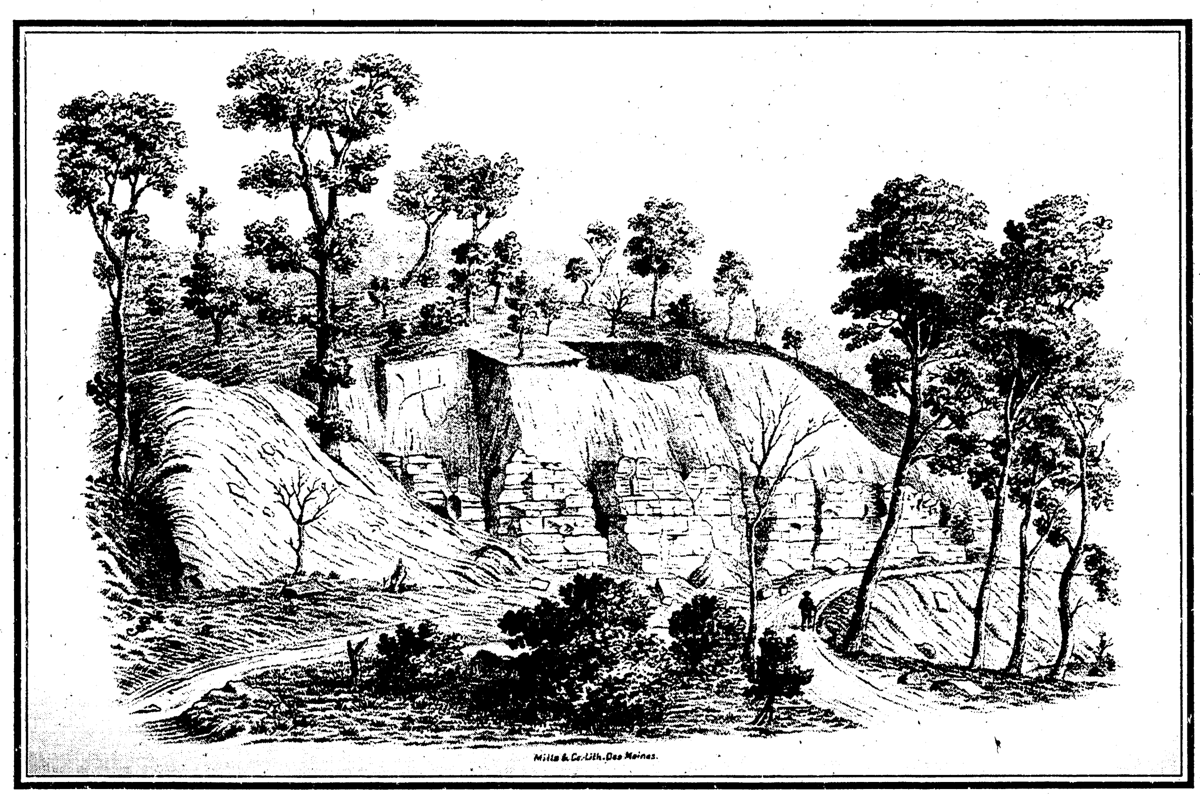
GEOLOGY
of the
FORT DODGE FORMATION (UPPER JURASSIC) WEBSTER COUNTY, IOWA

Geological Survey Bureau
Guidebook Series No. 19



Iowa Department of Natural Resources
Larry J. Wilson, Director
May 1996

Cover: In the nineteenth century, geologists relied on their artistic skills to record the appearance of geologic strata. One-such artist was Orestes St. John who utilized his skills to document a number of Iowa's geologic and landscape features. The St. John lithograph on the front cover shows the Cummins Quarry (in what is now Snell Park, Fort Dodge) as it appeared in 1868 (published in White, 1870, facing p. 297). The Cummins Quarry was the first recorded gypsum quarry in the Fort Dodge area and was utilized to extract dimension stone. The site of the Cummins Quarry in Snell Park will be visited at Field Trip Stop 3

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GEOLOGY OF THE FORT DODGE FORMATION (UPPER JURASSIC) WEBSTER COUNTY, IOWA

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North-Central Section Annual Meeting
Geological Society of America

Iowa State University
Ames, Iowa

Field Trip No. 4

May 1996

Iowa Department of Natural Resources
Larry J. Wilson, Director

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INTRODUCTION

The rocks of the Fort Dodge Formation (Upper Jurassic) are the most intensely exploited of the bedrock units in Iowa. The formation includes a basal conglomerate, overlying very dark gray shale, a thick gypsum unit, and an upper suite of sandstones and mudstones locally referred to as the 'Soldier Creek beds.' The formation has an extremely restricted areal extent, with its only known occurrences in central Webster County, Iowa. The thick and exceptionally high quality gypsum unit that dominates the formation has been mined for a variety of economic products since the mid-1800's. The formation was the target of several early geologic investigations in the late 1800's and early 1900's. While these early studies discussed many details of the lithology, structure, and economic features of these strata, especially the gypsum beds, they failed to adequately answer many basic questions, such as the age, depositional environments, and the mechanics of their preservation. The high quality gypsum in the formation has been intensely mined for over 125 years, and recently the finite nature of this very limited resource has prompted a renewed interest in trying to better-understand this geologic unit before it is consumed by mining activity. In the last decade a number of geology students at Iowa State University have investigated various aspects of the formation as a part of their thesis and dissertation programs. Last year the Iowa Department of Natural Resources Geological Survey Bureau embarked on a detailed investigation of the formation which will culminate in a report on the geology of the Fort Dodge Formation later this year. The hosting of the 30th Annual Meeting of the North-Central Section of the Geological Society of America by the Department of Geological and Atmospheric Science of Iowa State University in Ames provides an excellent opportunity to show this rock unit to regional geologists, and to encourage them to take part in this, perhaps the final detailed investigation of the Fort Dodge Formation before the majority of the formation is mined away.

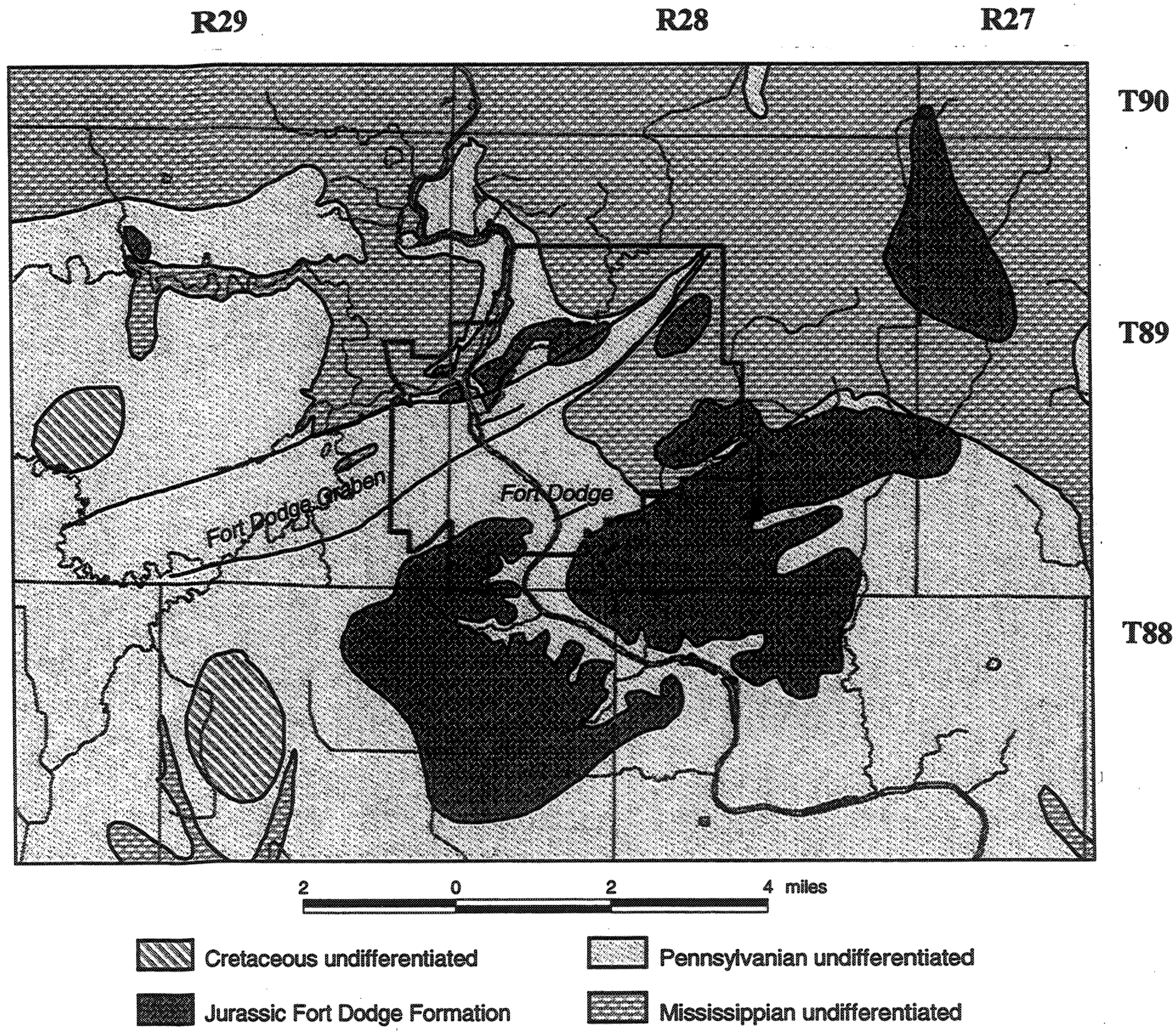

Figure 1. Map of Fort Dodge gypsum occurrence.

GEOLOGY OF THE FORT DODGE FORMATION

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INTRODUCTION

The Fort Dodge Formation of Webster County, Iowa, is an isolated outlier of Jurassic rocks and contains one of the purest gypsum commercial deposits in the United States. The gypsum and associated rocks are known to occur only in the vicinity of Fort Dodge (Fig. 1). Its true extent is uncertain, however, because glacial till almost completely obscures bedrock in north-central Iowa, except along deeply incised river courses. Locations in addition to those currently known may yet be discovered through water well drilling or by geophysical/geochemical exploration. Active strip mining of the gypsum continually exposes fresh faces and has facilitated detailed study.

A Late Jurassic age is accepted for the gypsum and probably applies to the entire formation. The term '*Lost Interval*' was applied to the Mesozoic of the Michigan Basin (Dorr and Eschman, 1970), and could well be applied to the Jurassic of the north central United States. The Fort Dodge Formation represents the only Jurassic strata between Nebraska and the Michigan Basin, and provides a valuable indicator of Jurassic climates and environments. Because of its unique features and setting, conclusive interpretations of many geologic features of the Fort Dodge Formation are not simple. The Fort Dodge Formation contains no fossils suitable for interpretations of depositional environment. It is a small deposit, $<40\ km^2$ in area, and is completely isolated from other Jurassic deposits by several hundred kilometers. It is separated from earlier and later deposits by pronounced upper and lower unconformities, each representing well over 100 million years of time.

In spite of its potential importance in understanding local Jurassic conditions, the deposit will be available for detailed study for only a few more years because of its destruction by active mining. Maximum estimated gypsum reserves are sufficient for about 30 years. Reclamation laws exacerbate the transitory nature of Fort Dodge gypsum exposures, because they require that all quarries must be backfilled to controlled slopes, burying highwall exposures. All of the recent studies of the gypsum and overlying clastics were performed on quarry exposures, and all these exposures have been lost as a result of continued quarrying. A number of small, poorly visible, and extremely discontinuous exposures exist in and near the city of Fort Dodge, but most of the sedimentologic features of the gypsum and associated clastics are not apparent at these highly weathered and partially covered locations.

DISTRIBUTION OF JURASSIC STRATA IN CENTRAL NORTH AMERICA

The breakup of the Pangea supercontinent began with the onset of the Jurassic. In general, the Jurassic was marked by significant marine transgressions on a world-wide scale, with seaways advancing into the heartlands of the existing continents. A progressive rise in world-wide sea level through the Jurassic was probably the result of the growth of submarine oceanic ridges that accompanied the widening of the Jurassic oceans (Sellwood, 1978). Seas transgressed onto the North American craton from three sides during the Jurassic, the north, the west, and the south. From the north the Western Interior (Logan or Sundance) sea extended southward as far as New Mexico and Arizona along the trend of the modern Rocky Mountains (Sellards et al., 1981). Periodic transgressions of these seas were followed by regressions and erosional episodes that divide the three major subdivisions of the Jurassic, the Lower, Middle, and Upper. Surviving strata show pro-

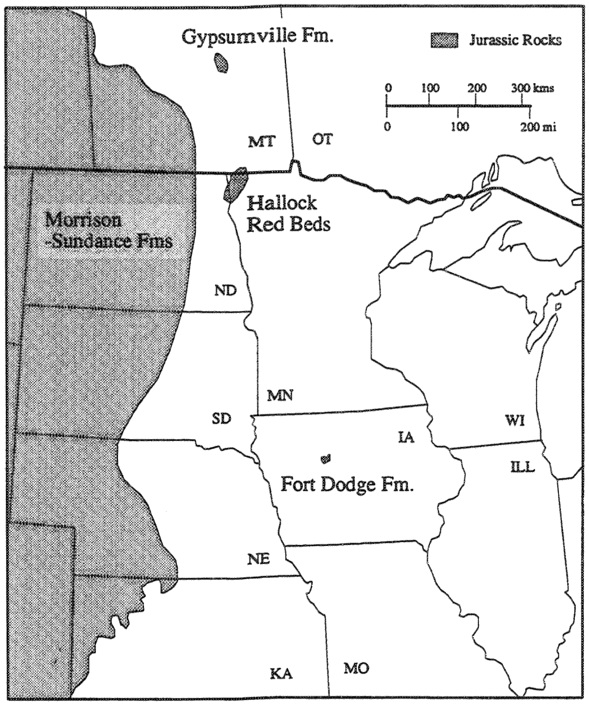

Figure 2. Map of Jurassic occurrences in mid-continent.

gressive overlap by each successive sequence.

The climate in central North America appears to have been relatively uniform throughout the 64 million years of the Jurassic (208 - 144 Ma). Circulation through the oceans that lay at both the north and south polar regions probably prevented the formation of polar ice caps accounting for this general climatic amelioration (Sellwood, 1978). However, the onset of the Late Jurassic was marked by a significant climatic change, expressed by overall warming of the climate in the Northern Hemisphere (Vakhrameev, 1988). Vast areas of the continent were flooded by shallow epicontinental seas during the Middle and Late Jurassic, but the seaways regressed from continental interiors by the end of the period. Evaporite deposition was extensive in North America in the areas marginal to the inland seas (see Brenner, 1983).

The maximum limits of the Jurassic marine transgressions are not known due to extensive post-Jurassic erosion. However, the presence of a limited number of outliers of Jurassic evaporites and other strata provides minimum limits. The Fort Dodge beds are one of only a few of the remnants of these formerly extensive evaporite deposits to survive subsequent erosion. Others include the Hallock Red Beds (Mossler, 1978) in northwestern Minnesota, and the Gypsumville Gypsum (Banatynee, 1959) in east-central Manitoba (see map, Fig. 2). These outliers are located hundreds of kilometers east of the main body of North American Jurassic strata in the western plains states and Rocky Mountains (Bunker et al., 1988; Brenner, 1983). The Fort Dodge Formation was probably deposited contemporaneously with the vast, dinosaur-bearing strata of the Morrison-Sundance formations of the western interior.

GEOLOGY OF THE FORT DODGE FORMATION

The Fort Dodge Formation is comprised of four distinct, stratigraphic units: a thin, discontinuous basal conglomerate, and overlying very dark gray shale, a thicker middle gypsum bed, and an upper series of siltstone/mudstones /sandstones. Rarely are all four units exposed at the same location. These strata occur only in the vicinity of Fort Dodge, and rest unconformably on older rocks, generally of Pennsylvanian age or of Mississippian age in the vicinity of North Lizard Creek and the upper reaches of Soldier Creek (Wilder, 1923). They are overlain by 10 m - 30 m of Pleistocene till. Because of the pervasive cover of till, the only natural exposures are along the Des Moines River where the river has eroded through the formation, and in tributary stream valley walls near their intersections with the larger river valley. One of the most extensive natural outcrops was along Gypsum Creek at Gypsum Hollow, the site of the earliest quarries, but these outcrops are now almost entirely lost to mining. Other outcrops occur in the unnamed ravine immediately across the river from Gypsum Creek; along Soldier Creek near its confluence with the Des Moines River and upstream in Snell Park; along Lizard Creek near its confluence with the Des Moines River; and about 10 km west of the Des Moines River along the 219

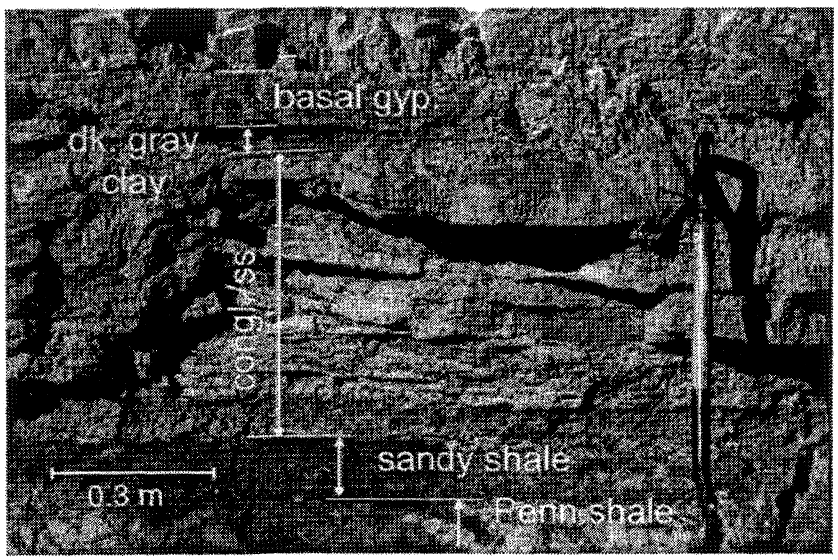

Figure 3. Basal conglomerate exposed in ravine at Georgia Pacific Quarry.

Ditch where it enters Lizard Creek, and about 1 km upstream.

In the following discussion, the basal conglomerate and overlying claystone will be discussed first, then the upper clastic units, and finally the intervening gypsum member. Emphasis will be placed on the gypsum because it has been studied in more detail than the other units.

Basal Conglomerate

Outcrops of basal conglomerate have been reported only from the vicinity of the intersection of Gypsum Creek with the Des Moines River on both sides of the river. It was well exposed in a natural ravine in the Georgia Pacific Quarry (Fig. 3). A section at this location is given in Table 1.

At the Georgia Pacific Quarry, the lower contact of the basal conglomerate with underlying highly fractured Pennsylvanian strata is visible. A thin blue-gray shale sequence lies immediately beneath the gypsum, and the basal 0.2 m of the gypsum is dark brown to tan.

The conglomerate has also been described along a valley, formerly used by a railway, along the west side of the Des Moines River opposite Gypsum Creek, about 1 km southeast of the Georgia-Pacific Quarry outcrop. At this location, the unit is 0.7 m thick, overlies Pennsylvanian shales, and is separated from gypsum by about 15 cm of gray clay (Lees, 1918; Wilder, 1923). At nearby exposures in the ravine, the gypsum layer is missing and the basal conglomerate directly underlies glacial till. The conglomerate contains abundant reworked Pennsylvanian fossils including crinoid stems, brachiopod fragments, and fusulinids which are concentrated in conglomeratic lenses in the coarse sandstone (Lees, 1918). According to Wilder (1923) the conglomerate also occurs in Gypsum Hollow near the mouth of Gypsum Creek on the east side of the Des Moines River. Zaskalicky (1956) reported that the conglomerate occurs in Wells northeast of Fort Dodge in the vicinity of the town of Industry (about half-way between Fort Dodge and Vincent), and in the National Gypsum Quarry northeast of Fort Dodge.

At most locations where gypsum occurs, there is no basal conglomerate, and the gypsum and underlying dark-gray, sometimes scaly (from horizontal selenite flakes) basal shale lies unconformably on either Pennsylvanian or Mississippian rocks. In rare locations the shale beneath the gypsum may be thin or absent. The clay below the gypsum may be partly residual from gypsum dissolution. This clay has a range in thickness from 0 to over 7 m in the Fort Dodge area.

Table 1. Natural Revine Exposure of Fort Dodge Formation Basal Conglomerate and Overlying Claystone at Georgia-Pacific Quarry. Section measured by R. Cody and F. Mazella, 15 December, 1994.

Unit No.	Lithology	Description	Thickness (m)
	Jurassic		
	Fort Dodge Formation		
4.	Claystone	Dark blue gray, plastic, very clay-rich	0.03
3.	Conglomerate	Buff, rounded limestone/dolostone clasts with max. dia., 1 cm and angular white clay clasts ranging to about 2 cm., reworked crinoid columnals. Other clasts include minor amounts of hematite and dark chert Inter-tongues with buff colored coarse sandstone.	0.75
2.	Claystone	Dark brown, sandy	0.1
1.	**Pennsylvanian Shales**		

Using Iowa Department of Natural Resources Geological Survey Bureau (IGSB) well log data, a map was constructed of the reported occurrences of thin conglomerates at the base of Pleistocene till (Fig. 4) in the area around Fort Dodge (Mazzella, 1996). The assumption was that the highly-calcareous conglomerate weathered rapidly upon exposure, and its component clasts may be incorporated into the basal till. The map does not distinguish between Pleistocene conglomerates of other origins and those derived from the Fort Dodge Formation, but attempts were made to minimize this ambiguity by omitting reported conglomerates thicker than 4.6 m, those with descriptions indicating that most of the clasts are igneous or metamorphic, and at all locations above Cretaceous bedrock. As shown in Figure 4, the basal till conglomerate, as defined in this study, occurs chiefly in the area of known gypsum occurrence, and also in an area northeast of Fort Dodge.

Upper Clastic Units

In the present discussion, the informal name 'Soldier Creek beds' will be used for the series of clastic strata above the gypsum. Although not accepted for formal nomenclature, the name is widely used by miners in the area and seems to have originated in an unpublished study by personnel of the USG Corporation (Zaskalicky, 1956) from its outcrops along Soldier Creek in the city of Fort Dodge. The clastic units occurring above the gypsum are much thicker and more pervasive than the basal conglomerate. They have a greater known extent than the gypsum, although present only in the general vicinity of Fort Dodge, and extend both west and north of the gypsum (Fig. 1). The clastic beds consist of up to 16 m of red, buff, and green shales, and red, highly calcareous, sandstones/siltstones. Numerous outcrops in the city of Fort Dodge have been described, especially along Soldier Creek near its confluence with the Des Moines River, and in Snell Park in the city. Nodules of celestite have been reported in the shales (Wilder, 1923), and for many years have been found by mineral collectors.

A detailed study of the 'Soldier Creek beds' at the USG North Welles Quarry was performed in 1986 (Meekins, 1995) but unfortunately on strata that are no longer present at that quarry. At that location, reworked fusulinid microfossils were very common in the 'Soldier Creek' rocks. These fossils are characteristic of Upper Pennsylvanian-Lower Permian strata. Although many were reported to be slightly abraded, long-distance transport seems ruled out, and the source rocks presum-

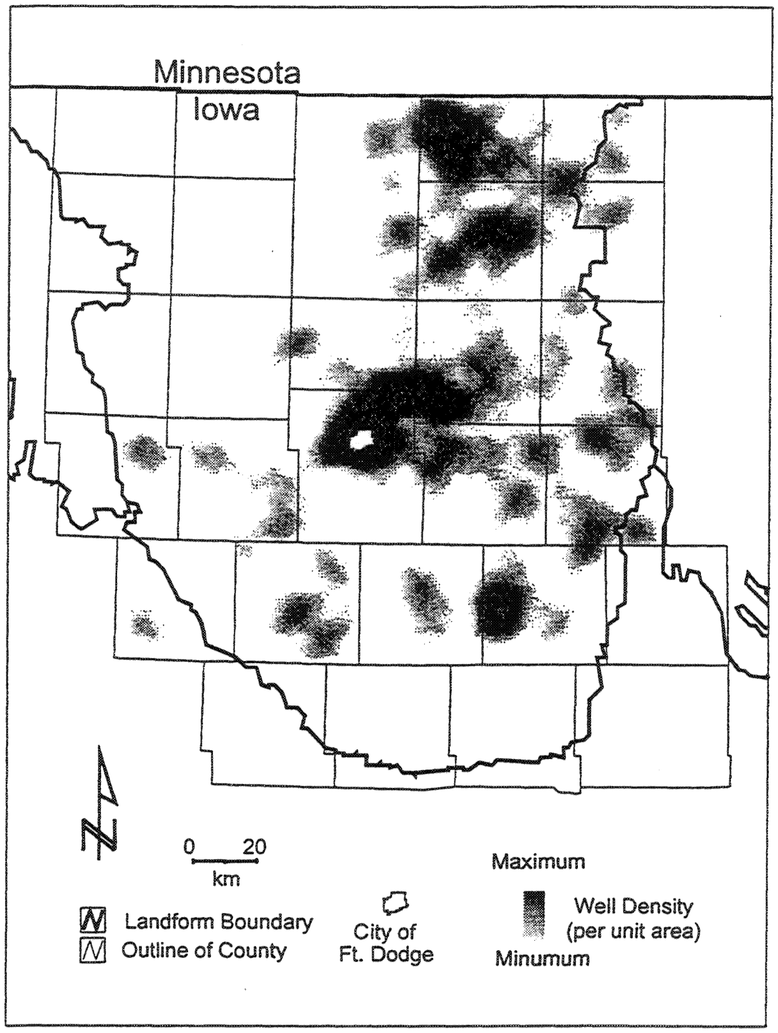

Figure 4. Map of basal till conglomerate occurrences in a 24 county region in north central Iowa (from Mazzella 1996). The conglomerate at the base of the till is derived from interpreted geologic well logs from IDNR-GSB. Those wells indicating the presence of the conglomerate unit have been processed through a 17 x 17 cell 2-dimensional distance weighted filter with cell size of 1000 m x 1000 m. The landform outlined on the map is the Late Wisconsinan Des Moines Lobe glacial till plain. County outlines are included for geographic reference. All filtering in preparation for this map and the construction of the map took place in ARC/INFO™, a commercial GIS.

ably occurred within a few kilometers of the depositional site. Nine discontinuous stratigraphic units were described at the North Welles Quarry and a general synopsis of the rocks along the west wall of the quarry is given in Table 2.

A section measured by Hale (1955) at Snell Park in Fort Dodge consisted of similar strata which he also divided into 9 lithologic units. The Hale (1955) section is reproduced in the road log section of this guidebook (see Stop 3, p. 55). Hale's nine units are only coincidentally the same in number as those of Meekins (1995) and are not correlative, because 'Soldier Creek' strata are highly discontinuous even within a single quarry.

Table 2. 'Soldier Creek beds' at USG North Welles Quarry from Meekins, 1995.

Unit No.	Lithology	Description	Thickness (m)*
Jurassic			
Fort Dodge Formation 'Soldier Creek beds'			
9.	Sandstone	Reddish-brown, thin clay partings, faint cross-lamination. Highly calcareous, friable, well-rounded quartz sand grains.	0.6
8	Mudstone.	Red, green, gray, calcareous. reworked microfossils.	0.3
7.	Sandstone	Fine-grained, very pale brown, highly calcareous, reworked microfossils, well-sorted, well-rounded sand grains, micaceous.	0.4
6.	Mudstone	Olive-gray, red, brown, yellow. Friable, calcareous, faint laminations, reworked microfossils	0.6
5.	Sandstone	Light brown, calcareous, distinct almost horizontal laminations, micaeous, reworked microfossils.	0.3
4.	Mudstone/ Sandstone	Red-brown, friable, calcareous	0.4
3.	Sandstone	Fine-grained, olive gray to reddish-brown clay-rich, medium to fine-grained, highly calcareous, olive-gray clay partings.	0.8
2.	Mudstone	Red brown, silty.	0.9
1.	Sandstone	Gray, cross-laminated, extremely friable, highly calcareous, fine-grained.	0.3

* Typical thickness, based on 13 measured sections along west wall of quarry.

A particularly interesting core of Soldier Creek material was described by Zaskalicky (1956) is given in Table 3. Two thin Soldier Creek 'limestone beds' were encountered in the well. Zaskalicky (1956) concluded that calcareous sandstones in the southwest graded into limestones in the northeast, and that this facies change implied that the strata were deposited in an evaporite basin with a shoreline located to the southwest of Fort Dodge. However, this interpretation is currently being reevaluated.

X-ray diffraction analysis of clay minerals at North Welles Quarry (Meekins, 1995) determined that both illite and kaolinite occur in almost all units, and generally illite was much more abundant than kaolinite.

The geologic age of the clastic units is unknown, but early workers concluded they are only slightly younger than the gypsum because of their close association (Wilder, 1923) and the presence of thin gypsum layers interbedded with the clastics (Wilder, 1903). Zaskalecky (1956), however, con-

Table 3. 'Soldier Creek beds', Borehole, Sec. 31, T90N, R27W.

Unit No.	Lithology	Description	Thickness (m)
Jurassic			
Fort Dodge Formation			
6	Shale	Light gray, soft, micaceous, calcareous, containing some pyrite.	1.5
5	Limestone	Yellow, with interbedded sand fine to medium. Also contains abundant rounded pellets of limestone, dolomite, and quartz.	1.5
4	Sandstone	Light gray, calcareous cement. Very fine angular with coarse sand of quartz, angular chert, limestone, and dolomite.	3.5
3	Limestone	Light creamy gray with fine sand, limestone and dolomite pellets embedded in the limestone.	1.5
2	Gypsum	White, clear, crystalline, amorphous.	4.6
1	Limestone Conglomerate	Light yellowish gray and pinkish, containing bryzoan, fusulinid, and crinoid fragments. Much pyrite.	0.9

Description slightly modified from Zaskalicky, 1956

cluded they were Cretaceous and related to the Dakota Formation. Clay mineral analyses, however, seem to disprove a Cretaceous age because the Dakota Formation clay minerals are almost entirely kaolinite, whereas illite is the primary mineral in the 'Soldier Creek beds' (Meekins, 1995). The pronounced red color is also not typical of Dakota lithologies in the Fort Dodge area. For a more detailed discussion of the age of the Fort Dodge Formation see page 20 of this guidebook.

Based on lithology and primary structures, Meekins (1995) concluded that the 'Soldier Creek beds' in the North Welles Quarry represent fluvial and deltaic depositional environments. Since no fossils, other than reworked ones, were discovered, she concluded that the water body into which the delta extended presumably was highly saline. It may have been either marine or continental lacustrine; evidence supporting or contradicting either contention is lacking.

Gypsum Unit

Introduction

The gypsum is discontinuously preserved within isolated low areas present on an older erosion surface cutting across Pennsylvanian and Mississippian strata. Presumably, the currently isolated gypsum masses (Fig. 1) were once continuous and were deposited in a single Jurassic evaporite basin because there are no known facies differences from one location to another. Separation into isolated masses occurred by erosion and dissolution before Pleistocene till deposition. The maximum extent of the evaporite basin is unknown, but lack of facies changes over its present lateral extent support a conclusion it was larger. The gypsum bed occurs at different elevations throughout the Fort Dodge area. Lees (1922) found a difference in elevation of about 20 m occurs be-

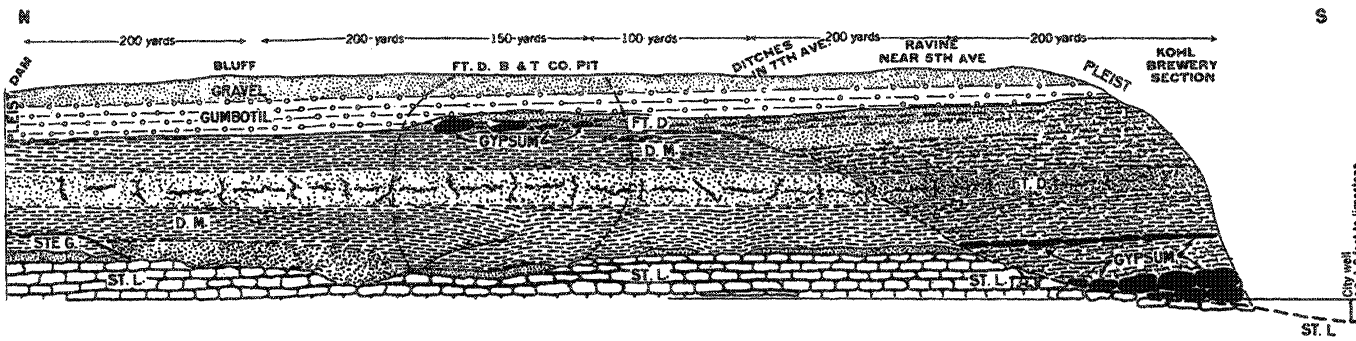

Figure 5. Lees' Soldier Creek section showing elevation differences of gypsum. The image is computer enhanced from Wilder (1923).

tween two outcrops located about 500 m apart along the east side of the Des Moines River near Soldier Creek (Fig. 5). Elevational differences have been ascribed to faulting (Keyes, 1902), but Lees (1922) discounted faulting as an explanation after careful field studies. Lees (1922) concluded that the differences resulted from original elevation differences on the evaporite basin floor during gypsum deposition. Subsequent investigations have confirmed a series of east northeast-trending faults and an associated central graben that is now called the Fort Dodge Graben. However, the graben does not appear to have played a significant role in the deposition or preservation of Fort Dodge Formation strata. (See page 18 of this guidebook for a more detailed discussion of the deposition and preservation of the Fort Dodge Formation).

The maximum thickness of the gypsum is about 10 m, but considerable variation exists because of topographic relief within the evaporite basin during deposition, and because later erosion and dissolution differentially reduced thickness. According to Wilder (1923), early miners recognized five laterally persistent subdivisions or ledges in the gypsum (Table 4).

The Upper Rock unit is variable in thickness because its upper surface may have undergone exceedingly irregular dissolution (Fig. 6). This surface is especially evident at locations where the overlying Soldier Creek beds are missing and the gypsum is directly in contact with Pleistocene till. It should be visible at the North Welles Quarry during the field trip (Stop 5) unless obliterated by mining activity. Where mining has removed overburden and exposed the gypsum, hollow dome-like structures may develop on top of the gypsum (Fig. 7). The base of the gypsum is generally not visible at quarries because a thin floor of gypsum is left for movement of machinery, but it is visible in a natural ravine at the Georgia-Pacific Quarry (Fig 3) and during the final stages of the mining operation when the floor is removed. At the Georgia-Pacific Quarry location the basal 0.2 m thick gypsum ledge is dark brown and distinctively different from overlying gypsum. The rock is calcareous, and is composed almost entirely of tightly-packed, partly interlocking, buff, coarsely-crystalline gypsum nodules and clasts separated

Table 4. Subdivisions of the Gypsum Bed from Wilder, 1923.

Ledge No.	Description	Thickness (m)
5.	Upper Rock	1-4
4	Six-foot Ledge	2
3.	Hard Ledge	0.3
2.	Eighteen Inch Ledge	0.5

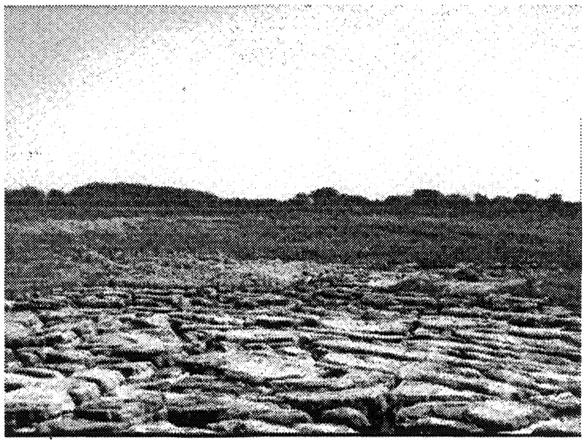

Figure 6. Enlarged fracture channels at top of gypsum, North Welles Quarry 1984.

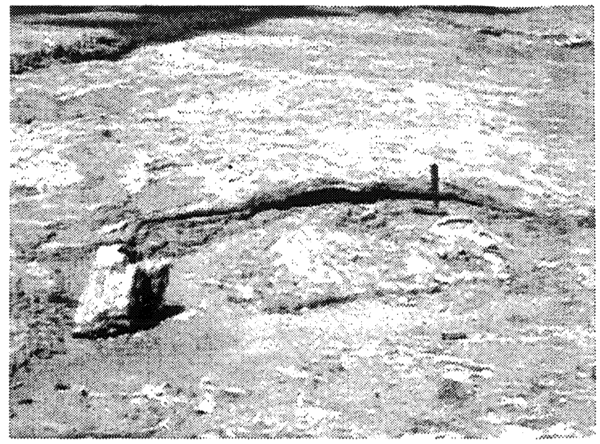

Figure 7. Hollow expansion dome on upper gypsum surface. The hollow space created by doming is about 4" - 6" high. Doming is due to overburden removal during quarrying. Overburden reduction by glacier ice retreat may have created similar domes beneath glacial till with simultaneous filling of the fractures and hollows by double-tier fibrous gypsum. Note that the gypsum surface at this location does not exhibit enlarged fracture channels.

from each other by pronounced dark brown clay/silt impurities which gives a chicken wire appearance to the rock. Nodules usually are less than about 0.5 cm in diameter. The ledge has horizontal parting and contains short segments of thin, horizontal single-tier fibrous gypsum veins.

Chemistry and Mineralogy

The Fort Dodge gypsum is characterized by small amounts of impurities, and contains between 89% and 96% $CaSO_4 \cdot 2H_2O$ (Bard, 1982). Although present in small quantities, mineral impurities impart the distinctive banding and color to the rock. Major impurities are quartz, iron oxide, clay, and calcite/dolomite, as shown by USG Corporation chemical analyses (Table 5). The high purity of Fort Dodge gypsum makes the rock particularly valuable for industrial use. This feature, together with the low cost of strip mining, and the central location of the deposit in relation to large urban centers of wallboard use has created a resource which is mined even when economic conditions were forcing closings or cut-backs in gypsum mining at many other locations.

Trace element data for the gypsum (Table 6) shows marked differences in SiO_2, K_2O, MgO, total Fe, Al_2O_3, and TiO_2 between white and dark bands (Bard, 1982). These differences confirm thin-section analyses that show the dark bands to be enriched in accessory minerals. XRD analysis of the bulk gypsum reveals small amounts of quartz, K-feldspar, plagioclase, and hematite (which occurs chiefly as coatings on detrital grains), and trace amounts of muscovite and zircon. Dolomite and calcite also are present in the gypsum, but are concentrated in marl stringers which are most abundant adjacent to fibrous gypsum layers (Dasenbrock, 1984). Minor amounts of illite and kaolinite are also present.

Dissolution of gypsum in a soxhlet extractor was performed by Hayes (1986) in order to precisely determine concentrations of mineral impurities. Soxhlet extraction was used because it will not dissolve carbonates (Hayes and Cody 1987). He found that extractor-insolubles constitute between 1.0% and 3.5% of the rock, and nodules contained < 0.5% insolubles. Hayes (1986) confirmed the presence of the minerals observed by Dasenbrock (1984), and also detected pyrite, limonite, and possibly tourmaline. Quartz is the most abundant impurity, and is present both as detrital

Table 5. Major Element Chemistry of Fort Dodge Gypsum from U.S. Gypsum Corp.

Constituents	Sample I	Sample II	Sample III
CaO	32.48	32.30	32.20
SO_3	43.30	44.30	44.60
MgO	0.05	0.13	0.12
SiO_2	0.49	1.58	1.43
Fe_2O_3	0.03	0.11	0.11
Al_2O_3	0.09	0.32	0.28
CO_2	0.43	0.56	0.50
Free H_2O	18.8	0.02	<0.01
Combined H_2O	1.74	19.00	19.30
LOI*	1.73	1.50	1.30
$CaSO_4{\cdot}2H_2O$	94.58	95.60	96.10

Data from Bard (1982). * Loss on ignition.

Table 6. Trace Element Analyses, Light and Dark Bands.

Constituent	Light Bands	Dark Bands
SiO_2	2,033	8,233
Na_2O	1,176	1,085
K_2O	488	957
SrO	333	377
MgO	345	1575
Al_2O_3	308	6,808
TiO_2	148	760
FeO + Fe_2O_3	378	732
MnO	73	87

From Bard 1982.

fine-sand and silt-size grains and as authigenic quartz crystals (Fig. 8). Most of the detrital quartz is poorly sorted, angular to well-rounded, frosted, and stained yellow to orange by hematite coatings. Typically, it has a maximum diameter <0.1 mm. Surface textures of the detrital quartz exhibit aeolian features, indicating wind transport. Single crystals and clusters of authigenic quartz have a range between 0.1 mm and 0.3 mm length, but occasionally crystals as long as 1.0 mm were observed. Authigenic quartz is most common in the upper part of the section at the North Welles Quarry and was not found below about 3 m from the top. Calcite was next in abundance, but only the lower half of the deposit at the North Welles Quarry contained calcite crystals large enough to study with an optical microscope. These crystals were typically euhedral to subhedral in habit. Clay minerals were not observed in the soxhlet-extracted insolubles, although extremely fine clay may have passed through the cellulose filter used during extraction.

Laminations

Probably the most striking feature of the gypsum is the distinctive and highly characteristic bands or laminations (Fig. 9) consisting of white lamina alternating with thinner dark ones. From a distance, the color banding gives an impression of continuous laminations but closer study shows that individual bands extend only for a few meters or less before blending with others and disappearing. Lamina typically are irregular, and many are contorted to various degrees. Dark banding is predominately blue-gray, but yellow, red, or brown colors also occur.

The white bands are of three types. The first is comprised of approximately horizontal laminations of single-tiered, vertically-oriented elongate gypsum crystals (Fig. 10). These fibrous laminations occur throughout the section and typically extend laterally for < 15-20 m (Dasenbrock, 1984). The second type appears to result from the coalescence of small nodules concentrated in horizontal planes. This type has a mild to moderate contorted, or enterolithic, appearance (Fig. 11). The lamina are at least partly diagenetic, and diagenesis may have caused expansion of thin primary layers. Growth and coalescence of the nodules excluded mineral impurities so that these white lamina are particularly devoid of impurities (Dasenbrock, 1984). In thin-sections, nodular white laminations are invisible and cannot be distinguished from

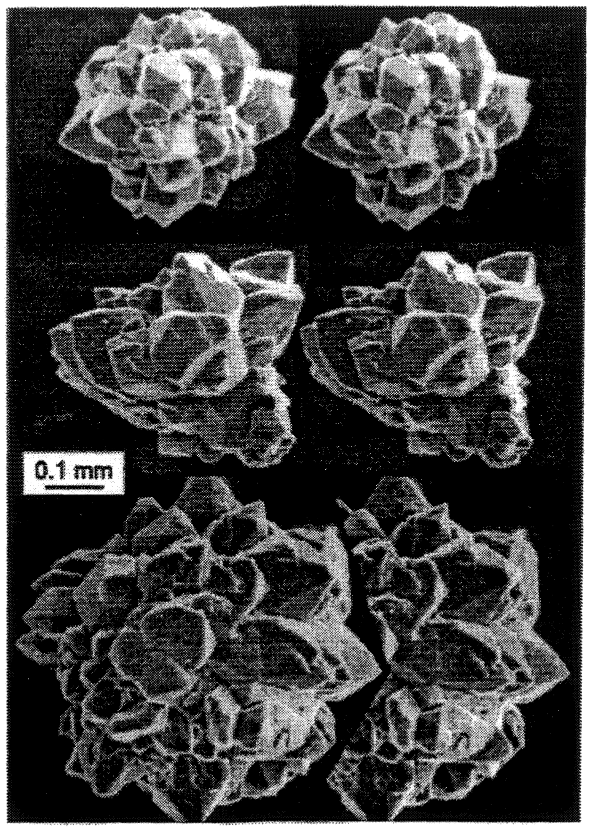

Figure 8. Authigenic quartz crystal aggregates (from Hayes, 1986). These crystals were isolated by dissolution of gypsum from North Welles Quarry in a Soxhlet extractor. Dissolution of long-exposed gypsum surfaces by rain may create rough textures resulting from aggregates exposure.

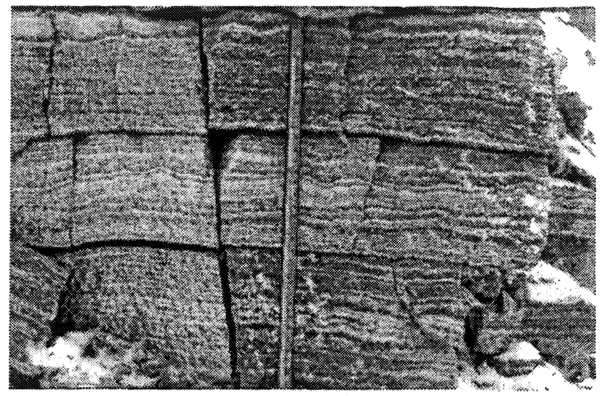

Figure 9. White/dark laminations in Fort Dodge gypsum. The scale is 1-meter. North Welles Quarry.

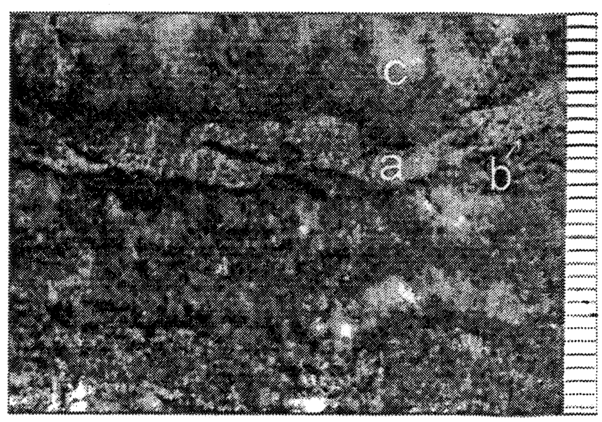

Figure 10. Single-tier fiber vein, **a**. Another, thinner, single-tier vein occurs along the lower left margin. Impurities are concentrated, along the vein, as for example at **b**. Nodular gypsum occurs at **c**. Scale is in millimeters.

dark laminations. Details are best seen in transmitted light through a 'thick section' of about 2 mm thickness (Fig. 12). The greater thickness, compared to thin sections, creates overlap of irregular and discontinuous impurity wisps so that they impede light penetration. A third and last type of light/dark banding results from intercalations of marl layers within the gypsum. Typically the marl layers are ≤ 2 mm thick and are usually light gray to yellow gray. Marl is most apparent on freshly-broken surfaces because weathering tends to rapidly erase its color distinction.

Each dark band is comprised of several very thin darker horizons separated by slightly lighter regions. The dark horizons appear to be composed of mineral impurities, but only discontinuous stringers of accessory mineral inclusions are visible in thin-sections. Part of the darkness of the wide dark laminations results from mineral impurities, but part seems be caused by larger gypsum crystals in dark lamina compared to those in nodular white ones. Larger crystals scatter less light and allow greater light penetration than smaller ones, so that bands composed of larger crystals appear darker than those composed of very small crystals.

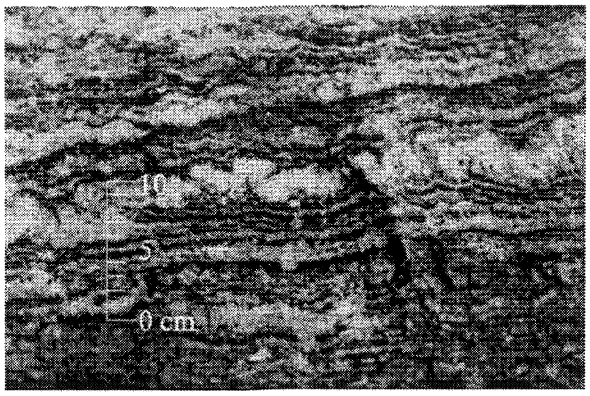

Figure 11. Dark/light laminae, with contorted (enteriolithic) lamina near middle of photograph. The lamina change character across the photograph, and several nodules are present. North Welles Quarry.

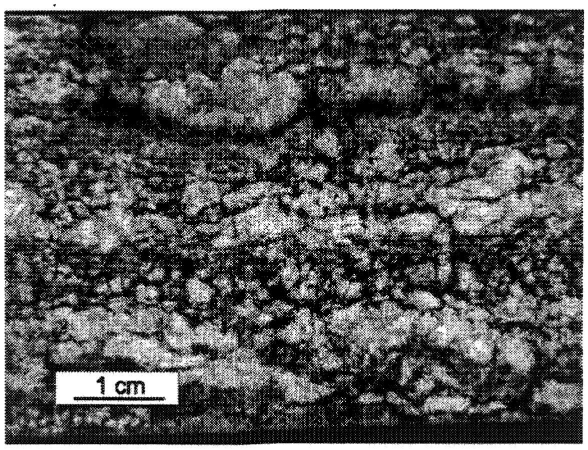

Figure 12. 'Thick section' of gypsum showing nodular character of laminations. This section is about 2 mm thick, cut perpendicular to bedding, and viewed in unpolarized transmitted light.

Nodules

Nodules in the Fort Dodge gypsum are of two types, both being composed of fine-grained alabastrine gypsum. One distinctive type occurs in the upper rock layer (Fig. 13). Nodules are typically up to about 20 cm in diameter, and miners have occasionally reported nodules of 1 m or more (Bard, 1982). Large nodules occur chiefly in horizontal to subhorizontal bands, and are typically composed of several smaller coalesced nodules separated from each other by a faint outline of darker material. In some nodules, however, evidence of coalescense is lacking. The second type of nodule is much smaller in size and occurs throughout the section. This type has already been described in the previous section on lamina. They occur in enterolithic bands formed by coalescence of nodules when viewed perpendicular to bedding. Often these nodules are most visible on bedding surfaces exposed by mining where the nodules appear as blisters (Fig. 14). Both types of nodules often have relict anhydrite textures, that is, tiny blocky gypsum crystals aligned in a swirled pile of bricks texture (Dasenbrock, 1984) .

Other Structures

Ripple marks occur at numerous locations in the Upper Rock layer (Fig. 15). They are most common on bedding planes adjacent to thin marl layers which typically are planes of weakness allowing the rock to split apart at those horizons. A sketch (Fig. 16, from Dasenbrock, 1984, after Withington, 1961) shows the internal structure of one such mark. Ripple marks may occur at lower horizons in the section, but the rarity of marl stringers in those parts of the section may obscure their occurrence because the rock does not easily split apart at bedding planes without marl interlayers. Non-tectonic folds occur in the upper part of the section. One example (Fig. 17) shows a gradual upward increase followed by a decrease in amplitude.

Joint-Controlled Channels

A striking feature of the upper gypsum surface at some quarry locations is the presence of deep channels (or slips as they are called by miners) extending downward into the gypsum (Fig. 18). These fissures are due to pre-Pleistocene dissolution along earlier fractures. Channels often > 1 m wide may extend through the entire gypsum bed. According to miners, the channels are particularly well-developed at locations lacking a cover of Soldier Creek clastics, where the gypsum is directly in contact with till. The enlarged fractures are filled with till or other Pleistocene materials, although in some locations they may be filled by red 'Soldier Creek beds' material. Fractures are not always visible beneath channels so that gypsum recrystallization must have healed earlier fractures that controlled channel locations.

Channel orientation was studied by Hayes (1986) at three quarries, and one of his illustrations is included here (Fig. 19). Orientation of the enlarged fractures is essentially random when all three quarries are compared, and was ascribed to the effects of underlying bedrock topography and differential compaction of underlying sedimentary rocks during stresses developed by glacier advances.

Fibrous Gypsum Veins

Although fibrous gypsum could be considered as a textural feature, it will be discussed under structures, because the fibrous veins and laminae are distinctive features visible on outcrop and in hand specimens. There are two types of fibrous gypsum in the Fort Dodge Formation. The first is white, single-tiers of vertically oriented fibers that occur in bands parallel to bedding planes, and have been discussed in the section on laminations. Single-tier fibrous lamina occur throughout the section and are typically ≤ 0.5 cm wide (Bard, 1982). The second and more distinctive type is composed of two tiers of elongate crystals. These sub-horizontal veins occur only in the uppermost 2-3 m of the section at the North Welles Quarry. The central parting, a thin region of impurities or non-fibrous gypsum crystals, separates the tiers (Richardson, 1920). Machel (1985) concludes that double-tier fibrous gypsum grew in fractures opened by vertically-oriented tensile stress. He maintains that the central parting represents the initial plane of fracturing. In his model, the fibers grew centrifugally in both directions from this plane at rates approximately equal to fracture enlargement, and open spaces never existed along the fractures. Tensile stresses that caused fracturing in the Fort Dodge beds probably were at least partially due to reduction of overburden by glacier retreat. Double-tier fibers usually contain tan clay inclusions derived from overlying sediments,

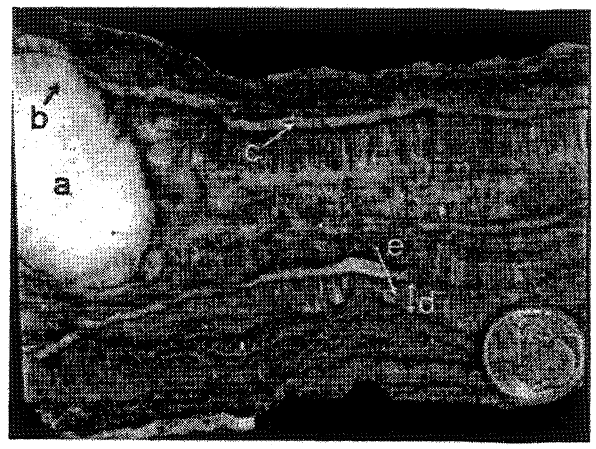

Figure 13. Nodule and complex double-tier fiber veins. An alabaster nodule occurs at **a**, fibrous gypsum at the margins of the nodule, **b**. A dark rim of impurities occurs at the outer margin of the fibers, but a second rim of impurities is not visible at the inner margin where the fibers grade into alabaster. A single-tier vein occurs at **c**, with dark impurity rims at both upper and lower margins. A double-tier fibrous vein occurs at **d**, with a central parting at **e**.

Figure 14. Abundant alabaster nodules which resemble blisters on the bedding plane surface. North Welles Quarry.

and abundant tan to dark brown impurities occur adjacent to the fibrous bands. Single-tier veins, usually light colored, may occur with the double-tiers. These veins may be highly complex (Fig. 13). For example, a double tier may laterally

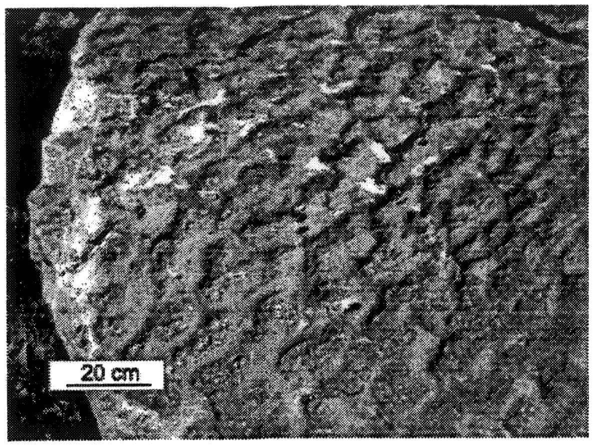

Figure 15. Gypsum ripple marks, North Welles Quarry.

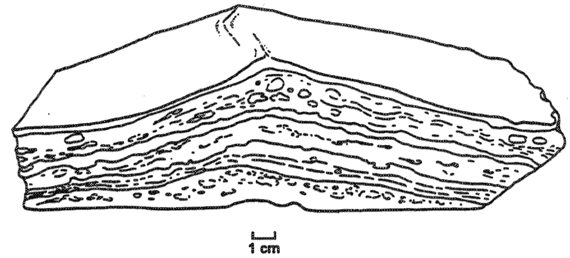

Figure 16. Sketch of internal structures of ripple mark, from Dasenbrock, 1984. The sketch is from a photograph in Withington (1961). Withington (1961) concluded that the loss of ripple structures beneath the crest was due to compaction, recrystallization, and perhaps to rehydration of earlier anhydrite.

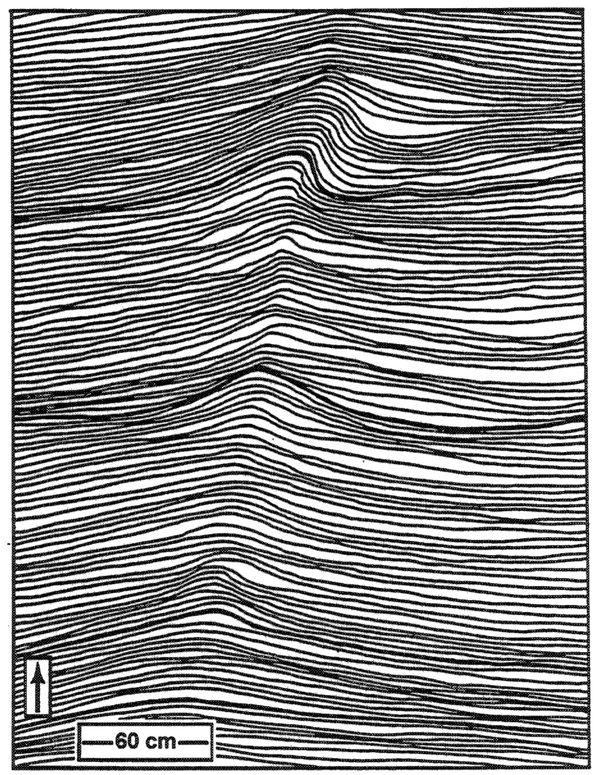

Figure 17. Sketch of non-tectonic fold, from Dasenbrock, 1984.

change into a single tier or into one with three or more tiers separated by anhedral gypsum masses. Different generations of veins may cross-cut each other.

The term *satin spar* has been applied to both single-tier and double-tier fibrous bands in the Fort Dodge Formation, but these crystals do not closely resemble true satin spar which consists of acicular gypsum having a distinctive sheen or luster (Dasenbrock, 1984). In the Fort Dodge gypsum, elongate fibers are much thicker than those in satin spar, and the c-axis orientation of Fort Dodge fibers are less consistent compared with that of satin spar as shown by x-ray diffraction analyses of sections cut perpendicular to the fibers (Dasenbrock, 1984; Machel, 1985). The lack of central parting in the single-tier laminations also is inconsistent with satin spar.

Gypsum Breccias

Gypsum breccias occur at a few locations in the North Welles Quarry (Dasenbrock, 1984). They occur in the uppermost meter of section and are composed of broken gypsum rock, double and single-tier fibrous veins, and detrital material from overlying clastics.

Textures of the Fort Dodge Gypsum

Four varieties of gypsum have been observed in the Fort Dodge gypsum. They are alabastrine, euhedral, porphyroblastic, and fibrous. Alabastrine gypsum, the most common variety, is found in nodules and enteriolithic bands consisting of coalescing nodules. It has crystal sizes < 100 µm

Figure 18. Enlarged fractures at North Welles Quarry, with the channels partly filled with water. White marks on the channel walls are due to abrasion by machinery used to clear clastic sediments from the channels. The 'Soldier Creek beds' occur in the background.

to 500 µm, and often exhibits a swirled pattern suggesting relict anhydrite crystal textures (Dasenbrock 1984). The swirled pattern and the abundance of nodules has been used as evidence for gypsum dehydration to anhydrite. Sometimes alabastrine nodules have a central porphyroblast of larger anhedral gypsum. Porphyroblastic gypsum crystals have a range size from < 1 mm to about 2 mm in length; have anhedral outlines; occur in interlocking clusters, and are next to alabastrine gypsum in abundance. Although commonly occurring with alabaster in nodules and nodular bands, some white bands and many dark ones are largely composed of porphyroblastic gypsum (Bard, 1982; Dasenbrock, 1984). Fibrous gypsum is second in abundance. Euhedral to subhedral stubby prismatic gypsum crystals are the least common variety and randomly occur throughout the section. They have maximum lengths of about 250 µm to 1 cm, and a median length of 1.5 mm (Bard, 1982)..

Pervasive diagenetic alteration and recrystallization since its deposition produce major difficulties in interpreting depositional environments of the Fort Dodge gypsum. In primary gypsum deposits such as those in the Mediterranean Miocene

Figure 19. Airphotograph of fracture pattern in gypsum at National Quarry, north-east of Fort Dodge (Hayes, 1986).

or the Paris Basin Eocene, a wide variety of bottom-growth and other types of gypsum textures are common. These features are completely lacking in the Fort Dodge gypsum. For example, compare a thin-section of the Paris Basin gypsum (Fig. 20) with one of a typical section of Fort Dodge gypsum (Fig. 21). Originally, the Fort Dodge gypsum probably was similar to the Miocene or Eocene gypsum, but partial or complete dehydration followed by rehydration and recrystallization have obliterated primary textures. Dasènbrock (1984) has outlined a possible sequence of primary deposition and diagenetic modifications. He concluded that the earliest gypsum would have resembled that of the Paris Basin gypsum with a variety of shallow-water bottom-growth crystals and early diagenetic shallow subsediment lenticular gypsum crystals. The dark, impurity-rich laminations

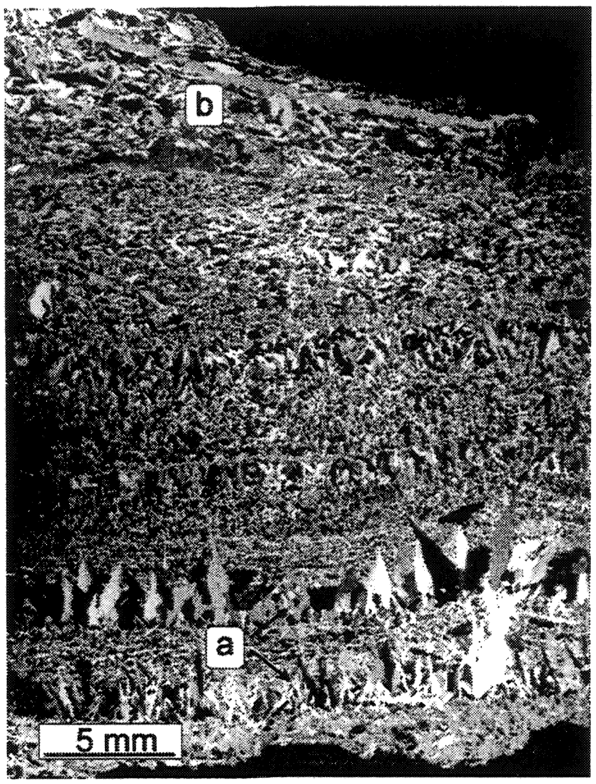

Figure 20. Thin-section of Paris Basin Eocene gypsum, viewed in crossed-polarized light. This section shows features characteristic of gypsum deposits that have undergone very little alteration since deposition. Near the bottom of the photograph are two layers, **a**, showing pronounced bottom-growth gypsum crystals. These subaqueous crystals were attached to sediments on the evaporite basin floor, and grew upward into the overlying water. Gypsum at **b** is composed of lenticular, very early diagenetic, crystals that grew at shallow burial depths in unconsolidated sediments.

probably precipitated during storm events that contributed wind blown dust, and the light laminations represent clear-water precipitation. Shallowing water depths developed during precipitation of the Upper Ledge exhibits ripple marks which are rare in underlying material. Porosity probably was greater during this stage. Dasenbrock (1984) concluded that the gypsum then underwent a series of at least six sequential stages of diagenesis (Table 7).

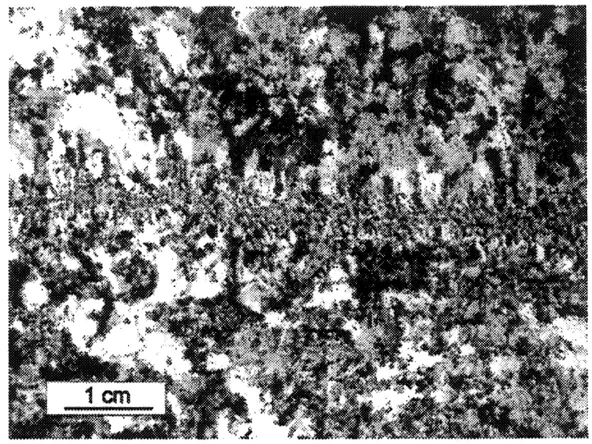

Figure 21. Thin-section of Ft. Dodge gypsum, viewed in cross-polarized light. This photograph shows essentially the same area as that of Figure 12 in thick-section. The nodular character which is clearly evident in Figure 12 is not visible in thin-section. Compared these textures to those exhibited by the Eocene gypsum of Figure 20. Shortly after deposition, the Fort Dodge gypsum probably resembled the Paris gypsum but a complex history of recrystallization and hydration changes has completely destroyed primary textures.

ORIGIN OF THE FORT DODGE GYPSUM

There is little controversy about the general features of gypsum deposition. It was deposited in a closed or restricted basin or basins in an arid climate where evaporation exceeded precipitation. Beyond that generality, however, there is much uncertainty concerning the Fort Dodge gypsum. Was it deposited in a marine or inland continental lake environment, and was the evaporite basin originally much larger than the gypsum's currently known extent or did it approximately coincide with the present-day extent of gypsum?

Among the difficulties in trying to answer these questions are: (1) the lack of autochthonous marine or continental fossils; (2) the complete lack of time-related strata in nearby areas, the nearest being in the subsurface of central Nebraska, Michigan, or northwest Minnesota; (3) unconformable

Table 7. Diagenetic Sequence Stages of Fort Dodge Gypsum

Stage I.	Compaction and Early Recrystallization.
Stage II.	Maximum Burial and Dehydration
Stage III.	Uplift, Erosion, and Initial Rehydration. Porphyrblastic gypsum crystallized during slow hydration of deeply buried anhydrite phase.
Stage IV.	Later Rehydration. Alabastrine gypsum crystallized under relatively rapid rehydration of anhydrite with moderate burial depth.
Stage V.	Euhedral Gypsum Growth. Euhedral crystals formed at expense of earlier-formed crystals, probably being a more energetic habit than that of smaller highly-strained crystals.
Stage VI.	Fibrous Vein Formation. There may have been two stages in fibrous veins, older single-tier formed in fractures caused by pressure release during uplift and erosion, and more recent double-tier veins in fractures caused by pressure release during glacial retreats.
Stage VII	Brecciation of Upper Gypsum Layers.

upper and lower surfaces, precluding the use of sequence stratigraphy; (4) underlying shale and basal conglomerate and overlying 'Soldier Creek beds' also lack autochthonous fossils and other marine/continental indicators; (5) pervasive recrystallization; (6) near absence of primary structures and textures, even in relict form.

In contrast with these problems, several known features place restrictions on proposed hypotheses. These are: (1) purity of the gypsum; (2) apparent lack of lateral facies differences from one gypsum location to another; (3) near absence of vertical facies changes, with the exception of shallow water indicators in upper one-third of the section; and (4) similarity of sulfur isotope $\delta^{34}S$ o/oo values to those of the marine Jurassic isotope age curve (Claypool et al., 1979; Hansen, 1983).

The primary question is whether the gypsum is marine or continental. If marine, then the obvious source of calcium sulfate was ocean water, and deposition must have occurred in an evaporite basin with restricted connection to an open ocean which presumably was located to the west. Late Jurassic shorelines must have been farther to the east than is commonly believed. If the Fort Dodge gypsum was deposited in an inland continental lake, then calcium sulfate must have been derived from dissolution of older nearby evaporites. Both Devonian and Mississippian gypsum/anhydrite deposits occur in southern Iowa (McKay, 1985). Near Fort Dodge, gypsum/anhydrite occurs in Devonian rocks at about 200 - 400 m depth, but shallower Mississippian gypsum may have once been present and subsequently disappeared through dissolution. Widespread brecciation of buried Mississippian limestones may be evidence of collapse resulting from subsurface evaporite dissolution.

Gypsum purity and lack of lateral facies change support the contention that gypsum deposition was once more widespread than its present-day occurrence suggests. Deposition probably occurred in a large evaporite basin but there is no evidence available to confirm the lateral extent of evaporite deposition. Both factors argue against an inland continental lake setting. In inland continental lakes which are distant from an ocean, $CaSO_4$ input is from groundwater supplemented by $CaSO_4$-

bearing surface water. Gypsum precipitation would be relatively slow, and wind-derived and seasonal river clastic input would prevent pure gypsum from being deposited. Fort Dodge gypsum contains wind-blown silt, but no larger silicate particles that might have been transported by rivers. The silt usually constitutes < 4% of the rock, and seems insufficient in concentration for a continental groundwater-fed evaporite lake with slowly precipitating gypsum.

The only 90%+ pure gypsum lake deposits we know of occur in a few, relatively small, sea-marginal lakes. Thick, relatively pure, laminated gypsum deposits occur in the sea-marginal dune lakes of South Australia (Warren, 1982, 1989). In sea-marginal Lake MacLeod in northwest Australia (Logan 1987), halite deposits are relatively clean because the NaCl concentration in seawater seeping through permeable coastal sediments requires that relatively small volumes of water evaporate to produce thick salt deposits. Rapid precipitation of halite, therefore, easily overwhelms clastic input from wind and other sources. In comparison to halite, seawater contains relatively small amounts of $CaSO_4$, so that large amounts of seawater must evaporate to form thick pure gypsum deposits. This process can be relatively rapid in sea-marginal lakes supplied by seawater flowing through permeable coastal sand dunes, but gypsum in these lakes is not always of high purity. Lake MacLeod gypsum is mixed with clay and aragonite (Logan, 1987).

Other problems related to a continental lake origin are the absence of carbonates which would be expected in lakes fed largely by groundwater. Fort Dodge area Devonian and Mississippian gypsum was closely associated with limestone/dolomite, and groundwater rich in calcium sulfate would be expected to carry abundant carbonates in solution. Carbonates are abundant in both the underlying conglomerate and in the 'Soldier Creek beds' however, and lake margin carbonate deposits may have once been present but might have been eroded in pre-Pleistocene times.

The similarity of $\delta\ ^{34}S$ o/oo of the Fort Dodge gypsum to marine Jurassic values seems surprising if the sulfate were derived from buried Devonian or Mississippian gypsum, but this evidence could be stronger because sulfur isotope values of both Devonian and Mississipian Iowa sulfates overlap those of the Jurassic (Hansen, 1983).

In summary, lithologic features suggest a relatively large sea-marginal lake or restricted marine evaporite basin, but strong proof is lacking for either a inland continental lake or marine/coastal setting.

AGE OF THE FORT DODGE GYPSUM

Various age assignments, from Pennsylvanian to Cretaceous, have been proposed for the gypsum. Owen (1852) observed that the gypsum overlies Pennsylvanian rocks, and he concluded that its contact was conformable and that the gypsum should be considered Pennsylvanian. In 1858 Worthen concluded that the underlying relationship was unconformable. Keyes (1895) agreed that an unconformity exists between gypsum and underlying rocks, and concluded that the gypsum correlated with the Cretaceous Niobrara chalk to the west. Later he speculated that the gypsum might be Miocene (Keyes, 1915). Wilder (1903) performed the first detailed studies of the formation. From outcrops apparently now covered, he found thin gypsum layers in the shales along Soldier Creek, and he observed that the red 'Soldier Creek beds' are closely associated spacially with the gypsum. He concluded that the overlying red shales and sandstones were only slightly younger than the gypsum and presumably represented a gradual waning of conditions favoring gypsum precipitation. In attempting to assess their age, Wilder (1903) observed that the combination of the Fort Dodge redbeds and gypsum was similar to Permian lithologies in Kansas, and consequently that the most probable age of the gypsum and overlying red 'Soldier Creek' clastics was Permian. Moore and others (1944) cited Pennsylvanian fusulinids collected from the Fort Dodge Formation as evidence of a mid-Virgilian age, but Hale (1955) pointed out that these fossils are worn and may have been reworked from older beds, and he cautiously agreed with the Permian (?) age.

Until the 1960s the most accepted geologic age estimate remained Permian.

All age assignment studies were hampered by a lack of meaningful faunal and macroscopic floral remains in the gypsum and clastics. Even though numerous workers studied the formation in detail for over 100 years, and miners typically collected gypsum with unusual features during mining, no fossils were discovered until Cross (1966) investigated the gypsum for palynomorphs. As far as we are aware this study provides the only published evidence of the unit's geologic age. An excerpt from Cross' abstract (1966) is reproduced below:

"Rocks representing mid-Mesozoic have been identified by palynologic analysis from central Michigan and Iowa. Cross and Shaffer reported in 1964 the 'Red Beds', a sequence of gypsiferous gray-red shales in the Michigan Basin, are probably Upper Jurassic Kimmeridgian (Morrison?), though possibly lowermost Cretaceous. The Fort Dodge (Iowa) gypsum is probably of comparable age; much older than previously identified Cretaceous rocks elsewhere in Iowa and Minnesota. The presence of *Clasopollis*, in profusion, primitive gymnospermous pollen (podocarps, tsugoid, laricoid) in abundance, paucity of *Anemia*-type ferns and absence of angiospermous pollen characterize both deposits. These plants contrast clearly from the mid-Pennsylvanian floras below, with no genera bridging the unconformity....The Iowa and Michigan deposits, therefore, appear to be the only representatives of Upper Jurassic rocks in east central United States."

Later in a personal letter to Cody, Cross (1984) states "*I have spent some time on the problem of the age of the Fort Dodge Beds as compared with the Michigan Redbeds and I have not yet come to any final decision ... However, it looks like it very well could be older than Kimmeridgian (=Morrison) and might be as old as Gypsum Springs (for which there is no conclusive palynological study at this time).*"

Most recently, Ludvigson (1996) interpreted paleogeographic reconstructions by Scotese (1991) as indicating that North America was moving northward from the Middle Jurassic through the Lower Cretaceous, and that the Fort Dodge area was at dry, evaporite latitudes (~10-30°) during the Upper Jurassic. This suggests that the Fort Dodge Formation is probably an Upper Jurassic unit. The distance between the outliers at Fort Dodge and the main body of similar-age rocks to the west further suggest that the Fort Dodge gypsum was probably deposited at a time of near maximum marine transgression, probably coeval with the deposition of the Sundance Formation (or possibly basal Morrison Formation) and equivalent strata of the Rocky Mountain states.

The best age assignment of the gypsum at this time is probably Kimmeridgian (≈ 155 my BP) but it might be as old as Bajocian (≈ 180 my BP), the age of the Wyoming Gypsum Springs Formation (Imlay, 1956). Personnel of the Iowa Geological Survey are currently engaged in a more detailed palynological study of the gypsum and associated sediments.

PRESERVATION OF THE FORT DODGE FORMATION

The mode of preservation of the Fort Dodge Formation in central Webster County, Iowa, is not clear at this time. There was some variability in the surface of the basin in which the lower shale and associate gypsum were deposited. In some areas, such as the USG Carbon 20 Quarry in the southeast part of the formation's outcrop belt, the basal claystone is very thin or absent, with the gypsum lying directly on Pennsylvanian sediments. About 1 km to the north, in the Celotex Corporation Quarry, the claystone beneath the gypsum is more than 7 m thick. It is also clear that there was faulting and graben development in the region.

Fort Dodge Fault

The first suggestion of a fault in the Fort Dodge area was by Keyes (1915) who published data inferring that a structure extended for 130 km from the area of Clarion in Wright County, southwest to Wall Lake in Sac County. He also suggested that near Fort Dodge, along the trend of the structure, the Fort Dodge Formation was structurally preserved by faulting. Lees (1922), in his investigation of the structure of the Fort Dodge beds, specifically ruled out the presence of faulting. The actual location of the Fort Dodge Fault was first mapped by Hale (1955), who mapped a pair of east northeast trending faults that bounded a graben and passed through the outcrop area of the Fort Dodge Formation. The north-most fault runs parallel to, and just south of Lizard Creek west of the Des Moines River and parallels Soldier Creek east of the river (see Fig. 1). Hale (1955) described an exposure of the north fault in the Fort Dodge Limestone Company mine, about 2 km west of the Des Moines River, that displayed a strike of N 66° E with dips of 66° S. Within the graben, Hale (1955) described maximum Mississippian strata displacements of 50 m near the southwest end of the graben and 75 m near the northeast end. However, he identified only 15 to 22 m of displacement of the Fort Dodge Formation. This demonstrates that most of the graben displacement occurred after the Mississippian and before deposition of the Fort Dodge Formation strata. Since the city of Fort Dodge lies just west of the Northern Boundary Fault Zone, the major north-northeast trending fault zone that forms the western boundary of the Iowa Horst within the Middle Proterozoic Midcontinent Rift System in Iowa, it is probable that the Fort Dodge Fault represents the reactivation of pre-existing structures. One additional item of interest was mentioned by Hale (1955) who noted that the city of Fort Dodge had located its municipal well field near the southern fault zone. He suggested that the very large yields obtained from these Wells resulted from fault brecciation of the carbonate aquifer rocks.

Fort Dodge Graben

Although the Fort Dodge Graben passes through the outcrop area of the Fort Dodge Formation, there is no evidence that it was involved in the structural preservation of the unit. As previously stated, most of the subsidence of the graben occurred prior to the deposition of the Fort Dodge Formation, and the unit is preserved both north and south of the graben, as well as within it. The vast majority of the gypsum mined has been extracted south of the graben, however, gypsum was also quarried within the graben near the confluence of Soldier Creek and the Des Moines River and north of the graben at Snell Park. The base of the gypsum lies at elevations between 1020 and 1025 feet above sea level north and south of the graben and about 960 feet within the graben.

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GYPSUM MINING IN THE AREA OF FORT DODGE, IOWA

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INTRODUCTION

The Fort Dodge area is one of the leading gypsum producing areas in the United States. About 1.5 million metric tons of gypsum (with a raw value of $10 million) was mined and processed in the area in 1994 by four companies: United States Gypsum Corporation, National Gypsum Company, Georgia-Pacific Corporation, and the Celotex Corporation. This production accounts for about 75% of the total gypsum mined in Iowa, making Iowa second only to Oklahoma among the states in annual gypsum production. Most (over 70%) of the gypsum mined in the United States (and in the Fort Dodge area) today is used to produce plaster of Paris, primarily for production of wallboard (drywall). Most of the rest of the gypsum (18%) is used as a retarder to slow the setting of portland cement. Gypsum is also used as plaster, soil conditioner, inert filler in pharmaceuticals and foods, and a small amount is carved into ornaments and sculptures (including the Cardiff Giant.)

The history of gypsum production in the Fort Dodge area was most recently summarized by McKay (1985). He reported that gypsum had been utilized by people in the Fort Dodge area since the 1850s. The gypsum occurrence was first reported in the geologic literature by geologist David Dale Owen (1852, p.98) who reported exposures along the Des Moines River, and estimated that 190 million tons of gypsum was present, a "supply (that) may be considered as almost inexhaustible.". Keyes (1893) described the gypsum beds at Fort Dodge as "by far the most important bed of plaster-stone known west of the Appalachian chain, if not in the United States." At first Fort Dodge residents used gypsum only for building stones which they "preferred to the limestone of good quality" that also existed in the area (White, 1870). The building stone was quarried from the first known gypsum quarry in the area, the Cummins Quarry.

In 1872 Captain George Ringland, Web Vincent, and Stillman T. Meservey built the Fort Dodge Plaster Mill, first gypsum mill in the area, to grind gypsum for commercial products. The success of this mill led to the construction of others, and by 1902 seven mills were operating in the area, producing a variety of products including building blocks, mortar, plaster, roofing, and flooring products.

The original quarrying operations soon gave way to underground mining, Although most of the underground mine areas have subsequently been stripped and the remainder of the gypsum removed, some areas south of Fort Dodge are still undermined. Collapse in these mined areas, with only a few feet of gypsum left as a roof beneath the glacial drift, is not uncommon. In some places the landscape takes on the appearance of a karst terrain. Today all mining is done by open pit operations, using a variety of equipment to strip off the glacial till, blasting the gypsum, and hauling it to the mills.

The four gypsum-producing companies that currently operate in the Fort Dodge area run their mills 24 hours a day and most of the quarries run two shifts seven days a week. The gypsum resource at Fort Dodge is extremely limited, existing as a small outlier of about 20 km^2, and completely isolated from other Late Jurassic deposits by several hundred kilometers. Gypsum reserves are sufficient for about 30 years at the current rate of extraction for some of the companies, others have only minimal reserves that will be depleted in a few years.

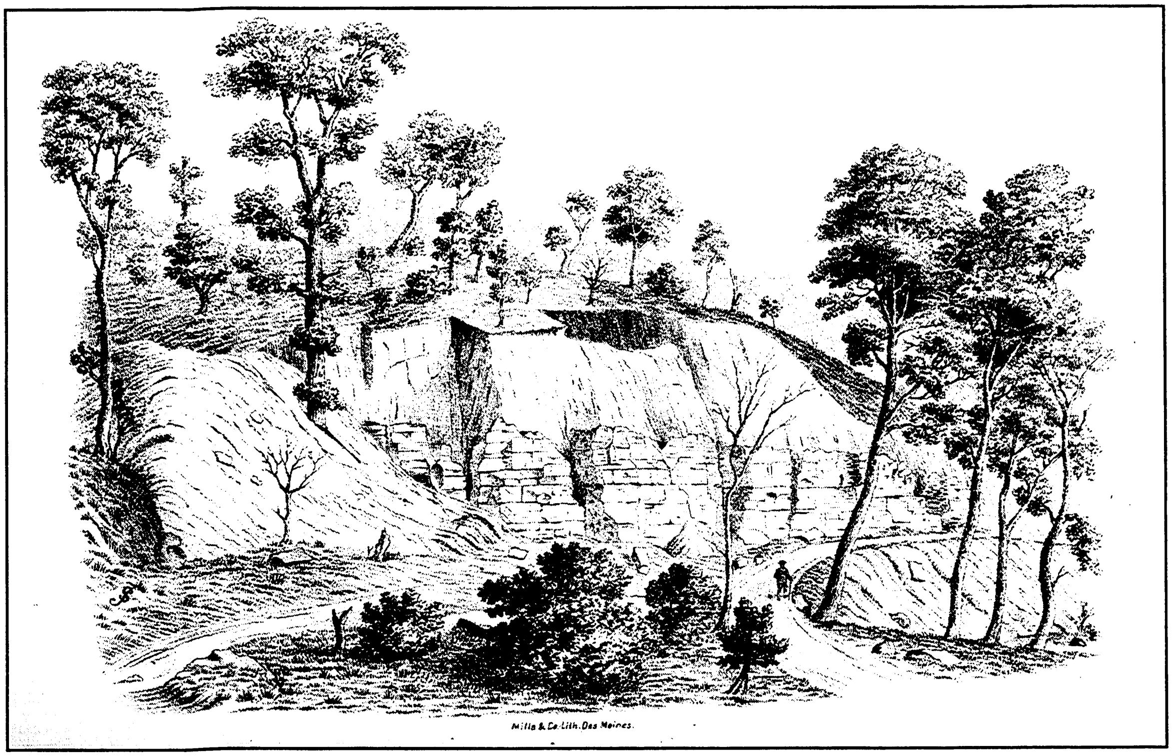

Figure 1. Lithograph by Orestes St. John showing a gypsum quarry on Two Mile Creek (now Gypsum Creek, south of Fort Dodge) as it appeared in 1868 (published in White, 1870, facing p. 297).

EARLY USES OF GYPSUM

The earliest mining of gypsum in the Fort Dodge area was for building stone. There is no record of the date of first use, but it was certainly before 1868 since an early lithograph (Fig. 1) from White (1870) depicts an 1868 quarry located on Two Mile Creek (now Gypsum Creek) and mentions Cummin's quarry which was operating in 1870 on Soldier Creek in sec. 17, T89W, R28W, considerably north of the city limits at that date. The stone being soft, easily mined, and exposed in creek valleys (Fig. 2) was used in place of limestone for both exterior and interior use. According to McGee (1884) it was extensively used twenty or so years earlier. Well-known gypsum structures included an arched culvert over Two-Mile Creek (Gypsum Creek) on the Illinois Central railroad and the depot building for the company. Both were built in the 1860's. McGee (1884) observed in 1880 that the culvert was in good condition, and the depot building appeared to be in good condition in 1883. He noted, however, that gypsum was poorly suited for foundations because of its solubility, and foundation failures were common. By the 1880's gypsum building stone was rarely used because of its poor reputation for durability. Gypsum block can still be found in basement walls of older homes and in a few small old retaining walls, but none of the buildings with exterior gypsum block walls are still standing.

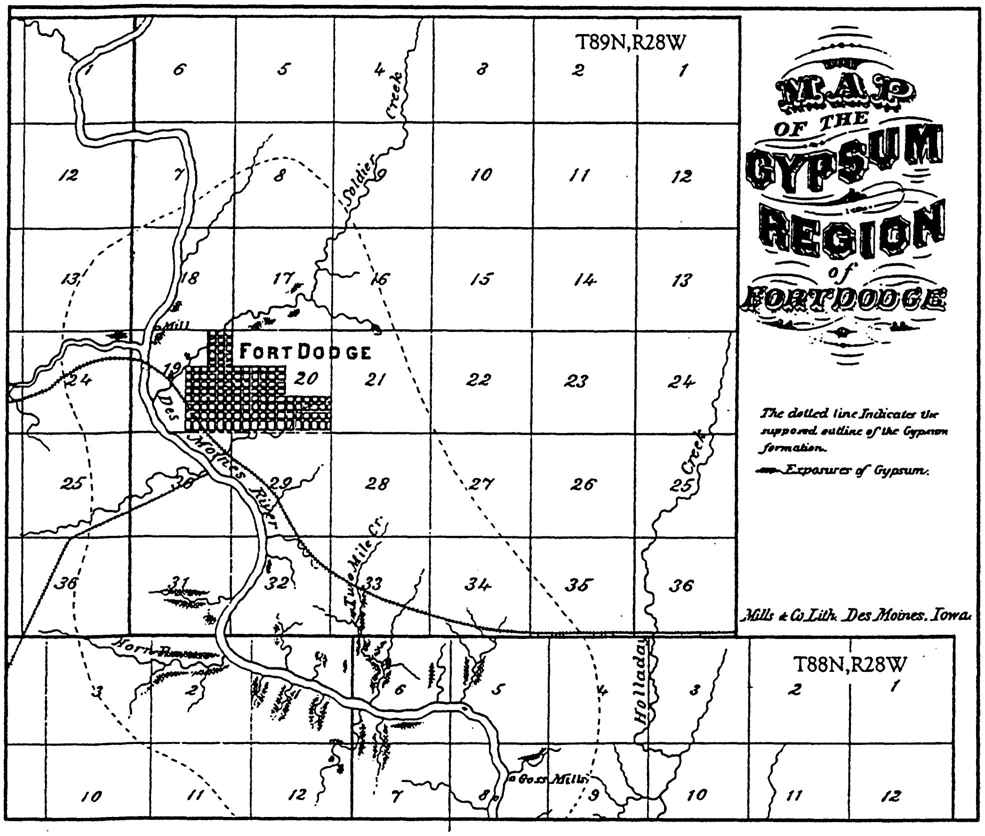

Figure 2. Portion of a map of the Fort Dodge area as it appeared in 1870 (from White, 1870, facing p. 292).

PLASTER INDUSTRY

The first calcining mill in the United States began in 1835 on Staten Island in New Brighton, New York. By the late 1860's investors saw the potential of the Fort Dodge gypsum for plaster of Paris, and three wealthy local businessmen formed a partnership, and in May, 1872, started work on the first commercial gypsum mill, the Fort Dodge Plaster Mills. It was located in sec 33, T89N, R28W overlooking Gypsum Hollow and began operations in October 1872. Later in 1873, the name of the plant was changed to the Cardiff Mills (Roddenborn 1972), presumably from the fact that the block used for the Cardiff Giant came from the vicinity. This mill has the distinction of being the first gypsum calcining plant west of the Mississippi River. In 1881 the original partnership was dissolved and a new one, the Iowa Plaster Company, was formed. This company, and later ones usually owned quarries or underground mines to supply gypsum to their calcining plants. In the following years a complex series of new companies and mergers formed, and by 1972 a total of at least 30 different business entities related to gypsum mining had existed in the Fort Dodge area during the first one hundred years (Rodenborn 1972).

Because of easy access to gypsum all of the initial gypsum material was taken from quarries, most of which were located near Gypsum Creek or along the Des Moines River. Later, underground mines were often used because most of the gypsum occurred away from river valleys. In these areas

Figure 3. Photograph underground in the mine of the Fort Dodge Plaster Company c.a. 1900 (from Rodenborn, 1971, p. 69.).

gypsum was covered by 20 meters or more of glacial till which at the time was considered too deep for stripping. Apparently the cost of underground mining was competitive with stripping at this time. According to Rodenborn (1972), the first underground mine was opened in 1896 by the Cardiff Gypsum Plaster Company, the fifth milling company in the area. The Fort Dodge Plaster Company opened the Crawford Mine in 1893 (Fig. 3), and the Iowa Hard Plaster Company started an underground mine in 1906. Certain-Teed Corporation, which began operations in Fort Dodge in 1923, operated an underground mine until 1945 when three miners died in a severe underground accident. This led to permanent closing of the mine. In these mines the room and pillar method was employed after sinking a shaft to within a few feet of the gypsum base. The underlying material was left as mine floor and enough gypsum was left in the ceiling for roof support. After the mine had nearly exhausted all the rock on company property, the floor, walls, pillars, and ceiling were the removed, as far as possible. The unsupported roof of these mines was highly unstable and eventually most of the mines collapsed, with the location of the mines marked by sinkholes. One such collapse occurred near the entrance to the USG Corporation wallboard plant, and several other sinkholes will be visible during the field trip.

After 1900, large out-of-state corporations became interested in the Fort Dodge gypsum. The most successful of these companies was the United States Gypsum Company, later to become a subsidiary of USG Corporation, which was incorporated in New Jersey in 1901 with the purpose of merging or otherwise consolidating the gypsum plaster industry. Several local companies merged with it in 1902 and subsequent years. In 1902 USG acquired the plant and land of a local company, the Mineral City Plaster Company, and commenced operations. In September 1907 the Sackett Plaster Board Company of New York began mining and producing plaster and plaster board near the city. The Sackett plaster board was the first plaster board manufactured in Fort Dodge, and resembled modern wallboard but contained six cores of gypsum separated by seven paper layers compared to the single core and inner and outer paper layers of modern board. After being pressed between rollers, the Sackett board was 5/16" thick. It was used in place of wood lath as a base for application of conventional gypsum plaster, and it differs from modern wallboard which eliminates plastering. Sackett was a relatively large company with plants in Grand Rapids, Michigan, and Rochester, New York. It was purchased by USG in 1913. Prior to its purchase, the USG had supplied calcined gypsum to the Sackett plaster board plant in Fort Dodge (Rodenborn 1972).

By 1923 six companies operated mills in the

Table 1. Production of Iowa Gypsum*

Date	Iowa Production, 10^3 metric tons	Value 10^3 \$	Value, in 1990 \$***	% of US Production
1905	179	344	4,813	18
1910	323	436	5,668	15
1915	496	486	4,433	22
1920	572	2,236	13,818	20
1925	800	2,174**	15,348	14
1930	322	437	3,240	13
1934	180	276	2,558	12
1940	487	587	5,183	13
1950	982	2,507	12,011	12
1960	1,283	5,428	22,743	13
1970	1,136	4,223	13,471	9
1980	1,486	13,136	19,704	12
1990	2,192	14,243	14,243	13

* Data from Minerals Yearbook, for each year.

** Values prior to 1935 in Mineral Yearbooks included both calcined and uncalcined gypsum , whereas those after that date are for crude gypsum before calcining. An attempt was made to correct for this change by assuming all produced gypsum had the value of uncalcined ground agricultural gypsum, but this approach may not be very accurate.

*** Corrections for inflation used the composite consumer price index data from Derks 1994. Inflation for commodities will be slightly different than given by the CPI.

area. Listed in order in which they began operations,. they were The Cardiff Gypsum Plaster Company, United States Gypsum Company, Universal Gypsum Company, American Cement Plaster Company, Wasem Plaster Company, and the Iowana Plaster Company (Wilder 1923). Of these companies, only United States Gypsum is still in operation.

By 1972, only four companies were operating quarries and mills (Rodenborn, 1972). They were USG, National Gypsum, Georgia Pacific, and Celotex. USG Corporation, with its main office in Chicago, is by far the largest operator in Fort Dodge. Georgia Pacific Corporation was incorporated in Georgia in 1927 and became involved in plaster production when it merged with Bestwall Gypsum Company in 1965. Bestwall had previously bought all the gypsum operations of Certain-Teed Corporation in 1956. Celotex was incorporated in Delaware in 1935 after reorganization of the company which first began in Louisiana in 1920. It began gypsum operations after buying part of the American Gypsum Company of Ohio, and in 1950 purchased the Wasem Plaster Company in Fort Dodge. Celotex, in turn, was purchased by Jim Walter Corp., a private company based in Florida. National Gypsum Company, incorporated in Delaware in 1924, and began Fort Dodge operations in 1935 when it purchased the assets of another company. The current mill and plaster board plant was built in 1956. National, in turn, was purchased in September 1995 by Delcor, Inc., an investment concern controlled by a former chairman of the company. In 1995 the same four companies as in 1972 were still located in Fort Dodge, although under different ownership (with the exception of USG).

GYPSUM PRODUCTION

The gypsum industry in Fort Dodge is an excellent example of current trends in gypsum production in the United States. During the early days of production, numerous small local companies started, with later consolidation taking place as more successful companies merged or purchased less successful or wealthy ones. At the current time, a few companies are predominant and most are involved in both mining gypsum and producing gypsum products. According to Stone and Jakacki (1989) there are 10 major companies in the United States that produce wallboard and plaster systems, but 5 of these mined 80% of the total crude gypsum and 6 produced over 85% of calcined products (McKetta 1987). Raw material is generally obtained from captive mines/quarries closely associated with calcining plants, but plants on the east coast often import gypsum from Canada and those of the west coast from Mexico. In 1986, USG operated 12 mines and 22 calcining plants; National gypsum, 7 mines and 18 plants; Georgia-Pacific, 6 mines and 9 plants; Celotex, 3 mines and 4 plants.

Fort Dodge gypsum meets all requirements for an ideal source. It is exceptionally pure, is located close to markets including Minneapolis, Omaha, and Kansas City, and can be mined by inexpensive stripping. Consequently it has been a significant source in the United States since 1900. Table 1 presents data on production from 1905 through 1990. In all years after about 1900 Iowa was either second or third in U. S. gypsum production, and most of that gypsum came from the Fort Dodge area. Generally Iowa gypsum constituted about 12% - 13% of U. S. production. Although the nominal values of gypsum produced in Iowa were highest in 1980 and 1990 (Table 1), when corrected for inflation 1960 was the best year. The 1990 inflation-correction production value of crude gypsum was less than that in 1925.

The future of gypsum mining in Iowa is probably good because of the abundance of subsurface Mississippian gypsum in southern Iowa, although the cost of locating and mining this gypsum must be evaluated. Gypsum produced during flue gas desulfurization may create severe competition in the future. Unless new deposits are located, gypsum mining in Fort Dodge is limited to less than about 30 years for USG and probably even less for the other three companies that have less reserves.

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MODERN AND ANCIENT USES OF GYPSUM

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INTRODUCTION

A gypsum wallboard manufacturing plant will be visited at Stop 8 on the trip. The following discussion is designed to outline processes involved in wallboard manufacture for those with little prior knowledge of the subject, and to aquaint geologists with the general economic value of gypsum to modern societies. A few historically-interesting ancient uses of gypsum are also discussed.

EARLY SCIENTIFIC STUDIES

Much practical understanding of the use of gypsum for construction and other purposes was achieved early in the history of civilization as discussed in the second section of this paper, but very little scientific knowledge was achieved until the middle 16th century. In his first scientific publication, Lavoisier (1768) determined gypsum solubility, the presence of water of crystallization, and confirmed that heating gypsum to very high temperatures prevents plaster hardening (Wilder, 1923). In 1883, Le Chatelier published a notable research study of gypsum and plaster from Paris. When heating gypsum in an oil bath and observing two temperature halts at ≈ 128°C and at ≈ 165°C during heating of gypsum, he concluded that gypsum dehydrated in two stages, with most of its water lost at the lower temperature and the remainder at the higher temperature. These values compare well with those obtained by modern methods (Figure 1 shows dehydration temperatures at 133.7°C and 161.0°C). He also accurately determined the amount of water in the hemihydrate. Since then there have been an immense number of studies of all aspects of gypsum, including its crystallography, dehydration behavior, geology, product technologies, and current and past uses. A brief synopsis of gypsum and other related phases is given in Table I.

PART I. GYPSUM USE TODAY

Introduction

Today, the largest use of gypsum is based on its property of giving up, or taking on, water of crystallization (Fig. 1). Over 70% of the gypsum mined in the United States is to manufacture plaster of Paris manufacture, with most of this material used in wallboard (drywall) manufacture. Another 18% of mined gypsum is used as a retarder to slow the setting of portland cement (concrete), with 4% to 6% by weight of gypsum being mixed with the cement to provide sufficient time for working the concrete. Five to six percent of mined gypsum is powdered and used as a soil conditioner, a minor amount is used as an inert filler in pharmaceuticals and foods (Appleyard, 1983b), and a small quantity of alabaster is carved into ornaments and sculptures. In Europe where masonry construction is more common than in the United States, a relatively large portion of gypsum is used in hand and machine applied wall coatings or plasters.

Plaster of Paris

The material used for plaster is called plaster of Paris (the name being derived from the occurrence of large gypsum deposits in the Montmartre district of Paris, France), or gypsum plaster if there is any possibility of confusing it with other types of plaster. Rock gypsum is ground and heated to relatively low temperatures, between about 110°C

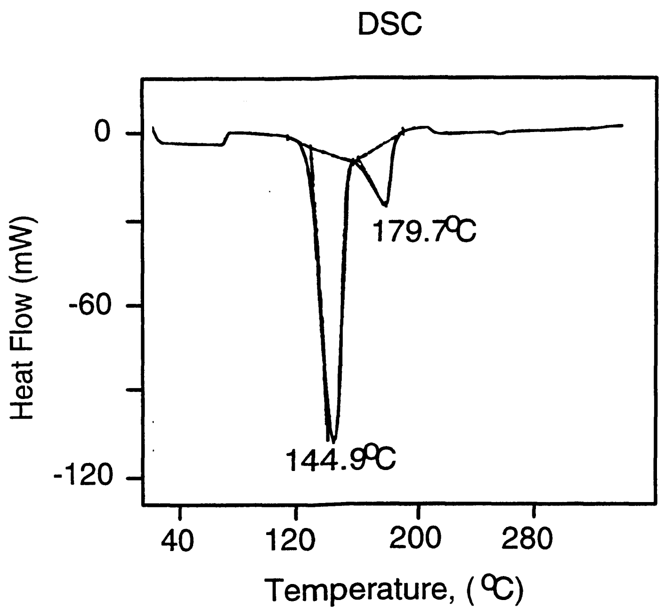

Figure 1. Differential scanning calorimeter (DSC) trace of gypsum. The sample weighed 18.7 mg, and was heated 5°C/min in nitrogen gas using a DuPont 1090 DSC, and Interactive DSC program, v. 3.0. The first dehydration (with 1 1/2 water molecules lost) started at 133.7°C and the second (with the remaining 1/2 water molecules lost) at 161.0°C. Both values are comparable to those obtained by LeChatelier (1883) who used different experimental conditions to first determine the dehydration temperatures of gypsum.

and 165°C where gypsum loses one and one-half of its two water of hydration molecules and forms the mineral, bassanite, also referred to as hemihydrate or more precisely β-hemihydrate (Table 1). When water is added to the hemihydrate, it rapidly dissolves and elongate gypsum crystals slowly form (Montgomery, 1987). Hardness of the set plaster results from the interlocking character of the newly formed needle-shaped gypsum crystals. The initially-set plaster contains an excess of water and is damp. Evaporation of water from the damp material, however, has nothing to do with setting of gypsum plaster.

Wallboard

Plaster wallboard or *drywall* was invented in the United States about 1890 and became widely used in the construction industry after WWII. It has almost entirely taken the place of applied plaster in construction because of its versatility, fire-retarding properties, and rapid installation with greatly reduced the labor costs. When wallboard is exposed to fire or extreme heat, the gypum loses water and changes back to hemihydrate, releasing steam that provides a natural fire damper. Many building codes recognize the value of gypsum wallboard and require its use between potential fire hazards and apartments or other living spaces.

The modern industrial mining and manufacture of gypsum products follows the flow-chart sequence shown in Figure 2. The basic wallboard processing methods involve (1) rock preparation, (2) calcining or heating to cause partial dehydration, and (3) processing into wallboard (Appleyard, 1983a). Rock preparation chiefly involves crushing, grinding and sieving, and drying to remove excess water. Beneficiation methods may be required at some locations because of excess contamination by quartz, limestone, or anhydrite. To keep costs low, however, beneficiation is avoided unless absolutely necessary for very high-grade products. Most gypsum such as that at Fort Dodge does not require beneficiation.

Calcining is the industrial term for the dehydration of gypsum to hemihydrate or to other partially or completely dehydrated calcium sulfate phases. It is performed in vessels called kettles, of which there are many designs. Both batch and continuous kettles are used. In a batch operation, ground gypsum, of -100 mesh (<.15 mm), designated as land plaster (any type of ground and uncalcined gypsum is land plaster, regardless of use) is introduced into the top of the kettle, heated and stirred, and the calcined material is dumped by gravity into a holding bin called the hot pit. About 2-3 hours are required from filling to dumping of a batch kettle. The kettle at USG Corporation in Fort Dodge is a continuous type and requires about 1 hour retention time (Hollender, USG Corp., pers. comm.

Table 1. Solid Phases in the System Calcium-Sulfate-Water

Designation	Gypsum	β-Hemihydrate	α-Hemihydrate	Anhydrite III Soluble Anhydrite γ-Anhydrite	Anhydrite II Insol. Anhydrite	Anhydrite I High Temp. Anhyd.
Formula	$CaSO_3 \cdot 2H_2O$	$CaSO_4 \cdot 1/2H_2O$	$CaSO_4 \cdot 1/2H_2O$	$CaSO_4$	$CaSO_4$	$CaSO_4$
Combined H_2O, %	20.92	6.21	6.21	<1	0	0
Molecular Weight	172.17	145.15	145.15	136.14	136.14	136.14
Molecular Volume	74.5	52.8	55.2	52.8	46.4-45.8	
Moh's Hardness	1.5-2.0				3.0-3.5	
Stability	<60°C	metastable	metastable	metastable	60°C-1280°C	>1280°C
Synthesis	<60°C*	heat 45-200°C in dry air	heat >45°C in steam or aqueous sol.	prolonged ≈100°C	900-1280°C	>1280°C
Density, g/c^3	2.31	2.76	2.6-2.64	2.58	2.93-2.97	
Solubility g/100 g solution	0.21	0.67	0.88	hydrates	0.27	
Crystal System	Monoclinic	Rhombohedral*	Rhombohedral	Hexagonal	Orthorhombic	Cubic

Data slightly modified from Wenk and Summerfield (1987) and Wirsching (1985)
* Lager et al. (1984) dispute the rhombohedral character of β-Hemihydrate. They propose a monoclinic space group I2.

1996). Temperatures in the calcining kettle must be closely controlled in order to obtain the proper degree of dehydration. Figure 3 shows a schematic temperature/time curve for the kettle during a batch operation. In the figure, point A is the introduction point of land plaster. Introduction of cold gypsum causes the temperature to drop to about 75°C and then to rise. At about 43°C gypsum begin to dehydrate, and the kettle temperature is kept at 104°C during this first dehydration. The interval between B and C is known as 'first boil' and occurs between 116°-121°C where the gypsum mass appears to boil because of released steam. After boiling ceases, the material consists chiefly of β-hemihydrate together with small amounts of α-hemihydrate, soluble anhydrite, and undehydrated gypsum (Fig. 3). The latter three phases are present because conditions are not precisely the same in different parts of the kettle. This stage is referred to as first settle because the solid phases settle to the bottom of the heating vessel when boiling no longer helps keep them in suspension. The kettle temperature is then increased to 150-166°C at which point the solids are dumped (Point D). The volume of solid material at this point is about 15% less than the original volume. After dumping at point D on Figure 3, the cycle may be started over.

Dumping is omitted if further dehydration is required to produce soluble anhydrite (Anhydrite III). The kettle will continue to heat to point E at ≈ 177°C (Fig. 3) when a second boil occurs until hemihydrate is completely dehydrated. This occurs to point F at which a second settle occurs. Heating is continued to about 204°C (point G) after which Anhydrite III is dumped (Appleyard, 1983a; Wenk and Henkels, 1978).

Wallboard is manufactured by pouring a water slurry of β-hemihydrate (referred to as stucco in the wallboard industry) onto a continuous strip of special paper with turned-up edges forming a broad, shallow, trough. The hemihydrate rapidly reacts with water in the slurry to produce tiny, needle-shaped gypsum crystals, and these crystals grow and interlock with each other to form a rigid sheet. The solidifying gypsum layer is covered with another paper layer, and rollers and other guides insure the proper width and thickness of the paper/plaster sandwich. Bonding of the newly-formed gypsum layer to the top and bottom paper occurs because gypsum crystals penetrate into and interlock with the porous paper fibers (Appleyard, 1983a). The soldified wallboard is then heated to remove excess moisture but without dehydrating

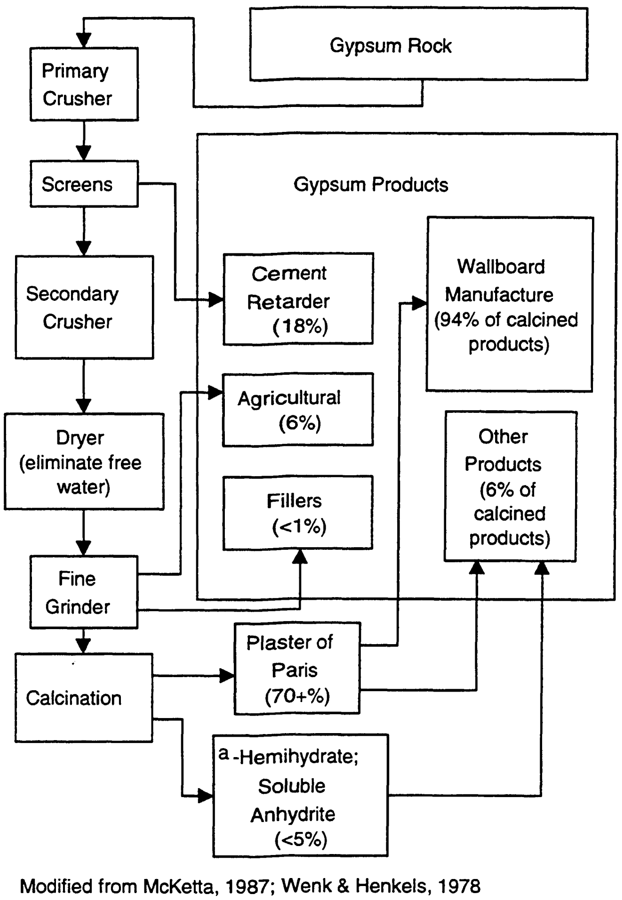

Figure 2. Flow Diagram for gypsum production and use.

the newly formed gypsum. Finally it is cut into proper lengths and stacked for delivery.

One of the early problems with wallboard manufacture was that plaster set too slowly for efficient industrial production. This problem was solved by the addition of certain chemicals that accelerate setting. Accelerators such as powdered gypsum or potassium sulfate when added to the initial stucco/water slurry reduce setting time from ≈ 30 minutes to ≈ 5 minutes. Other additives such as foaming agents are usually added to increase operational efficiency by reducing the amount of water required to produce a rapidly flowing slurry. The time required to manufacture a single piece of wallboard, from initial pouring of the stucco slurry to final drying generally is less than about 10 minutes. Special types of wallboard may be manufactured using a wide variety of additives and/or coatings.

As in so many industries wallboard has become a significant problem in groundwater contamination. Nearly 30 million tons of wallboard are manufactured in North America each year, but about 3% to 5% of wallboard is wasted during construction because trimming and breakage of sheets. According to Musick (1992) about one pound of wallboard scrap will be created for each square foot of house floor area, so that about one ton of waste wallboard is generated for each home built. This large volume of waste wallboard is buried in landfills, and plays an important part in the tremendous volume of waste material that is rapidly exhausting the landfill capacity in highly urbanized regions. Although the gypsum wallboard material itself is harmless, after burial the sulfate may be reduced to sulfide gas which is both noxious and toxic. Decay of wallboard paper and binders also may accelerate the reduction of sulfate to sulfide. The problem has not passed unnoticed by municipalities. For example, as a result of major groundwater contamination problems in British Columbia, in 1984, Vancouver banned all waste gypsum wallboard from municipal landfills. This ban has stimulated efforts to recycle waste wallboard into new wallboard manufacture, and some observers believe that recycled gypsum will soon become a signficant part of new wallboard.

Other Dehydrated Gypsum Products

In the late 19th and early 20th century, calcined gypsum was largely used in plasterwork and related uses (Wilder, 1923) that were similar to its uses in antiquity. Extensive practical experimentation, led to greater diversity of use and materials. One was the development of denser plaster products produced by calcining gypsum to much higher temperatures than required for producing plaster of Paris. Normal gypsum plaster has up to 45% porosity. This relatively low density material is ideal for wallboard because the relatively lightweight sheets can be handled more easily than

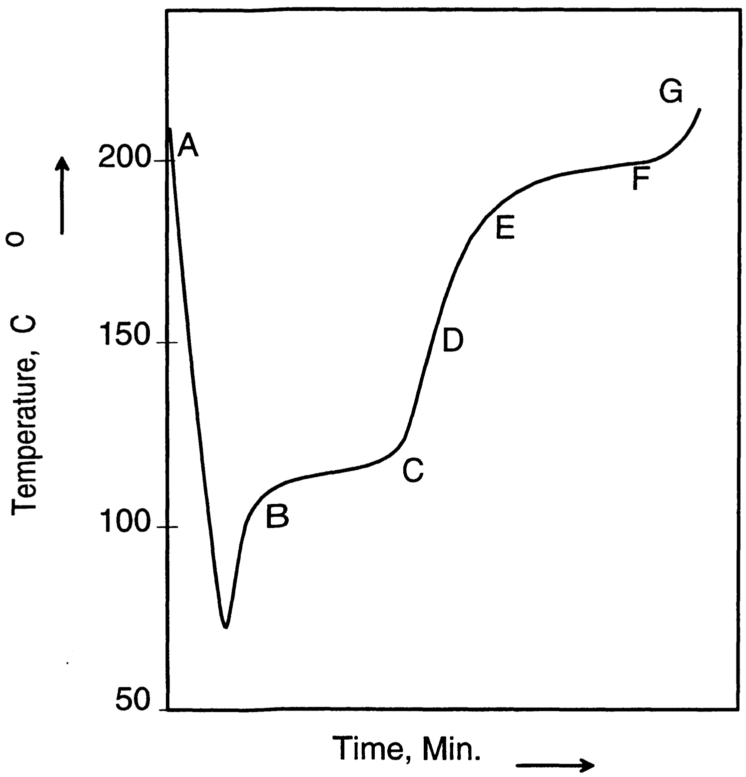

Figure 3. Schematic temperature/time curve for batch kettle calcining of gypsum. **A** marks the introduction of ground gypsum (stucco) into the kettle, and the kettle temperature drops because of introduction of cold gypsum. The temperature then rises to **B** at which point boiling occurs during gypsum dehydration, and the kettle temperature is constant because of the endothermic reaction. At point **C**, 1 1/2 water molecules/molecular weight gypsum have been lost and hemihydrate has formed, and the temperature again rises. At point **D** the hemihydrate is removed from the kettle. If further dehydration is required to produce anhydrous $CaSO_4$, the material remains in the kettle. The second boil occurs at **E**, is finished by **F**, and the anhydrite is removed at **G**. From Wenk and Henkels (1978).

those composed of heavier, denser material. Low density material also reduces the cost of raw materials. However, low density gypsum plaster is not suitable for high wear area such flooring because it abrades easily. It was discovered that high temperature calcining, between about 900°C and 1400°C, produces a material that forms very dense gypsum plaster. The high-calcined material is known as hydraulic gypsum, or Estrich gypsum in Germany (Appleyard, 1983a). High temperatures produce complete dehydration of gypsum with the formation of insoluble anhydrite (Anhydrite II). Some of the sulfur is also expelled so that the product contains both insoluble anhydrite and quicklime, CaO. Addition of water to this calcined material causes slow rehydration to gypsum with setting taking several days. Further hardening develops over several weeks as the lime slowly reacts with air to form calcite crystals. $Ca(OH)_2$ which forms from CaO on addition of water to the dry material acts as an accelerator to promote hydration to gypsum (Wirsching, 1985; Kawiak, 1991), although other accelerators such as potassium sulfate, aluminum sulfate, or borax may also be added to increase hydration rates. Without an accelerator, hydration of Anhydrite II is extremely slow and will take many years in a damp environment to develop. Insoluble anhydrite was found persisting in mortar of a 12th century church in Poland. Change from insoluble anhydrite to gypsum does not involve an intermediate hemihydrate stage (Wirsching, 1985). The product requires tamping of the almost hardened paste so that there is a significant reduction of intial porosity. Because setting does not involve the growth of needle-like crystals, tamping does not damage further setting as it would for normal gypsum plaster. Tamping facilitates development of hard setting by bringing newly-formed gypsum crystals into close contact with each other so that their continued growth results in an interlocking texture. The texture of hardened hydraulic gypsum is much different than that of traditional low-temperature calcined gypsum plaster, in that hydraulic gypsum is composed of almost equant gypsum/calcite crystals with an interlocking texture compared to the porous intergrown elongate crystals of set plaster of Paris. Unlike set plaster of Paris, hardened hydraulic gypsum is relatively resistant to damage by short-term exposure to water. Hydraulic plaster is not widely used in the United States, but normal β-hemihydrate plaster is used as flooring in commercial building in the United States as long as it is covered with carpet, tile, or other material. Hydraulic plaster was widely and successfully used for flooring and other purposes in Germany during the early 20th century, and is still used there for a variety of purposes. It is commonly used in Europe for gallery and roof supports in subsurface mines where a relatively hard and dense material is needed (Wirsching, 1985).

Keene's cement is a closely related commercial product sometimes used for molding statues and similar items. It is produced by heating gypsum to ≈ 900°C and combining it with accelerators which induce rapid hardening after addition of water. The hardened material will take a high polish and has a relatively high density that resembles marble. The resemblance to natural marble often is enhanced by additions of pigments.

α-Hemihydrate is occasionally used for special plasters because it has lower water demand for mixing into a slurry, so that less excess heat is required to dry the hardened product. It sets more slowly and produces a denser product than that from β-Hemihydrate. It is more expensive to produce, and consequently, is not used for standard wallboard (Wenk and Summerfield, 1987).

Gypsum in Agriculture

Although the major uses of gypsum are in construction, a large amount of gypsum is also used for soil conditioning on farms and ranches. Gypsum is a key ingredient of proper maintenance of soil fertility. It increases stability of soil organic matter, produces more rapid seed emergence, improves water penetration, and helps in the reclamation of alkaline saline sodium-rich soils by replacing Na with Ca on the exchange sites of soil clay minerals (Davis, 1994). It provides sulfur to plants and aids fertilizer utilization and production of legumes. Wallace (1994) listed 33 agricultural benefits of gypsum application for specific types of soils.

Gypsum applications on certain soils may also help reduce global warming. Although most of the current attention on global warming focuses on carbon dioxide, methane is also an effective green house gas. Calculations indicate it may have been responsible for about 17% of greenhouse warming in the 1980's (Lelieveld et al., 1993). Experiments on Philippine rice paddy soils which emit large quantities of CH_4 found that 6.6 tons/hectare of ground gypsum reduced methane emission by 55-70%. (Denier van der Gon and Neue, 1994). It was concluded that methane reduction was due to inhibition of methanogenesis by sulfate reducing bacteria.

Other Uses

Another use of gypsum is in the manufacture of molds and casts. Molding and casting plaster is similar to wallboard plaster, but requires much greater production control to insure high purity, close tolerance for its expansion/shrinkage properties, and very rapid setting. The advantage of plaster of Paris for molding and casting is that it expands during setting and facilitates complete filling of molds with preservation of detail without shrinkage cracks. During the setting of plaster of Paris, the hemihydrate becomes rehydrated to gypsum which has a crystal volume that is ≈ 7% less than the original hemihydrate plus the water required (Paffenbarger and Rupp, 1979). On the basis of these volume comparisons, a logical conclusion would be that plaster should shrink during setting. The unexpected expansion during setting results because the growing needle-like gypsum crystals push away from each other and create voids between the growing crystals. The void space in hardened plaster of Paris typically is as high as 45% of the total volume, and the linear volume increase is about 0.5% (Paffenbarger and Rupp, 1979) and gypsum plaster is typically much less dense than solid gypsum.

A wide variety of special plasters are also produced by mixing calcined gypsum with various additives which increase the strength or change the properties of the material upon rehydration. Included in these special plaster are those used in the oil and gas industry as a cementing material to seal porous rock layers encountered during drilling.

PART II. ANCIENT USES OF GYPSUM

Introduction

Although pre-industrial times are considered as lacking technological inovations, practical understanding of many modern aspects of gypsum use were developed hundreds to thousands of years ago. Other uses in antiquity have no modern analogue because of the introduction of new materials that rendered gypsum use obsolete.

Window Panes

Selenite was given a variety of names by early naturalists. One was Lapis specularis which described its use. Lapis is Latin for stone, and specularium refers to a window with a transparent cover, so that Lapis specularis is any type of stone used as a window pane. From very ancient times into the 15th and 16th centuries, transparent selenite was used for windows. Selenite crystals are easily separated into thin plates along perfect b(010) cleavage planes to produce thin and very transparent window covers. Miocene selenite of Cyprus was especially sought because of its transparency and the large size of single crystals (Bromehead, 1943). The precise locality of the best Cyprus selenite is unknown, probably because the best localities have disappeared as a result of early mining activities. In our own visits to gypsum quarries and outcrops in Cyprus in 1992, we never observed very large cleaveage sheets. The largest and best crystals were secondary fillings in thin fractures cutting across rock gypsum strata. Some of the material was exceedingly clear, although with a slight tan color. Nearly perfect cleavage sheets up to about 8 cm to 10 cm on a side could be obtained from a quarry near the southern town of Tokhni.

During the Middle Ages another name for selenite was Marienglas or Mary's glass because of its widespread use in Christian churches of Europe (Bromehead, 1943). Use of the term Lapis specularis has produced much confusion. Most mineral collectors are familiar with the use of muscovite mica (muscovy glass) for window material in the Middle Ages, but Broomehead (1943) argues convincingly from geological evidence that many of the locations listed in ancient writings as sources of mica for windows are known to contain many selenite deposits but few, if any, large mica crystals. Consequently, many ancient authors probably often misidentified window covering minerals, and selenite rather than muscovite was used for many of the windows described in their books. Because the hardness of the two minerals is similar (gypsum has a hardness of 2 whereas muscovite hardness is 2 1/2 on the cleavage surface), and both have a perfect cleavage, it is easy to misidentify them. The most obvious difference in the two minerals is in the flexibility of cleavage sheets. Gypsum cleavage sheets are not flexible; if the sheets are bent, they remain bent and may easily break, whereas mica sheets are flexible and will regain their original shape after bending. Mica, and never selenite, however, was used for oven windows because selenite will dehydrate and crumble during heating.

The widespread use of selenite cleavage plates for windows in earlier times has been proposed as the reason for diamond-shaped panes of glass which are common in both ancient and modern churches and in other decorative settings (Bromehead, 1943). In addition to a perfect b(010) cleavage, selenite also has two other cleavages along a(100) and $n(\bar{1}11)$ which produce a diamond-shaped cleavage plate similar to diamond-shaped glass ornamental window panes. A early English writer, John Woodward (1729, v. 1, p. 67) substantiated the relationship between selenite cleavage rhombs and diamond-shaped glass panes by writing about selenite: "The Plates of this Body were anciently employ'd for the Lights of Windows: and when Glass came afterwards to be more commonly made, and generally to obtain, they cut it into Rhomboidal Panes in Imitation of these Plates".

Building Stone

In ancient time, quarried gypsum rock, like limestone. was used in many buildings. Solubility and hardness differences dictate the uses of the two rocks. Gypsum solubility is about 0.24 grams/100 cc of cold water whereas that of limestone (calcite) is 0.0014 g/cc (Weast, 1979); thus rock gypsum is about 200 times more soluble than limestone. The relatively high solubility of gypsum renders it inappropriate for building stone in climates with high precipitation, but does not present a problem in dry climates. In Cyprus, for example, rock gypsum slabs, locally referred to as marmara were commonly used as roof and floor covering in homes and are still used to a lesser extent today (Fig. 4). The relatively high solubility of gypsum might seem to render it inappropriate for roofing material in the Mediterranean area, but such is not the case. Although dissolution of gypsum roof slabs will occur, replacement of the slabs when needed is practical because of its low cost and easy availability, and the small amount of precipitation which prevents rapid dissolution. The low Mohs hardness of marmara floor slabs apparently does not present a wear problem even in museums open to the public where they encounter heavy traffic of hard-soled shoes and boots.

In the later 1800's, few houses in Fort Dodge, Iowa, were built with gypsum wall block. A photograph of one was published by Wilder (1923) and is reproduced in Figure 5. Exterior use proved unsatisfactory and apparently all of the gypsum houses have been destroyed, because in 1996 we were unable to locate any in the older parts of the city, and residents of the city maintain that the last such house was destroyed in the 1960's. Several older houses in the city, however, still have gypsum block basement walls.

Plaster and Mortar

The word plaster comes from the Greek word emplastron which means to 'daub on' (Diehl, 1965). In both modern and ancient usage, a plaster is any type of material which will form a paste with water and which will adhere to a surface

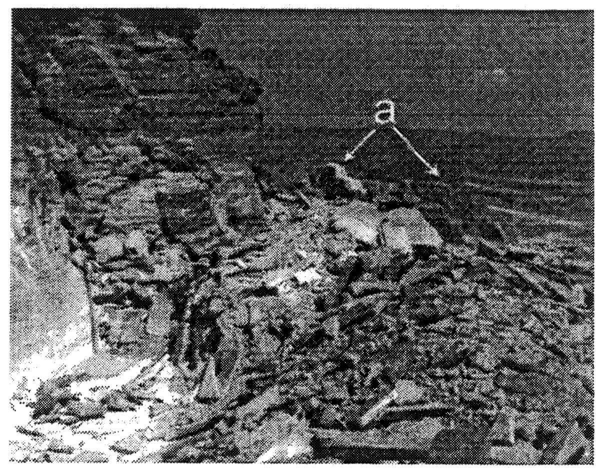

Figure 4. Small cottage-industry gypsum quarry, Cyprus. It is located north-east of Paphos, near the town of Letimbou. The size of the cut marmara gypsum (**a**) indicates that it probably will be used for floor tiles.

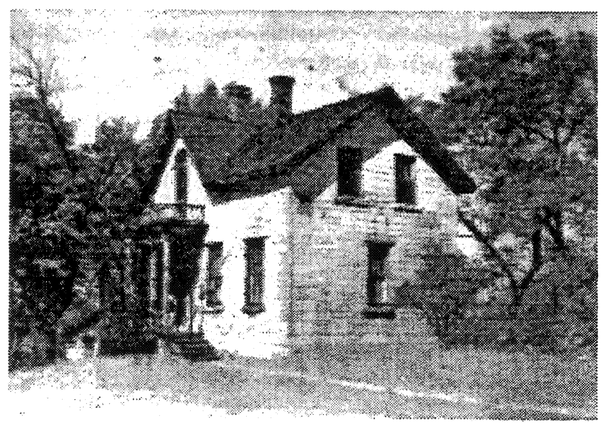

Figure 5. House in Fort Dodge constructed of gypsum blocks. All such houses have either been destroyed or the gypsum blocks have been covered by siding. No information is available about when the house was built. The image was scanned and computer enhanced from Wilder (1923, p. 201).

on which it is applied.

In ancient times, excluding the earliest plaster composed of clay and water, two major types of rock material, limestone and gypsum, were used to make plaster. Both types are still widely used today, 14,000 or more years after their first use in prehistory.

Lime Plaster

In order to clarify the distinction between the two major types of plaster used in antiquity, lime plaster will be briefly discussed. Calcining relatively pure limestone to a high temperature of 800° - 900°C causes decomposition of the calcite with carbon dioxide, CO_2, being lost. The material remaining after calcining is calcium oxide, CaO, or quicklime. On the addition of water to quicklime, an exothermic reaction occurs as the quicklime is rapidly converted to a mixture of calcium hydroxide, $Ca(OH)_2$, slaked lime (often the term *lime* is used for limestone, quicklime, and/or slaked lime) and minor amounts of calcite from the reaction of CaO with atmospheric CO_2). The material is then dried. Addition of a small amount of water to dry slaked lime creates a paste which is ideal for plaster work because it sets slowly and gives sufficient time for working. After the plaster is applied, the material becomes hard by drying out and later by slow uptake of carbon dioxide from the air to form interlocking crystals of calcite. Probably lime plaster post-dates gypsum plaster because its manufacture requires much higher temperatures, but lime plaster was used very early.

Stucco

Some authorities make a distinction between plaster and stucco, but the distinctions are not clearly defined and the two terms apparently often were used interchangeably in describing early work, especially that used for exteriors. According to Lander (1986), the term stucco originated in Italian Renaissance times, and was used for a mixture of lime (= slaked lime, $Ca(OH)_2$), and powdered marble, whereas plaster (= lime plaster) consisted of lime and sand, reinforced by animal hair. According to Beard (1983), however, stucco was composed of gypsum, lime, and marble dust (Sprengel, 1772, quoted by Beard, 1983). In contrast, stucco for exterior plastering in the United States construction industry is usually made from Portland cement mixed with hydrated (slaked) lime. Portland cement was invented in 1824 and is the basic material for modern concrete and mortar. It apparently was never used in ancient times.

Gypsum Plaster

The knowledge of plaster of Paris extends far back into antiquity and existed long before written records were kept. The relatively low temperature at which plaster of Paris is produced probably led to its discovery when rock gypsum was accidently introduced near a camp fire after which it was later noticed that water used to put the fire out had produced a lump of newly hardened material. Because of low degree of technology involved, archeologists are convinced that gypsum plaster most likely was independently discovered many times in the past. In pre-modern construction before the advent of wallboard in the late 1900's, plaster of Paris was used for two major purposes, plastering of surfaces and for decorative and ornamental castings. It was also used for interior mortar and for exterior mortar in dry climates. Detailed studies of the mineralogy and textures of floor cements, mortar, and artifacts from the Near East documents that lime plaster can be traced back to about 12,000 BC. Because both limestone and rock gypsum typically occur in the Near East, archeologists assume that both types of plaster were used at that time (Goudin and Kingery 1975). Probably gypsum plaster was used first because it is so much easier to manufacture, so the technology of gypsum plaster is almost certainly older than 12,000 BC. Gypsum plaster was widely used in parts of Syria and the Levant (eastern coastal areas of the Mediterranean Ocean), but has not be found at early sites in Anatolia or Iraq. Rollefson (1990) concludes that the earliest known gypsum plaster was commonly used in the grasslands and steppes of northern and eastern Syria, whereas lime plaster use was restricted to the hills and valleys of the Mediterranean vegation zone south of Tripoli and west of Damascus. Archeological studies of the Near East noted that the two types of plaster are never found together in the same region; lime plaster was exclusively used in many areas, and gypsum in other areas (Kingery et al., 1988). These authors concluded that the lack of overlapping plaster types is evidence for two separate cultures with little technological transfer between them. Another reason may be the lack of abundant gypsum or limestone deposits in specific areas. Presumably raw materials must have been obtainable near the sites where the plaster was used.

Gypsum was widely used as plaster and as mortar between building stones in ancient Egypt about 5000 years ago (Appleyard, 1983a). The early Egyptian high-quality plasterwork was exclusively of gypsum plaster (Lloyd, 1954; Lucas and Harris, 1962). Later, in the reign of Ptolemy I (323-285 B.C.), the Egyptians apparently first learned to use lime plaster even though it had been used much earlier in other areas of the eastern Mediterranean. The Pyramids of Egypt, including the often visited Pyramids at Gizeh near Cairo, contain gypsum interior plasterwork and mortar executed about 4000 years ago, and the plaster is still in good condition where it hasn't been vandalized. Gypsum plaster was used as a floor covering and examples made about 3500 years ago occur at Tel-el-Amarna in the principal room of the harem of King Amenhotep IV (Millar, 1929). Plaster was also used to cover limestone surfaces preparatory to painting by making the surfaces smoother and less porous (Beard, 1983), and in this context was widely used in the ancient world. Gypsum plaster was also used in Greece, and details of Grecian production of gypsum plaster by heating gypsum was given by Theophrastus (c. 370 - 287 BC) in his work *Concerning Stones* (Adams, 1938).

During Renaissance (1300-1600 AD) and later times in Europe, plaster of Paris became widely used in construction, either in the pure state or combined with other materials such as lime. It was used both for plasterwork and as molding/casting material for decorations. Although probably used earlier, apparently the first record of gypsum plaster manufacture in England was during the reign of James II, 1633-1701 (McKetta 1987). During those times a complex variety of uses developed, and one of the major problems which had previously involved the use of plaster of Paris was solved. After water has been added to plaster of Paris, setting normally begins to occur within a few minutes with complete set occurring within about 30 minutes. After hardening commences, the material cannot be applied as plaster because agitation and reworking prevents further hardening by breaking the rapidly growing tiny gypsum crystals whose interlocking growth is responsible for setting. Rapid set requires rapid work and excludes many uses where considerable time is necessary for completion. Setting can be slowed by the addition of substances, now referred to as *retarders*, to the plaster of Paris paste. The exact date when set-retarders were discovered is unknown, but they were widely used in Europe by the 17th century. The most effective retarders were entirely organic substances such as milk, glue, fermented grape-juice, beer, wine, sugar, and plant roots (Beard, 1983). Modern equivalents include a wide variety of synthetic organic substances.

There is evidence that both gypsum plaster and anhydrite plaster were used in construction in medieval Europe. Kawaik (1991) concludes that anhydrite plaster of two different types was used in a twelfth-century church discovered in the 1950's during archaeological excavations under a later church. Although the process of rehydration of the anhydrite during plaster setting together with long-term damp conditions prevailing during centuries of burial has almost entirely rehydrated the anhydrite, remnants still exist in the mortar. Apparently, anhydrite plaster (Estrich plaster or hydraulic gypsum) was used to provide a relatively hard plaster which resisted abrasion. In the church, one type produced at higher calcining temperatures contained more setting accelerator CaO so that setting would have been relatively fast. It was coarse-grained and was used for mortar. The other type contained less CaO, was calcined at lower temperature, and set much slower. It was fine-grained and was used for the engraved floor. Grooves in the decorated floor were filled with normal hemihydrate plaster. If Kawaik (1991) is correct in his assessment, then plaster technology in Europe was considerably advanced by the 12th century.

Molding and Casting Plaster

Examples of molded decorations in Europe are widespread and date back at least to Medieval times. Many 8th Century churches in Italy have intricate decorations made of lime and gypsum plaster. By the 15th century molded, cast, and sculpted decorations were common, and the art of plaster was highly developed as can be seen by the numerous, complex plaster sculptures and decorations in churches and palaces throughout Europe. By the mid 1700's plaster casting was extremely widespread, especially in England where numerous plaster casting shops were opened in order to satisfy the increased demand for casts of sculptures and other works of fine art, and for ornate plaster moldings for homes and other buildings. Original works of art were too expensive and scarce, so that many middle and upper class English turned to cheaper plaster casts. A high level of skill was rapidly developed by artesans, and many types of casts were manufactured and finished to resemble marble, other natural stone, and even bronze. Demand was such that numerous shops copied or plagerized casts manufactured by other plaster shops, an activity that damaged the profits of the original casters. Because of the outrage expressed by many shop ownders, a law, Garrard's Act of 1798 was passed that gave 14 years copyright protection to the original castings. Shops that wanted to obtain legal protection from copying engraved their works with the date of manufacture and the name of the caster. In the 1830's, however, changing tastes and decreased profits led to a gradual decline of these previously numerous specialized plaster shops. As of 1992, only two such shops continued to exist in Britain (Clifford, 1992).

Carved Gypsum

Because gypsum can be carved so easily, it was used extensively in ancient times to create sculptures, utensils, and ornaments. Its softness and compact nature allows very delicate carving even without the use of metal instruments. Alabaster, finely crystalline and massive rock gypsum, was a common medium for carving because it could be obtained in large pieces without bedding planes or other discontinuities which would render it more difficult to carve. The name alabaster itself comes from the Latin Alabastrum which is a type of handleless flask or vase (Bromehead, 1943). Many of the Greek and Roman vases were carved from gypsum alabaster. In Egypt, however, gypsum was only rarely used for vessels, and the alabaster of Egypt is almost entirely calcite, a material now usually called onyx (Lucas and Harris, 1962). Egyptian preferences for vessel material was documented by Lucas and Harris (1962) in their study of vessels from Fayum, Nile Valley, and Aswan. Of the 302 vessels studied from these areas, 52% were carved from calcite (including both onyx and limestone) and only 0.5% were from gypsum. The rest were carved from harder substances such as basalt, diorite, and granite. Some authorities believe that the modern use of the term alabaster for gypsum is historically incorrect and that the first use of the word was for calcite material (Lucas and Harris, 1962).

In Greece and Rome, both calcite and gypsum alabaster were used, but gypsum was the preferred material for ointment boxes because the ancients believed that compared to other material it had an unusual property of coldness which helped to preserve items that might spoil in hot climates. It was also used in ancient Greece for tombs because its coldness was thought to help preserve dead bodies (Magnus, Tr. Wycoff, 1967). This perceived property of coldness may have been due to the fact that alabaster often is translucent and reminiscent of ice in appearance. An alabaster urn from Cyprus is shown in Figure 6 in which the surface of the urn is marked by large twin selenite crystals which are typical of many of the gypsum deposits of the island.

In Assyria, rock gypsum was used for the majority of sculptures (Lloyd, 1954). In England and the continent, it was widely used for carving. Its earliest known use in England was at Tutbury

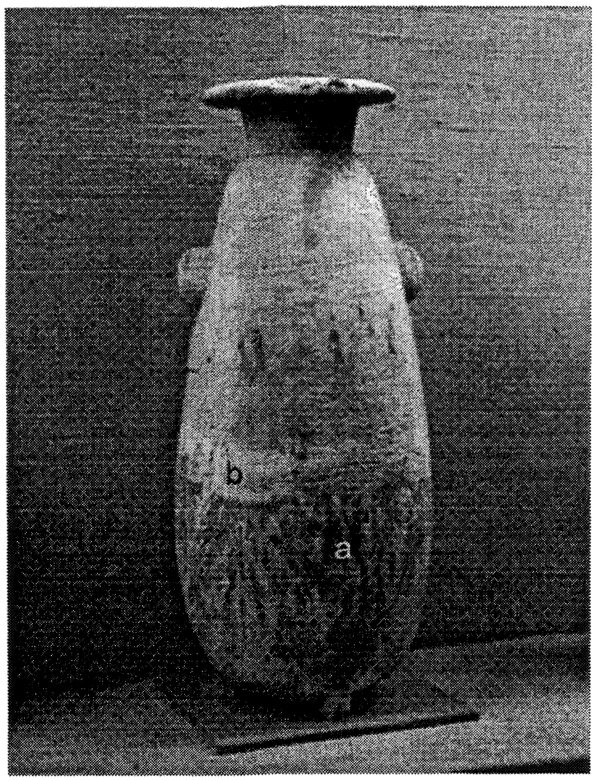

Figure 6. Carved 4th century gypsum vase in the Cyprus Museum, Nicosia. The bottom of the vase showed large bottom-growth elongate gypsum crystals (**a**) in a fine-grained matrix of gypsum and calcite. The crystals are inverted in the vase. Note the bedding planes at **b**.

where it was carved into a molding of a Norman doorway dated about 1160 A. D. Beginning in about the 14th century it was widely used in England for carved effigies and small sculptured scenes for parts of altars. Probably the most famous alabaster effigies were of King Edward II (d 1327) which is located at Gloucester, and of his son John of Eltham (d 1336) at Westminster (Bromehead, 1957). English alabaster was sent to many countries, including Iceland, Spain, and Italy.

Gypsum, being soft, is easily scratched and abraided, and consequently is not an ideal material for jewelry even though some varieties have an attractive appearance. The fibrous variety, satin spar, was used in antiquity as inexpensive ornaments because it has a cat's eye or chatoyancy sheen. Its use as jewely probably was also related to superstitions attached to the mineral (Adams, 1938). Even in the early 20 century it was still used for ornaments with superstituous overtones, as for example, at Niagrara Falls where it was sold as a lucky stone with the claim that the gypsum was obtained from beneath the falls (Kunz, 1913).

An unusual use of carved gypsum was the production of the famous Cardiff Giant in 1868 from gypsum obtained at Fort Dodge (Gallaher, 1921). The block used for the giant came from a location known as Shady Oaks near the junction of Gypsum Creek with the Des Moines River (Mills, 1970). The giant was unearthed at Cardiff, New York, a small town near Syracuse, hence its name. It was also referred to as the Onondaga Giant from Onondaga County, New York. Its finders claimed that the figure was actually a fossilized human, and it was a highly successful hoax for several years. The giant, which measures about 10' 4"in length and weighs 2990 lbs., is currently on display at the Cooperstown Museum in New York, and a replica is located in the Fort Museum of Fort Dodge. More details on the Cardiff Giant story see the road log section of this guidebook, pages 68.

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FORT DODGE FORMATION
FIELD TRIP ROAD LOG

[1]Raymond R. Anderson, [2]Robert D. Cody, and [1]Robert M. McKay
[1]Iowa Department of Natural Resources Geological Survey Bureau
[2]Department of Geological and Atmospheric Sciences, Iowa State University

miles	discussion
0.0	Depart the east end of the parking lot north of the Scheman Building of the Iowa State Center on the Iowa State University campus. Turn left (east) onto Center Drive and turn right onto Elwood Drive. Proceed on Elwood through the underpass on the south edge of Ames and turn left (east) up the ramp onto Highway 30. Proceed on Highway 30 past the Duff Ave. exit and Dayton Ave. exit to EXIT 151B immediately after passing through the underpass. Turn right onto the EXIT 151B ramp to Interstate 35.
5.3	Head north on Interstate 35.

The Des Moines Lobe.
The city of Ames is centrally located near the southern end of the Des Moines Lobe, a lobate accumulation of glacial drift deposited by the last continental ice advance into Iowa. This Wisconsinan ice sheet advanced into Iowa about 17,000 B.P. (years before present) and reached its terminus at what is now the city of Des Moines about 13,500 B.P. (Kemmis, et al., 1981) The glacial ice began to retreat, finally melting back into Minnesota about 11,000 years ago (Bettis, 1988). The topography that we see in the area of the Des Moines lobe today is still very immature. The landscape is very flat, with numerous, poorly drained kettle depressions. This topography is broken by several major curvilinear ridges of sand and gravel, moraines identifying the edge of the retreating ice sheet during periods of stagnation.

miles	discussion
15.5	The hummocky topography in this area identifies the Altamont I Moraine.

The Altamont I Moraine.
The Altamont I Moraine marks a point of stagnation of the retreating glacial ice of the Des Moines Lobe about 13,000 B.P. The stagnation indicated that the melting of the leading edge of the glacier was matching the advance of the ice, being squeezed towards the edge of the ice sheet by its own mass With this stagnation, rock materials incorporated in the glacial ice that normally move towards the edges and melt out were piled in a linear ridge paralleling the ice edge, rather than being spread behind the retreating ice. I-35 follows the western edge of the Altamont I Moraine, so we will be driving in the moraine until we turn west on Highway 20.

miles	discussion
34.0	Exit I-35 and proceed west on Highway 20.
37.6	Crossing the Altamont II Moraine.

The Altamont II Moraine.
The hilly topography for the next couple of miles is the Altamont II Moraine. This moraine, formed a few hundred years after the Altamont I, represents a shorter period of stagnation. The southern end of the moraine was destroyed by a minor readvance of the glacier, and the

surviving remnants of the moraine is restricted to this area.

61.9 Pass exit 124 (County Road P-59), east edge of Fort Dodge.

62.8 Cross the Des Moines River Valley.

Mine spoils.
Unreclaimed spoils on the right are from mines that extracted Pennsylvanian coal and clay and Jurassic gypsum. The coal mines were the Johnson Mine and Irving Slope (both underground operations), the clay pit was the Kalo Brick and Tile Company, and the gypsum was extracted by the National Gypsum company.

The Des Moines River Valley.
The Des Moines River and its tributary the East Fork of the Des Moines River flow down the axis of the Des Moines Lobe. At about the time of the building of Altamont I Moraine, the Des Moines River began carrying huge volumes of melt water. This continued until the glacial ice had advanced out of Iowa, deeply incising the valley into the fresh glacial drift.

65.0 Exit 121 (Highway 169). Exit and head north on Hwy. 169.

66.1 Turn right on gravel road (230th Street) just north of Department of Transportation maintenance garage and continue east..

66.8 Park at the Georgia-Pacific Corporation's quarry operations headquarters.

STOP 1. SUB-GYPSUM CLASTIC SEDIMENTS AT GEORGIA-PACIFIC QUARRY

Georgia-Pacific Corporation Quarry
Quarry Manager: Dale Baker

Introduction

This quarry, the only current gypsum quarry west of the Des Moines River, was opened by Georgia-Pacific about 3 years ago. The gypsum in this area was deeply eroded prior to the Pleistocene, and the thickness of the remaining gypsum is variable, ranging from 0 to 4.2 m in thickness, making the deposit only marginally economic.

Sub-Gypsum Clastic Rocks

The Georgia-Pacific Quarry is an especially important location in studies of the Fort Dodge Formation, because at the base of the gypsum bed it exposes a siltstone and underlying sequence of sandstones and conglomerates above Pennsylvanian siltstones. Similar beds were first described in a creek drainage about 0.5 km southeast of the quarry by Lees (1919, p. 587-591) and later by Hale (1955, p. 131-132). These natural exposures are currently very difficult to access.

The clastic rocks beneath the gypsum in the Georgia-Pacific Quarry have been measured in three locations within the mine. They are currently visible in a drainage ditch (Fig. 1) on the southwest side of the quarry. Although there is some lateral variability in the composition and thickness of these units, a few general statements about these rocks are possible (see Fig. 2). A gray, silty claystone lies directly, and apparently conformably, beneath the gypsum beds. This unit is underlain by a series of upward-fining sequence of sandstones and conglomerates, with some mudstone lenses. The sandstones are mottled brick red to tan, calcareous, dominantly medium-grained to granular, horizontal to cross stratified, with quartz and carbonate grains. The basal Fort Dodge Formation unit is a brick red to tan sandy conglomerate, poorly sorted, and calcareous with rounded to angular clasts to 2.5 cm. Poorly defined horizontal stratification was observed, and low angle cross-stratification is present. Coarse clasts include quartz, carbonates, and reworked Mississippian and Pennsylvanian fossils (foraminifera, echinoderms, brachiopods, and crinoids). The upper portion of this conglomerate is locally dominated by carbonate clasts. Below this sequence is a thin bedded mudstone, dominantly light green, with red mottles, noncalcareous with red sideritic bands. The contact of this unit and the overlying conglomerate displays an erosional unconformity, and this unit is interpreted to be Pennsylvanian.

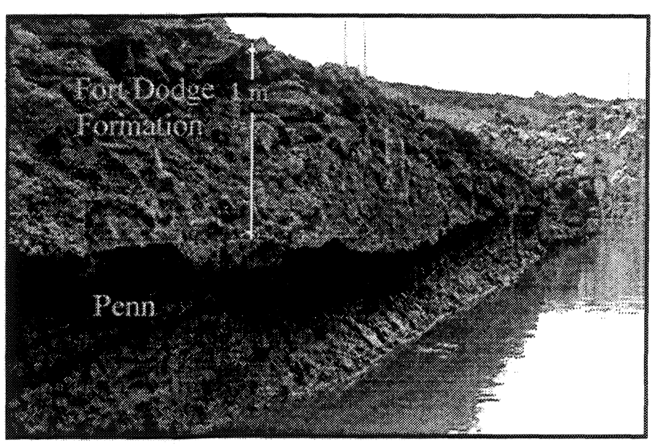

Figure 1. Photograph (looking west) of a drainage ditch at the Georgia-Pacific Quarry. The ditch exposes well-consolidated Fort Dodge Formation basal sandstone and conglomerate over Pennsylvanian siltstones.

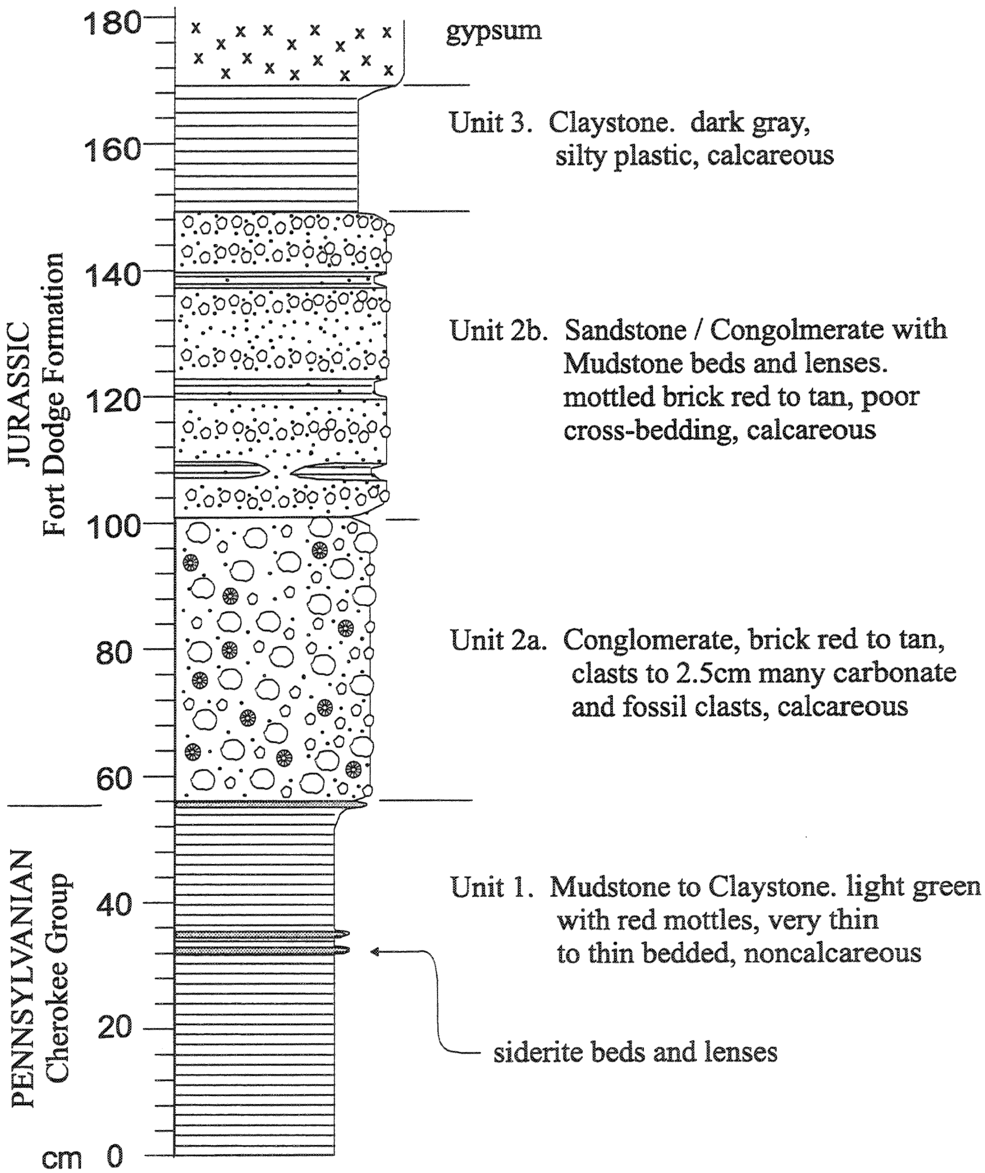

Figure 2. Graphic section of the sub-gypsum rocks of the Fort Dodge Formation exposed in a drainage ditch at the Georgia-Pacific Quarry. See written section description for details.

SUB-GYPSUM CLASTIC ROCKS AT THE GEORGIA-PACIFIC QUARRY, FORT DODGE

NW¼, NW¼, NW¼, NE¼, sec.12, T.88N., R.28W.

Section measured by Robert McKay and Raymond Anderson, 18 September, 1995

Bed	Description	Thickness (meters)
Upper Jurassic System		
	Unnamed basal clastics	
3.	Claystone, silty, dark gray, calcareous, plastic, with brick red iron stained horizontal and vertical fractures	0.20
2.	Sandstone / Conglomerate, brick red to tan calcareous, has been divided into two sub-units	0.93
	2b. Sandstone / conglomerate interbedded with mudstone lenses. Mottled brick red to tan, calcareous, medium-grained to granular with some pebbles, poorly stratified, some poor cross bedding, crude horizontal stratification, with one 10 cm thick cross strata set near the middle of the section, cross stratified lenses (one 1.5 m wide), cross statifications trend east to N.85°E. Tabular red mudstone clasts to 2.5 cm thick and 14 cm long were observed as were minor discontinuous red mudstone layers 3-4 cm thick.	0.48
	2a. Conglomerate, brick red to tan with medium-grained sand, poorly sorted with clasts to pebbles angular to rounded to 2.5 cm, large clasts include carbonate Mississippian and Pennsylvanian fossils (forams, echinoderms, brachiopods, bryozoans), quartz, and carbonate grains, poorly defined horizontal to low angle cross stratification	0.45
Pennsylvanian System		
1.	Mudstone to claystone, dominantly light green with red mottles, very thin to thin bedded, silty, noncalcareous, erosional upper contact, basal contact not observed.	0.56

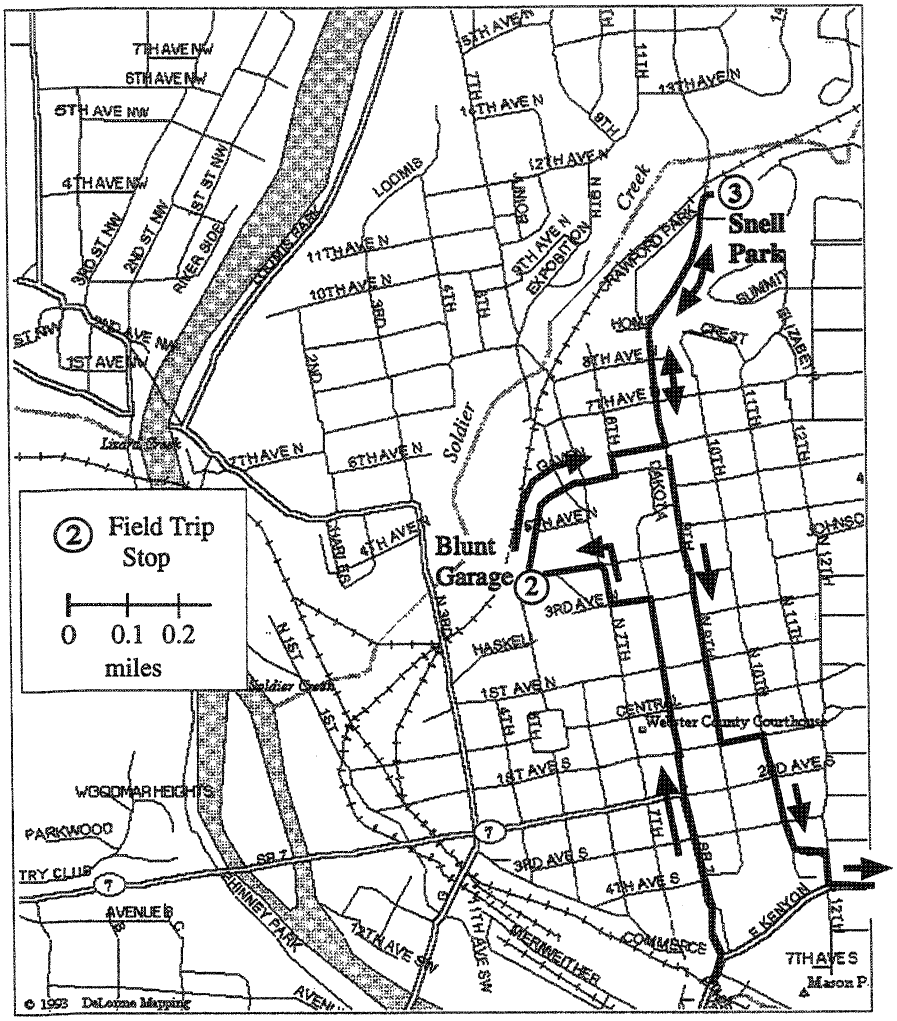

Figure 3. Map of the downtown area of Fort Dodge showing field trip route to Stops 2 and 3.

Return west on 230th street to Hwy. 169.

67.7 Turn right and head north on Hwy. 169.

69.9 Turn right on Business 20 and proceed east. Past campus of Iowa Central Community College and Historic Fort Dodge and Museum.

71.2 Cross Des Moines River. Note the high railroad bridge to the right (south).

71.5 Turn left (north) on 8th Street (first road after bridge). Proceed through Fort Dodge business district (see map in Fig. 3).

72.1 Turn left (west) on 3rd Ave., proceed one block, then turn right (north) on 7th Street.

72.3 Turn left (west) on 4th Ave. and continue down the hill into the valley of Soldier Creek. Stop at the base of the hill, at the intersection with 5th Street.

STOP 2. 'SOLDIER CREEK CLASTICS' AT BLUNT GARAGE SECTION.

Introduction

The Blunt Garage Section, is located at the residence of Mr. and Mrs. Melvin E. Blunt at 185 North 5th Street (the southeast corner of the intersection of 5th Street and 4th Avenue) in the valley of Soldier Creek in Fort Dodge. The exposure was created when the Blunts cut back a hill in their back yard to make room for a new garage (Fig. 4). A few years ago the original retaining wall was removed and the rocks cleaned off, producing the exposure we see today. This is the best, easily accessible section of the 'Soldier Creek beds' of the Fort Dodge Formation.

The rocks present at this section (Fig. 5) represent the central part of the known 'Soldier Creek beds.' Using the facies subdivisions of Meekins (1995), the basal mudstone-dominated portion of the section would fall within the Middle Facies, while the upper sandstone (unit 3) is the basal sandstone of her Upper Facies. Based on stratigraphic relationships with other sections, it is estimated that the Fort Dodge gypsum beds lie about 25 feet below the base of the Blunt Garage Section.

Remember that this is private property, and we are here at the invitation of the Blunts, so please respect their property.

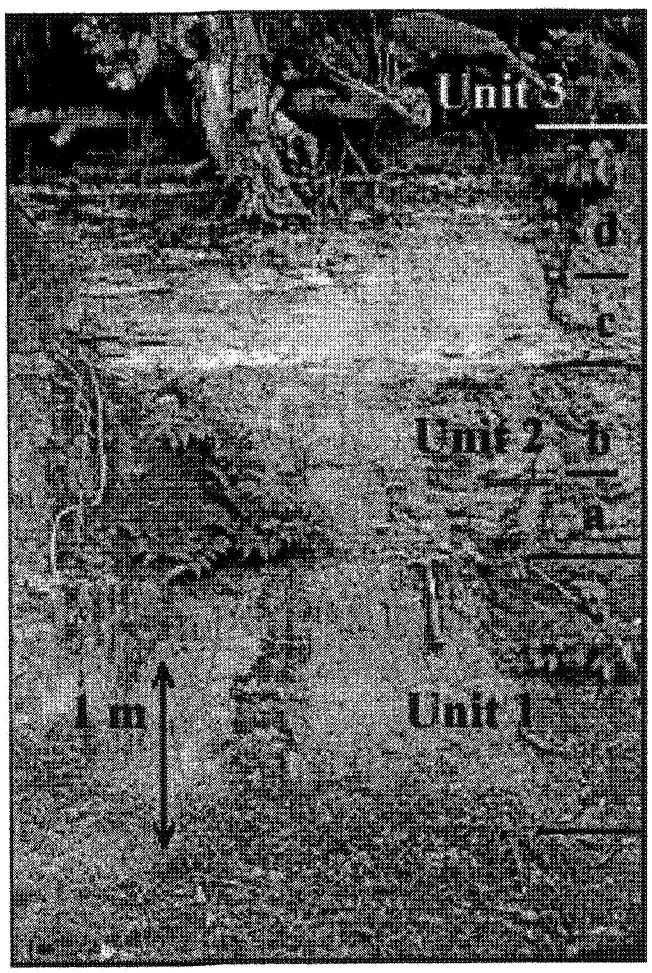

Figure 4. Photograph (looking east) of the "Soldier Creek beds" of the Fort Dodge Formation exposed east the garage at the home of Melvin Blunt at the intersection of 5th Street and 4th Avenue. See graphic (Fig. 5) and written log for description.

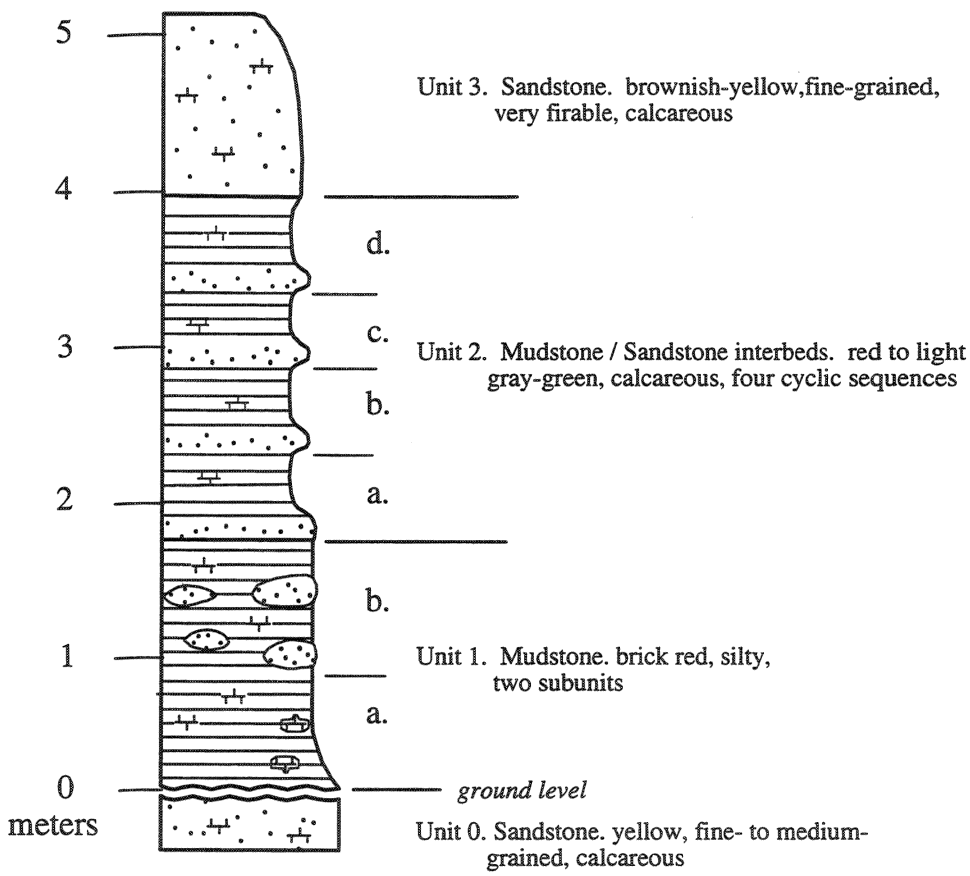

Figure 5. Graphic section of the "Soldier Creek beds" of the Fort Dodge Formation exposed beside the garage at the home of Melvin Blunt at the intersection of 5th Street and 4th Avenue. See written log for details.

'SOLDIER CREEK BEDS' EXPOSURE AT THE BLUNT GARAGE SECTION, FORT DODGE.

NW¼, NW¼, NW¼, SE¼, sec.19, T.89N., R.28W.

Section measured by Robert McKay and Raymond Anderson, 16 August, 1995

Bed	Description	Thickness (meters)
	Upper Jurassic System	
	'Soldier Creek beds', Fort Dodge Formation	
3.	Sandstone, uniformly fine-grained, brownish-yellow, calcareous poorly-cemented, very friable, faint small-scale ripple cross-stratification, a single thick bed, 0.1 m thin- to very thin-bedded (1-3 cm) at base, some load structures at base, very sharp basal contact.	1.13
2.	Mudstone / Sandstone Interbeds, a cyclic sequence of four interbedded silty mudstones(80% of section) and fine-grained sandstones (20% of section).	2.31
	2d. 66 cm, silty mudstone, mottled brick red to light gray-green, blocky fracture, no bedding apparent. Basal fine-grained sandstone (0-5 cm), light gray to gray-green, very fine-grained, calcareous, small-scale ripple laminations, probable flasiers to clay drapes. Silty mudstone.	
	2c. 55 cm, silty mudstone as above. Basal fine-grained sandstone (10 cm) as above.	
	2b. 56 cm, silty mudstone as above, medium to thick-bedded, bioturbated (rooted?). Basal fine-grained sandstone (0-5 cm) as above, laterally continuous.	
	2a. 54 cm, silty mudstone as above. Basal fine-grained sandstone (14 cm) as above.	
1.	Silty Mudstone, dominantly brick red with minor zones of brownish-yellow at base, base of unit about 15 cm below base of section, unit divided into two sub-units.	1.58
	1b. 92 cm, silty mudstone, brick red, calcareous, non-laminated, weathers to blocky structure. Discontinuous sandstone lenses, very light to light gray, calcareous, 3-30 cm long and 0.5-7 cm thick. Upper contact sharp and well-defined.	
	1a. 66 cm, silty mudstone, brick red, calcareous, nonlaminated, weathers to blocky structure.	
0.	Sandstone (sampled in shallow pit in front of storage shed, about 3 m west of exposure face), yellow, fine- to medium-grained, calcareous, poorly cemented, neither upper nor lower contact observed, thickness not known.	>0.20

Depart Stop 2. proceed north on 5th Street for 2 blocks then follow road as it curves right, becomes Dakota Ave., and heads east up the hill out of the creek valley.

73.0 Turn left (north) on 9th Street and continue back down into the valley of Soldier Creek. Follow main road curve to right (it becomes Williams Drive).

73.3 Just before Soldier Creek, turn right into Snell Park.

STOP 3. 'SOLDIER CREEK BEDS' OVER GYPSUM AT SNELL PARK, FORT DODGE: AND LUNCH.

Introduction

The exposures in Snell Park present one of the few opportunities to observe the 'Soldier Creek beds' overlying the Fort Dodge gypsum. The area of the exposures was the site of the old Cummins Quarry, where 7 m of gypsum was present at the time the quarry was described by Keyes (1895) (Fig. 6).

THIS EXPOSURE IS VERY STEEP AND POTENTIALLY DANGEROUS.

PLEASE OBSERVE THE SECTION FROM ACROSS SOLDIER CREEK.

DO NOT ATTEMPT TO CLIMB ON THE EXPOSURE.

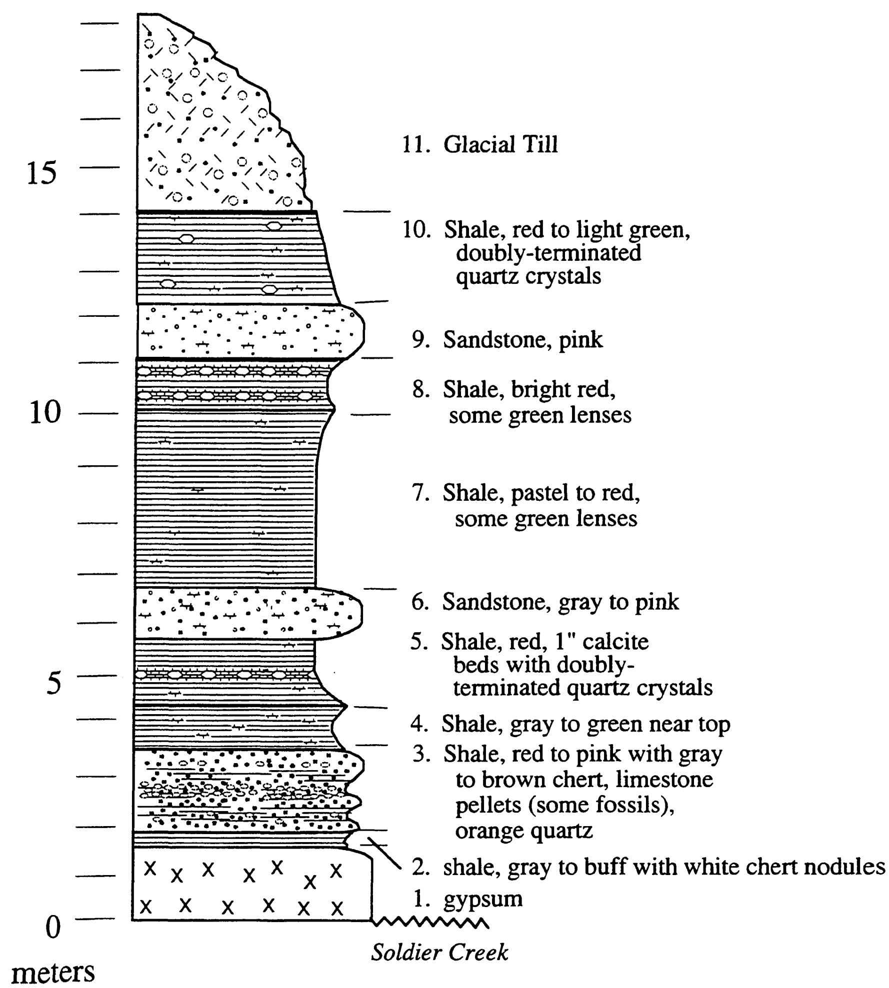

Figure 6. Graphic log of the Fort Dodge Formation rocks exposed at Snell Park in 1955 as observed by Hale (1955, p.131-132). See written description for details.

FORT DODGE FORMATION ROCKS EXPOSURE IN SNELL PARK, FORT DODGE.

NE¼, SE¼, SW¼, sec. 17, T.89N., R.28W.

The following description of the Fort Dodge Formation exposures at Snell Park is from Hale (1955, p.131-132)

Bed	Description	Thickness (meters)
Pleistocene system		
	Undifferentiated beds	
11.	Till, buff, unleached.	3.4
Permian (?) system		
	Fort Dodge Formation	
10.	Shale, red and some light-green, very calcareous, soft, slightly sandy, with doubly terminated quartz crystals.	1.5
9.	Sandstone, pink, very fine-grained, angular, soft, very calcareous; contains a few coarse, rounded quartz grains and occasional pink and gray chert fragments.	0.9
8.	Shale, bright red and pale-red with green lenses and blotches, soft; lower part calcareous; upper pale-red shales are noncalcareous; thin, lenticular beds of calcite contain doubly terminated quartz crystals.	0.9
7.	Shale, pastel-red with some green lenses, soft, slightly silty, calcareous. There is a 1-inch bed of calcite containing doubly terminated quartz crystals about 1 foot from base.	2.6
6.	Sandstone, pale gray-pink, very fine-grained, soft, argillaceous calcareous.	0.8
5.	Shale, red, soft, silty, calcareous, and some flakes of mica.	1.2
4.	Shale, olive-gray near base to gray-green in upper part, soft, silt, calcareous.	0.8
3.	Sandstone or shale, red to pink, hard to soft, calcareous. Clay with inclusions of subrounded course limestone grains, predominates in places. Roughly 10 percent of limestone grains are worn fusulinid and other fossil fragments. These small limestone pellets make up bulk of rock in places. Occasional fragments of gray-brown chert, bright-orange quartz, and coarse rounded sand grains.	1.4
2.	Shale, gray, buff, soft, very calcareous; contains druses and gray watery chert nodules.	0.2
1.	Gypsum, gray-white, massive, banded, heavily bedded. To water level in Soldier Creek.	2.4
	(Altitude of water level about 1,025 feet)	

Most of the rocks present at the Snell Park section are stratigraphically lower that the rocks at the Blunt Garage Section. The upper 10 feet of the Snell section is tentatively correlated to the basal portions of the Blunt Section.

Norton's units 2 through 7 correspond to the Lower Facies of the 'Soldier Creek' as defined by Meekins (1995). Beds 8 through 10 are in the lower part of her Middle Facies.

Depart Stop 3. Exit Snell Park and turn left (south) on Williams Dr. Continue south (road becomes 9th Street) and through the Fort Dodge business district.

74.4 Turn left (east) on 2nd Ave., continue one block, then turn right (south) on 12th Street.

74.7 Turn left (east) on 5th Ave. (Business 20) and continue through the business strip.

76.7 The land behind the business on the right (south) has been strip-mined for gypsum and reclaimed.

77.5 Turn right (south) at traffic signal onto County Road P-59 (also Business 20).

Unreclaimed mined lands.

An unreclaimed area on the left (east) was strip-mined for gypsum in the early 1970s by The Georgia Pacific Corporation. This area has become a very popular recreation site. The water in the ponds is relatively clean and the fishing is excellent.

78.6 The Celotex Corporation wallboard plant is on the right (west). South of the plant are the Cellotex gypsum quarries.

79.3 Cross railroad tracks.

79.5 Turn left (east) into the parking area of the United States Gypsum Company's quarry office and shop. Turn is opposite Mill Road.

Meet with U.S. Gypsum Quarry Department Manager Larry Pawlosky

Depart U.S Gypsum quarry operations headquarters and head west on Mill Road.

79.8 Strip-mined and partially reclaimed land on both sides of road.

80.1 Road curves to north. Georgia Pacific wallboard plant west of road, unreclaimed quarry land on east.

80.4 Cross railroad tracks. Many sinkhole-like features on left (west) are collapse into underground gypsum mines. Collapse features also present to northeast. Road curves left (west); many more collapse features on left (south) of road. Road curves right (north) and becomes Paragon Road.

81.1 Cross bridge over U.S. Gypsum haul road. The large quarry to the left (west) is the U.S. Gypsum North Welles Quarry.

81.4 Turn into United States Gypsum Corporation headquarters and wallboard plant. Bear right on first gravel road.

81.8 U.S. Gypsum's primary crusher. This cone crusher takes boulder-size gypsum blocks and crushes them to about a cm diameter. Continue west on haul road.

FROM THIS POINT YOU ARE IN THE QUARRY.
YOU <u>MUST WEAR HARD HATS AT ALL TIMES</u>
AND <u>DRIVE ON THE LEFT SIDE OF THE ROAD</u>

82.0 Cross under Paragon Road.

This is a single lane passage.

YIELD TO QUARRY VEHICLES.

THE NORTH WELLES QUARRY

The U.S. Gypsum North Welles Quarry has been active periodically since the 1980s, and is still a major active pit, producing approximately 80,000 tons of gypsum per year. The photograph below (Fig. 7) shows an area of the North Welles Quarry as it appeared in 1984, just prior to stripping of the gypsum. The Pleistocene till and 'Soldier Creek bed' rocks had been removed and the slips (the quarry term for the dissolution enlarged joints in the gypsum) hydraulically cleaned out. The gypsum was subsequently broken up by blasting and hauled to the crushers.

The gypsum resources of the North Welles Quarry are now nearly depleted, and reclamation is burying the remaining highwalls, however the quarry has provided some of the best exposures of Fort Dodge Formation rocks, especially the gypsum bed and overlying 'Soldier Creek beds'. In her comprehensive examination of the 'Soldier Creek beds', Meekins (1995) measured 12 sections on the west and north walls of the North Welles Quarry. Her sections show the discontinuous nature and lateral variability of these units. Her descriptions and conclusions are summarized in the discussion that precedes the Road Log.

Although the thickness and lithologies of the 'Soldier Creek beds' are quite variable, a representative section is very informative. The following section (Fig. 8), measured by Ray Anderson and Mike Farmer along the center of the north highwall in 1984 (see photograph above), is typical of the sequence that was visible in the North Welles Quarry over much of its lifetime.

Figure 7. Photograph of the exposed gypsum in the North Welles Quarry prior to blasting and removal in 1984. The solutionally enlarged fracture system is evident.

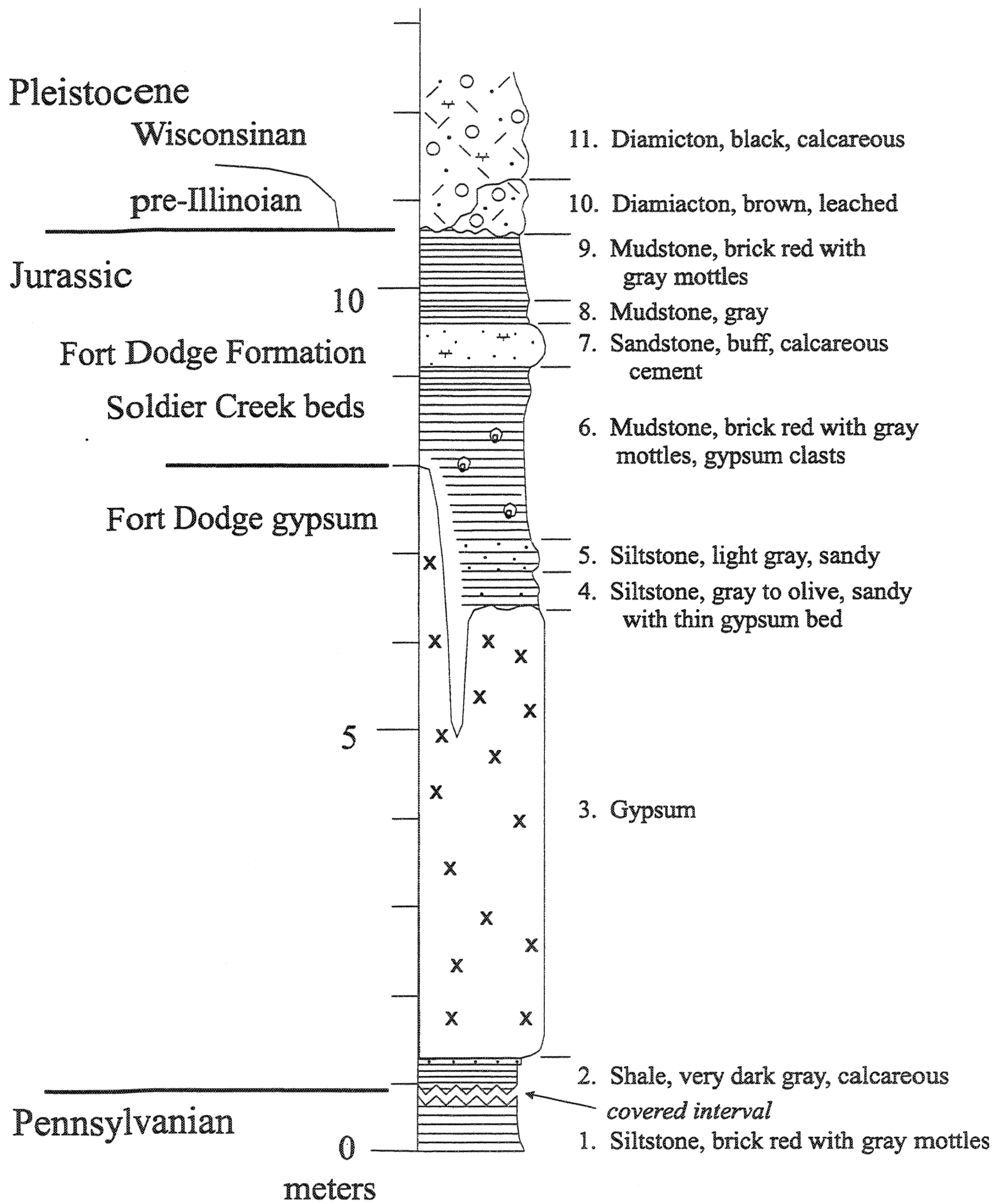

Figure 8. Graphic section of the Fort Dodge Formation rocks present in the north wall of the North Welles Quarry in 1984. For details see written description.

U.S. GYPSUM NORTH WELLES QUARRY, FORT DODGE.

NE¼, NW¼, NW¼, sec.33, T.89N., R.28W.
Section measured by Raymond Anderson and Michael Farmer
11 September, 1984

Bed	Description	Thickness (meters)
Pleistocene Series		
	Wisconsin Episode	
11.	Till, black, unleached.	< 1.5
pre-Illinoian Episode		
10.	Till, olive-brown, leached.	0 - 0.2
Jurassic System		
	Fort Dodge Formation	
9.	Mudstone, brick-red with gray mottling, calcareous	0.8
8.	Mudstone, light gray, silty, calcareous.	0.3
7	Sandstone, buff, fine- to medium-grained, calcareous, well lithified, massive, no bedding or structures observed.	0.4
6.	Mudstone, brick red with white to yellowish mottles, gray, sandy bed near top, calcareous, large clasts (?) of gypsum in lower 5.5 feet.	1.9
5.	Siltstone, pale gray to green, sandy, calcareous.	0.4
4.	Mudstone, dark to light gray to olive drab, calcareous, sandy, thin (0.2') gypsum bed at top of unit.	0.4
3.	Gypsum, white with gray mm scale banding, top eroded to 5 ' above this section and 5 feet below.	3.7
2.	Shale, very dark gray, plastic, calcareous, bright brown mottling below sandstone bed, brown, calcite-cemented medium-grained friable at top of unit. Base covered.	0.3
Pennsylvanian System		
	Cherokee Group	
1.	Siltstone, finely-laminated-red, gray, and buff, 1 mm to 1 cm scale laminations, no fossils identified.	0.6

82.0 Stop to view old underground mine adits.

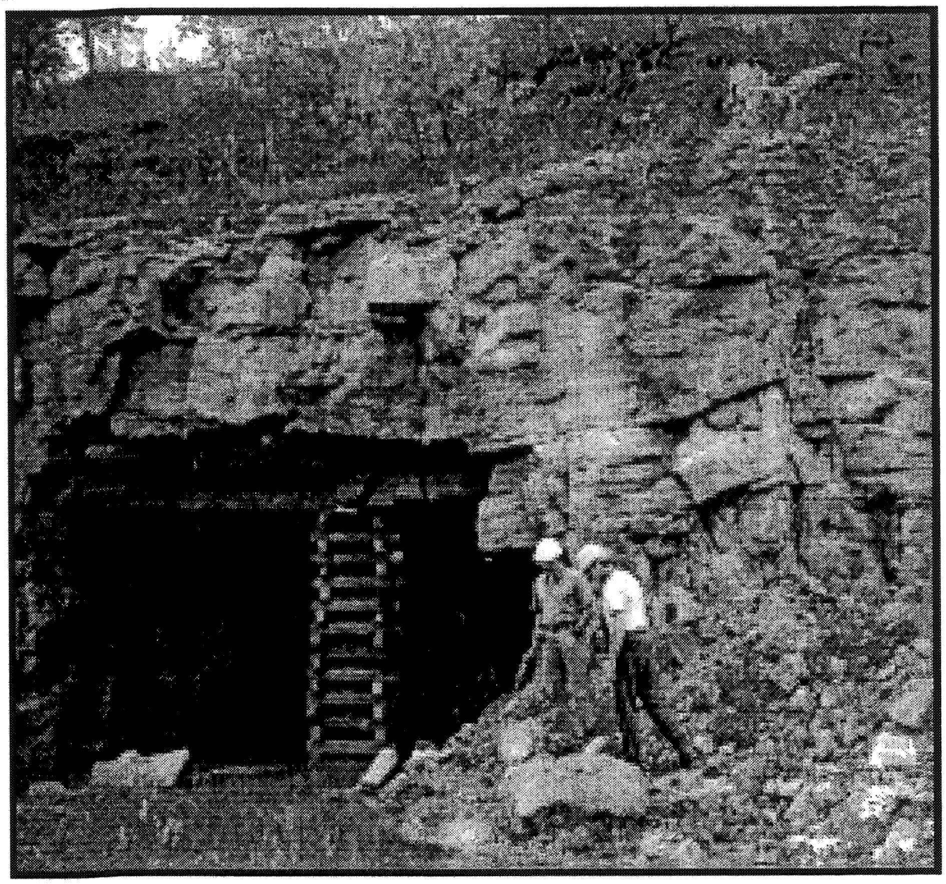

Figure 9. Photograph of old gypsum mine adit in the east wall of the North Welles Quarry.

STOP 4. OLD U.S. GYPSUM UNDERGROUND MINE ADITS.

by Larry Pawlosky, U.S. Gypsum Corp.

PLEASE GET OFF THE ROAD AND AVOID THE MINING VEHICLES.

Looking north northeast two large mine openings can be observed (Fig. 9). These adits are part of an extensive underground mine complex located directly under the U.S. Gypsum plant and property east of the Mill Road. These openings were exposed during more recent open pit quarrying activity during the last 20 years. However, the openings have been maintained to provide access to the complex of underground workings for de-watering of the underground mined areas. The original vertical access shaft to this underground mine complex still exists on the plant grounds, but is no longer active. The underground mine has officially been closed, and access by U.S Gypsum employees is strictly forbidden due to current mining laws. However, in an effort to control mine de-watering and sink hole subsidence, U.S. Gypsum has arranged to use a contract mine service to enter the mines when necessary.

Depart Stop 4 and continue west on haul road

82.2 Turn left (south) off haul road and proceed into mining area.

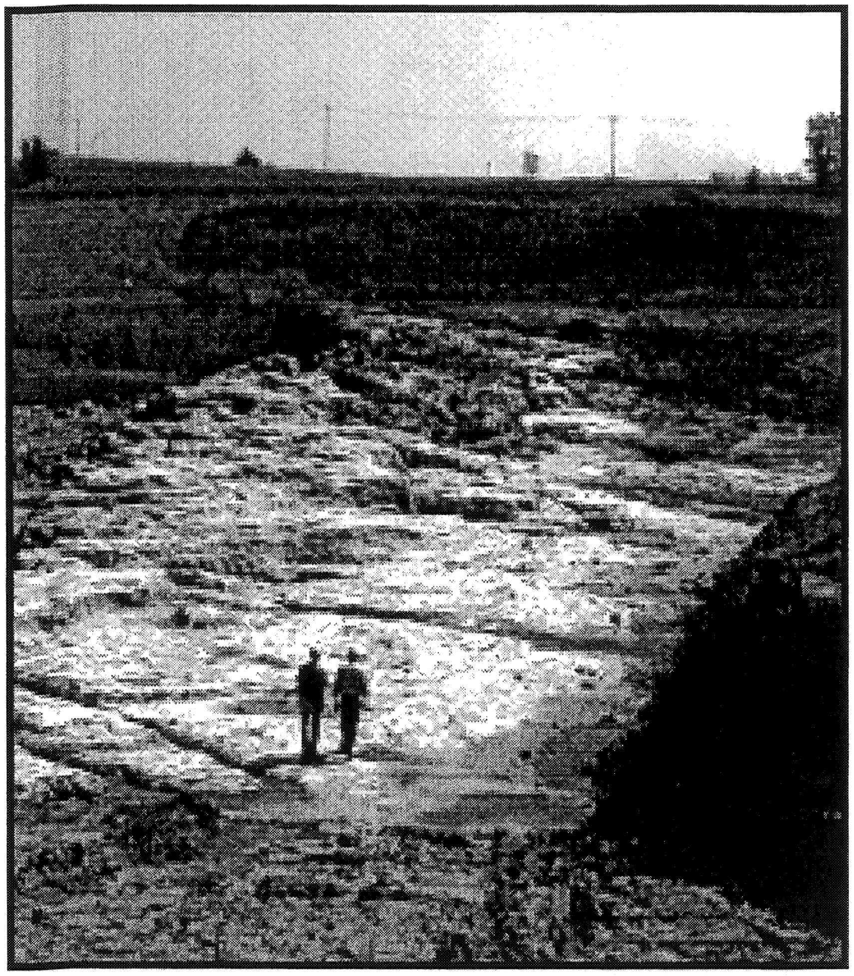

Figure 10. Photograph of the Fort Dodge gypsum surface exposed during mining activities in the North Welles Quarry. People are standing on the axis of a Quaternary cut-out channel in the gypsum.

STOP 5. FORT DODGE GYPSUM AT NORTH WELLES QUARRY

Introduction

This stop is the only area of the North Welles Quarry currently being mined. In this area, about 7 m of gypsum is being removed. An additional meter or so of gypsum is left on the floor during mining operations, because the underlying dark gray shale is extremely plastic and creates a very muddy, messy floor. The lower gypsum is pulled out as the last stage of the mining operation.

The Quaternary section at this site is about 20 m thick, and three units are exposed. The thin basal till unit is pre-Illinoian in age and is identifiable by its brown to olive color. This material fills some of the slips (the quarry term for the dissolution enlarged joints in the gypsum) in the North Welles Quarry. Unconformable above the pre-Illinoian till lies the dark black tills of the Sheldon Creek Formation, the basal unit of the Wisconsinan Des Moines Lobe tills. About half-way up the till exposure, a series of seeps mark the contact between the Sheldon Creek and the overlying Dows Formation. Near the center of the cut face, a small channel can be seen. Sand and numerous snail shells are abundant in this channel.

When the Quaternary materials were removed to the current face, a east-west trending Wisconsinan channel was discovered, that had cut out about half of the thickness of the gypsum (see Fig. 10). The channel was filled with sand, and within the sand U.S. Gypsum geologist Larry Pawlosky discovered an excellently-preserved mammoth molar.

Because there is no mining activity at this location at this time, this stop will provide an opportunity to closely examine and sample the gypsum and to observe its structures.

PLEASE EXERCISE CARE WHEN CLIMBING ON LOOSE ROCKS AND BE AWARE OF THE PEOPLE BELOW YOU.

Discussion

Fibrous gypsum bands and veins occur at this stop. They consist of two types: white single-tier types which occur throughout the section, and tan double-tier veins that occur almost exclusively in the uppermost part. Complex cross-cutting multiple veins and nodules may also be found at this stop. The fibrous gypsum has been referred to as 'satin spar' but is different in morphology and orientation. The origin of satin spar and other forms of fibrous veins has long been discussed. Typically the fibers are perpendicular to bedding or to the land surface and most occurrences result from filling of fractures. The tensile fractures have been attributed to unloading through erosion of overlying rocks. Fractures, especially those in the upper part of the gypsum, probably resulted from melting of overlying Pleistocene glacial ice. Directional stresses presumably resulted in growth of the fibrous habit within fractures that slowly moved apart.

Depart Stop 5. Drive back to haul road, turn left and continue west then south on haul road.

DRIVE ON LEFT SIDE OF ROAD.

82.7 Pass under railroad tracks.
This is a single lane passage.

YIELD TO QUARRY VEHICLES.

82.9 Weathered exposures of gypsum along road.

83.0 Turn right (south) on gravel road. Unclaimed strip spoils on both sides of road. Continue straight ahead pass crossroads.

83.9 Reclaimed area.

STOP 6. RECLAIMED GYPSUM MINE AREA.

Overview of Mine Reclamation Law

In 1968 the State of Iowa enacted legislation requiring that mined areas be reclaimed. The law was amended in 1985, and with a few subsequent minor changes now exists as Iowa Code Chapter 208. The law forbids the burial of topsoil during the mining process. Upon completion of the mining, it requires mine operators to grade affected lands (except for impoundments), pit floors, and highwalls to slopes having a maximum of one foot vertical rise for each four feet of horizontal distance, or to conform with surrounding terrain in areas of greater relief. They must provide for the approved vegetation of the affected lands. And, all of this reclamation must be completed within three years of the completion of mining activities in the area. Mining, crushing areas and spoil piles that were operated prior to 1968 are exempt from these laws.

South Welles Reclamation Area

Looking due west from the road, a large area of reclaimed quarry pits can be observed. The gypsum was removed about 20 years ago, with the area then reclaimed to as near original condition as possible. The area has become a very well used recreational area for local hunting, fishing, hiking and nature observation. A wide variety of flora and fauna are thriving in the area. The area has also been cited by the Iowa Department of Natural Resources as an excellent example of reclamation practices and results.

Return to haul road and turn right (east).

DRIVE ON LEFT SIDE OF ROAD.

87.2 Cross under County Road P-59

This is a single lane passage.

YIELD TO QUARRY VEHICLES.

Continue east on haul road into the U.S Gypsum Carbon 20 Quarry. Follow road as it curves left (north).

87.2 U.S. Gypsum Carbon 20 Quarry on right (east). Continue north on haul road; road curves left (west).

The Cardiff Quarry

The area just beyond the Carbon 20 quarry face to the east is the old Gypsum Hollow area, later named the Cardiff Quarry. The quarry was named after the Cardiff Giant, a great statue carved from gypsum extracted from this site and buried for later discovery on a New York farm. The story of the Cardiff Giant that follows was modified from The History of the Gypsum Industry in Fort Dodge and Webster County, Iowa; 1872-1972 by Leo V. Rodenborn.

The Cardiff Giant

Gypsum from this quarry was carved to create one of the great hoaxes in U.S history. In the late 1860s George Hull purchased an acre of land in Gypsum Hollow and engaged quarrymen to fracture out as large a block of gypsum as possible. A 4 x 1 x .6 m block was recovered and shipped to a barn in Chicago where 3 sculptors were engaged to carve the gypsum into the semblance of a human form. Hull then removed the chisel marks by scouring the image with a sandy sponge and "aged" by pitting it with a hammer tipped with needles and discoloring it with sulfuric acid. With the carving now having the appearance of great age, he shipped it to Binghamton, New York, where he buried it on the Newell farm near Cardiff and buried it in an appropriate spot when the Newells were absent. A year later, in 1869 Hull arranged to have a well dug on the Newell property, and the laborers employed for the task "discovered" the petrified man, referred to by one enthusiast as "the eighth wonder of the world." The news of the discovery created a tremendous sensation all over New York State, with thousands of visitors swarming to the farm discovery site. Soon news of the discovery had been telegraphed all over the country and even to England, prompting a group of British scientists to travel to the U.S. to investigate the "remains".

One description of the giant in its Newell farm discovery pit was recorded by Andrew D. White who noted, "Upon entering a tent that covered the spot we saw a large pit or grave and at the bottom of it, perhaps five feet below the surface, an enormous figure, apparently of Onondaga limestone. It was a stout giant with massive features, the whole body nude, the limbs contracted as if in agony. It had a color as if it had lain long in the earth, and over its surface were minute punctures like pores. A special appearance of great awe was given it by deep groves and channels on its underside, apparently worn by water, which was flowing in streams through the earth and along the rock on which the figure rested. Lying in its grave, with a subdued light from the roof of the tent falling upon it, and with the limbs contorted as if in a death struggle, it produced a most weird effect. An air of great solemnity pervaded the place and visitors hardly spoke above a whisper."

The carving was raised from its burial spot and exhibited in several cities as the Cardiff Giant by "Colonel" Wood, an eminent showman of the day. However, the exhibition tour had not progressed far when eminent Yale paleontologist O.C. Marsh examined the giant and pronounced it to be of recent origin. Hull was soon exposed and confessed to the charade, but not before he had cleared about $20,000 from the swindle.

This was not the end of the Cardiff Giant hoax. Failing to purchase the giant at the height of its fame, P.T. Barnam had an imitation produced and displayed it with great success until 1875. The original giant resurfaced in 1900 when it was placed on exhibit at the Pan American Exposition. In 1913 J.R. Mulroney of Fort Dodge purchased the giant for a reported sum of $10,000 and toured the Midwest with it. After a subsequent tour of the west coast, the giant was returned to Fort Dodge. It was exhibited at a fair in Fort Dodge in 1923, then leased to the Syracuse, New York, Chamber of Commerce for a tour of the state and display at the New York

State Fair 1935. The Cardiff Giant is now on permanent display at the Farmer's Museum in Cooperstown, New York. A replica of the Cardiff Giant is on display at the Fort Dodge Historical Museum and Fort.

Continue north on haul road into Carbon 23 Quarry.

The U.S. Gypsum Company's Carbon 23 Quarry

At its Carbon 23 Quarry, the U.S. Gypsum Company is quarrying 7 m of gypsum, the thickest gypsum bed currently exposed in the Fort Dodge area. The company removes 500,000 tons of gypsum a year from this complex of quarries. To access the gypsum, they removed 2.4 million cubic yards of overburden last year. As the resource is depleted in this area, U.S Gypsum will move north of the railroad tracks, accessing that area via a haul road that will pass under the tracks.

87.6 Note weathering of gypsum along joints exposed in roadcut on left (south). Continue west on haul road to Carbon 23 Quarry face.

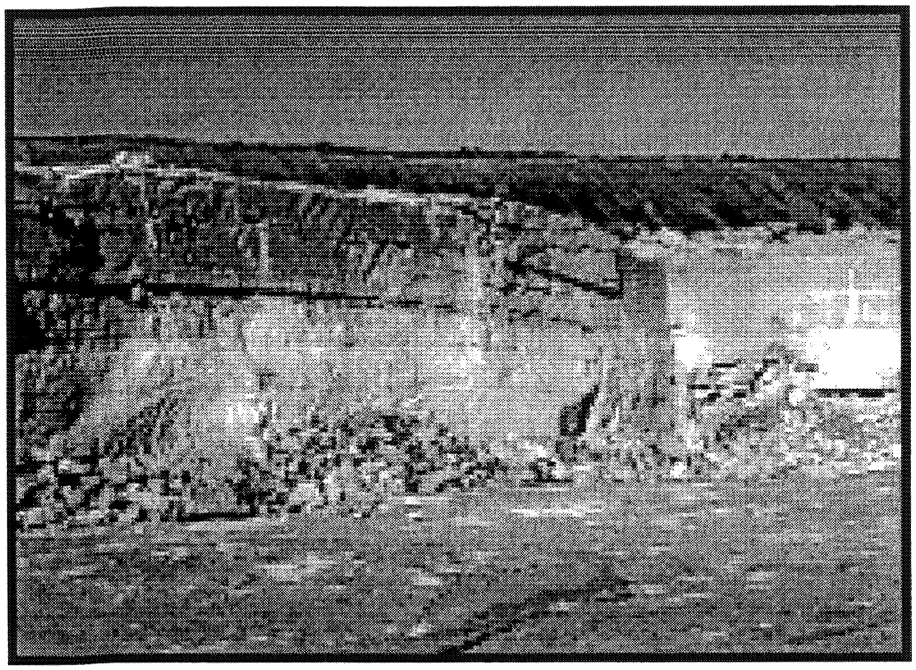

Figure 11. Photograph of working face of gypsum at the Carbon 23 Quarry.

STOP 7. WORKING FACE AT U.S. GYPSUM CARBON 23 QUARRY

Structures and Textures in the Fort Dodge Gypsum

Depending on mining activity which constantly changes the working face (Fig. 11), a variety of structures and textures may be visible in the gypsum. Dark/light laminations are well represented in this quarry. Dark laminations usually are composed of several thin lamina of silicate/carbonate impurities, and part of the dark color may develop because of relatively large crystal sizes which allows better light penetration compared to that in layers composed of smaller crystals. Light-colored laminations typically contain almost no impurities and often are composed of very finely crystalline gypsum. Many white bands have a nodular appearance; others are composed of perpendicular fibers of gypsum. Enteriolithic or contorted layers, minor non-tectonic folds, nodules and nodular layers, ripple marks. and dark gray to black fine-grained pyritic concentrations also may be seen. Very little, if any, of the primary depositional textures such as bottom-growth gypsum occur in the gypsum because of pervasive recrystallization.

Depart Stop 7. Drive east on haul road.

DRIVE ON LEFT SIDE OF ROAD.

YIELD TO QUARRY VEHICLES.

88.1 Turn right (west) on gravel road and proceed up to U.S. Gypsum quarry operations headquarters.

88.5 Drive out of parking area, cross County Road P-59, and continue on Mill Road, along previously-traveled route, to Paragon Road and to the entrance to the United States Gypsum Corporation wallboard plant.

DRIVE ON RIGHT SIDE OF ROAD FOR REMAINDER OF TRIP.

90.4 Turn right (east) into United States Gypsum Corporation headquarters and wallboard plant and park at office.

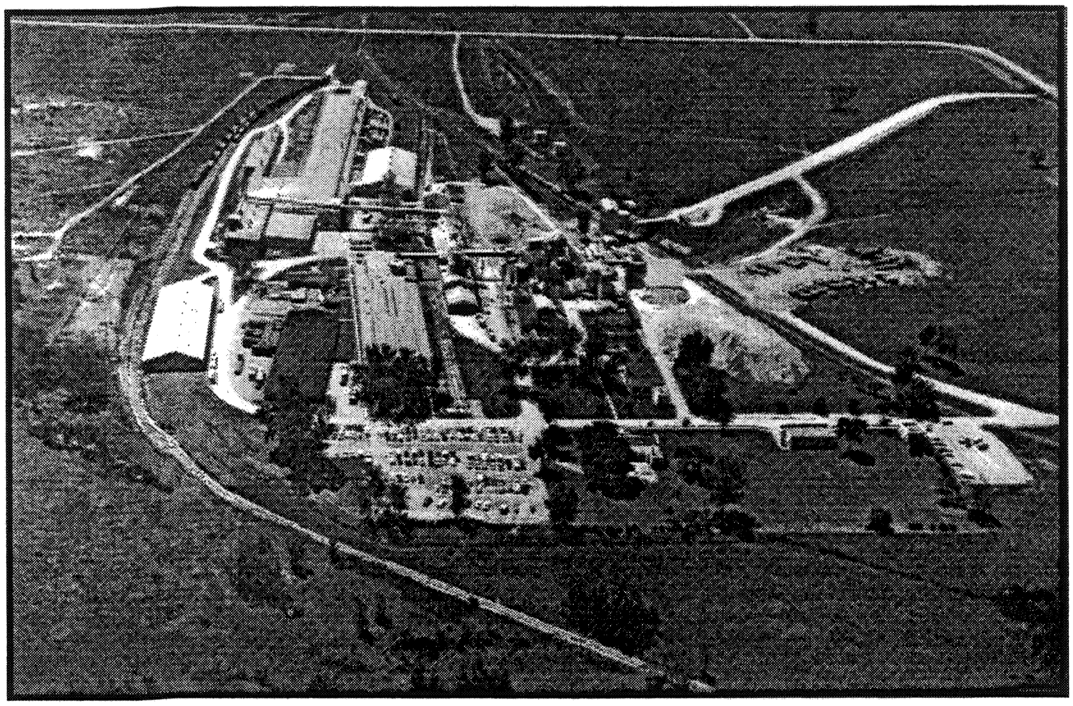

Figure 12. Aerial photograph of the U.S. Gypsum Company headquarters and mill as it appeared in 1972. Modified from Rodenborn(1972).

STOP 8. TOUR OF UNITED STATES GYPSUM CORPORATION WALLBOARD PLANT

Ron Hollander, Wallboard Plant Manager

NO PHOTOGRAPHY IS ALLOWED IN THE WALLBOARD PLANT. LEAVE CAMERAS IN VEHICLES

Introduction

The United States Gypsum Company was incorporated in New Jersey on December 27, 1901. with corporate offices in Chicago, Illinois. The company became a leading gypsum producer in 1920 when it was consolidated with 34 other gypsum companies, and it has been the top gypsum producer in the Fort Dodge area for many years.

U.S. Gypsum has been making gypsum building products in Fort Dodge since 1902. The plant (Fig.12) operates 24 hours a day, and last year it produced 65 million square feet of wallboard. In addition to wallboard, the factory produces industrial plasters and joint compounds. Please refer to the accompanying guidebook article on the Modern and Ancient Uses of Gypsum for a discussion of wallboard manufacturing.

Depart Stop 8, turn left (south) on Paragon Road and proceed to Mill Road and to County Road P-59.

92.3 Turn right (south) on County Road P-59 and proceed to Highway 20.

93.2 Turn left (east) on Highway 20.

121.1 Turn right (south) on Interstate 35.

149.8 Turn off I-35 at Ames Exit 113 (Highway 13) and proceed west.

Turn left (south) on Stange.

154.6 Return to Iowa State University campus.

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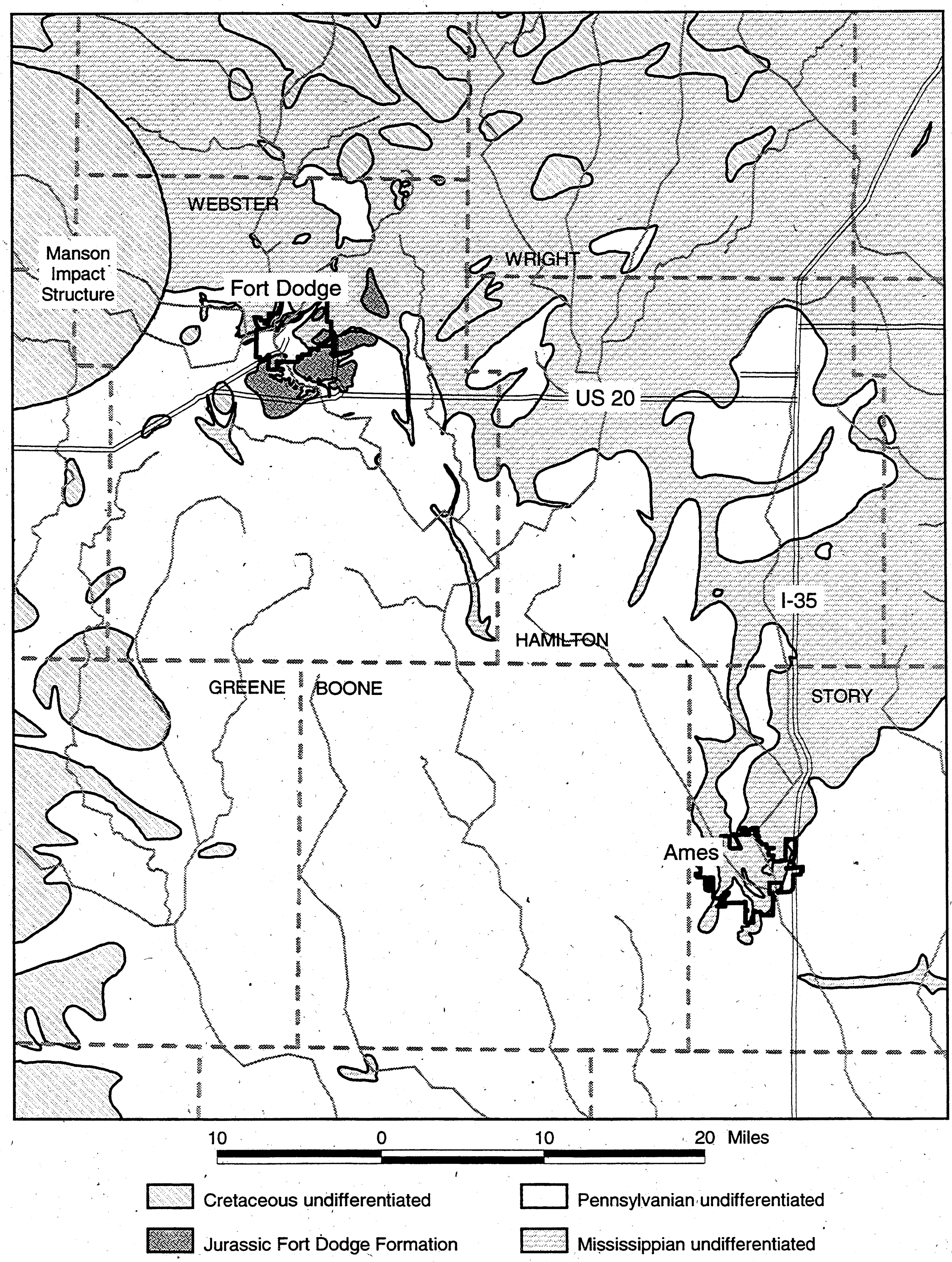
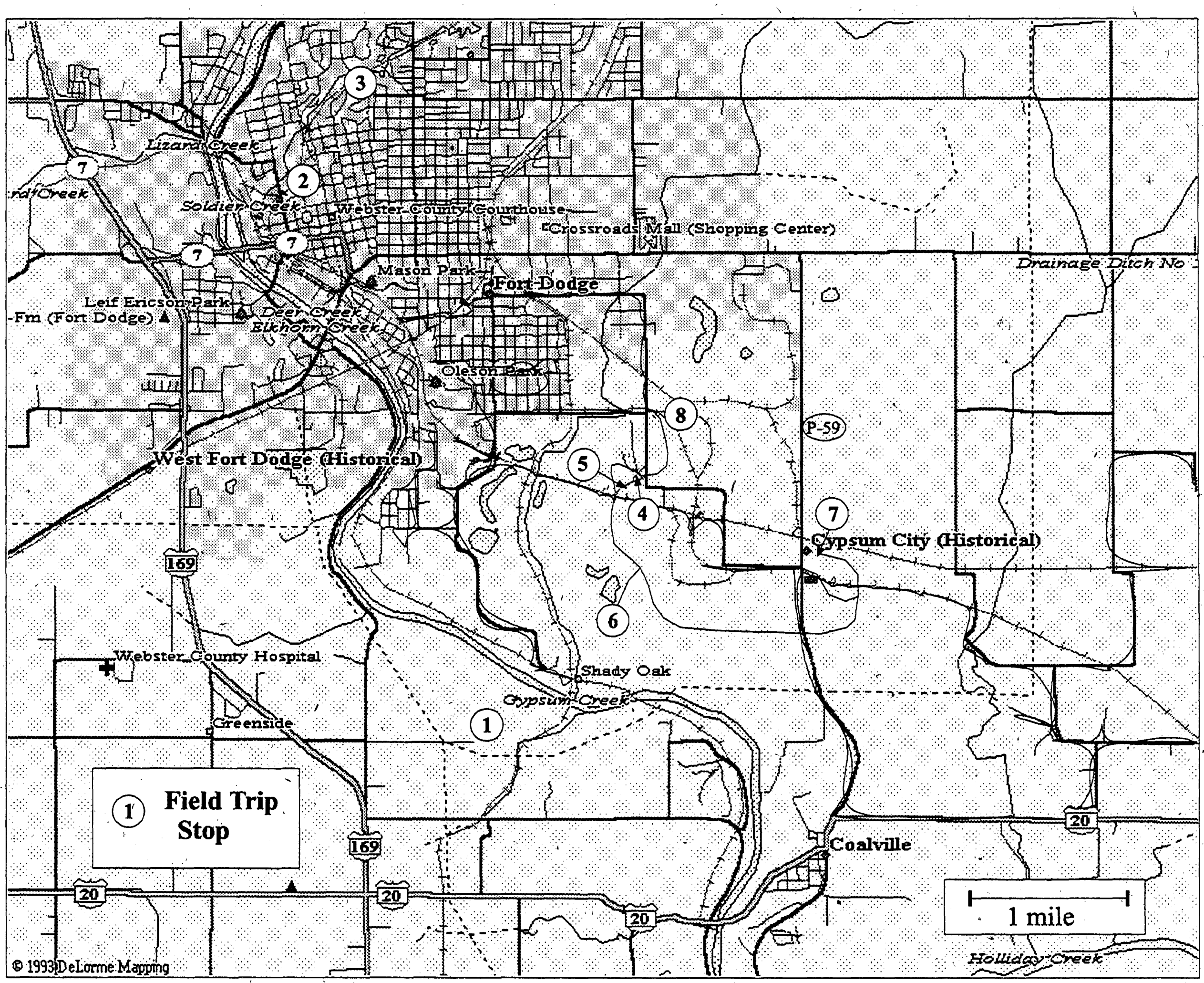


WEBSTER
Manson
Impact
Structure
Fort Dodge
WRIGHT
US 20
I-35
HAMILTON
GREENE
BOONE
STORY
Ames
10
0
10
20 Miles
Cretaceous undifferentiated
Pennsylvanian undifferentiated
Jurassic Fort Dodge Formation
Mississippian undifferentiated



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