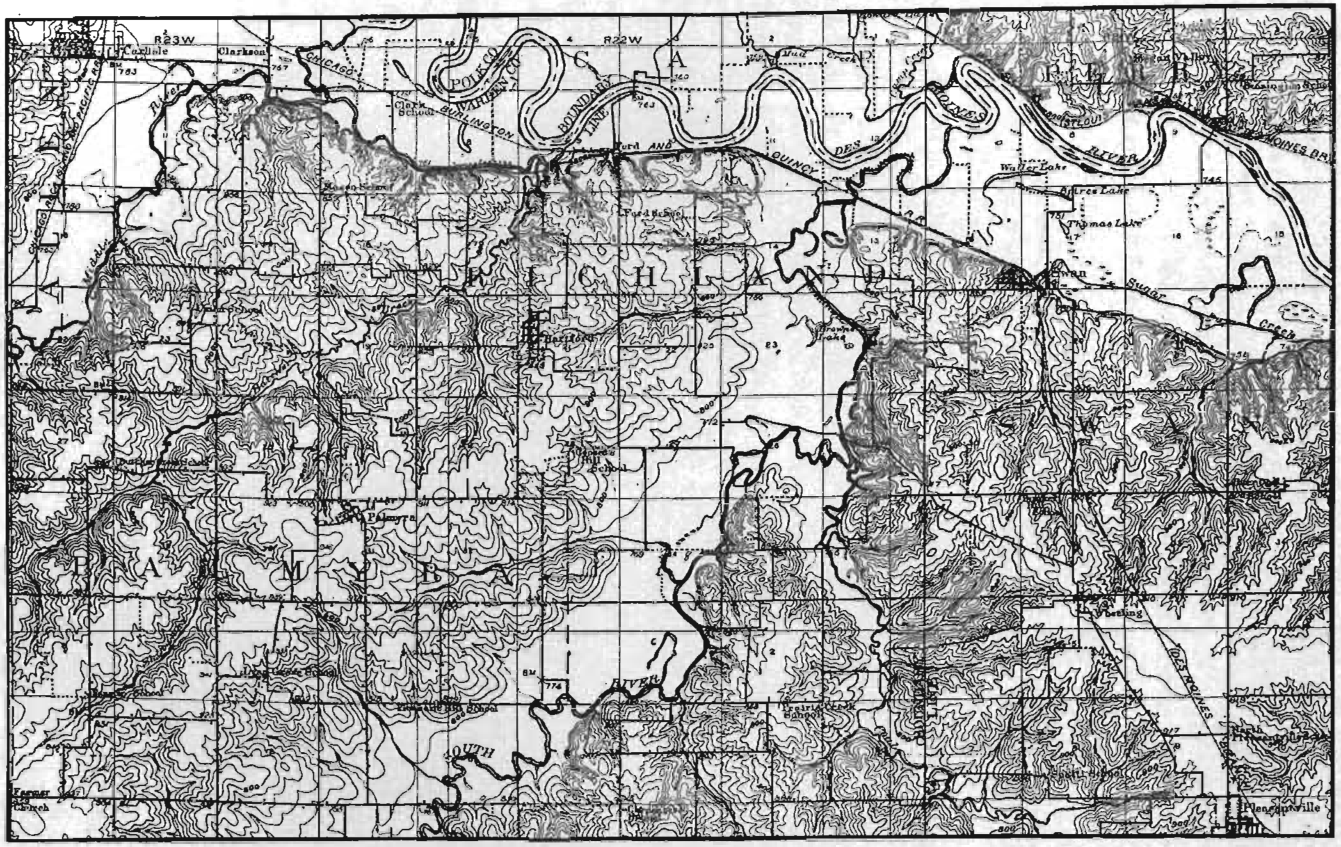
Map showing Des Moines valley from Des Moines to Ottumwa.

In places the wall is steep and rugged as, for instance, between Clarkson and Swan (Plate LX). In such places the walls and the neighboring region are much cut up by ravines and are heavily wooded.

There is no relation here between the character of opposing slopes such as is found in the younger parts of the valley. There steep bluffs face long gentle slopes; here the slopes facing one another may be both steep or both gentle or of differing angle. The valley is now too wide for any close relationship to exist between its walls.

There is a notable difference in the height and character of the walls above and below Des Moines. The depth and steepness of wall of the valley in Boone county have been given already. In contrast, the elevation of Fifield, at the edge of the valley, is 727 feet. See Plate LXI. The immediate slope rises to about 840 feet within one-fourth to one-half mile. The uplands lie at 900 feet about Otley and Knoxville, at a maximum of 880 feet at Pella, but these heights are reached only at distances of three to five miles from the crest of the inner walls. In other words, the valley here has an actual width of six to ten miles. Contrast this with the equally deep gorge near Boone where the distance from upland to upland is compassed within a mile or little more! Certainly such proportions bespeak a long and busy life, as time counts with features so ephemeral as rivers. Compare Plate XLVI with Plates LX and LXI.

Topography of the Region.—Contrasts in the character of the topography of the bordering region and of the tributary valleys are no less marked, as may be seen readily from inspection of the topographic maps. Compare again Plates XLVI and XLIX with Plates LX, LXI or LXIV, page 571. Instead of flat prairies incised by a few short steep-sided ravines, the entire country is gently rolling, except near the steep bluffs, and there are numerous long ravines and valleys, most of them with gentle gradients, and with slopes rising easily to the uplands from very wide bottom lands. The larger tributaries, such as North, Middle and South rivers, flow in valleys of remarkable width, with very low gradients and gentle side walls.



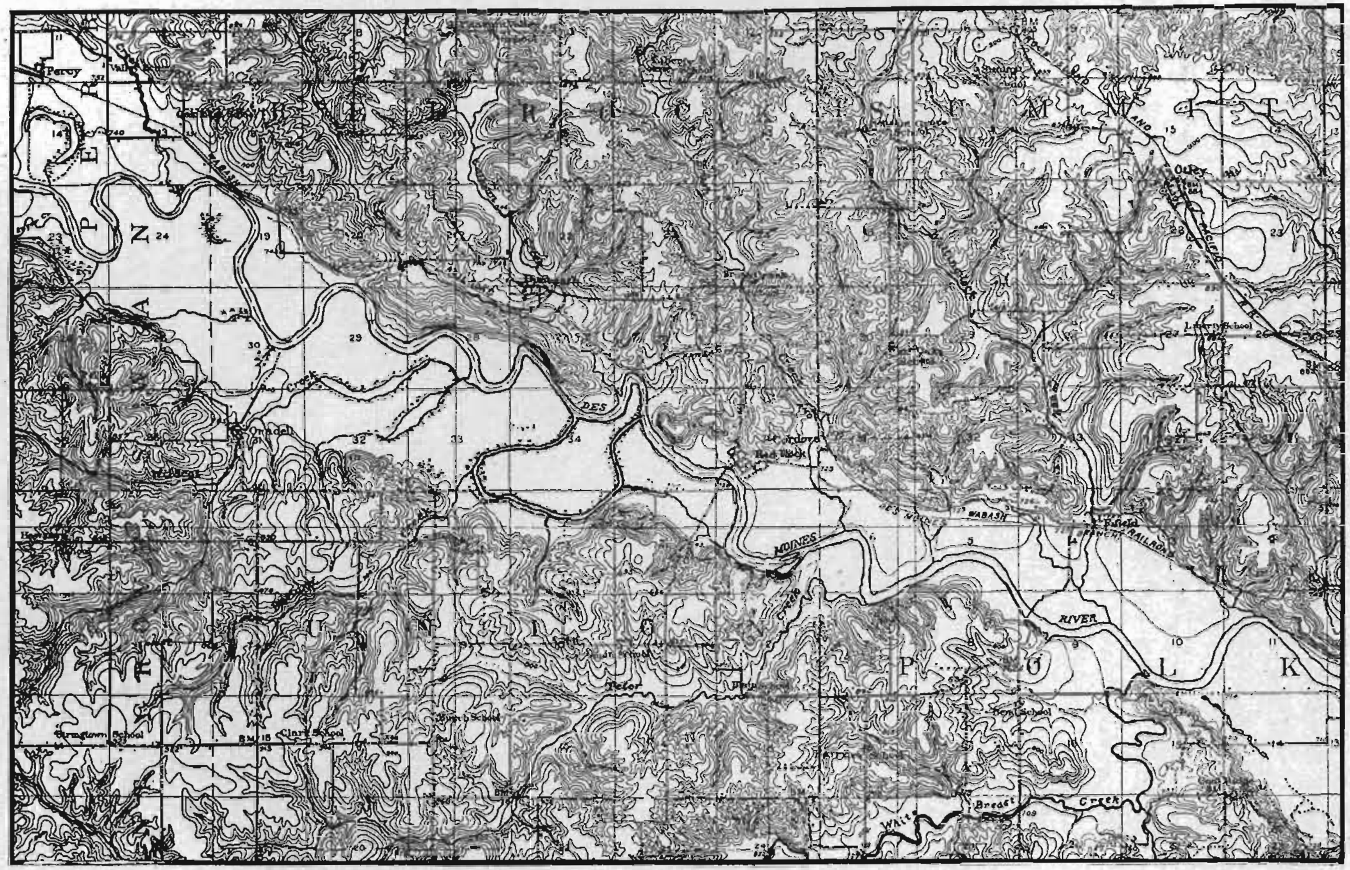
Topographic map of northern part of Milo quadrangle, including parts of Polk, Warren and Marion counties.

But the student cannot fail to observe that the south walls of many of these valleys, and especially of the three mentioned, are much more steep than are the opposite slopes (Plate LX). These south walls are generally well timbered while those opposite are bare of trees and grade imperceptibly into the uplands, owing to their greater exposure to sun and wind with attendant desiccation and degradation.

A further word regarding differential weathering of valley slopes may be in place. Freezing and thawing together with lesser alternations of temperature are the great aids of streams in widening valleys and toning down their slopes. A north-facing slope does not undergo these alternations very much, hence is not broken down a great deal during the winter season. A south face, however, may be repeatedly frozen and thawed and a great deal of material thus be loosened for the spring and summer rains to wash down to the stream. Again, during the warm season evaporation from the north-fronting walls is less than from those facing the sun and the south winds; hence trees gain a better foothold on the north-facing slopes and assist in retaining soil, rock and other material against wastage.

Another feature which will not be overlooked is that while the lateral streams on the Wisconsin plain approach the master valley between parallel walls, the side valleys on the Kansan area show widely diverging walls where they open into the main valley. This is illustrated very well by the debouchure of Mud creek valley a mile west of Runnells. This has the appearance of a wide, alluvium-filled embayment bounded by very gently sloping walls which are a mile apart where they join those of the main valley but converge rapidly upstream. The same feature is well developed by the valley of Brush creek at Cordova (Plate LXI).

The Kansan Drift.—Everywhere below Des Moines the difference in the character of the drift exposed as compared with that north of the city, is plainly marked. The Kansan drift is reddened by the oxidation of its iron content, the contained pebbles are mostly of dark color, and the surface material is in nearly all cases loess, except where this has been washed



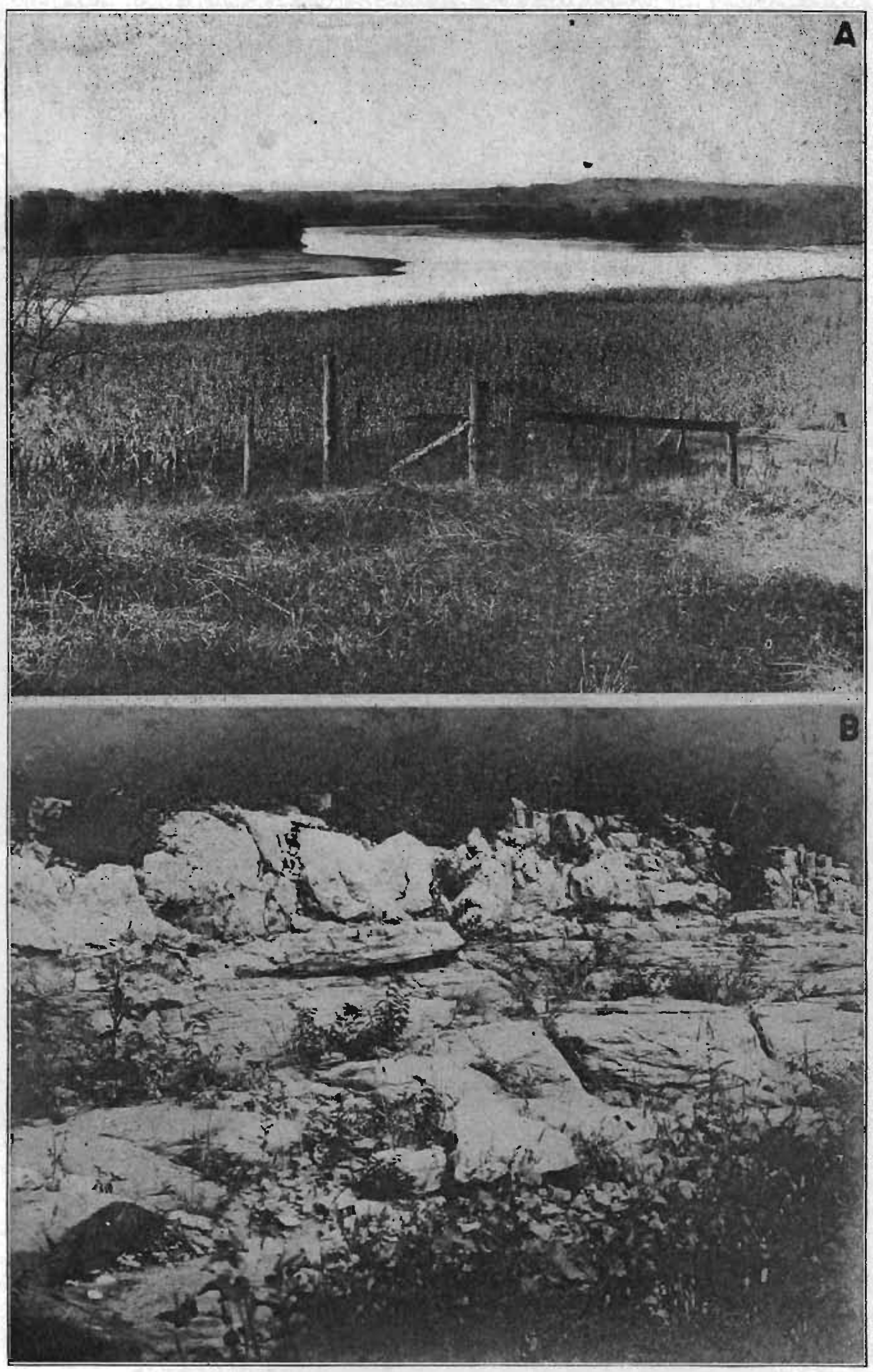
Topographic map of central part of Knoxville quadrangle, in Marion county.

away from the steep slopes. The contrast with the yellow Wisconsin drift with its abundance of limestone pebbles and absence of loess covering, is very striking.

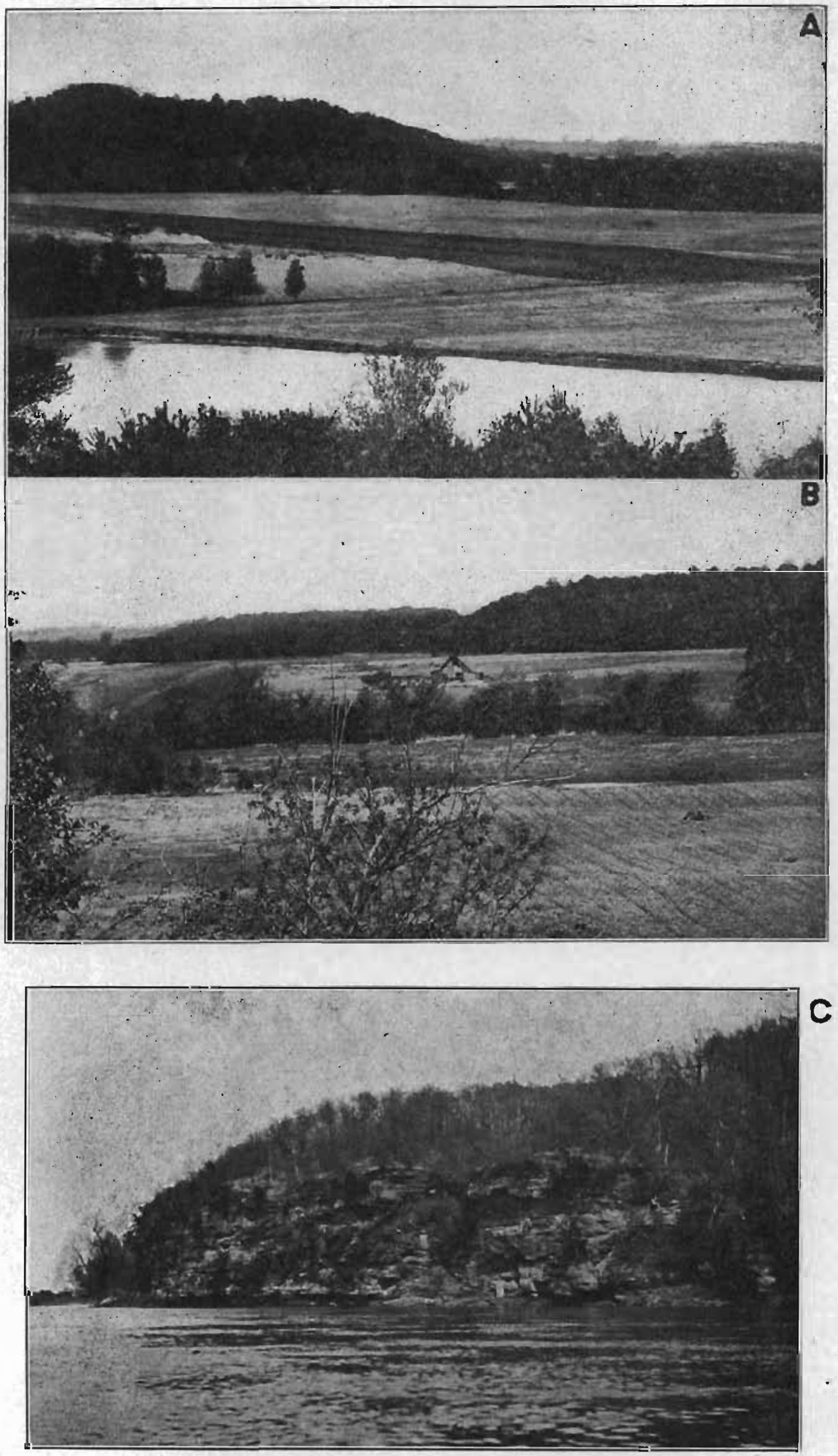
Sand Beds.—The valley below Des Moines shows none of the high gravel benches which are so common in Webster and Boone counties. There are, it is true, abundant deposits of sand in the valley, as within the limits of Des Moines, at Avon, Eddyville and elsewhere, but they are down on the flood plain or form low terraces at its margin. A common characteristic is a gentle backward slope from the river bank to the edge of the valley. Thus a United States Geological Survey bench mark at the southeast corner of Runnells reads 750 feet above tide, while the flood plain near the river, a mile south and southwest rises to 758 and 760 feet (Plate LX). This is due to the building up of a natural levee during times of flood where the swiftly flowing current of the main channel meets the sluggish waters covering the flood plain.

Numerous oxbows scattered over the flood plain mark old meanders of the channel and show that the stream is practically at grade. It long ago ceased cutting downward and has since been devoting its energies to side cutting and widening its valley. See Plate LXII, A, for illustration of this phenomenon.

Red Rock Sandstone.—Between Des Moines and Red Rock the valley walls are cut in Coal Measures, chiefly soft, easily eroded shales, with a capping of Kansan drift and loess. Here the valley is wide, its flat is two to three miles across, and, as before mentioned, most of the slopes are rather gentle. About a mile above Red Rock, however, the valley narrows suddenly to a width of a mile or even less. See Plates LXI and LXIII. The bluffs are high and steep, and present bold scarps of bright red sandstone, which has given its name to the nearby village. These features continue down the valley for several miles, at least to Fifield and the mouth of Whitebreast creek. Below this creek the Red Rock sandstone gives place to shales, and the valley widens somewhat, although it nowhere attains the width it has above Red Rock, owing to the fact that within a



A. Des Moines valley two miles above Dunreath. Shows its mature character and the meandering stream. B. Alternating sandy and limy beds of the St. Louis east of Tracy.



A. Where the valley narrows at Red Rock. Note the wide valley at the right. The bluff at the left is Red Rock sandstone. View looking southwest from Red Rock bluff. B. Looking north from the bluff shown in A to Red Rock bluff, which appears at the right. C. Elk cliff, two miles below Red Rock.

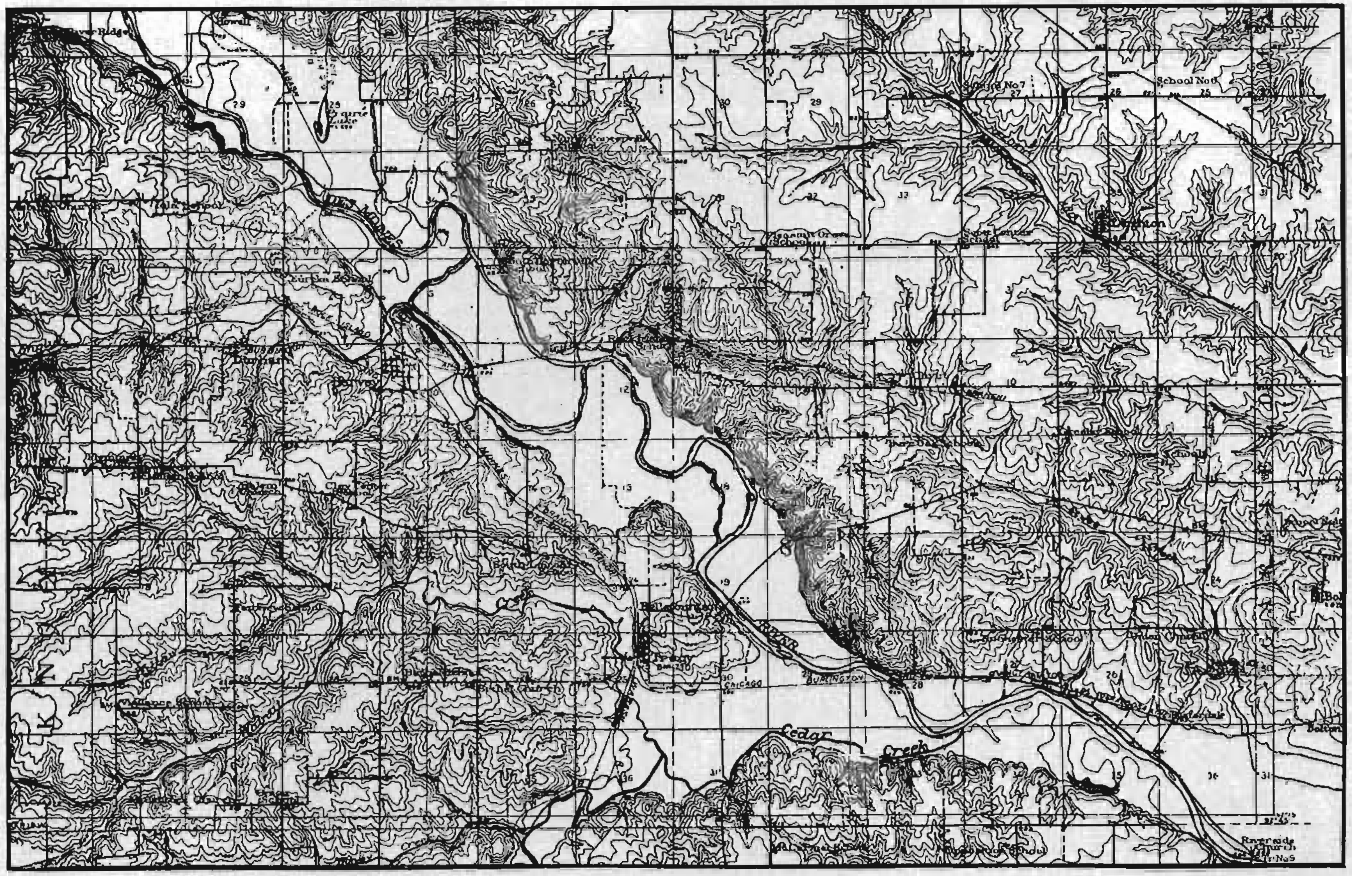
few miles the river cuts into the somewhat resistant arenaceo-calcareous beds of the St. Louis stage, as shown on Plate LXII, B.

The Dunreath Ridge.—A peculiar feature of the valley in central Marion county is the presence opposite Dunreath of a long ridge rising steeply above the plain and extending parallel to the valley for nearly three miles. The character and boundaries of this ridge are well shown on the map of the Knoxville quadrangle, Plate LXI. Possibly it is the result of the diversion of Prairie creek at a time when both it and the river flowed at a much higher level than now. More likely, however, it is not a case of stream diversion at all, but rather of the simple growth of a valley parallel to the main valley instead of in the more customary transverse direction. The recess into which the valley opens, and which is now invaded by a swing of the river, is another example of the type of valley mouth described on page 562. The ridge has been isolated still more by the cutting down of the col at the north end, through headward erosion of a ravine working back from the main valley.

Ridges Near Harvey.—Another conspicuous feature of the topography in this region is the presence between Harvey and Tracy of a series of isolated ridges and hills set off by wide swales and gaps. These are shown on the Pella topographic sheet and need but brief description (Plate LXIV). The first and second members of the series are long ridges rising rather steeply 100 and sixty feet respectively above the broad swale which lies behind them. The third and fourth members are high rounded knobs, the third rising 140 feet above the river. The gaps between these eminences and the swales which lie behind them are broad and for the most part are bounded by gentle slopes. The northern ridge, at least, has a core of Coal Measures rock, and a clay pit is operated in it. Walnut creek turns from its northeasterly and easterly course to flow south past the southern hill to join Cedar creek just beyond. The remarkable flat across which the lower part of Cedar creek finds its way to the river is worthy of note.

Here, then, are four isolated hills cut off from the uplands by long swales, only one of which is occupied by a stream of any consequence—Walnut creek. How are these phenomena to be accounted for? We can see that if the ridges were made continuous we would have behind them a valley extending from English creek to Cedar creek, and lying but little above the level of the Des Moines flood plain. Now it is to be noted that opposite the northernmost swale, English creek is diverted from its southeast course and turns northeast, in which direction it enters the main valley. It seems quite possible that at a time when it ran at a little higher level the creek may have continued southeast down the swale, perhaps to unite its waters with those of Walnut and Cedar creeks. Or possibly it may have entered the Des Moines through one of the gaps between the hills. Perhaps, too, the Des Moines once washed the western slopes of the two southern hills and utilized the spacious valley of Cedar creek. The sudden narrowing of the main valley opposite the two southern knolls may be significant in this connection, although this may be due to stratigraphic reasons. Some of the gaps between the hills may be due to lateral erosion by ravines whose lower parts have been cut away by the widening of the main valley by side cutting. The embayment at the second gap undoubtedly is the result of an incursion of the river, which has cut into what was once a gentle slope like the other gaps. These changes in the courses of the valleys may be attributed (1) to the effect of the Kansan glacier or its deposits, if the tributary valleys are pre-Kansan in age, or, as seems rather more probable, they may be due (2) entirely to the erosive work of running water, including the capture of English creek by a short tributary of the Des Moines, the possible diversion of a fragment of the Des Moines and consequent changes in lower Cedar creek.

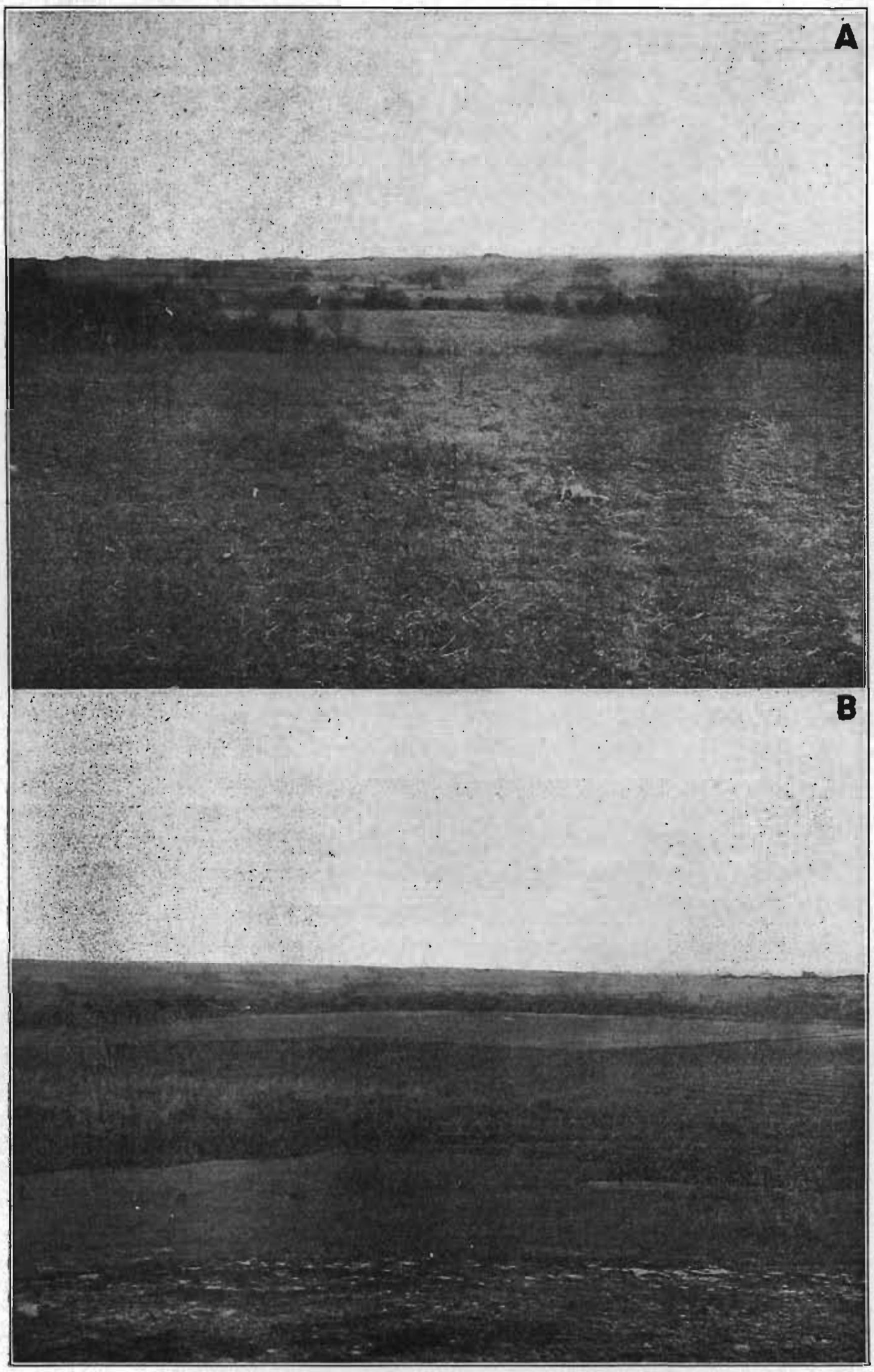
A Pre-Pennsylvanian Valley.—The depth to which the valley of the Des Moines has been filled is revealed by a sand-pumping station located at the Chicago, Burlington and Quincy railroad bridge over the river east of Tracy. This has taken out sand to a depth of thirty-five feet below the level of the flood plain. The sand was said to rest on "slate," which probably repre-



Topographic map of southern part of Pella quadrangle, including parts of Marion and Mahaska counties sents the Coal Measures shales. Bain, in his report on Mahaska county, maps Coal Measures here, although St. Louis beds are found up the river and below. It is interesting to note that east of Oskaloosa, on both North and South Skunk rivers, the same phenomenon occurs—the Saint Louis beds evidently have been cut away and the depressions filled with Coal Measures shales. These depressions seem to represent a pre-Pennsylvanian line of drainage, leading to the southwest and extending under Cedar creek valley. The comparative ease of erosion of the Coal Measures strata no doubt accounts for the width of the lower part of this valley.

Benches and Terraces.—The steep bluffs which border Cedar creek on the south and blend with those of the main valley soon lose their steepness and are separated from the valley by a series of wide, fairly level benches lying seventy-five feet above the river and sloping down at angles of 10° to 20° to a rather narrow flat which rises about twenty-five feet above water level. Behind the benches a long gentle slope rises a hundred feet to the uplands, which here lie at about 840 feet above sea level.

On the east side of the river there is a broad plain extending from the railroad bridge above the mouth of Cedar creek southeast for several miles (Plate LXIV). It is about twenty feet above the water at the free edge and has a very gentle, almost imperceptible rise to the north of ten to fifteen feet per mile. Along the railroad track the plain, or terrace, as probably it should be called, is bounded by a gentle slope and its eastern margin is marked by high steep bluffs which are followed closely by Saint Joseph creek. These bluffs rise 150 to 175 feet above the river and form the west slope of a long, narrow ridge whose east face overlooks Muchakinock valley. The southern part of this ridge is buried beneath hills of sand and it terminates in a sandy point a mile north of Eddyville. Opposite this point Muchakinock creek cuts the wall of the main valley by an opening which has been so restricted by sand hills that it is not over 400 feet wide. Above the opening, however, the creek presents the characters typical of Kansan streams—a broad valley, easy gradient and gentle slopes, although not much flood plain has



A. Looking northeast across Muchakinock creek two miles below Given. B. Looking west across Des Moines valley from the ridge north of Eddyville. These views show the great width of the valleys and the fairly gentle slopes of the walls.

been developed. Below Given the valley is between two and three miles wide from ridge to ridge (Plate LXV, A) and even in its upper reaches above Beacon and Evans it already has assumed mature proportions. A road grading over the valley wall in the eastern edge of Eddyville shows, near the brow of the hill, six feet of deep red and yellow sand, overlying which is a heavy body of loess, gray at the top of the hill, but buff lower down, which caps the hill top to a depth of twenty feet. The sand evidently is to be correlated with the Buchanan gravels.

Below Eddyville conditions on the east side of the valley are somewhat reversed, for with the exception of the bluffs near the town, which are fairly steep, the valley wall is long and gently sloping all the way to Ottumwa. In places this wall is broken by benches which rise seventy-five feet above the river. These are separated at Kirkville Station by a terrace thirty feet high, backed by a long rise to the prairie. At Ottumwa the gentle slopes are succeeded by high bluffs which are crowned by many of the best residences of the city.

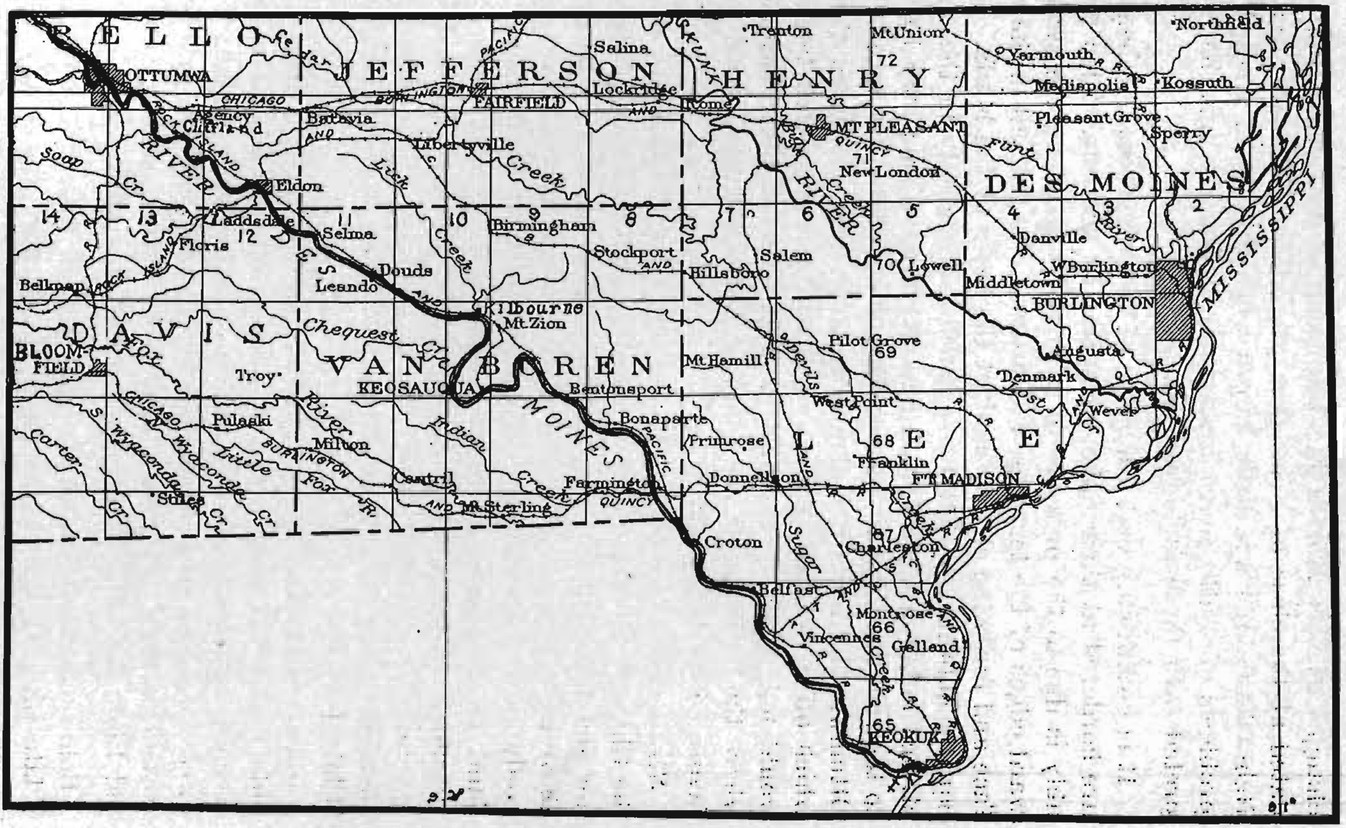
Much of the west slope is fairly steep, descending 100 to 150 feet within a short distance. There is not much evidence of benches on this side, except in the vicinity of Chillicothe, between North and South Avery creeks, where one lies thirty feet above the river, at the same level as the terrace opposite Kirkville Station. Evidently these date from the same period and are due to the same causes.

The bottom lands of the Des Moines in most of this region are limited to a width of one-half or even one-fourth of a mile. The entire valley, however, is much wider. Opposite the narrow ridge mentioned on page 572, where bluffs bound its east margin, the valley still is three miles from rim to rim and above and below here, where the high benches and terraces increase its width, there must be a distance of three and four to six miles from upland to upland. See Plate LXV, B. The lower part of the valley is cut in limestone, of which numerous exposures occur, especially between Eddyville and Ottumwa. The uplands are underlain by Coal Measures and are dotted with the top-works of coal mines.

Origin of the Benches and Terraces.—The terraces at the lower levels may well be of river origin, as their free margins are built entirely of sand and alluvium. The slopes at the back may be due to wash from above. Near the east end of the low wide plain described on page 572 there are some well-defined oxbows which lie near the edge of the terrace. They indicate that the river ran at this level at a date not so very far removed and that therefore the river, in reaching its present level, must have cut this terrace during recent, post-Wisconsin time. Eddyville is built on a low terrace which is continuous with the sand hills mentioned on page 572. This terrace like the others at a similar level is due, doubtless, to river work, while the sand hills owe their form to wind action.

The high benches must be of different origin. Where steep bluffs face the river they are seen to be composed of rock, but where the slopes are gentle, only drift or loess is seen. Hence it is not certain whether rock underlies all the high benches, although it seems probable that it does for the most part. The benches are covered with Kansan drift and loess. The drift is weathered and reddened and appears in strong contrast with the loess, which generally is grayish at the surface and buff at depth. In places, however, a gray, iron-stained type appears beneath the buff variety. Locally there is a pebble band between drift and loess, indicative of the greatly superior age of the drift.

The presence of drift on these benches shows that they represent pre-Kansan erosion by the ancestor of the modern Des Moines. Probably the Coal Measures were cut away by the meandering stream, but when hard limestones of Saint Louis age were reached, the river, unable to erode these so readily, narrowed its valley as it sank into the more resistant strata. Bain evidently has mapped the superficial distribution of the Saint Louis in Mahaska county according to this theory, although the same is not true of Leonard's map of Wapello county. It was assumed by the earlier students of the region—Gordon, Bain, Leonard and others—that the present features of the valley are preglacial in age, but as stated in connection with



Map showing Des Moines valley between Des Moines and Keokuk.

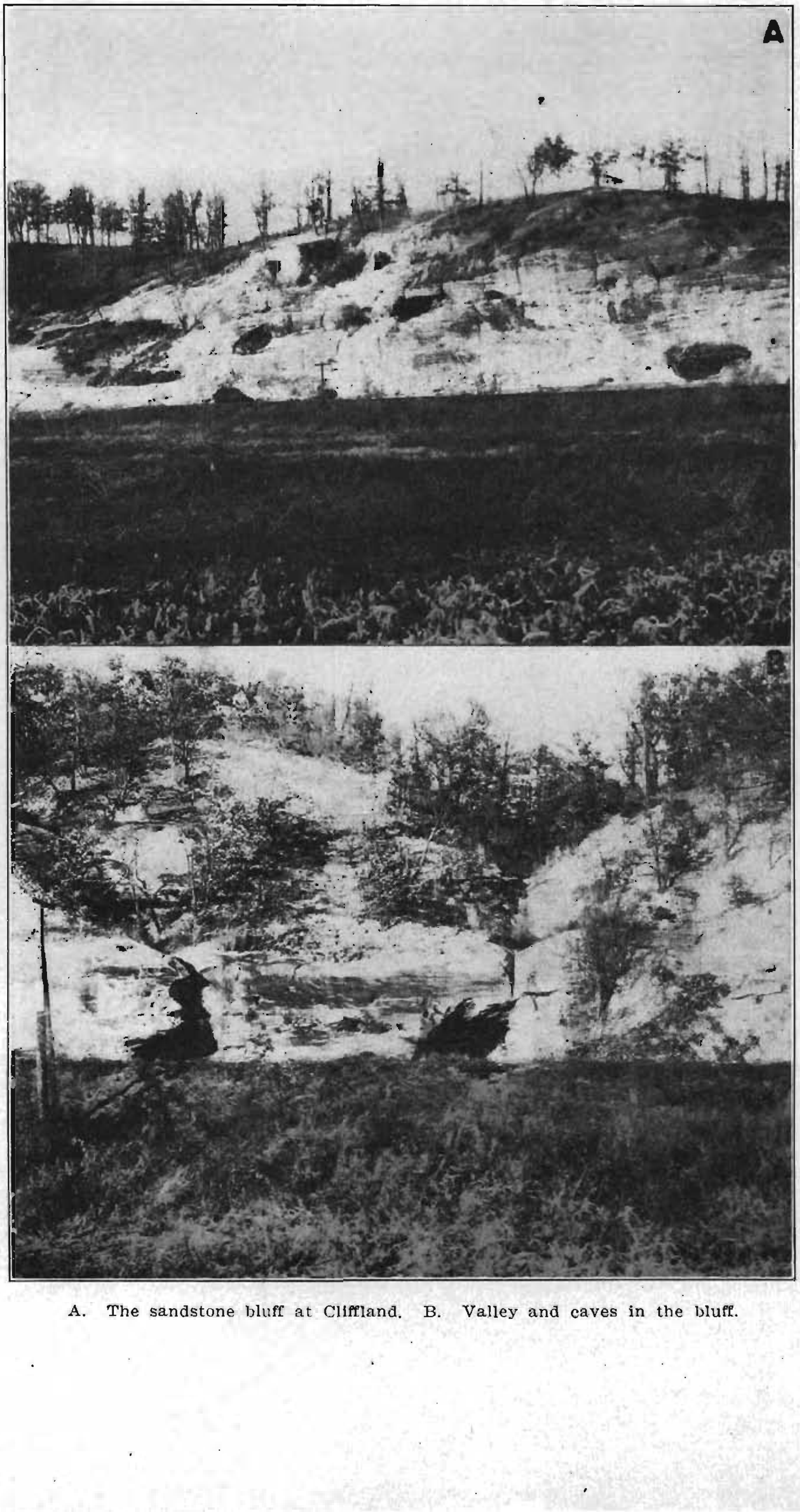
changes at Des Moines the beginning of the valley must be dated at the close of Nebraskan glaciation. Moreover, as the Nebraskan stage was little known when these men studied the problems of southeastern Iowa, their statements must be interpreted with these facts in mind.

It is noteworthy that a number of these terraces and benches are bordered at their upland margins by streams. This probably is due to the presence of natural levees along the streamward edges of the terraces, which cause a slight fall in the surface and force the stream against the bases of the bluffs. It is equally noteworthy that these benches occur only in the short stretch between Cedar creek and Ottumwa. This may be due to the fact that above Cedar creek and also for a distance below Ottumwa, the walls are almost entirely Coal Measures strata, which offer so nearly equal resistance to erosion that terraces would not be likely to develop. But between these localities, where the Saint Louis rises high in the bluffs, conditions were favorable for terracing.

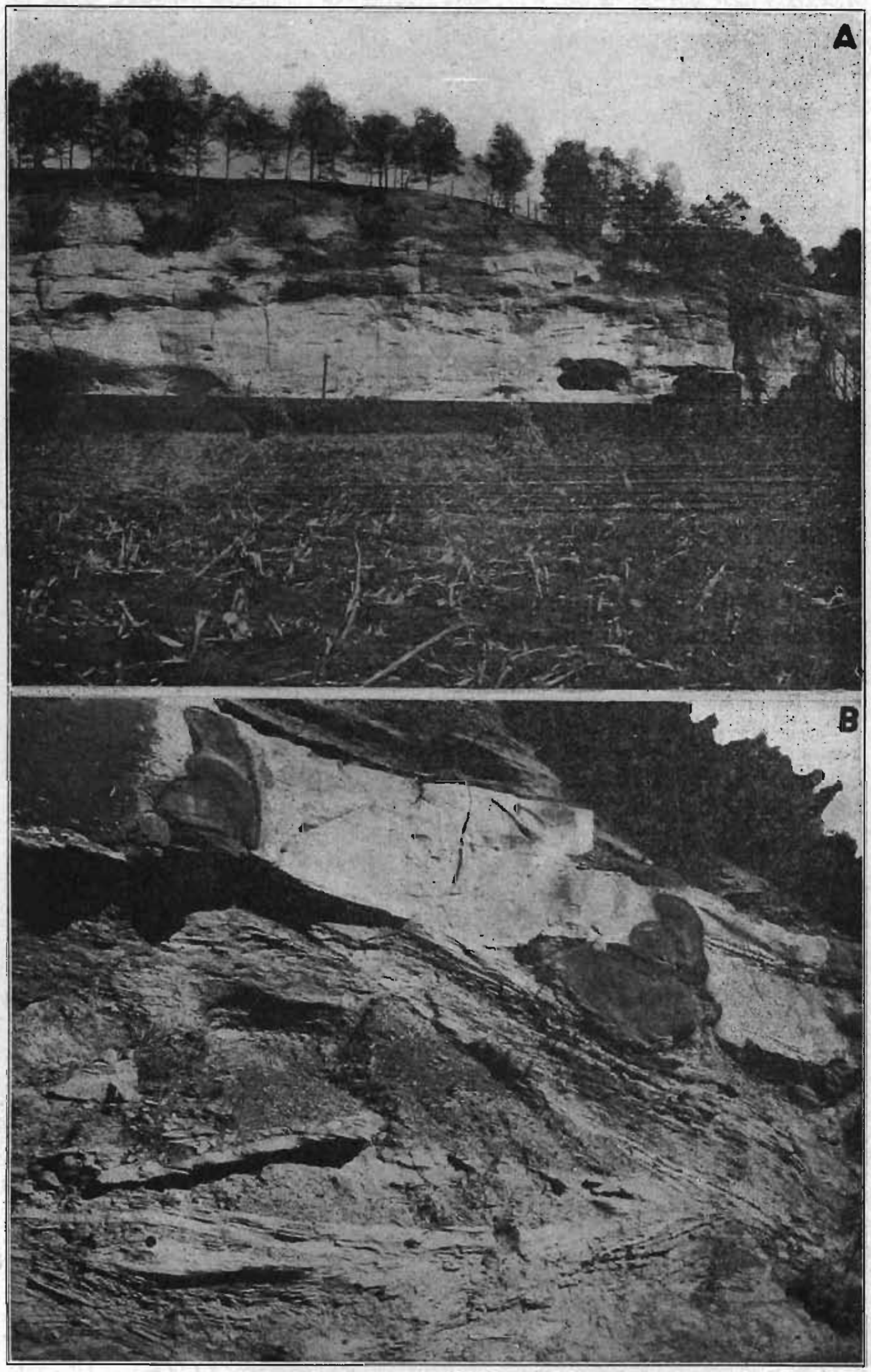
Strata below Ottumwa.—At the east edge of Ottumwa, where the Chicago, Rock Island and Pacific and the Chicago, Burlington and Quincy railroads cross, the bluff is seen to be built, above black shales of the Des Moines stage, of sands, silts and sandy silts of Pleistocene age. In the vicinity of Ottumwa the Saint Louis strata dip below water level, so that black Coal Measures shales outcrop in the bluffs, although Saint Louis limestone is quarried in the northern part of the city. The limestone reappears in the bed of the river as Eldon is neared (Plate LXVI).

Beyond Ottumwa the eastern wall of the valley swings in a wide curve and soon becomes a steep bluff which presents a precipitous sandstone scarp fifty to seventy-five feet high. This scarp continues with occasional breaks, to Cliffland, where it presents a very picturesque view. See Plate LXVII, A and B, and Plate LXVIII, A, for portions of this cliff.

Below Cliffland, shales are interbedded with the sandstones (Plate LXVIII, B) and gradually form more and finally all of the exposure. Here the wall is somewhat less steep. About



A. The sandstone bluff at Cliffland. B. Valley and caves in the bluff.



A. The continuation of the bluff at Cliffland. B. Shales and interbedded sandstone one-half mile below Cliffland. Note the crossbedding and concretions.

two miles below Cliffland a high wall of sandstone locally replaces the shales above the level of the railroad. It seems to fill a valley in the shales— a valley, perhaps, of contemporaneous erosion. From these exposures to Eldon the rocks are not exposed and the slopes are quite gentle. On the outskirts of Eldon is a bluff fifty feet or more in height composed entirely of a buff loesslike silt with sandy streaks in the lower part.

Along the west side of the valley the wall is quite steep nearly all the way from Ottumwa to Eldon. These steep slopes give way, however, as Soap creek is approached and grade down to the wide valley of the tributary. Beyond the space of half a mile occupied by the flood plain of the creek, the high slope is resumed.

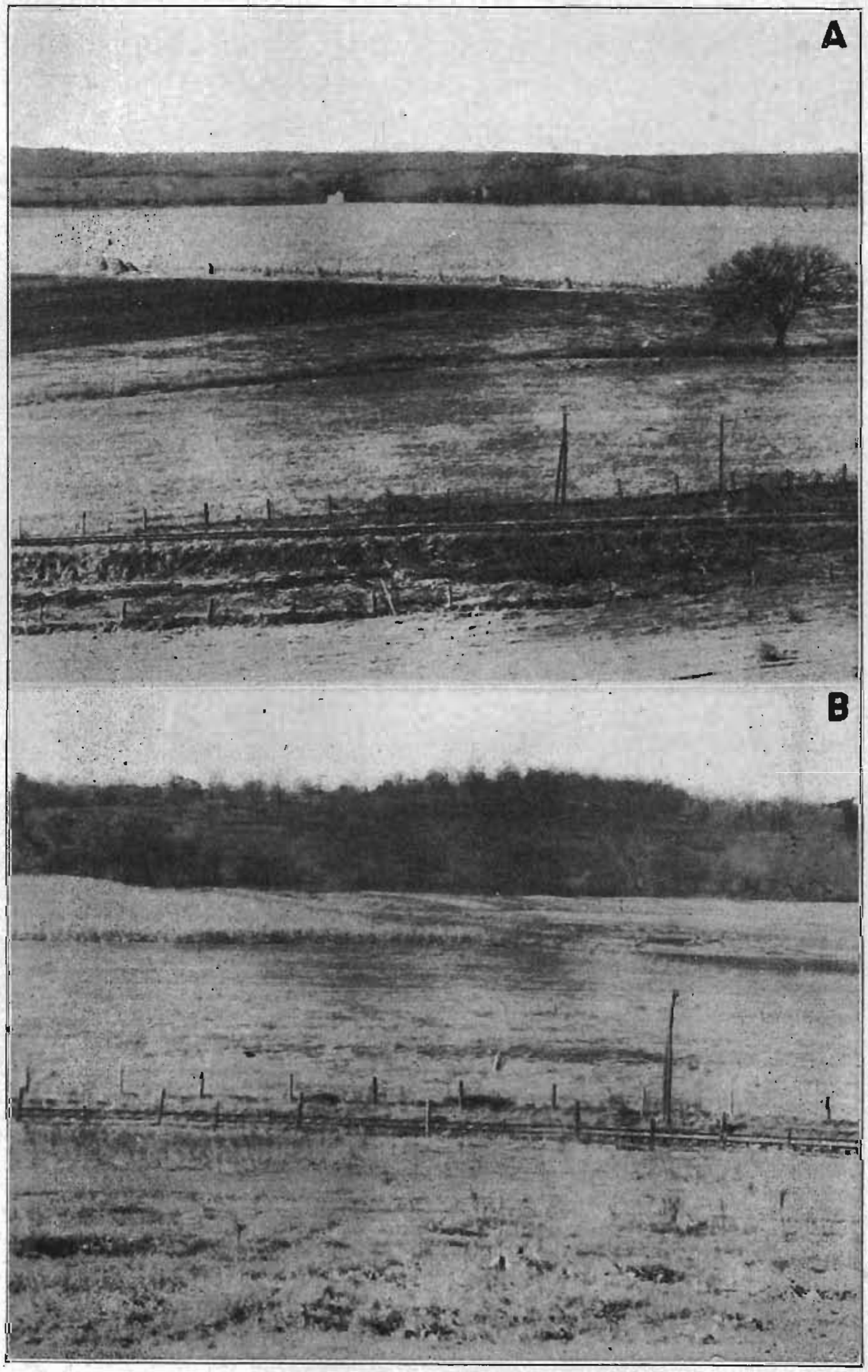
FIG. 48—The wide valley of the Des Moines between Cliffland and Eldon.

Between Eldon and Kilbourne the east side of the valley rises with gentle slopes of 2° to 5° inclination from the flood plain to the uplands. These gentle slopes are interrupted only at Selma and Douds, where for a brief space, steeper, rougher walls intervene. The gentle slopes reach back one-fourth to one-half of a mile to the uplands. The west wall, contrariwise, is quite steep all the way from Soap creek to Kilbourne. Here it assumes a gentle grade, while the opposite wall rises to a bold steep bluff, owing to the abrupt change in direction at this point.

The fact that the soft strata of the Des Moines stage dip below river level between Ottumwa and Eldon explains why the flood plain here is one and one-half to two miles in width instead of one-half to three-fourths of a mile, as above Ottumwa. See figure 48. Below Eldon the Mississippian limestones rise above water level and, as a result, at Selma the valley suffers a remarkable constriction, as here the flood plain is narrowed quite abruptly to a width of about one-fourth of a mile. Plate LXIX, A and B, show the character of the valley in this vicinity and the profiles taken near Selma will show how abrupt and how great this change is (Plate XLIV, C and D). As the resistant limestones of the Mississippian stage rise higher and higher above the valley floor, they become more and more a determining factor in the development of the topography, and hence the river is straitened in its course and compelled to flow in a singularly direct path, in strong contrast to its meandering progress between Des Moines and Eldon.

At Douds Leando there is a terrace extending one-half mile or more along the west side of the valley. It is fifty to sixty feet above the flood plain and back of it the uplands rise by about the same amount. It runs out to the south and is succeeded by a narrow flood plain not over one-fourth of a mile wide. Three miles farther down the valley another ill-defined terrace cuts out the flood plain and beyond it the steep bluffs rise from the water's edge to the prairie levels. Across the river a strip of bottom land perhaps 200 yards wide separates the channel from the slopes and extends down the valley as far as Kilbourne.

Below Selma, limestone outcrops are abundant in the bed and walls of the master valley as well as in those of its tributaries. On both sides of the Davis-Van Buren county line quarries have been opened in Saint Louis strata well up on the hillsides. On the other hand, in a creek valley on the Davis county side of



A. The wide valley a mile north of Selma. B. The narrow valley just below the village.

the line, Des Moines sandstones are found at the base of the bluffs. This is one of many illustrations of the irregularity of the old Saint Louis surface.

The Keosauqua Oxbow.—Below Kilbourne the valley presents what is probably the most singular phenomenon of its entire course—the Keosauqua oxbow. Plate LXVI shows the relations of this oxbow to the valley and figure 49 presents a topographic map of the oxbow. In this great bend the valley leaves its direct course, swings six miles to the southwest, then bends on itself and after coming back into line with its upper course

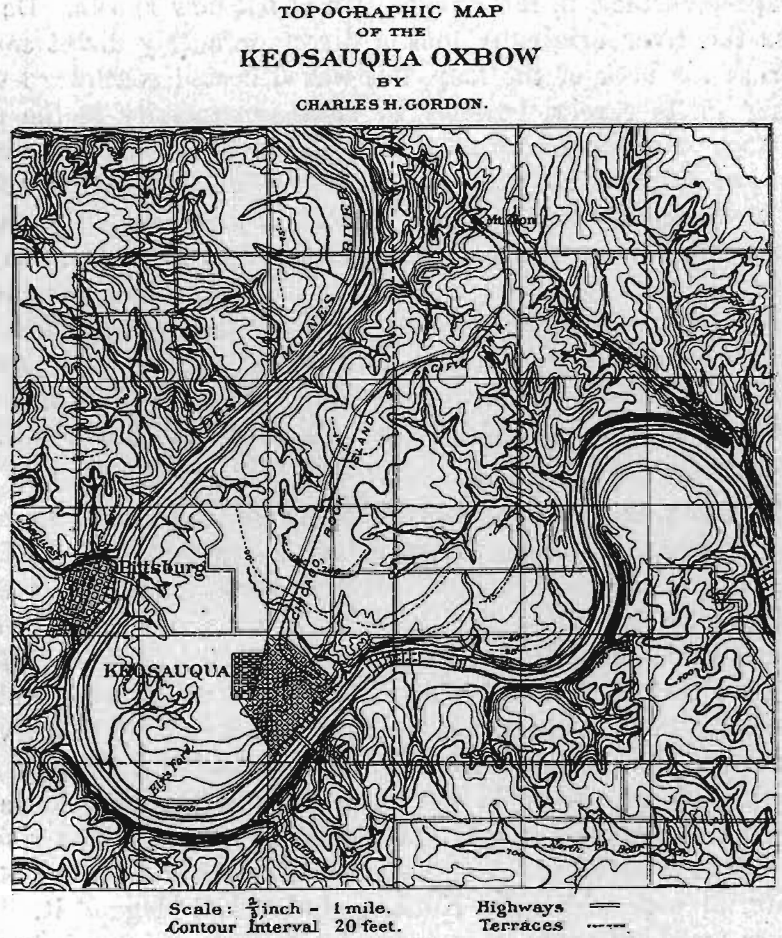


FIG. 49—Topographic map of the Keosauqua oxbow, Van Buren county.

continues in the southeasterly direction common to the valley below Des Moines. This oxbow illustrates beautifully the tendency of rivers to develop steep bluffs on the outer side of their curves while long gentle slopes are formed on the inner side.

It seems difficult to account satisfactorily for this great detour of the river. There is no material difference in the rock strata of the region, but whether there was at any time a topographic obstacle in the river's path is not now known. Doubtless the river originally took a direct or nearly direct course across the neck of the loop, but was deflected southward very early in its career, possibly by some irregularity in the rock surface or in the glacial deposits. The level of the ridge within the loop is about the same as that of the land outside the valley, to the northeast (760 feet above sea) so that this early course could not have affected the topography very seriously. In accordance with the laws of stream work the river constantly increased its curvature. When the hard limestones below the Coal Measures were reached, this lateral erosion was carried on at the expense of the deepening of the channel and so there was planed out the broad terrace on which the upper part of Keosauqua is built.

Terraces in the Oxbow.—A number of sand terraces have been developed on the valley sides as remnants of old flood plains, marking stages in the river's history, and these were mapped by Gordon at the following levels above low water at Keosauqua: 145 feet, 120 feet, 90 feet, 75 feet, 50 feet, 25 feet, 15 feet and 10 feet. See figure 49. The most prominent of these are those lying at the 50 foot, 90 foot and 145 foot levels. Since the oxbow must date from early Aftonian time these terraces may represent in part the great Aftonian gravels of western Iowa, and in part they are the result of the river's efforts to clear its valley of the accumulations of drift and other material with which the Kansan glacier had clogged it. The lower members probably represent a similar activity following the Wisconsin stage, since sand and silt would be carried down the valley by the floods while the Wisconsin ice was melting.

Topographic map [illegible] the Kahoka quadrangle, including part of Lee county, Iowa, and of northeastern Missouri.

The Narrow Valley near Keosauqua.—The river valley is narrow and rock-bound in this region and every tributary flows on a floor of rock, limestone for the most part, although shales are found at numerous points. The uplands are covered with a heavy blanket of loess which in general is light gray with iron stains and with local changes to bluish color. The drift also is quite thick and is very pebbly.

The Bentonsport Ridge and Terrace.—Three miles above Bentonsport a high steep ridge half a mile long flanks the river closely on the east side. Behind it is a narrow, rather shallow swale which opens into the river valley to the north, into a creek valley at its lower end. There is no stream of any consequence in the swale, and the reason for its existence is not clear. It must be due to some drainage element not now evident, or to some change necessitated by glaciation.

Beyond this ridge gentle slopes border the river as far as Bentonsport, while across the valley these are faced by steep walls. At Vernon, however, across the river from Bentonsport, these walls give way to a terrace sixty to eighty feet high and varying in width from one-third to one-half of a mile. There seems to be no clear reason for this terrace nor for those between Douds Leando and Kilbourne, since in both of these localities the river is flowing in a straight course. But evidently they date from a period when the river, flowing at a higher level, was swinging from side to side in its valley and was cutting away its walls. As it sank to lower levels the stream pursued a straighter and narrower path.

The Valley near Farmington.—Below Bentonsport the valley is increasingly narrow until at Bonaparte there is practically no flood plain. The walls, more or less steep, come in quite close to the river banks. The alternation of steep and gentle slopes, with the reversal of the succession across the valley, is even more pronounced than above Bentonsport. The character of the walls changes every mile or two. Two miles above Farmington the valley widens a little and a sand flat occupies the bottom lands east of the stream. This flat is twenty to thirty feet above the water, and at Farmington attains a width of half a mile. On its landward side it is bounded by gently rising hills which are built of Coal Measures and faced with sand which in places is overlain by a light gray loess. At the south edge of town a large pit has been sunk thirty feet below the level of the flat into cross-bedded, waterlaid sands and gravels.

It may be noted that from the Keosauqua oxbow southward within two miles of Farmington limestone outcrops abundantly in the floors and lower walls of tributary valleys. A mile below Farmington, too, a ravine shows Mississippian limestones in its floor, while the Des Moines shales and sandstones are found higher up the valley. At the village, as is shown by coal mines and prospects, Coal Measures strata lie in an ancient basin cut in the limestones. In the light of these facts we can understand how the valley was cut wide and deep across the strip of soft

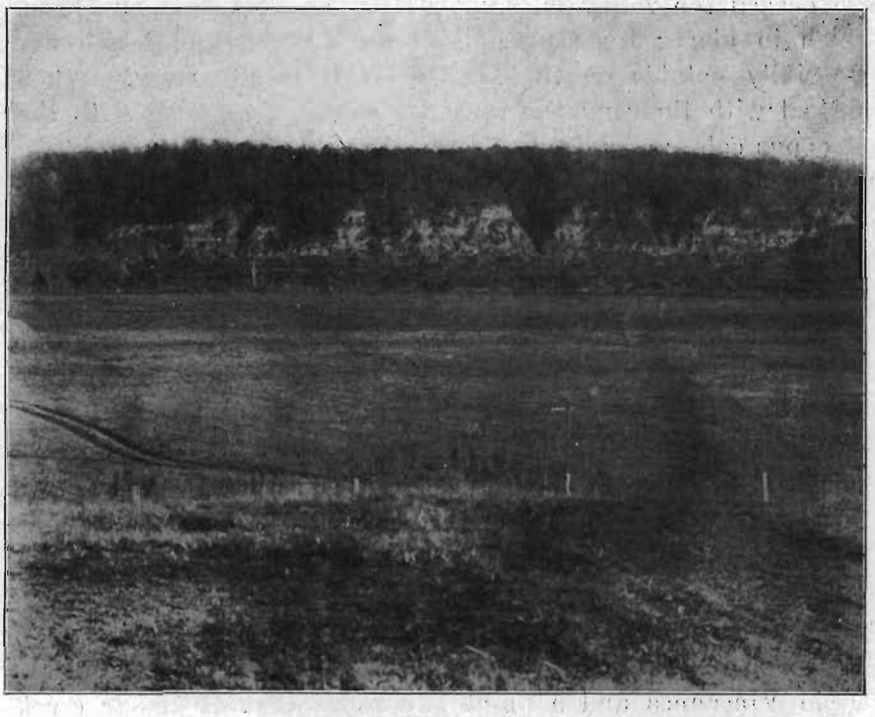


FIG. 50—The narrow flood plain just below Croton. View taken from the edge of the terrace on the Missouri side.

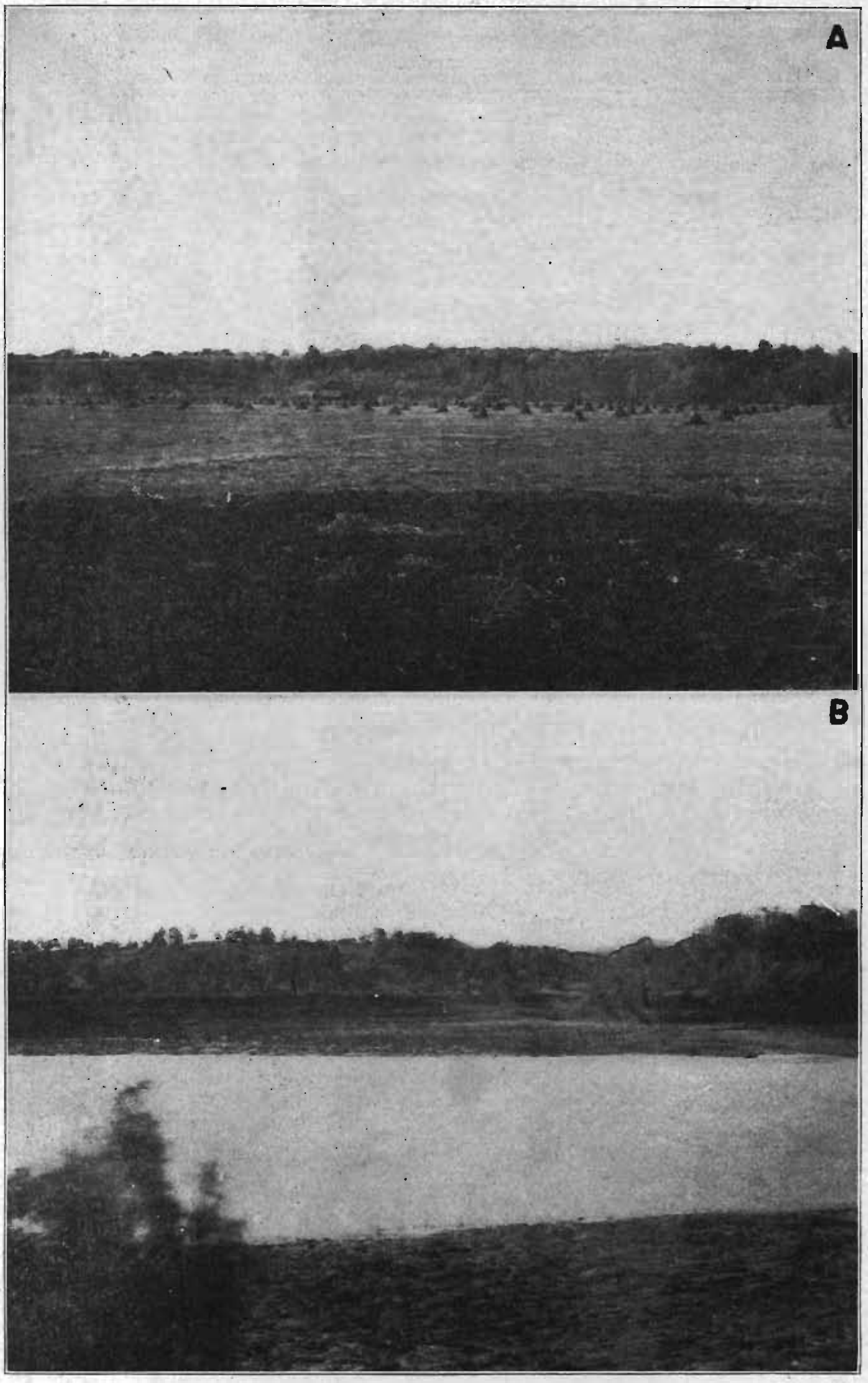
Coal Measures and since then, following the close of one or more of the glacial periods, was partly filled with sand and gravel. From this source came the sand veneer which now mantles the hills to the east of the valley.

Below Farmington the sand flat shrinks to a mere strip and thenceforward a narrow sandy flood plain lies between river and bluffs, now on one side of the stream, now on the other. South of Croton this flood plain is less than one-fourth mile wide (figure 50) and at Belfast it narrows to 300 yards, a width which it retains beyond Hinsdale, just below the bridge of the Atchison, Topeka and Santa Fe Railway over the river. Everywhere the valley is filled with sand to the practical exclusion of the customary fine alluvium. After the Farmington sand hills are passed the valley is bounded for the most part by bluffs, which in places form precipitous rock cliffs, and which are especially notable on the Missouri side of the river. When clothed with their mantle of green or when glowing with the gorgeous colors of autumn foliage these bluffs and scarps make most charming and delightful scenes.

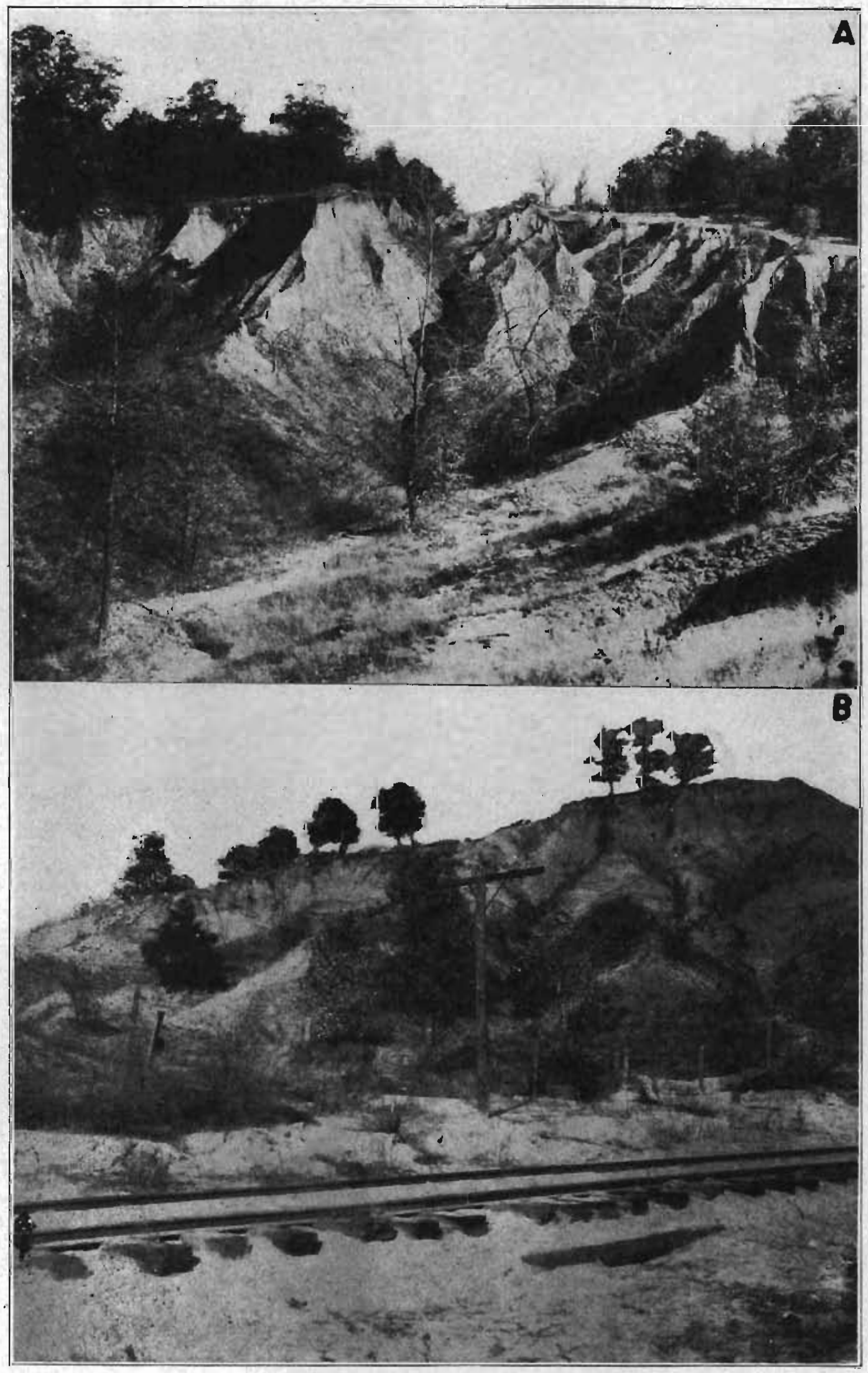
Just above Hinsdale, where the Atchison, Topeka and Santa Fe railroad skirts the hills, these are built up to a height of seventy-five feet of yellow sand. However, the rock basement rises to the level of the flood plain, as it is seen in the creek beds. A little farther along, too, the bluffs show rock to their summits, so that this sand probably is banked against rock walls. The sand hills are capped with the gray loess which is so abundant along the valley.

The Vincennes Plain.—In the vicinity of Sand Prairie, or Vincennes, the bluffs bend away from the river and leave a wide sandy plain twenty to forty feet high, stretching from their bases one to three miles south to the stream (Plate LXX). Here also the rock walls are replaced by hills of sand and between Vincennes and a point two miles east of Sugar creek (Plate LXVI) no more rock is seen; only sand and silt, which rise in steep embankments a hundred feet or more above the plain below. The wide sandy flat opposite Vincennes in general is quite level save for minor irregularities which perhaps

PLATE LXXI



A. The wide valley two miles below Vincennes. The valley is cut in the filling of the buried Mississippi gorge. B. Where the west wall of Des Moines valley unites with the wall of the Mississippi valley and swings away to the south. View at Saint Francisville.



A. Badland topography eroded in the old valley filling at Connables. B. Erosion in the valley filling two miles below Connables.

are dunes. Plate LXXI, A, shows the character of this plain. A typical example of the material of the valley wall is seen a mile and a half east of Sugar creek. Here blue gravelly clay, probably Kansan drift, rises six feet above the railroad tracks. This is overlain by red and yellow sand seventy feet or more thick, and this is capped by fifteen feet of gray silt. From the edge of the escarpment the uplands slope gently up to the divides. A similar exposure is found two miles southeast of Vincennes, at a little station known as Connables, where the road climbs the hills. See Plate LXX and Plate LXXII, A. The material here is a yellow gravelly clay. Plate LXXII, B, shows a bluff of sand about one hundred feet high which is located two miles south of Connables.

The Valley near Keokuk.—Just where rock begins to reappear in the wall, about a mile above the Chicago, Burlington and Quincy railroad bridge crossing the Des Moines, a hill of circumdenudation stands at the edge of the valley, cut off from the rock plateau by a sag one-fourth of a mile wide. This sag may represent an abandoned fragment of the Des Moines valley, or it may be a remnant of some pre-Pleistocene drainage line or of some tributary of the Mississippi. The hill consists of limestone and from here to Keokuk the valley on the north side is rock-bound with but little bottom land between wall and stream. This wall, however, really marks the valley of the Mississippi since at Keokuk this river swings westward about three miles to meet the Des Moines. See Plate LXVI and figure 51, page 598. This part of the valley near Keokuk bears evidences of immaturity in the steepness of its walls and their bare rocky character. Time and the elements have not yet been able to smooth out its roughness and cover its nakedness with a protection of soil and vegetation.

The Mississippi Plain.—It is to be noted that the steep bluff which has faced Des Moines river on the Missouri side, where it reaches the village of Saint Francisville, opposite Vincennes, bends abruptly and swings off to the south, far away from either the Des Moines or the Mississippi. See Plate LXX and Plate LXXI, B. And yet the wide stretch of plain sloping gently to the east now constitutes the immediate valley of the Mississippi, and to a less extent of the Des Moines also. This plain is rather high near the bluffs, but soon runs down to a lower level—the great flood plain of the Father of Waters. Oxbows and lakelets in its northern part show that here it has been occupied by the Des Moines within recent time.

The Mississippi Valley Between Burlington and Keokuk.

In order better to understand the phenomena we have just been describing let us note the character of the Mississippi valley between Keokuk and Burlington (figure 51). Between Keokuk and Montrose the great river flows between steep, rocky, closely restraining walls. There is hardly any room for a flood

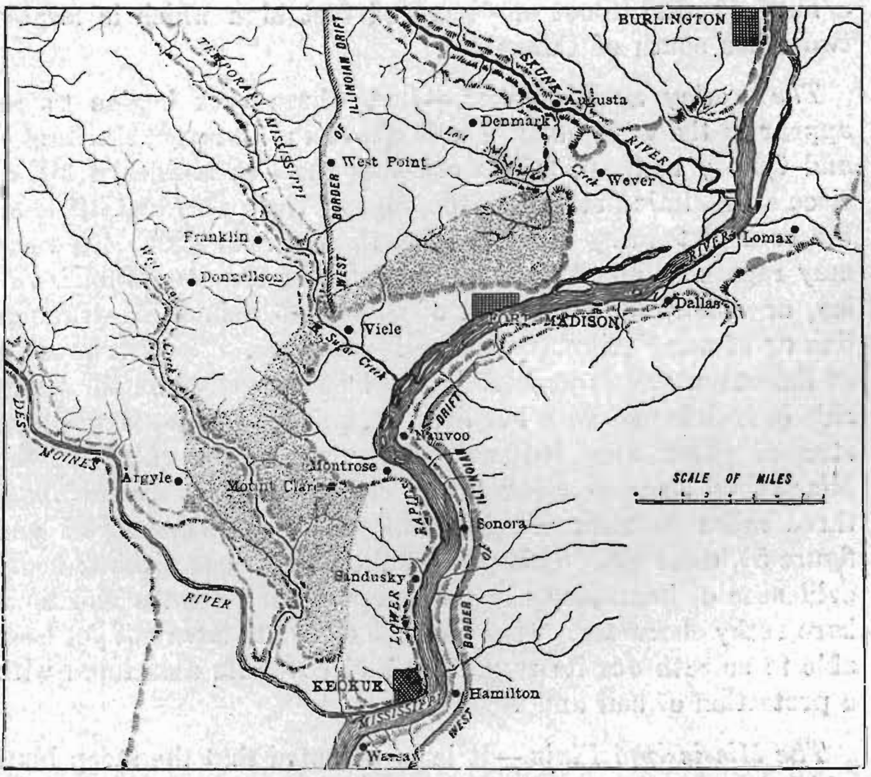


FIG. 51—Map showing drainage changes in southeastern Iowa. The buried valley of Mississippi river is dotted. Present valleys are indicated by hachures. From Leverett.

plain. Between Montrose and Fort Madison the east wall bounds the river almost as closely, but on the Iowa side the bluffs recede far to the west and leave a crescentic, sandy flat four or five miles wide. Moreover, these bluffs, unlike those below Montrose, but just like those facing the Des Moines valley at Vincennes only a few miles southwest, are composed entirely of loose detrital material—sand and silt. Even where they sweep in to reach the river at Fort Madison the same is true, and one exposure on the east edge of the city shows a face 150 feet high composed entirely of bedded sands and silts. These sand hills continue past Wever three or four miles north of

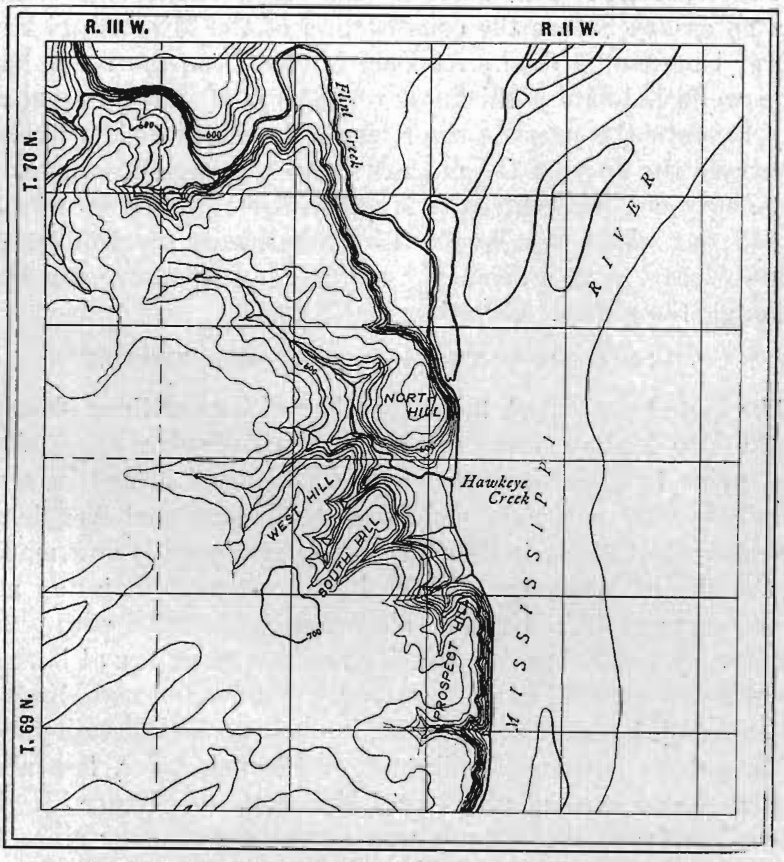


FIG. 52—Topographic map of vicinity of Burlington, showing the high rock bluffs on the Iowa side of the valley.

Skunk river, where they are replaced by rock walls which extend to Burlington and beyond (figure 52). They look down upon a low plain which is crossed by Skunk river and which is similar to the plain above Montrose except for its larger size. See figure 51.

Between Keokuk and Montrose the river is flowing over rock and the channel is obstructed by rapids, so that a ship channel was necessary before the construction of the Mississippi River Power Company's dam. At Fort Madison, on the other hand, deep wells indicate a thickness of 125 to 140 feet of sand and clay beneath the present river level. In other words, while at Montrose the floor of the modern rock-cut channel is about 495 feet above sea level, at Fort Madison the rock bed is only 380 to 365 feet above sea level. Two miles west of Montrose, at Mount Clare, a well reached rock at 374 feet above sea level, although the surface elevation is 679 feet.

THE HISTORY OF THE MISSISSIPPI NEAR KEOKUK.

The facts here stated, taken together with conditions observed in the Des Moines valley, point to the following conclusions: Just prior to Pleistocene time the Mississippi flowed in a valley whose west wall extended from Burlington past Argyle and Vincennes to Canton in Missouri. The east wall is now marked by the site of Montrose and the hill of circumdenudation mentioned on page 597. But this old channel was filled with glacial detritus by the Nebraskan glacier and the river found it easier to cut a new channel in part. Between Burlington and Montrose it succeeded, by lateral corrasion, in clearing its old valley more or less, more between Burlington and Skunk river, less above Montrose and least of all at Fort Madison. See figure 51. But below Montrose the stream was diverted and ever since has been excavating a passage in the hard rocks of the Mississippian. This new course extends past Keokuk to the mouth of Des Moines river, where the Mississippi again found its old valley. It will be seen from Plate LXX and figure 51 that the bluffs south of Saint Francisville mark the ancient as well as the modern western bounds of the valley, while on the east the river hugs the high wall stretching past Hamilton and Warsaw which bounded its valley on this side in preglacial as in postglacial times. South of the Des Moines the two rivers together have succeeded in clearing out the upper 150 or 175 feet of the valley filling, and a little has been accomplished north of the Des Moines, as witness the flat at Vincennes and one east of West Sugar creek (figure 51). This great buried valley had a width of six miles, and a depth which must have approached 300 feet—dimensions which indicate the vast amount of work performed by the ancient river (figure 53).

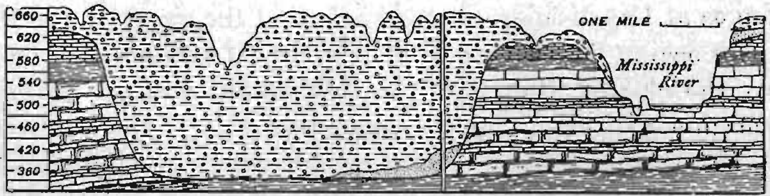


FIG. 53—Section across present and former valleys of Mississippi river in Lee county between Sonora and Argyle. From Gordon.

A BURIED TRIBUTARY OF MISSISSIPPI RIVER.

A number of years ago Gordon described the buried valley of the Mississippi, and also made mention of a smaller buried channel which lies beneath the valley of West Sugar creek and opens into the larger valley north of Vincennes, as shown in figure 51. The smaller valley he interpreted as being a former channel of the Des Moines. However, water level in Des Moines river at Saint Francisville, 500 feet above sea level, is 130 feet above the rock floor of the old valley. Moreover, Des Moines river is rockbound for many miles above Saint Francisville, and flows over rock at numerous localities, as for instance Bentonsport, Selma, Eldon and Ottumwa. The physiographic evidence shows that the valley from Des Moines to Keokuk is a unit, and so far as rock structure permits, is in the same stage of development. There is no point at which the valley could be divided on a physiographic basis and a part joined to this ancient channel, and besides, it is impossible for the present valley to join the ancient one without assuming an abnormal gradient. This buried channel must have contained some minor tributary of the former Mississippi, not Des Moines river.

The Age of Des Moines River Valley.

It must be clear from the above statements that the Des Moines valley can have no relationship with any pre-Pleistocene Mississippi valley, that it must be of the same age as the valley at present occupied by the Mississippi between Montrose and Keokuk, unless we conceive of an interglacial Mississippi as partly re-excavating and occupying the older valley between Montrose and Vincennes, and that is a needless assumption. It was stated in connection with the discussion of drainage changes at Des Moines, on page 545, that the greatest age which we can assign to the Des Moines is the Aftonian epoch or possibly the closing stages of the Nebraskan, and the preceding discussion will have made it plain that this is the case. If it can be proven that the Mississippi valley is younger than Pliocene, the Des Moines valley must be given a date of later origin than Nebraskan, and conversely the establishment of a Kansan or of a Nebraskan date for the origin of the lower Des Moines valley would place the beginning of the oldest Mississippi channel at an earlier time. The drainage changes which have taken place at Des Moines seem to be critical if the view adopted in this paper be the correct one and they required so much time and so many geological events that they necessitate a pre-Pleistocene Mississippi to cut out the great buried valley west of Keokuk and the still greater one to the south now partly cleared of its Quaternary filling. This valley, as was stated above, was cut out and filled again before the Des Moines came into being.

Filling of Des Moines Valley.—Above Ottumwa the Des Moines valley has been filled to varying depths above its original rock floor. Thus at Eddyville rock lies twenty-five feet below the bottoms, east of Tracy it is thirty-five feet below the present valley floor, and below Des Moines the valley filling is at least fifty or sixty feet thick. The valley for many miles below Des Moines is cut entirely in the soft, easily eroded strata of the Coal Measures, and where the sandy limestone layers of the Saint Louis appear in central Marion county and eastward, they are exposed only intermittently and for a few feet above water level. These softer strata have not been able to limit the activities of the river either horizontally or vertically to the same extent as is the case farther down the stream where limestones form a greater part of the restraining walls. These statements apply also to the situation at Farmington as described on page 591. It will be clear then that the depth of the rock floor below the flood plains represents scouring by the river in past time, and has no relation to the question of the unity of the valley. That is, it does not mean that the valley above Ottumwa is of different age from that below that city, or that below Farmington it extended across southwestern Lee county instead of along the course which it now occupies.

SUMMARY.

Provinces of the Valley.—By way of review it may be noted that the valley is divided topographically into two provinces, which correspond with the areas of Wisconsin and of Kansan drift. The differences in the character of the valley in these two areas are strongly marked, as is to be expected in regions which differ so greatly in their topographic development. In the first province, the river is relatively small and inefficient as a physiographic agent and the valley bears all the marks of youth and immaturity. In the second province on the other hand, the signs of the long activity of the river and of the maturity of the valley are on every hand. Moreover, as is to be expected, the transition between the two areas is abrupt and decisive.

As regards the age of the drainage lines the present valley may be divided into two parts, interglacial and postglacial, although it is not always possible to distinguish clearly between them. On the East Fork of the Des Moines the part above the mouth of Buffalo creek is clearly postglacial while the lower part is interglacial. The West Fork is postglacial in Minnesota and across Emmet and Palo Alto counties, if we make exception of a short stretch above Windom as explained on page 508. Between Bradgate and Des Moines the river occupies a post-Kansan valley, while below the latter city the valley is Aftonian (post-Nebraskan) in age.

If we consider the dependence of the topography of the valley upon the underlying rock, the distinctness of the two topographic provinces is very plain. It is largely true that within the area of Wisconsin drift the present relation of topography and bed rock is not very close. In the postglacial stretches of the valley there is no relation whatever between them, and lower down where the river flows in an older, but still post-Kansan, valley, it has been occupied during recent time in clearing out the obstructions and has come in contact with the rock foundations but little. In its pre-Kansan portions, however, where the river crosses the Kansan drift, the character of its valley is influenced very strongly by the underlying strata, and in places is determined by them.

Area and Declivity of the Valley.—The valley of the Des Moines, using the term in its larger sense, includes an area of 12,500 square miles in Iowa, besides 1,525 miles in Minnesota and 75 miles in Missouri, making a total area of about 14,100 square miles. Of this, 1,200 miles belong to the East Fork, 2,420 miles to the West Fork and the balance, 10,475 miles, to the combined valley. Of course the area actually considered in this report is very much less, as was stated in the introductory paragraphs.

The sources of the West Fork lie at altitudes of about 1,850 feet and where it crosses the state line the river is about 1,250 feet above sea. In the 100 miles of its course in Minnesota, therefore, the river falls practically 600 feet. However, the first 200 feet of this are accomplished within ten miles from the heads of the stream and the outlet of Lake Shetek, not over 35 miles from the sources, is practically 400 feet below the headwaters. Between the state line and Fort Dodge, 100 miles, the valley drops to 975 feet, or nearly three feet per mile. Through Palo Alto and Pocahontas counties the slope is from two and one-half to three feet per mile, although the fall of the stream is only one-half this amount. In Humboldt county the valley declines about eight and one-half feet per mile near its outlet. From Fort Dodge to Des Moines the river falls practically 200 feet in 100 miles, and between Des Moines and the mouth—175 miles—the fall is 301 feet, or less than two feet per mile. Low water at Keokuk is 477 feet above sea level, hence the total fall of the river in its extent of 475 miles is about 1,375 feet.

The elevation of the sources of the East Fork is about 1,350 feet and Tuttle lake, on the state line, lies practically 100 feet lower. The Minneapolis and Saint Louis railroad bridge over the river at its mouth stands 1,067 feet above tide and so the river is at about 1,050 feet or 300 feet below its source 100 miles to the northwest.

Physiographic Principles Illustrated by the Valley.—Perhaps the physiographic principle which is most strikingly illustrated in this valley is that of the close relation which exists between the age of a stream and the direction in which its energies are being expended, and the consequent character of its valley. Another point which is well shown is the relation which the materials wherein a valley is cut bear to its size and proportions. Thus above Des Moines, where the river dates only from the Wisconsin ice epoch, it is engaged in down-cutting; its valley, where this is erosional, is narrow; it is bounded by steep walls. Below the edge of the Wisconsin drift the stream is much older; it has been long widening its valley by side-cutting; to a larger extent the limiting slopes are rather gentle. Again, between Des Moines and Eldon the greater part of the valley is cut in Des Moines shales and it is very wide, although where it crosses the more resistant Red Rock sandstone it is temporarily narrowed very decidedly. After the valley enters the region of the Saint Louis limestone below Eldon it once more becomes narrow and steep-sided, and retains these characters until it unites with the valley of the Mississippi.

Another principle which is well illustrated is the close connection between the character of the valley and the topographic development of the surrounding region. That these two go hand in hand and progress simultaneously is shown clearly in the two provinces of the valley. In the upper province, both are young and incompletely developed. In the lower province the reverse is true. In the younger province the topography is glacial and chiefly constructional. In the older area the topographic forms are erosional, and are the result chiefly of downcutting activity.

The development of tributaries in harmony with that of their master also is well shown. Where the main valley is young its tributaries are of a similar stage of development. Where it is mature the secondaries have progressed to the same stage.

Bibliography of Des Moines Valley.

In order to avoid distracting the attention of the reader with footnotes, references to literature have been omitted from the text. The region through which the Des Moines flows has all been covered by geological surveys, however, and a list of the published reports dealing with the area will be found below. These reports have been in constant use in the preparation of this paper and the writer wishes at this time to acknowledge his indebtedness to the authors for many suggestions which have come from their writings in the course of his work. Even where he had reason to differ in details these suggestions have served as an inspiration in formulating his own thoughts.

In addition to the reports on county geology of Minnesota and Iowa several other reports and text-books on geology have been used and are cited here on account of their usefulness. Any reliable text-book will give discussions in more or less detail of the physiographic principles which are illustrated in the Des Moines valley, and the geologic history outlined in this paper will be found described in more expanded and complete form in the references here given. Liberal use should be made of the works mentioned in this bibliography, and of any others which have any bearing in connection with this report.

The most complete and elaborate exposition of principles and of earth history is found in **Chamberlin and Salisbury's** Geology, a three volume work. A more condensed statement is given in College Geology, by the same authors, and in the second edition of An Introduction to Geology, by **W. B. Scott.**

The pre-Pleistocene elevation of Iowa is discussed by **Samuel Calvin** in Iowa Geol. Survey, Vol. XIII, pp. 297-299. A possible postglacial elevation is described by **T. C. Chamberlin** in Third Ann. Rept., U. S. Geol. Survey, p. 390.

Data regarding time relations of the Pleistocene are based upon **Chamberlin and Salisbury:** Geology, Vol. III, pp. 414, 420; also upon **Calvin:** Introduction to County Geology, a brief summary of Iowa geology bound with the separate reports on counties of the state. In this connection see also **T. C. Chamberlin**, The Future Habitability of the Earth: Ann. Rept. Smithsonian Institution, 1910, pp. 371-389.

In connection with valley development see **J. E. Carman**, The Mississippi Valley Between Savanna and Davenport: Bull. Illinois Geol. Survey, No. 13, pp. 22-27. This report also discusses several other features which are connected with the development of Des Moines valley.

Another clear and concise discussion of valley development and stream work is given by **Salisbury and Atwood**, Geography of Region About Devil's Lake, Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey, No. V, pp. 36-59.

The figures for the denudation of the Des Moines Valley are taken from Papers on the Conservation of Water Resources: Denudation, by **R. B. Dole and H. Stabler**, Water Supply Papers, U. S. Geol. Survey No. 234, pp. 89, 90.

The data concerning the amount of water in the earth's crust are given by **W J McGee**, Principles of Water-Power Development: Science, N. S., Vol. XXXIV, Dec. 15, 1911, p. 814.

The section on the history of the valley has been abstracted from History of Iowa, by **B. F. Gue**, and from the chapter on Geographical Exploration of Iowa-Land in Vol. XXII, Iowa Geol. Survey, Bibliography, 1912, by **Charles Keyes**.

Among the early workers on the geology of the state the members of the Hall survey make brief mention of the Des Moines valley. See **J. D. Whitney**, Geology of Iowa, Vol. I, Part I, 1858, p. 10; also **A. H. Worthen**, Ibid, pp. 219, 248. On pages 186 to 188 **Mr. Worthen** discusses the bluffs and terraces between Montrose and Fort Madison which are described on pages 598 to 600 of this paper. While Mr. Worthen did not realize the extent of the preglacial erosion between these points and did not know of the old valley extending south to the present Des Moines, he understood that a great basin had been scooped out of the limestones in this region.

Professor **C. A. White** in Geology of Iowa, Vol. I, 1870, pp. 57-60, gives an excellent summary of the general features of Des Moines valley. Mr. White, however, considers the East Fork as rising in Union slough, which is now considered to be of merely subsidiary importance as a source of supply.

The geological sections across Iowa which are given by **W. H. Norton**, Artesian Wells of Iowa: Iowa Geol. Survey, Vol. VI; and Underground Waters of Iowa: Op. Cit., Vol. XXI, will give a good idea of the strata underlying the valley. A good conception of the topography of southern Minnesota and its relations to drainage may be had by studying the maps accompanying a report on Geology and Underground Waters of Southern Minnesota, by **Hall, Meinzer and Fuller,** Water Supply Papers, U. S. Geol. Survey No. 256.

For a theory regarding the preglacial Des Moines Valley see **J. E. Todd**, The Pleistocene History of the Missouri River: Science, N. S., Vol. XXXIX, Feb. 20, 1914, pp. 263-274.

Some valuable data on the river are given by **The Iowa State Drainage, Waterways and Conservation Commission,** The Des Moines River Valley: Biennial Report, 1909-1910, pp. 67-69, 123. See also maps of West Fork.

The Report of the Secretary of War regarding an examination and survey of Des Moines river contains maps and profiles of the river which will be of interest in this study. The report was printed as House of Representatives Document No. 1063, 62d Congress, 3d Session.

See also for information concerning gravel deposits **S. W. Beyer and H. F. Wright,** Road and Concrete Materials of Iowa: Iowa Geol. Survey, Vol. XXIV, 1913. The gravels of Humboldt county are discussed on pages 339 to 342. Each county of the state receives treatment.

An excellent discussion of the Pleistocene is given by **O. P. Hay**, The Pleistocene Period in Iowa: Iowa Geol. Survey, Vol. XXIII, pp. 9-99.

For detailed descriptions of the valley in the different counties across which it extends see the following reports:

The East Fork of Des Moines river:

Warren Upham, Geology of Watonwan and Martin Counties: Final Report, Geol. and Nat. Hist. Survey of Minnesota, Vol. I, 1872-1882, pp. 473, 479-485. The chain lakes are described and their origin explained.

Warren Upham, Geology of Faribault County: Op. Cit., Vol. I, pp. 460-461. Describes a glacial lake in the basin of Blue Earth river, and its outlet through Union slough. A briefer description also is given in 9th Ann. Rept. State Geologist, Minnesota, 1880, p. 341, pl. VI.

T. H. Macbride, Geology of Emmet, Palo Alto and Pocahontas Counties: Iowa Geol. Survey, Vol. XV, 1904, p. 243.

T. H. Macbride, Geology of Kossuth, Hancock and Winnebago Counties: Op. Cit., Vol. XIII, 1902, pp. 93-96, 104.

T. H. Macbride, Geology of Humboldt County: Op. Cit., Vol. IX, 1898, pp. 117-119.

The West Fork of Des Moines river:

Warren Upham, Geology of Murray and Nobles Counties: Final Report, Geol. and Nat. Hist. Survey of Minnesota, Vol. I, pp. 518 and 519.

Warren Upham, Geology of Cottonwood and Jackson Counties: Op. Cit., Vol. I, pp. 492-496, 507-509. A supposed interglacial line of drainage is described in this report. See also the description of the Coteau des Prairies on pages 68 and 494.

T. H. Macbride, Geology of Emmet, Palo Alto and Pocahontas Counties: Iowa Geol. Survey, Vol. XV, 1904, pp. 238-242, 245-250.

T. H. Macbride, Geology of Humboldt County: Op. Cit., Vol. IX, 1898, pp. 118, 119, 138.

F. A. Wilder, Geology of Webster County: Op. Cit., Vol. XII, 1901, pp. 70-75, 136-138.

S. W. Beyer, Geology of Boone County: Op. Cit., Vol. V, 1895, pp. 182, 183, 202.

A. G. Leonard, Geology of Dallas County: Op. Cit., Vol. VIII, 1897, pp. 61, 62, 90.

H. F. Bain, Geology of Polk County: Op. Cit., Vol. VII, 1896, pp. 273-284, 348-352. Describes drainage changes.

J. L. Tilton, Geology of Warren County: Op. Cit., Vol. V, 1895, pp. 306-314.

B. L. Miller, Geology of Marion County: Op. Cit., Vol. XI, 1900, pp. 132-140.

H. F. Bain, Geology of Mahaska County; Op. Cit., Vol. IV, 1894, pp. 318, 319, 321.

S. W. Beyer and L. E. Young, Geology of Monroe County: Op. Cit., Vol. XIII, 1902, pp. 361, 362, 380.

A. G. Leonard, Geology of Wapello County: Op. Cit., Vol. XII, 1901, pp. 444-448, 460, 475.

C. H. Gordon, Geology of Van Buren County: Op. Cit., Vol. IV, 1894, pp. 201, 203, 234-236.

C. H. Gordon, Buried River Channels in Southeastern Iowa: Op. Cit., Vol. III, 1893, pp. 239-255.

C. R. Keyes, Geology of Lee County: Op. Cit., Vol. III, 1893, pp. 312, 314-316, 366-369. Discusses old gorge of Mississippi River.

J. E. Todd, Formation of the Quaternary Deposits of Missouri: Missouri Geol. Survey, Vol. X, pp. 173-176. Discusses the old gorge of Mississippi river in Clarke county.

James H. Lees, The Pleistocene of Capitol Hill: Iowa Acad. Science, Vol. XXIII, 1916. Discusses the loess and the Wisconsin drift.

Topographic Maps of Des Moines Valley.

There are a number of the topographic maps published by the Iowa Geological Survey, in coöperation with the United States Geological Survey, which cover portions of the valley of

Des Moines river. These include the Boone, Madrid, Slater, Des Moines, Milo, Knoxville and Pella quadrangles in central Iowa, and the Kahoka quadrangle in the southeastern corner of the state. These maps will be found of great service in connection with the descriptions and discussions in this paper as they show so plainly the various features described herein and will enable the reader in many cases to follow more closely the arguments set forth than would be possible otherwise. The Boone and Madrid sheets show splendidly the young, narrow, immature valley crossing the Wisconsin plain; the broad, flat-bottomed, well-developed valley of the Kansan area is well illustrated by the Milo, Knoxville and Pella sheets; and the transition from young valley to old is shown upon the Des Moines sheet. This sheet also shows the abandoned and partly buried valley of the river in the vicinity of Des Moines, and the lower course of Raccoon river. The Kahoka sheet covers a few miles of the lower course of Des Moines river and shows the effect upon the topography of the valley of the soft materials filling the buried valley of Mississippi river. A portion of the wide old plain of the Mississippi also is included in this quadrangle.

These maps will furthermore serve the purpose of showing the character of the topographies developed upon the Wisconsin and Kansan drift sheets, the drainage incised on them and the varying efficiency of Des Moines river in controlling and modifying these features.

The outline maps of the valley in Minnesota and Iowa are reproduced from base maps of these states compiled and published by the United States Geological Survey. Acknowledgment is here gladly made of the kind permission of the Director of that organization to publish these and the topographic maps in this report.

Addendum.

When the foregoing paper was written it represented the state of knowledge at that time with reference to the Pleistocene epoch, its duration and its deposits. However, since then notable work has been done on the problems of the Pleistocene, and as some of these definitely affect the geologic history of Des Moines valley it seems well that note should be made of them here. One of these problems related to the gumbos of southern Iowa which have been the source of so much discussion among geologists, not alone in Iowa, but of other states as well. At the Washington, D. C., meeting of the Geological Society of America, December, 1915, Dr. George F. Kay, the Director of the Iowa Geological Survey, presented an outline of the results of his studies of this problem up to that time, and with Doctor Kay's permission this statement is reprinted here in full.

SOME FEATURES OF THE KANSAN DRIFT IN SOUTHERN IOWA.

In county reports issued by the Iowa Geological Survey and in other publications many of the features of the Kansan drift of southern Iowa have been described, including the original Kansan drift plain, the present topography of the Kansan drift, the tabular divides, the characteristics of the weathered and unweathered zones of the Kansan drift, the gumbo, which is closely related to the Kansan drift, and the fine loesslike clay overlying the Kansan drift surface, and which has been interpreted by several investigators to be material of eolian origin deposited after a mature topography had been developed on the Kansan drift. The origin of the gumbo has been interpreted differently by different authors, the most recently published view being that of Tilton, who considers the material to have been formed, in the main, during the retreating stages of the Kansan ice. To this gumbo and other materials which he considers to be related in age to the gumbo he has given the name Dallas deposits.

Detailed field studies which are still in progress in southern Iowa seem to warrant the author in making a preliminary statement involving some interpretations which differ from those previously advanced.

(1) The surface of the Kansan drift, after the Kansan ice withdrew, was, according to present evidence, a ground moraine plain, which from the main divide between the Mississippi and Missouri rivers, sloped gently to the southeast and south toward the Mississippi and to the southwestward toward the Missouri. This drift plain was so situated topographically that weathering agents were very effective, but erosion was slight. As a result of the weathering during an exceedingly long time a grayish, tenacious, thoroughly leached and non-laminated joint clay, which has been named gumbo, was developed to a maximum thickness of more than 20 feet. This gumbo contains only a few pebbles, which are almost wholly siliceous, and grades downward into yellowish and chocolate-colored Kansan drift from 3 to 7 feet in thickness, in many places with numerous pebbles, few, if any, of which are calcareous. This oxidized but non-calcareous drift, in turn, merges into unleached drift, oxidized yellowish for several feet, below which is the normal unleached and unoxidized dark-grayish to bluish-black Kansan drift. The gumbo is believed, therefore, to be essentially the result of the thorough chemical weathering of the Kansan drift; but, subordinately, other factors, such as the wind, freezing and thawing, burrowing of animals, slope wash, etcetera, have undoubtedly contributed to its formation. The Kansan drift which has been changed to gumbo may have differed somewhat from the normal Kansan drift that lies below the gumbo.

(2) After the gumbo plain had been developed by weathering processes on the Kansan drift plain, diastrophic movements seem to have occurred, the plain having been elevated to such an extent that erosion became effective and valleys began to be cut into the gumbo plain. Erosion of the gumbo plain progressed to such an extent that some valleys were cut to a depth of more than 150 feet before grade was reached and

a mature topography was developed. Only remnants of the original gumbo plain remain, the most conspicuous of these being flat, poorly drained areas, known as tabular divides. Where creep and slumping have occurred the gumbo, in places, may be found on slopes at an elevation several feet below the level of the gumbo plain. The tabular divides are more prevalent east of a line drawn north and south through south-central Iowa than west of such a line. In the southwestern part of the State the Kansan gumbo which is *in situ,* is found only where the divides, which are no longer distinctly tabular, retain the level of the former gumbo plain.

(3) While there is, in places, loess of eolian origin on the Kansan drift of southern Iowa, much of the material which has been described as loess is thought to be not of eolian origin, but to be related more or less closely to the gumbo. The upper few feet of the Kansan gumbo, which is now limited to the tabular divides, is a fine-grained, loesslike, joint clay, in which, if diligent search is made, it is possible to find a few very small siliceous pebbles similar to those in the normal gumbo, and it is thought that this loesslike clay is the result of changes that have been going on at and near the surface of the gumbo during the great length of time since the normal gumbo was formed. The loesslike clay which is now found as a mantle on the Kansan drift on the slopes and divides that have been brought by erosion considerably below the level of the original gumbo plain is believed to be the product not primarily of wind action, although wind may have been a factor, but chiefly the product of the weathering and concentration of the gumbo and to some extent of the underlying Kansan drift, where erosion has not kept pace with the weathering.

(4) The evidence indicates that the time taken to develop the present topography from the gumbo plain stage, although it represents a great length of time, is short when compared with the time taken to develop the gumbo plain from the Kansan drift. It is thought that the formation of the main part of the gumbo and the development of the present mature topography of the Kansan drift were effected between the close of

the Kansan epoch and the advance of the Illinoian ice into Iowa; in other words, during the Yarmouth inter-Glacial epoch. All the evidence indicates that the Yarmouth epoch was an exceedingly long interval of time.

(5) Detailed chemical analyses of gumbo, loesslike clay, etcetera, are now being made in the chemical laboratory of the University of Iowa by Dr. J. N. Pearce. The results of these analyses will go far to strengthen or weaken the interpretations given above from the field evidence.

Many of the chemical analyses mentioned in (5) have been completed and they serve to strengthen the interpretations given in Doctor Kay's paper. Continued field work gives results which are consistent with those of earlier studies. What then would be the effect of the events outlined in the paper quoted upon the history of Des Moines valley as sketched in foregoing pages? It does not seem to the writer that that history would be materially modified by the development of the Kansan gumbo plain as discussed by Doctor Kay, except that the active work of the river in cutting its post-Kansan valley would be postponed largely until after the Kansan gumbo plain had developed and diastrophism had elevated the stream valleys above grade. While the gumbo was forming the river was a sluggish, inactive stream flowing across the top of a ground moraine plain. When elevation set in the river sank into the underlying formations and widened its valley to its present proportions until it reached grade again.

The newer view emphasizes the great length of time required for the formation of the thick layer of Kansan gumbo and corroborates other lines of field evidence which point to the great age of the older portions of the valley; and probably all of these features taken together indicate a much greater duration of Pleistocene time than we have been accustomed to consider.

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