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Preface

Although many geologists recognized the need for more communication in the field of industrial minerals, nothing really came of it until Dr. Robert L. Bates organized the first Forum which was held at Ohio State University during the winter of 1965. Born in Ohio, the Forum on geology of industrial minerals has continued to live and grow as a very informal organization. Guidance is provided by a steering committee.

This volume, PROCEEDINGS of the EIGHTH FORUM ON THE GEOLOGY OF INDUSTRIAL MINERALS includes the published version of the papers presented at Iowa City on April 12-14, 1972.

The Eighth Forum was sponsored jointly by the Iowa Geological Survey and by the geology and earth science departments of the three state universities in Iowa. Program and meetings were organized by Dr. Wayne I. Anderson, University of Northern Iowa; Dr. Donald L. Biggs, Iowa State University; Drs. Kenneth F. Clark and Keene Swett, University of Iowa; and Fred H. Dorheim, Iowa Geological Survey.

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OF DINOSAURS, ECONOMISTS, AND OTHER MONSTERS

Lawrence F. Rooney
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In my last talk before this group I suggested that our society will return full cycle to the caves, and that for survival, we might all learn some primitive skill. In returning to Montana, I have taken the initial step. Flathead County is feeling the first invasions by land promoters, the first effects of industrialization, the first warnings that our forests are not infinite — yet the only political concern felt so deeply that voters bought ads to express it was fear that our guns might be registered. If our society must return to the caves, it is comforting to know that my tribe fosters the savage instincts and tools that will make us competitive. You Iowans might take heed and keep an eye cocked for plundering bands from the north.

I stand before you a somewhat reluctant speaker. When I died and went to Montana, I did not expect so early a resurrection. I had spoken my piece in Ann Arbor and was afraid that I had nothing more to say. When I did accept the invitation to keynote, I thought first of singing a hymn in praise of my mistress, the 7½ minute topographic quadrangle. But then, last fall, the Missouri Industry News scooped that topic. So I turned to other cherished obsessions, which I dare to express only because they are too brief to bore.

A few years ago I read a story about a boy in New England who found a dinosaur egg. In fact I have read aloud that same story about Uncle Beazly the dinosaur too many times since. The moral to Beazly — though I don't tell my children so — is that if you find a dinosaur egg, fry it. Otherwise, like the boy in the story, your life is committed to the nourishment of a monster, sweet and cuddly though he may be.

As industrial mineral geologists we are committed to nourishing an industrial monster not sweet and cuddly as Uncle Beazly, rather sprawling, multi-bellied, dim-witted, like-a-mushroom-cloud beautiful, and suffocating us with waste. Our role as monster-feeder is major and becomes more so with time, and we should feel justly proud in keeping industrial society on its feet. But here the analogy ends. Unlike Beazly, our monster keeps growing, and we know that we cannot feed it forever. Thus we have a responsibility to advise our citizenry of the finiteness of the natural resources on which our high standard of living depends. All of us share this responsibility but especially the economic geologist as teacher.

In this schizoid role of feeding the monster and warning of unrestricted growth, the geologist as teacher cannot pass his responsibility of sounding the alarm to others. The geologist has a gut feeling for life in the perspective of time. He has watched[1] the parade of trilobites, dinosaurs, and fusilinids

disappear. He knows that man is a johnny-come-lately and that his extinction is probable even if he did not so diligently seek it.

(Logically the economist should share the geologist's concern, but the geologist had better look elsewhere for allies. In this regard let me add that I am a gentle man and wish to quarrel with no one. My Irish blood is of the Bing Crosby strain, not Barry Fitzgerald's. Yet economists as a group bug me. Until recently, they seemed to have no perspective on the world other than the production and flow of goods, and some economists state explicitly that the only way to control pollution is to produce more goods so that we will be rich enough to control the pollution from producing more goods so that we will be rich enough. . .and on and on into the ever-retreating mirrors. I wonder if such economists ever hike in the mountains and drink from unpolluted streams. In my jaundiced eye they are ashen-faced, myoptic wordsmiths to whom the good life is suburbia. All water comes from faucets, all food comes in packages, and all energy comes from wires, pipes, and pumps. And the gross national product will increase forever. No, the geologist can ally himself better with the biologist, who has a clearer concept of population and survival.)

What we as geologist-teachers must do is make possible to each man a wise decision, whether it be in the voting booth or in the marriage bed, regarding the future of our society. We want him to be informed with regard to our petroleum reserves, the potential and problems of oil shales, the size and nature of our coal deposits, and the status of nuclear energy developments. We want him to know the relationship between irrigation and salting of soil. We want him to have some concept of the way metals are distributed in the earth's crust, the tenor of ores, the energy and waste factors of lean ores, and our dependence on overseas deposits. We want him to be more informed than the mineral producer who explained to me that when we run out of raw materials on this planet we will go to outer space for them.

When I was a student at Indiana University 20 years ago, a course called Geology and Man was introduced for non-geology majors. Both teachers and graduate students, it seemed to me, were somewhat patronizing toward the course, which was considered watered-down physical geology, thus palatable to the humanities major who needed to satisfy science electives. In retrospect, I believe that Geology and Man and similar courses are, or have the potential of being, the most valuable geology courses offered in our colleges today. Courses that relate geology to earth resources and environment should be useful to the prospective businessman, lawyer, politician, educator — in fact, every enlightened citizen, including economists. Geology departments should put their best efforts and best teachers into these courses. The classes should be lively, filled with discussion and debate, and with little emphasis on the old academic bugaboo, grades.

It is surprising how much a teacher can omit in geology courses and still include what is really worth the layman's time. In a course on Mineral Resources, I give the students copies of what would be my lecture notes if I lectured and thus leave much class time for discussion. Sometimes the talk catches fire. Sometimes it only smokes. One interesting exercise is to predict the effects of higher energy costs, especially gasoline costs, on living patterns

in Flathead Valley. Lindgren's ghost may not rest easy but the imminent disappearance of large automobiles is a better introduction to energy and metals than is a genetic classification of ores. I have far to go in doing my bit to establish the concept of "spaceship earth" among the citizens of Flathead Valley but I think I am at least on the right track.

Professional teachers are powerful forces within a society, especially if they themselves are informed and concerned. But generally, they are talking to persons who are years away from having an effective voice in change. All of us, however, whether professional teachers or industrial geologists, can reach a broader community through our personal contacts or through civic organizations. We need to inform the Rotarians and the Moose, our priest and our bartender of the finiteness of our resources. With our sense of the brief span of human history, we must temper their unwarranted faith in technology and their optimism in man's always muddling through.

An example shown by one of our colleagues deserves mention. Just two weeks ago a Kalispell geologist (yes, Virginia, there are two geologists in Kalispell) spoke to the Rotary Club about our diminishing resources. He is so convinced of the gravity of the problem that he presented each member (and there were 75) with a copy of Meadows' report, **The Limits to Growth.**

Most of us cannot afford to put our money where our mouth is, but we can do other things. For example, while explaining to the Daughters of the Nile the ultimate insanity of unlimited growth, we can also point out that the mineral industry is the root of the industrial tree. Thus we can act as a brake on the excesses of uninformed environmentalists: those who don't discriminate between the essential and the expendable in industrial society or those, monsters in their own right, who think the way to cure the blight is to cut down the tree.

Recently I attended a meeting in southwestern Utah. The weather was warm and sunny, the air clear. As I was being driven to the airport, the driver, an educator familiar with mining, commented approvingly that the people there appreciated beauty and had passed laws preventing the mining of gypsum. Because of the remoteness of the area, I suspect that banning gypsum in southwestern Utah was like banning beards in a nunnery. But the remark, whether entirely accurate or not, pointed out that even educated men with a fair knowledge of the mining industry do not always see their position clearly: that mineral production is fundamental to our civilization and pollution by mining is likely to be highly visible but relatively easily minimized. Society will learn these basic truths ultimately but its own self-interest will be served by learning them soon. As geologist-teachers, we need to do our part. Otherwise treasure will be lost and stomachs ulcerated unnecessarily.

So much for the call to action. (I told you I would be brief.)

In closing let me presume to be philosphical, as Montana hermits are wont to do. Most of us need goals to live by, codes by which to judge the good and the bad. Irrational codes have flourished since at least the time of the Druids, but the overriding, instinctive, **and** rational code of any species is its own preservation. On this code each of us can weave the fabric of his life.

When one's own species is jeopardized, all is jeopardized. Our species may or may not be in danger, but our civilization is, and in a way many people

do not recognize. As economic geologists, we must continue to provide mineral resources to prevent social chaos. But as geologist-teachers, we must also share our perspective on time and the earth so that our society can chain its monsters and live to the far point of human conception.

LIMESTONE QUARRY IN A GRAVEL PIT

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Abstract

In 1971, American Aggregates Corporation converted one of its gravel pits, on the floodplain of the Scioto River south of Columbus, Ohio, to a quarry for extraction of the limestone bedrock. Problems of development have included dewatering, removal of clayey till from joints and pockets in the limestone, and difficulty in getting the stone to fragment into small enough blocks on blasting.

Upper surface of the bedrock is approximately the top of the Columbus Limestone (Middle Devonian). This surface gives evidence of having been rippled and then later scoured by wave erosion shortly after deposition, to produce subparallel ripple-like forms of a type previously described by the writer and others. In its later history the limestone was jointed and the joints were enlarged by solution; during the Pleistocene they became filled with till. The bedrock has been abraded by meltwater heavily loaded with sand and gravel. As quarrying progresses, it is expected that further information on this exhumed limestone surface will become available.

Introduction

Outwash gravels as much as 60 feet thick, which underlie the floodplain of the Scioto River for some distance south of the city of Columbus, Ohio, have long been extracted commercially. The gravels lie beneath about 10 feet of alluvium, and rest on limestone bedrock. They are strongly cross-bedded, and contain a high proportion of locally derived sedimentary rocks, some scattered granitic boulders, and occasional masses of clayey till.

The largest operator is the area is American Aggregates Corporation, which utilizes large draglines for extraction and a private rail line for transportation of pit-run gravel to the company's plant on Frank Road. Because the gravel lies below river level — which is at 682 to 687 feet — excavation has been done from below the water table, and pits have remained flooded after the gravel was removed. In 1971, it was decided to pump out a pit then being worked, in order to investigate the feasibility of quarrying the limestone bedrock for crushed stone. This program was carried out successfully during the winter of 1971-72, when rock was quarried, crushed, screened, and stockpiled on a small scale using portable equipment. Full-scale operations are planned for the future.

This report, which is primarily descriptive, is an attempt to record the interesting geological information that has so far become available. It is a pleasure to acknowledge the courtesy of American Aggregates Corporation, which gave me permission to visit the quarry as desired, and also to publish this paper. I have profited from discussion of some of the problems with G. E. Klosterman, geologist with the company.

The pit is situated on the west side of the Scioto River just south of Columbus, Ohio. It is about ½ mile east of Interstate 71 and about ¼ mile north of I-270. Access is from State Route 104. The part of the pit in which preliminary work has been done and major quarrying will commence

measures about 1,000 feet in north-south dimension by 600 feet east-west. A northeastward extension, some 2,000 feet long, is being enlarged as removal of gravel proceeds.

Quarry Development

Three major developmental problems have been encountered. These involve keeping the pit dry, handling considerable volumes of muddy till, and breaking up excessively large blocks of stone. Water that seeps into the pit through the permeable gravel is taken by two drainage ditches to a sump at the southern end of the pit (Figure 1), from which it is pumped into a drainage channel beyond a protective dike. Both of the drainage ditches in the pit are joints in the bedrock. One has needed hardly any modification; the other has been straightened and enlarged by blasting. Water encountered in the limestone quarry is pumped into the sump.

Although bedding of the limestone is approximately horizontal, and its upper surface is generally smooth, there are many joints and allied solution features, and these are tightly plugged with dark-gray clayey till. In addition, masses of till were left from extraction of the gravel. The resulting mud constitutes a wet-weather problem. Extensive cleanup was done during preliminary development, however, and it is expected that difficulties can be minimized by careful planning in future quarrying.

Early blasting yielded many blocks 3 feet or more in thickness and 8 to 10 feet on a side. These had to be broken by a drop ball before being taken to the

Figure 1. General view of quarry, looking northeast. Test-run production of stone has been made, and portable crusher and stacker have been removed. Sump is in right foreground, beginnings of limestone quarry in center beyond bulldozer. Dragline removing gravel is partly visible in the distance.

crusher. Blasting may have been in part rendered ineffective because large masses of the thick-bedded limestone simply moved laterally into joint spaces, without shattering. With a hoped-for decrease in the size of fractures at depth, and improvement in blasting techniques with experience, the difficulties of rock breakage should disappear.

Geologic Features

As in most quarries, operations here are not geared to the niceties of geologic observation. Exposures of bedrock are partly obscured by gravel, till, and broken stone, and some areas of the upper surface of bedrock have been scraped and abraded by heavy equipment. Nevertheless it is possible to draw some conclusions with a fair degree of probability.

Over most of the quarry, the upper surface of the bedrock is approximately the top of the Columbus Limestone (Middle Devonian), and it is this formation that will furnish the stone to be quarried. As here exposed, the Columbus is a light grayish-tan, medium-grained relatively pure limestone, which contains abundant corals and other marine fossils and occurs in beds up to 3 feet or more in thickness. In all respects the strata resemble those of the upper Columbus as exposed at quarries on the west side of Columbus and elsewhere in Franklin County.

About 200 feet east of where the quarry will be situated — near the right edge of Figure 1, in the middle distance — a small patch of Delaware Limestone (Middle Devonian) is present overlying the Columbus. Characteristically for this vicinity, it consists of thin-bedded slabby brown limestone, which has a fetid odor when struck and contains lenses of dark chert and thin streaks of pyrite. About 30 feet from this exposure, but not traceable into it at present, is a well developed "bone bed," 2 to 6 inches thick, which lies at the top of the Columbus Limestone. It too seems to be present only as a remnant. The "bone bed" is tightly welded to the underlying limestone, on an irregular surface that has a relief of several inches.

The bedrock surface, where this is the top of the Columbus Limestone, is characterized by wide shallow subparallel linear features (Figure 2). Since this surface bevels fossils and is clearly a product of abrasion, and since it underlies Pleistocene deposits, a natural conclusion is that the aligned features must be related in origin to the work of ice. They are not grooves, however, but shallow troughs 2 feet or more in width and only an inch or two deep; wherever seen in the quarry, they trend almost directly east-west; and, in small areas where the upper 18 inches or so of Columbus Limestone has been removed by erosion, so that the bedrock surface is at a slightly older horizon, the linear features are absent. Thus it seems that they are of Devonian rather than Pleistocene age. They appear to be ripple marks of marine origin, of the type observed at other exposures of this horizon in central Ohio (Bates, 1971), which were scoured and abraded by Devonian waves long before exposure to Pleistocene ice or meltwater.

The crests of the ripples have been scraped and scarred by bulldozers, but most of the troughs are undisturbed. They typically show evidence of intense

Figure 2. Shallow sub-parallel linear features (ripples) on surface of the Columbus Limestone. These are believed to have been formed during deposition of the limestone. They are modified by glacier-produced scratches and by cuspate forms from stream abrasion (Figures 3, 4).

scour by water currents laden with course detritus. Shallow, saucer-like depressions (Figure 3) display a surface that is much smoother than that of an unmodified Devonian ripple, at places almost approaching a polish. Deeper, more sharply incised channels (Figure 4) are delicately etched, displaying small bumps and projections, apparently from silicified fossils.

Thin shallow scratches, but a few inches long and ¼ inch or less in depth, are present at places on the stream-scoured surfaces. These may represent weak abrasion by thin discontinuous bodies of ice, at or near the glacier margin, after earlier floods of meltwater had subsided.

The limestone is cut by joints, which have been enlarged by solution and possibly by abrasion, to widths ranging from a few inches to several feet (Figure 5). The limited information so far available from below the bedrock surface indicates that the joints may lead into a complex system of solution passages. All openings seen to date are packed with gray till (Figure 6). This material not only fills joints that are open upward but also spaces with considerable overhang. The clay is not bedded and does not seem to have been washed into the passages by water. It is envisioned as having been squeezed in when wet, like putty, probably by weight of overriding ice.

As additional sections of the pit floor are cleared of till and gravel, and as quarrying allows further insight into the bedrock, it will undoubtedly be possible to clarify some of the relations that are at present only imperfectly suggested.

Reference Cited

Bates, R.L., 1971, Abraded ripple-marked surfaces in Columbus Limestone, central Ohio: Ohio Jour. Sci. 71(4): 233-40.

Figure 3. Broad shallow trough on rippled surface, which has been scoured into cuspate and saucer-shaped forms by high-energy water currents carrying gravel. Light-colored roughened areas at right and left are ripple crests that have been scraped by a bulldozer blade.

Figure 4. Scoured bedrock surface. A few silicified fossils and other small features stand out in relief. Scale is shown by pocket knife just above dark shadow in center.

Figure 5. Drainage water at right occupies a joint, which has been enlarged by solution and probably also by abrasion. Smooth surface of bedrock is locally "plastered" with basal pebbly sand (under hammer).

Figure 6. Till-packed joint in the limestone. Joint is about 5 inches wide.

LIMESTONE AND DOLOMITE REQUIREMENTS
FOR GLASS CONTAINERS

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Abstract

Limestone and dolomite are the major sources of calcium and magnesium in container glass compositions. Brockway Glass Company, Inc. has chemical specifications for limestones and dolomites which specify tolerances for calcia, magnesia, silica and alumina, and a maximum for Fe_2O_3 of 0.1 percent. Daily measurements of glass density and softening point on each furnace are utilized to monitor variations in raw material compositions.

Limestone and dolomite grain size specifications were established to be compatible for mixing and handling with the other batch raw materials. Excessive fines will carry over into the regenerator sections of the furnace, resulting in buildup and clogging of air passages.

Decrepitation, or thermal fracturing and popping of certain limestones and dolomites, will also create fines and carryover conditions in the furnace.

Brockway Glass Company has utilized recycled glass for many years as a batch component. While the trend is for greater use of recycled glass for ecological reasons, the market for glass grade limestone and dolomite should continue to expand.

Introduction

Brockway Glass Company, Inc. is a manufacturer of glass containers and tubing, with fourteen plants averaging two furnaces/plant in nine states, Figure 1. The diverse geographic locations of these plants require that we utilize limestone and/or dolomite from eleven different locations. An average container glass furnace uses approximately 180 tons/day of raw materials,

FIGURE 1 - BROCKWAY GLASS COMPANY, INC., PLANT LOCATIONS
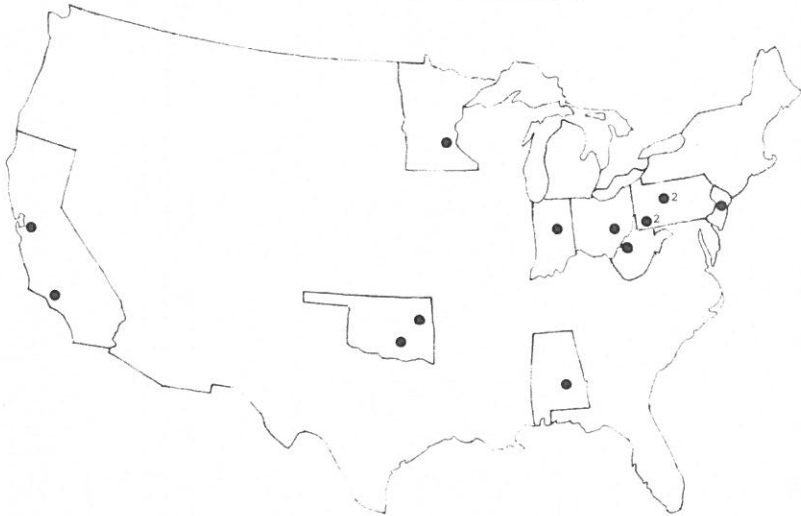
Figure 1. Brockway Glass Company, Inc., Plant Locations

including 32 tons of limestone and dolomite. In an average year, we would use over 300,000 tons of limestone and dolomite in our fourteen plants.

Typical Soda-Lime-Silica Glass Composition

As the name implies, the major components of container glass are silica, sodium, and limestone. A typical chemical composition for clear or flint glass is given in Table 1.

Table 1. Typical Soda-Lime-Silica Glass Composition

SiO_2	71.5 %
CaO	10.5 %
MgO	2.5 %
Na_2O	13.5 %
Al_2O_3	1.2 %

Minor variations from this composition will occur with changes in raw materials and the addition of minor ingredients for green and amber glass.

The major raw material for silica is quite naturally quartz sand, with a minor amount of silica contributed by the alumina source. The alumina raw material varies with our plant locations, but can be nepheline syenite, feldspar, aplite or feldspathic sands. The calcium and magnesium raw materials are limestone and dolomite, and the sodium component is primarily soda ash with minor sodium contributed by the alumina source.

Silica is the glass forming oxide, while the remaining oxides act as fluxes or impart desirable physical properties to the glass.

Chemical Specifications for Glass-Grade Limestone and Dolomite

Brockway Glass Company has standard specifications for glass-grade limestone and dolomite as shown in Table 2.

Table 2. Chemical Specifications for Glass-Grade
Limestone and Dolomite

MgO	within	$\pm$ 0.3 %
CaO	within	$\pm$ 0.3 %
SiO_2	within	$\pm$ 0.3 %
Al_2O_3	within	$\pm$ 0.5 %
Fe_2O_3	less than	$\pm$ 0.1 %

The calcia, magnesia, silica, and alumina are specified as tolerances rather than absolute values. For example, a limestone containing 1.0 percent SiO_2 could be used by making adjustments for silica in the other batch

components, but the silica content in the limestone must remain within the prescribed tolerances from one shipment to the next.

The Fe_2O_3 content is critical because iron will act as a colorant to the glass. The Fe_2O_3 level must therefore be held below 0.1 percent.

Brockway relies on their raw material suppliers to make routine production analyses so that long-term trends for chemical composition of the deposit can be established. We also request suppliers to inform us of changes in quarry or processing operations which would be reflected in the final glass composition.

Brockway Glass Concept of Central Composition Control

Brockway Glass maintains a Central Composition Control group as a part of their Research and Development Department in Brockway, Pennsylvania. One of the responsibilities of this group is to monitor various parameters measured daily on all furnaces. Two of the most sensitive properties, with regard to the composition of the glass, are density and viscosity.

Glass density is measured by the sink-float method against a standard of known density. A typical flint container glass has a density of 2.52 g/cc. Density measurements are made on all furnaces to 0.0001 ± .0002 g/cc.

The softening point is a temperature at which the glass has a specified viscosity in the annealing range. This measurement can be made to an accuracy of 0.2° C.

Brockway's raw materials are selected so that the known compositional variations will not cause the glass density to vary more than ± 0.0007 g/cc. or the softening point to vary more than ± 0.8° C. An example would be the change in composition of a glass-grade limestone in a 2000 pound sand base batch as shown in Table 3.

Table 3. Composition Change in a Glass-Grade Limestone

	Old Composition	New Composition
SiO_2	1.20 %	2.03 %
Fe_2O_3	.10 %	.10 %
Al_2O_3	.32 %	.28 %
CaO	54.32 %	53.37 %
MgO	.60 %	.55 %

This composition change would be reflected by a decrease in glass density of 0.0010 g/cc and a decrease in the softening point of 0.6° C.

Grain Size Specifications

The size specifications for limestone and dolomite were established to maintain a compatible range with the other batch raw materials. Such factors

as segregation of the batch materials during mixing and transport to the furnace, and the melting characteristics of the batch were considered in these specifications.

Brockway's size specifications for limestone and dolomite are shown in Table 4.

Table 4. Grain Size Specifications

Limestone

On U. S. 12 mesh	-	0 %
On U. S. 20 mesh	-	20 % max.
Through U. S. 170 mesh	-	5 % max.

Dolomite

On U. S. 8 mesh	-	0 %
On U. S. 20 mesh	-	20 % max.
Through U. S. 100 mesh	-	10 % max.

An excessive amount of fines can create dusting problems during handling and mixing of the batch materials. Fines will also be carried over into the regenerator sections of the furnace, causing buildup and eventual plugging of air passages.

Decrepitation of Limestones and Dolomites

Decrepitation is a physical oddity of certain limestones and dolomites. Fracturing and even violent popping of grains will occur in the range of 350° to 600° C, well below the temperature of dissociation. The result of using a high decrepitation limestone or dolomite in a glass batch would be similar to using a material with excessive fines. When the batch enters the furnace, the popping of the grains creates fines which are carried over into the regenerator sections of the furnace.

Brockway Glass Company has a specification of 10 percent maximum for decrepitation loss on limestones and dolomites. Periodic tests are run on all supplies, since variations in decrepitation have been noted within a deposit or from one section of a quarry to another.

Glass Recycling and Effects on Raw Material Requirements

Recycling of glass in container glass furnaces has been a common practice for years to utilize glass drained from the furnace during periods of routine maintenance and containers rejected for production defects. Recycled glass or cullet, as it is known in the container industry, commonly makes up 10 - 12 percent of a typical glass batch.

The advent of container recycling as related to the environment has increased cullet use in several of Brockway's plants, particularly those located

near metropolitan areas. Cullet levels as high as 30 percent of the total batch weight have been used with good success.

In spite of the increased use of recycled cullet, the market for glass container grade limestone and dolomite should continue to expand with the projected annual expansion of the glass container industry.

Summary

Limestone and/or dolomite constitute approximately 18 percent of a typical container glass batch. Chemical requirements are a Fe_2O_3 level below 0.1 percent and maintaining the major oxides within prescribed tolerances. The sizing requirements are specified to maintain compatibility with the other batch raw materials. Decrepitation should be held below 10 percent loss by weight.

Acknowledgments

USE OF LIMESTONE IN IOWA ROAD CONSTRUCTION

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Iowa State Highway Commission

Abstract

Most of the limestone produced in Iowa is used either in the construction of new highways and roads or in the renewal and maintenance of older ones. Surface or near-surface occurrences of rocks from the Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian Systems provide sources of crushed limestone utilized by the road construction industry.

The physical characteristics of a rock that determine its acceptability as a specific type of limestone aggregate are often persistent over large areas. Proceeding from the Ordovocian on through the Pennsylvanian, this paper describes the area of occurrence and types of aggregate available from the various members of the stratigraphic sequence.

Introduction

The State of Iowa contains vast supplies of limestone but the naturally occurring sand and gravel deposits, while numerous, generally contain only small quantities of coarse gravel. Consequently, most of the road construction aggregates are produced from limestone deposits. While the total supply of limestone is essentially inexhaustible, the distribution of economically accessible deposits is very poor. In northeast Iowa numerous surface and near-surface occurrences of Ordovician and Silurian rocks provide many readily available sources of high-quality aggregates, but progressing southwest from there, successively later Paleozoic rocks of generally decreasing quality and availability are encountered. In northwest Iowa, where the Paleozoic rocks are overlain by Cretaceous sediments, there are no sources of limestone aggregates.

Uses and Quality of Limestone Aggregates

Most mineral aggregates are used in subbase, base, and surface courses of constructed roadways and on the shoulders adjacent to the paved surfaces. There are several variations of each of these uses, each requiring a slightly different aggregate. All aggregates for these purposes are crushed to a maximum particle size of 1½″ and most to a ¾″ maximum size. There is also some use of limestone aggregates as backfill material and as revetment stone and riprap for slope protection on embankments where there is danger of erosional damage.

Subbase and base courses require only the low to moderate quality aggregates since they are protected from exposure to the elements and traffic wear by the covering pavement. The granular surfacing of unpaved rural roads also need not be of high quality since it is a temporary surface which is periodically renewed. Paved surfaces, however, portland cement or asphaltic concretes, are designed to perform for twenty to thirty years with a minimum of maintenance. Aggregates used in these surfaces must be of high quality in order to resist the wearing effects of vehicular traffic and exposure to weather

combined with the application of deicing sands and salts during the winter season.

Asphaltic concrete pavements are still in a relatively early developmental stage. Their serviceability is presently more affected by the mix design of the asphaltic concrete than by the quality of the aggregate used. The major area of general interest is in regard to the degree of skid resistance the aggregate imparts to wearing surfaces. Even though carbonate aggregates tend to polish readily under traffic, it is apparent that the normal traffic volumes encountered in Iowa are such that a number of limestone aggregates will be sufficiently skid resistant to allow their use in asphalt surfaces.

Determination of Aggregate Quality

There are many aspects to aggregate quality. Under the climatic conditions experienced in Iowa, the most important is the ability of the aggregate to withstand several seasons of Freeze-thaw activity with minimal particle breakdown. The tests employed to measure this are Iowa 211-B, Methods 'A' and 'C', which are Freeze-thaw tests of unconfined aggregate.

Portland cement concrete pavements, on the other hand, have been in use in Iowa since 1914. An extensive record of both good and poor pavement serviceability attributable directly to coarse aggregate type has been compiled. It is this record that prompted the few changes that have been made in the quality testing of aggregates.

Determination of Aggregate Quality

Method 'C' is 25 Freeze-thaw cycles in ordinary tap-water, for lower quality aggregates, and Method 'A' is 16 Freeze-thaw cycles in a water-alcohol solution, for higher quality aggregates. (Iowa State Highway Commission, 1971, Sec. 211-B).

During an extensive road-building program in the late 1920's and early 1930's, hundreds of miles of highway were paved with portland cement concrete. Some deteriorated rapidly after a few years while others are still in service after more than 40 years. The poor highways were later found to contain argillaceous limestones as the coarse aggregates. These proved to be very susceptible to the Method 'A' Freeze-thaw test and from 1952 until recently it was the only test measure of soundness for high-quality aggregates used by Iowa. In the late 1950's a type of early deterioration of concrete now known as 'd-cracking' became apparent. It is caused by the use of certain coarse aggregates, all of which in use now perform extremely well on the normal Freeze-thaw test. For aggregates with no service record, a test method similar to ASTM C 291 is now used to identify those which may cause 'd-cracking'. This test measures the decrease in resonant frequency of concrete beams during 300 cycles of freezing in air and thawing in water. It is fairly reliable but also is very expensive and time consuming. Other tests were tried but found to be ineffective.

The measured loss in the Method 'A' Freeze-thaw test is that portion of the sample which passes a Standard U. S . #8 sieve after testing. It has been

observed that those aggregates used in Iowa which cause 'd-cracking' also disintegrate under unconfined freezing and thawing, but not down to the #8 sieve size. Thus, it appears that a variation of the presently used Freeze-thaw test might identify susceptible aggregates and replace the test currently being conducted on concrete beams.

Sources of Limestone Aggregates

All of Iowa's limestone aggregates are derived from Paleozoic rocks. The Permian, absent in Iowa, and the Cambrian sandstones, exposed in the extreme northeast corner of Iowa, do not provide any sources of crushed aggregates. All other Paleozoic Systems do.

Ordovician System.

The Ordivician is an important source of aggregate in the northeast corner of Iowa.

The Oneota Member of the basal Prairie du Chien Formation contains many feet of massively bedded dolomites of high aggregate quality. The area of occurrence is limited, however, to portions of Allamakee and adjacent counties where aggregate demand is quite low. To date, 55 feet is the thickest unit of Oneota beds found to comply with specifications for use in concrete. Thicker sections are known to exist but have not been tested.

The Galena Formation has been used extensively. It is separated from the Prairie du Chien by the Saint Paint Sandstone, Platteville, and Decorah Formations in ascending order and occurs in a narrow belt from south of Dubuque for more than a hundred miles northwest through Decorah into Minnesota. Quarry ledges of 50 feet to more than 100 feet thick are common.

The basal Prosser Member of the Galena Formation is a cherty dolomite of good quality in the Dubuque area. To the northwest it becomes very argillaceous and is a good source of lower quality aggregates only.

The middle Stewartville Member is a non-cherty dolomite and changes laterally in a northwesterly direction to a limestone. Despite the lithologic change, the quality of the unit is very consistent and many quarries supply high quality aggregates throughout the area.

The upper Dubuque Member, seldom over 30 feet thick, is usually quarried only in conjunction with the underlying Stewartville. It is a source of lower quality aggregate only and must be removed by a separate operation when concrete-quality aggregate is being produced from the Stewartville Member.

The Maquoketa Formation overlies the Galena. It is primarily a shale and except for a small area in Winneshiek County contains no aggregate sources at all.

Silurian System

The Edgewood and Kankakee Formations of the basal Alexandrian Series are of little importance as sources of limestone aggregates. They are used locally in some areas and supply material of low to moderate quality.

The overlying Hopkinton and Gower Dolomites of the Niagaran Series, however, are quarried extensively throughout their outcrop area in eastern Iowa reaching from the Cedar Rapids, Davenport, and Clinton urban areas northwest into Fayette County. Uniformity of quality, vertically and laterally, is generally lacking in both the Hopkinton and Gower requiring fairly extensive prospecting and sampling to locate sources of consistent high quality. However, in the Cedar Rapids area there is in excess of 200 feet of Hopkinton and Gower beds that are of consistent high quality. The total Silurian thickness there is nearly 350 feet.

Devonian System

Devonian stone occurs under near surface conditions in a wide area from Muscatine northwest to Minnesota in the Mason City area, a distance of nearly 200 miles.

The basal Wapsipinicon Formation is quarried principally in an area from eastern Muscatine County northwest toward Buchanan County. The overlying Cedar Valley Formation is quarried throughout the entire area. Both of these are of Middle Devonian age and contain horizons of both poor and high-quality aggregates. These horizons are generally persistent over large areas with little change in quality. Thus the lower part of the Coralville Member of the Cedar Valley Formation is a source of concrete quality aggregate for more than one hundred miles from Chickasaw County south into Johnson County.

The Upper Devonian Shell Rock Formation overlies the Cedar Valley in a small part of northern Iowa in the Mason City area where it is a good source of aggregate. The remainder of the Upper Devonian, however, consists of shales or soft limestones and dolomites and provides no sources of crushed aggregates.

Mississippian System

Mississippian stone occurs west of the Devonian outcrop area from the southeast corner of Iowa northwest for about 230 miles into western Humboldt County. It contains several formations which supply aggregate of poor to excellent quality. Generally, the Gilmore City and Hampton Formations of the basal Kinderhook Series supply aggregates of consistent

high quality, principally in the central Iowa area between Ft. Dodge and Marshalltown. Formations of the overlying Osage and Meramec Series are found through southeastern Iowa and occasionally contain sources of high quality aggregate but generally are so variable in character and quality as to make the location of good aggregate sources difficult.

Pennsylvanian System

Pennsylvanian rocks occur throughout southwestern Iowa. They consist of cyclic deposits of relatively thin limestones and shales. The limestones are mostly of only poor to moderate quality and are generally covered with thick glacial drift or loess deposits. Consequently, southwestern Iowa, being nearly devoid also of suitable natural sands and gravels, is an aggregate-poor area. This situation is then aggravated by the fact that the few Pennsylvanian quarries that have supplied concrete-quality aggregates are also associated with the 'd-cracking' phenomenon. Southwestern Iowa is, then, one of the real problems of aggregate supply in Iowa.

Reference

Iowa State Hwy. Comm., 1971, Materials Dept. Lab. Manual, v. 1, sec. 211-B

PENNSYLVANIAN CLAYS & SHALES OF SOUTH-CENTRAL IOWA

by

George R. McCormick

Abstract

To date little systematic minerological and chemical investigation has been done on clays and shales associated with Pennsylvanian Coal deposits of South-Central Iowa. Clay products plants have in part used these clays for production of brick or tile. The operators choice of clays was based on outcrop availability and firing properties, rather than on mineralogy and chemistry.

This study was designed to determine by semi-quantitative methods the kinds and amounts of clay minerals present and by atomic absorption methods the parts-per-million of total iron content in the clay deposits. Samples were taken from the 15 available strip mines and two underground mines in Mahaska, Marion, Keokuk, Monroe, Appanoose and Lucas Counties. Clay samples were taken at two foot intervals in the mines beginning with the underclay. The less-than-two-micro fraction was separated from each sample of clay minerals present. A portion of the bulk samples were put in solution by perchloric-hydrofluoric acid treatment, diluted and analyzed by atomic absorption methods for total iron content.

Results of the investigation revealed that in all races the major component present beside kaolin and illite in the bulk samples was quartz, with minor amounts of calcite. The clay fraction analysis varied from 38% to 60% kaolin and 17%-56% illite with the remainder being mixed-layered material and minor chlorite.

In any given mine there was found to be little, if any, difference between percentage of individual clay minerals present in the underclay and the shales above the coal seam; the major difference is in the iron content. Underclays usually contain less than 1,000 gpm. iron; some were as low as 123 gpm. iron. Shales above the coals contain more than 4,000 gpm. iron; some contain as much as 106,000 gpm. iron.

Introduction

At the present time there is little information in the literature concerning the mineralogy and chemistry of Iowa clays. Lemish (1960) states "Kaolin rich clays such as the under clays which commonly occur beneath coal beds and the purer montmorillonite clays have not been identified in Iowa because of the lack of systematic study rather than their absence." Fifty years ago there were over 300 brick and tile plants in Iowa but today there are only 19. During these 50 years production of ceramic products has increased. Due to better production methods and improved transportation, the number of small inefficient plants has declined. Over half of all clay and shale mined in Iowa is used as a source of alumina and silica in the manufacture of Portland Cements; the rest of the clay is used primarily for structural clay products.

Sweeney and Hamlin (1963) conducted bloating experiments on selected Iowa shales, clays and loess to see if any were suitable for lightweight aggregate production. With the exception of samples from the upper portion of the Pleasanton Fm. near Centerville, all results were negative. Carter-Waters has subsequently put into operation a lightweight aggregate plant at Centerville. The report of Sweeney and Hamlin (1963) contains no mineralogy or chemistry for materials tested. The experiments of Sweeney and Hamlin consisted only of heating, flash melting, and shrinkage tests.

.Several states have undertaken systematic clay investigations, among the leaders are Illinois and Minnesota; works by Odam and Parham (1968), Grim and Alan (1938); Grim, Bradley and White (1957); and Schultz (1968) are examples. The Minnesota Geological Survey is rapidly gaining in the number of clay investigations with Walter Parham's move to Minnesota from Illinois; Parham and Austin (1969) and Parham and Austin (1967) are examples.

The most complete study to show correlations between the underclays of various geographical areas was done by Schultz (1968). Schultz collected and analyzed underclay samples in the Appalachian Basin, Illinois Basin, and Mid-Continent Basin of which Iowa is a part. Schultz included only three Iowa samples from the very southern part of the state in Appanoose County; two samples were from the upper Desmoinsian Marathon Group and one sample was from the Missourian. It is not clearly stated whether Schultz collected these samples himself or used data from a study by Cline (1941).

Schultz separated the clay minerals, analyzed them semi-quantitatively by X-ray diffraction, and presented the results on pie diagrams.

It was felt that a more thorough evaluation of Iowa clays for industrial use could be performed if a systematic mineralogic and chemical study of Iowa clays was first conducted. The study was begun on accessible Pennsylvanian underclays and shales of South-Central Iowa.

Location of Investigation

The geographic area considered for this investigation was a six-county area (fig. 1) in South-Central Iowa. This area is located on the Eastern-most edge of the mid-continent basin (fig. 2). Samples were collected from 9 active strip mines, 2 underground coal mines, 1 abandoned strip mine, and the 1 active clay pit at What Cheer, (fig. 1). All of the coal mines were recovering Lower Coal-Ford Coal from the Lower Cherokee; the What Cheer Clay pit is cut into an abandoned underground mine in the Lower Coal-Ford Coal.

This six-county area was chosen for the following reasons:

1) The area is currently the site of all coal-mining operations in Iowa and also contains the greatest coal reserves (1,288 million short tons of recoverable reserves) (Landes and Van Eck, 1965). Clays and shales which might be useful industrially but economically marginal to mine if pits were to be opened only for clay, could be recovered economically from coal mine operations where they have to be moved in order to recover the coal.

2) Due to the approching fuel crisis there is a good possibility of increased coal mining operations in Iowa. If this does occur a great part of the increase will be in the six-county area.

3) If good quality fireclay or bloating clay is to be found it would be expected in the Pennsylvanian underclays and shales.

Method of Sample Collecting

At each sample location, samples were taken at two-foot intervals starting with the underclay below the coal seam and proceeding up the section to as
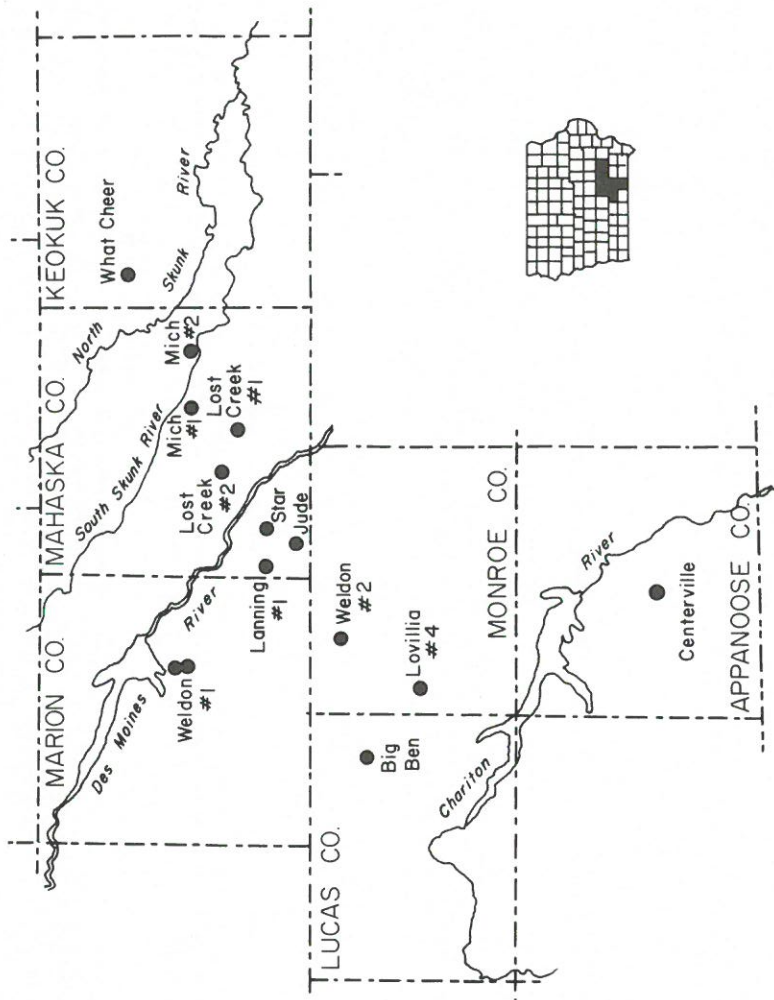
Figure 1. Index map of the 6 county area of study showing the coal mines that were sampled.
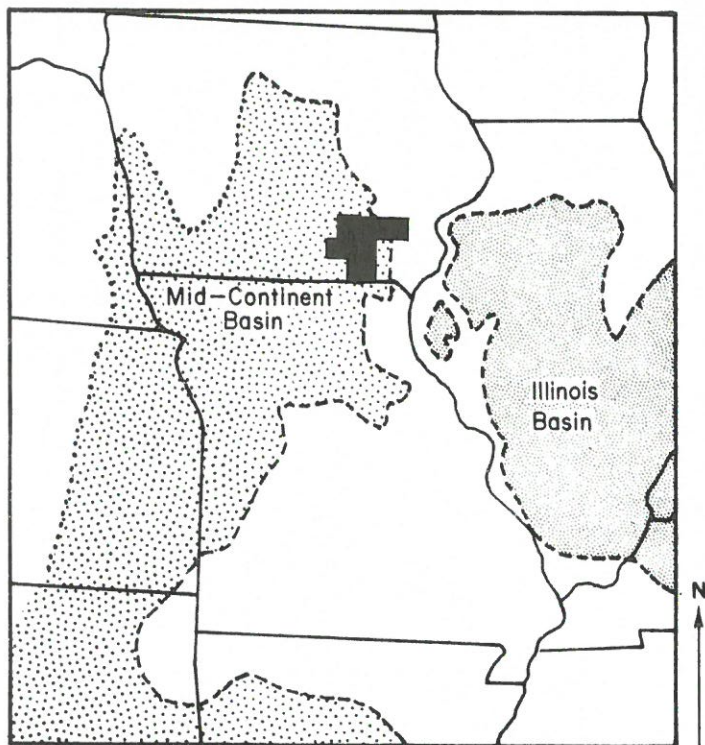
Figure 2. Map showing the relationship of the Mid-Continent Basin to the Illinois Basin. The Forest City Basin is the projection at the common corners of Kansas, Nebraska, Missouri and Iowa. The black area shows the relative position of this investigation.

near the surface of the pit as possible. When the bulk of the material appeared homogeneous, samples were taken at intervals of two feet; however, in the event of appearance of different lithologies, each layer was sampled, even if only two or three inches thick.

Method of Analyses

Qualitative and quantitative results obtained on clay fraction analysis are found to be affected by sample treatment (McLaughlin, 1955; McKenzie and Jackson, 1964; Jackson, 1956; Jackson, 1964; Ferrell and Grim, 1967). In this study the collected samples were processed to separate the less than 2 micron clay fraction using a slaking technique. About 10 grams of each sample was ground in water for 5 minutes, dispersed in 100 ml of water and allowed to stand for 10 minutes, then a dropper full of the resulting suspension was removed from just below the liquid surface. This suspension was placed on a glass slide and the water allowed to evaporate.
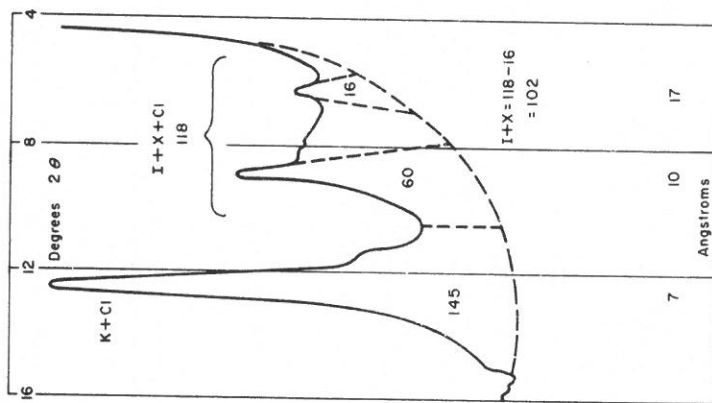
CALCULATIONS
Total Area = 145+102 = 247

$$\frac{K+Cl}{I+X} = \frac{145}{102} = \frac{59\%}{41\%}$$

$$\frac{1}{X} = \frac{60}{42} = \frac{59 \cdot 41}{41 \cdot 41} = \frac{24\%}{17\%}$$

$$\frac{K}{Cl} = \frac{145-16}{16} = \frac{89 \cdot 59}{1.1 \cdot 59} = \frac{53\%}{7\%}$$

K = Kaolinite
I = Illite
X = Mixed Layer
Cl = Chlorite

Figure 3. Calculations of clay percentages from spectrometer traces.

Qualitative identification of clay minerals by X-ray diffraction was done after the method of Dorothy Carroll (1970). Quantitative determination of clay minerals present was performed by the method of Schultz (1958) with one modification; the logarithmic chart was analyzed using the peak area rather than the peak height. Schultz found that illite and kaolinite are best determined by a 1/1 ratio of peak area on a logarithmic plot, regardless of the crystallinity; this same assumption has been made in this study. Figure 3 contains a smoother logarithmic trace and shows a sample calculation as used in this study to determine relative amounts of clays in each sample.

Chemical Analysis

Partial chemical analyses for Fe, Zn, Cu, Ba, Ni, Ca, and Mg were determined by the atomic absorption method using a calibration curve for each element. Based on Jackson's (1956) discussion of the removal of

exhangeable ions and Angino and Billings (1967) discussion of the preparation of samples, four means of preparing the samples for analyses were tried in an attempt to find a one solution process for all ions of interest. The one solution process was desired to avoid the problem of obtaining a constant weight for clays ground to 100 mesh in more samples than necessary. The four solutions tried were a sodium acetate at ph[5], sodium nitrate-bicarbonate-chelate-buffer solution, concentrated HNO_3 and concentrated HCL. The concentrated HCL gave the best results and was used for all samples in this study.

MONROE COUNTY

Figure 4. Clay fraction analysis of the shales sampled in the operating mines in Monroe County. The numbers along the edges of each column represent the position of the sample as measured from the coal seam.

LUCAS COUNTY

Figure 5. Clay fraction analysis of the shales sampled in the operating mine in Lucas County. The numbers along the edges of each column represent the position of the sample as measured from the coal seam.

MARION COUNTY
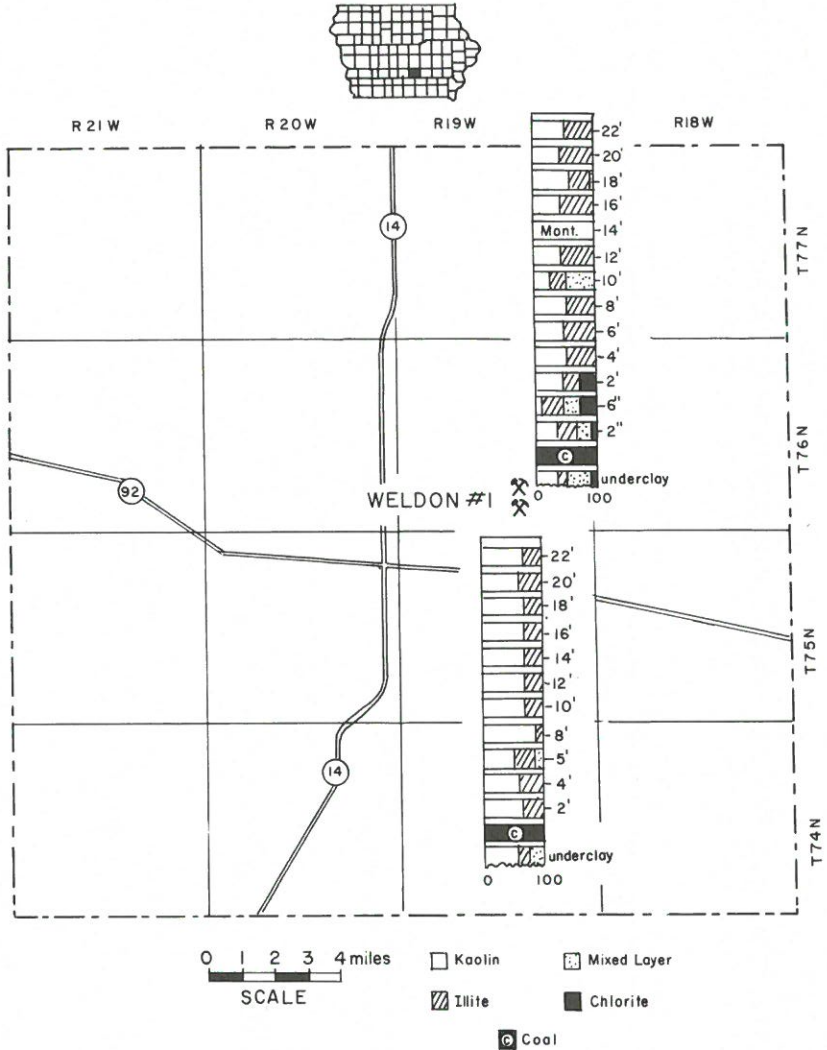
Figure 6. Clay fraction analysis of the shales sampled in the operating mines in Marion County. The numbers along the edges of each column represent the position of the sample as measured from the coal seam.

MAHASKA COUNTY
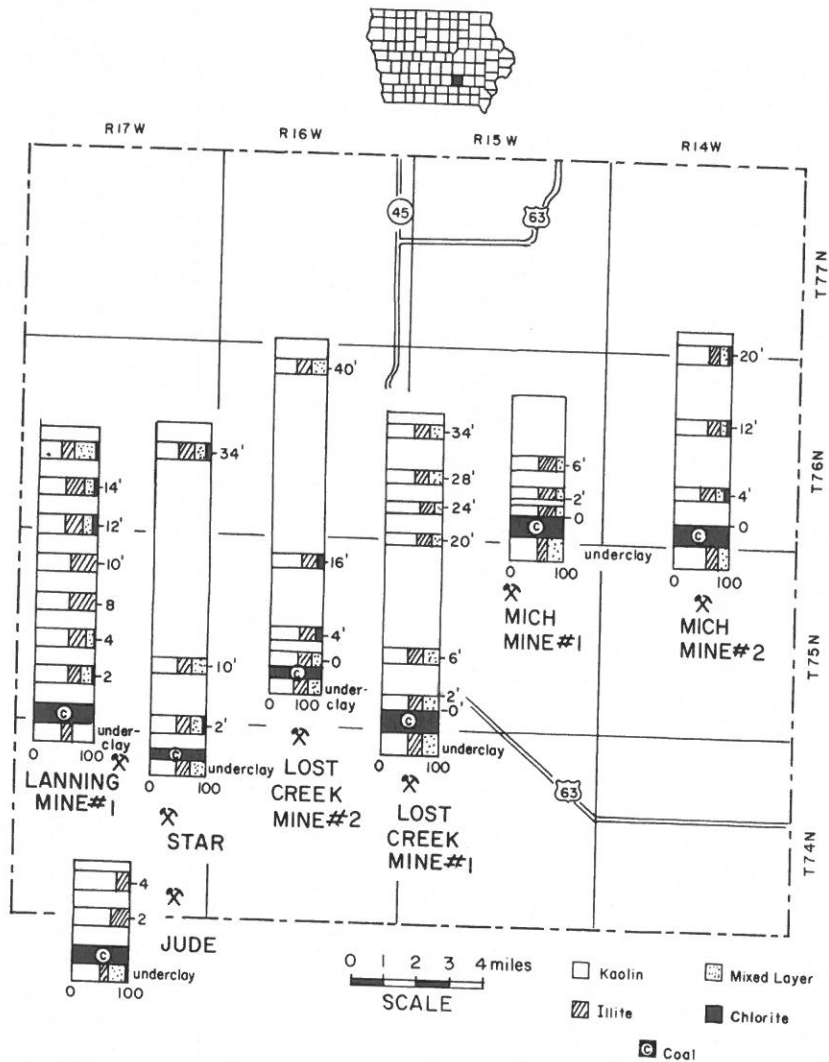
Figure 7. Clay fraction analysis of the shales sampled in the operating mines in Mahaska County. The numbers along the edges of each column represent the position of the sample as measured from the coal seam.

KEOKUK COUNTY

R13W   R12W   R11W   R10W

149

22

22

T77N

WHAT
CHEER
⚒

Mont. 28'
Mont. 26'
Mont. 24'
Mont. 22'
20'
18'
16'
Mont. 14'
12'
10'
8'
6'
4'
2'
Ⓒ
-2'
-3'
-4'
-5'
-6'

0   100

92

149

78

T76N

T75N

T74N

0 1 2 3 4 miles
SCALE

☐ Kaolin   ▦ Mixed Layer
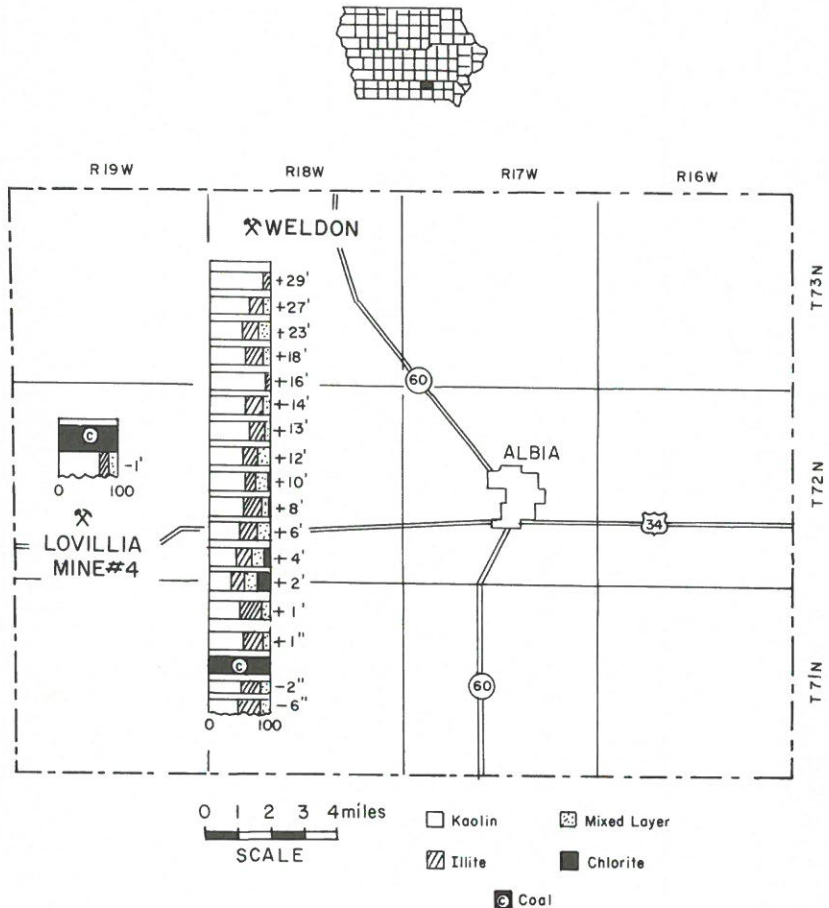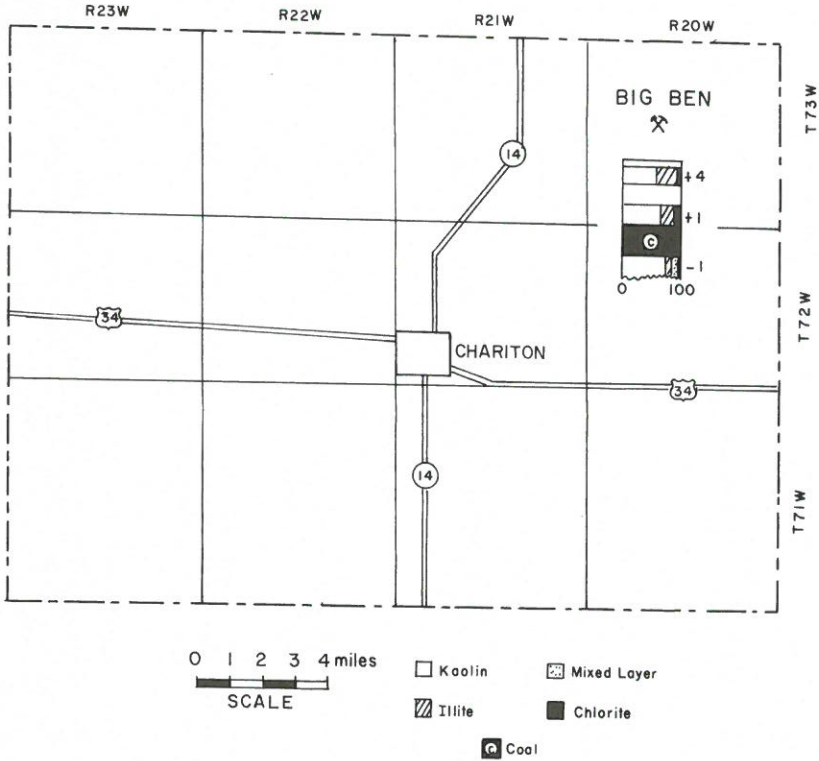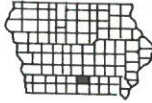▨ Illite   ■ Chlorite
Ⓒ Coal
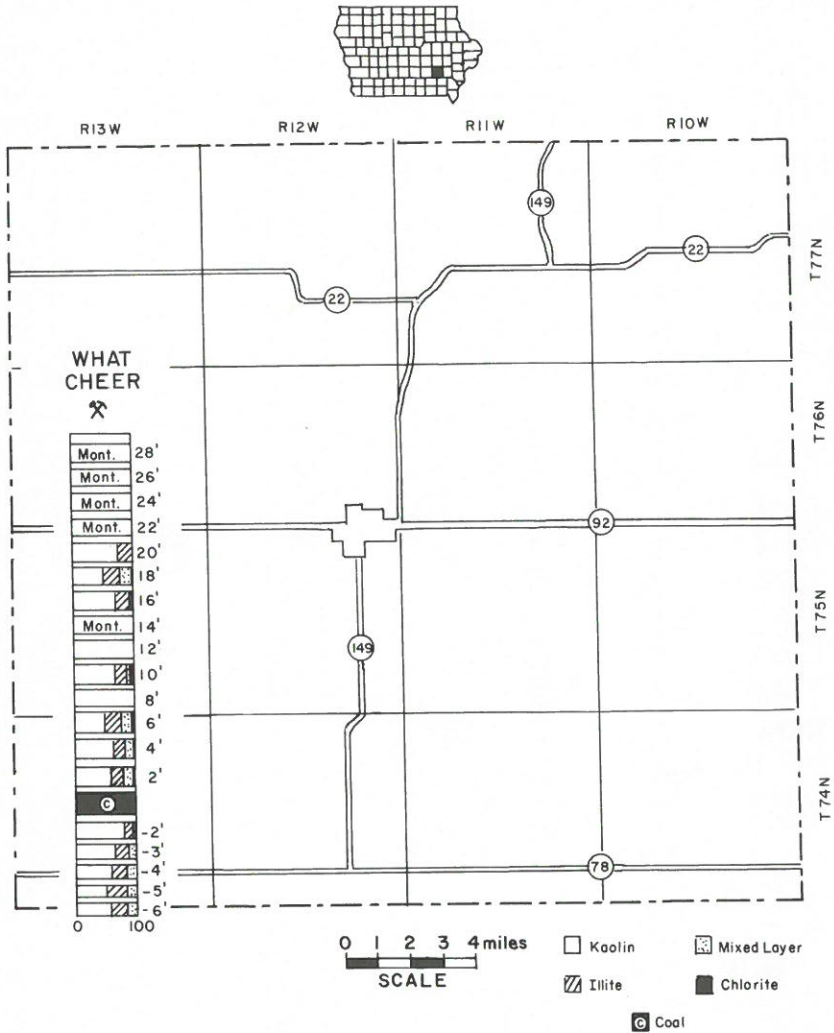
Figure 8. Clay fraction analysis of the shale samples in the operating clay mine in Keokuk County. The numbers along the edges of each column represent the position of the sample measured from the coal seam.

PARTIAL CHEMICAL ANALYSIS OF PENNSYLVANIAN
UNDERCLAYS AND SHALES OF SOUTH-CENTRAL IOWA
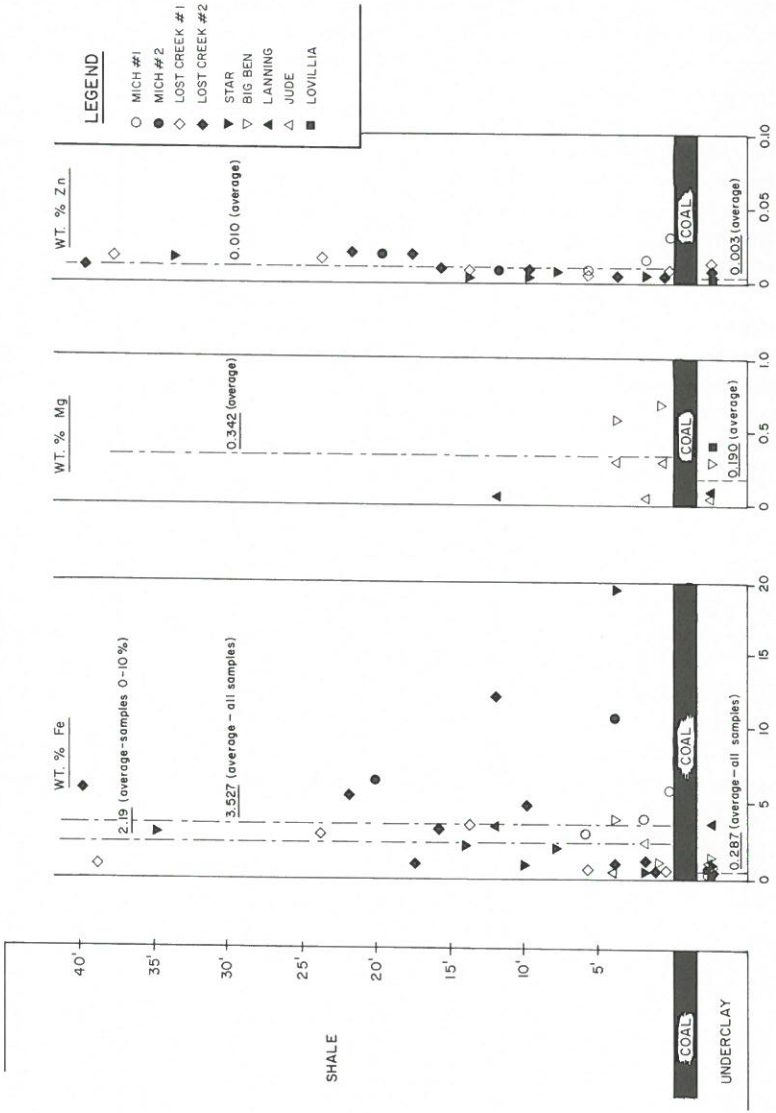
Results and Interpretation

The mineralogic study revealed that all underclays and shales above the coals are essentially a three phase mixture of kaolin-illite-mixed layered (illite-type) with minor amounts of chlorite in some samples. Montmorillonite was encountered only in the zone of weathering or along fissures through the shales. Figs. 4-8 contain the clay mineral analysis in bar graph form for all samples in each mine investigated.

It will readily be seen that kaolin on the average comprises 50% or better of each sample. There is no detectable clay mineralogy difference between underclays and shales above the coal. In outcrop the underclays are white to light buff and massive whereas the shales above the coals are bedded and dark grey to black. No iron sulfides were observed in the underclays but they were abundant in the dark shales above the coals.

Chemical analyses of selected bulk clay and shale samples revealed the major difference between underclays and shales above the coal was in the content of Fe, Mg, and Zn (Fig. 9). The weight percent of Cu, Ba, Ni, and Ca determined in all samples was less than 0.001%. The greatest difference was in iron content. Two averages for Fe content in the shales above the coal are shown in fig. 9. All samples containing from 0-10% Fe contained no visible sulfides; the three samples containing 10-20% Fe did contain visible sulfides.

Conclusions

1) All underclays and shales above the coal are basically a three phase assemblage of kaolinite-illite-mixed layered with minor Fe-rich chlorite.

2) The major difference between underclays and shales above the coal is the total Fe content. Visual examination indicates most of the Fe is tied up in sulfides which could be beneficiated out of the shales.

3) High percentage of kaolin and low percentage of montmorillonite indicates the prospect of the clays being suitable for bloating for lightweight aggregate is not good.

4) Shales above the coals which contain essentially a two-phase assemblage of kaolin and illite with illite greater than 34 wt., % might make good bloating refractory ladle bricks.

5) All underclays and shales above the coal in this study should be usable for structural clay products and portland cement; since Fe content is less than 5%; the underclays are all of fireclay quality.

6) Any further studies on these Pennsylvanian clays should include total chemical analyses of the shales in order to determine percent of organic material, silicon, and aluminum in addition to the alkalais and other trace elements.

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STRUCTURAL CLAY—WHERE IS IT?

Don W. Steffen
Can-Tex Industries

Abstract

The paper deals with the structural clay industry of the 1920's, the present and the future. It looks at all three periods in terms of types and processing of materials; production plants and handling equipment; and markets and end-use equipment. While the number of producing plants and companies is continually decreasing; automation, improvement of the final product and method changes in the end use of the product predict a strong future for the industry.

Introduction

The title of this paper is Structural Clay — Where is it? Before getting into "where is it", it would perhaps be best to say "what is it?" As most of you are aware, the Structural Clay Branch of the Ceramic Industry manufactures a relatively low-cost and high-tonnage material that is used in the construction industry. Brick, structural tile, drain tile, clay sewer pipe, flue lining and wall coping fall into this category of structural clay, as opposed to those higher-priced, lighter-weight members of the Ceramic Industry, such as glazed ceramic tile, dinnerware, electrical porcelains, etc.

Now, where is it? I prefer to think of it in the modern vernacular of where it's at, meaning, this is where it's happening or where the action is. Structural clay has been around for a long time and although the number of companies and factories seems to be rapidly decreasing, structural clay is changing and will be here for a long time to come. It is a modern progressive industry and it's great to be a part of it.

In order to look at the future, it is sometimes first necessary to look at the past. This paper will take a look at the materials, methods, end-products and usage of structural clay products in the recent history of the Twenties to Forties, the present of the late Sixties, and the future as it looks from the vantage point of this individual.

Recent History

This period of the late 1920's to the late 1940's, I am choosing to call recent history because structural clay goes way back over 5000 years. Brick was used back in those very early times as a building material for housing and brick and hand-turned clay pipe for storm drainage lines to carry away rain water and occasionally sewage from buildings.

I would like to deal first with the recent histroy of brick and structural tile. In the late Twenties, there were approximately 1975 plants throughout the United States that were producing 23,000,000 tons of brick and structural tile. This number of plants decreased over half to 826 producing about 15,000,000 tons by the late Forties. Much of this decline was due to the depression years followed by the shortage of male workers during World War

II when many plants were forced to close their doors. Following World War II, there was an upswing of production to try and catch up and make up for the war years. During these twenty years, the clays used and the methods used to process the clays changed very little. The clays were surface clays, fire clays, or shales, and, in many cases, were located immediately adjacent to the brick plant. In some cases, they were mined underground but mostly were mines in open pits by shale planers, shovels or drag lines and, in some cases, by hand. Once in awhile, clays were hauled to the crushing plant by conveyor, but were more likely to be hauled by mine cars and donkey locomotives or trucks. Extensive mineralogical and ceramic testing was rarely engaged in, although some testing for ceramic properties was done. Most of the brick and structural tile were extruded by auger machines and, in many cases, through the late Thirties and Forties, the clays were extruded under vacuum or de-airing to produce a denser, less laminated body. Brick and structural tile were hand-picked off the extrusion belts and loaded onto little railroad-type dryer cars which were hand-pushed into tunnel dryers where the moisture was removed. The cars were then pushed to periodic kilns where the material was hand-set for the firing process. Firing was done with coal unless gas or oil was cheap and available. The colors obtained were the natural ones of the clay or the flashed tan or black of coal smoke. Occasionally, a green flash was produced by a certain type of additive mixed with the fuel at the flashing process. Upon cooling, the material was hand-unloaded, sorted and stacked on the yard until it was ready to be loaded in boxcars or on trucks and sent to the jobsite. By the time the brick or structural tile got to the wall, it had been handled and sorted and mixed about eight times. Thus, the wide color variations caused by lack of control in firing became a blended part of the overall color of the wall.

Brick of this period were mostly in the standard size of 8″ x 4″ x 2-⅜″ high with the structural tile being in a wide variety of sizes depending on whether they were back-up or face material or partition tile. They were used extensively in residential and commercial construction and were hand-laid. Variety was achieved, aside from the colors mentioned, by the limited number of textures that were available at the time.

Drain tile, sewer pipe and flue lining were produced in 440 plants in the amount of 2,500,000 tons in the late Twenties. The number of plants had decreased to about 275 by the late Forties, but this number of plants was producing almost the same amount of tonnage as had been produced in the late Twenties. Clays and methods of mining were similar to those used for brick and structural tile with perhaps a little better selection of clays needed for pipe. Most drain tile were extruded, similar to the structural tile of the period, while most sewer pipe were vertically pressed with steam cylinder presses. De-airing of the sewer pipe body came into being in the late Thirties and early Forties. Pipe was made in short lengths with lots of hand labor. It was dried in four and five story loft-type buildings with slotted floors and natural ventilation with steam coils for heat and then fired in round periodics with coal, oil or gas. Sewer pipe of this period was all salt glazed during the final stages of firing to give an impervious surface and cover up a number of defects which were inherent in the clays, or the processing, of the period.

Shipping of drainage tile, sewer pipe, flue lining and wall coping was done mostly by rail to the city involved and then trucked by the customer to the jobsite. There was extensive breakage due to handling during the shipping in the railroad cars and also in the transfers involved before the material was in place on the job.

Flue lining and wall coping were used extensively for commercial construction during this period and lots of flue lining went into residential houses which had fireplaces or were heated with coal. Sewer pipe was used not only for sewers, but also for storm drains, either separately or combined in many cases. Generally, sewage was treated prior to being dumped into watersheds. Factory-applied jointing was unheard of at this time and all the pipe were put together in the field with cement or asphaltic joints of one type or another. In spite of the best of efforts, jointing was frequently poorly done. This allowed excessive ground water infiltration into the lines.

Drain tile was used in great quantities in the rural areas to eliminate swampy conditions in low lying areas and to enable the farmers to get into their fields earlier and utilize more of the fields. In the west, as the great irrigation projects were developed, it was found necessary to install drain tile within a very few years following irrigation to prevent swamp creation.

Present

The brick and structural tile industry of today is producing approximately 15,800,000 tons which is the same as the late Forties, but is producing it in 482 plants as opposed to the 826 of that time. This tonnage today, incidentally, has a dollar value of around $325,000,000. Today, the product is mostly face brick and through-the-wall units, which could be called vertical cell brick or tile. Substitutes of one type or another have taken over and back-up and partition work that used to be done by the structural tile part of the business.

To make the brick of today, just any old surface clay won't do. Modern laboratories incorporated in the plants study clays for mineralogical and ceramic properties. Clays are mined at different places or from different strata in pits and are blended to produce the desired bodies. In many cases, additives are used to enhance the properties. A wide variety of colors and textures from ultra-modern to ultra-antique are created by the use of colorants, engobes, sands and a variety of texturing equipment.

Current brick plants cost about $3,000,000 and employ the latest in automatic equipment. The various clays are crushed, ground and screened in huge crushing plants, mixed with water, and extruded under vacuum at tremendous pressure into dense slugs which are cut and stacked by machines onto tunnel kiln cars for drying and firing. Automatic transfers program these cars into and out of dryers and kilns and automatic de-hacking equipment unloads the cars and packages the bricks. Forklifts haul packages containing 500 brick to the yard for storage or for loading directly to trucks for shipments to the job where, in many cases, the brick are touched for the first time by human hands. With this type of modern equipment producing brick and tile, it is easy to see why the number of plants has decreased but the tonnage has stayed up.

In addition to the methods of manufacture, the sizes of brick have changed from the old basic brick to three basic non-modular brick and 13 modular sizes which vary from the familiar 4″ x 8″ x 2-¼″ high to as large as 8″ x 12″ x 4″ high. Many of these brick are still hand-laid in the wall by masons in the conventional manner. The development of exceptionally strong, fast setting mortars have increased the use of clay masonry for multi-story construction with thin load-bearing walls and shear walls. This type of construction also can use panels in many cases, and more and more brick panel construction is being done both in factories and at the job site. Brick panels also are being used for some residential construction both in individual houses and in apartments. The amount of brick used in panels, however, is still a relatively small percentage of the total brick made.

Approximately 2,000,000 tons of pipe products are now being produced in 50 sewer pipe plants and 90 drain tile plants at the present time. The dollar volume of this product is around $120,000,000. Most of this product is sewer pipe, drainage tile and some flue lining with wall coping almost out of existence. The new sewer pipe and drain tile plants are as modern and expensive to build as are the brick plants.

Clay for pipe products, like the modern brick clays, are mined mostly on the surface with shovels, scrapers, drag lines and are hauled by trucks or by rail to the plants. Continued exploration for better clays and selective mining result in some long hauls by rail. Constant laboratory studies result in blends of clays necessary to produce the quality pipe products that are required to meet the ever-increasing strength, absorption, percolation, and exfiltration specifications. Additives are, in some cases, used to increase density and dry strength. Ever-increasing quality control work and the quality control built into the modern manufacturing plant has enabled us to eliminate glazing of any type on present-day sewer pipe.

Modern drain tile plants produce dense, extruded drain tile, cut to length and automatically loaded on tunnel kiln cars for drying and firing. Similar to the brick plants, the cars are automatically transferred into and out of the dryers and kilns. Tunnel kilns fire from the side and the top to a controlled stage of vitrification and then are cooled under controlled conditions to eliminate any cracking. Close grading and sorting and packaging for storage and hauling insure a quality product arriving at the customer's field.

Modern sewer pipe plants extrude small pipe and either extrude horizontally or press vertically large pipe in long lengths under great pressures. Additives and high vacuum assure density and roundness. Automatic handling equipment finishes both ends of the pipe and loads the pipe either onto racks or pallets for rapid drying in one-story room dryers. Pipe are dried to controlled moisture contents and sorted closely prior to setting onto tunnel kiln cars or into periodics. Firing and cooling are closely scheduled to insure the top-quality product. As the pipe are drawn from the kiln cars or the kiln, they are graded and taken to the jointing department where approximately 90% to 95% of all the pipe produced has a factory joint of one type or another applied. This joint assures a tight line when properly installed and allows the contractor's pipe laying crews to keep up with his

digging machines. Some pipe is now being produced as plain-end, without the familiar bell, and are then put together with a flexible coupling. Most of the pipe are packaged or palletized in some fashion and trucked by lift truck to the storage yard to await shipment by truck to the trench site.

Modern drain tile is still used for the same purpose of draining fields but is currently fighting hard against some attractive looking substitutes. These plastic substitutes have the advantage of extremely light weight and flexibility, but appear to be relatively short-lived.

Flue lining is now mostly used in commercial and industrial building with occasional use in residential fireplaces. Clay pipe is being used almost entirely for sewers now, with storm drainage being taken care of by the concrete industry. The replacement of overloaded existing sewers, outfalls to new sewage treatment plants, and new subdivisions are the main markets for clay pipe. Because of increased demand for sewage treatment and the desire to treat only sewage and not ground water, ever-tighter sewer specifications are being written. To meet this demand, the industry is producing longer, stronger lengths of pipe and tighter joints.

Future

So what do we see in the future for the brick industry? Companies will probably be fewer still. Plants will possibly be bigger but spread farther apart as weight reductions will enable brick to be shipped longer distances. Dollar volumes of products shipped may be more important than tonnages because of the tendency toward the lighter weight product.

Mining of clays will be more selective than ever in the future with greater study and emphasis placed on complete laboratory analysis of the raw materials. Light weight grogs or aggregates may be added to plastic clays for manufacturing the brick or perhaps clays will be sintered and organically bonded by such things as epoxy adhesives. The brick plants of the future will probably be more continuous in operation than they are at the present time with completely automatic handling with more emphasis on single unit drying and firing. Automatic in-line panel building may well be part of the production operations.

For the end-use of products of the brick industry, I see more panels either factory or site built and of lighter weight and great structural strengths. Sandwich panels for exposed interior and exterior masonry, light-weight panels which include exterior masonry and interior insulation, wall surfacing and finishing are both going to come to the forefront. Larger individual masonry units may come into being so that the variety of permanent colors and textures that are available in clay products can compete with the large tilt-up units of concrete that are now in use.

And what of pipe? The pipe companies will be fewer and the plants bigger and more modern yet. Lighter weight pipe with greater structural strength will let the producers ship their product farther.

Clay bodies will be researched, clays blended, and chemicals added to produce dense, thin-wall high-strength pipe. These may possibly be reinforced

by plastics and fiberglasses and other materials to give the corrosion resistance, high strength, and agelessness of clay, with the impact resistance and lighter weight of plastic materials. Factories may see continuous in-line operation of extrusion, drying, firing, wrapping and jointing of long, long lengths of pipe. It is not inconceivable that the future could possibly see marriages of materials which would use clay granules extruded with organic bonding materials at the trench so that continuous lengths of pipe could be laid by the trenching equipment. Increased emphasis on pollution control and environmental upgrading will result in more and more conveying and treatment of all types of wastes. Clay sewers will play an increasing part in this.

Summary

This paper then has tried to give you an insight into the structural clay industry as it was in its recent history, as it is now and as it quite possibly will be in the future. Because of increasing research, quality control and the basic properties that are only available in clay brick and pipe, the structural clay industry, while undergoing constant change, has weathered and will continue to weather the attacks of substitute materials. It will continue as a leader in the environmental control field, as well as in the commercial, industrial and residential construction field.

INFLUENCE OF CYCLIC DEPOSITION, STRUCTURAL FEATURES, AND HYDROLOGIC CONTROLS ON EVAPORITE DEPOSITS IN THE ST. LOUIS LIMESTONE IN SOUTHWESTERN INDIANA

Duane B. Jorgensen[1] and Donald D. Carr[2]

Abstract

Beds of anhydrite and gypsum occur in the lower part of the St. Louis Limestone (Mississippian) along the northern and eastern parts of the Illinois Basin. These beds are part of an evaporite section, which includes silty dolomites and pellet-micritic limestones, that occupies the lower 60 to 80 percent of the total St. Louis within the evaporite area in Indiana. The thickest known beds of gypsum are in southwestern Indiana and are being exploited by the National Gypsum Co. near Shoals in Martin County.

Detailed examination of the St. Louis Limestone in Indiana Geological Survey drill hole 208, Greene County, indicates that the evaporite section consists of a distinctive sequence of lithologies in cyclic arrangement. A typical evaporite cycle, from the base upward, consists of light brownish-gray mottled silty dolomite with algal mat structures believed to have formed in an intertidal environment; dark-brown pellet-micritic limestone with birdseye structures believed to have formed in a subtidal open-lagoon environment; a repetition of silty dolomite; and nodular anhydrite believed to have formed in a supratidal sabkha adjacent to a restricted lagoon environment. Transgressions and regressions of the very shallow sea over a very broad tidal flat produced the cyclicity of sediments. Examination of other cores of the St. Louis evaporite section in Indiana indicates that similar lithologies and distinctive cycles of deposition are present.

Intensive investigation for commercial development has been conducted in an area of 12 square miles in Martin County, Indiana. One hundred sixty-one drill holes and cores and two underground mines provide definition of structural and depositional features, including the margin of evaporite deposition, structural deformation, and lateral stratigraphic changes. Varying thickness of the commercial deposit, as well as the thickness of the overlying St. Louis, Ste. Genevieve, and Paoli Limestones, do not indicate a well-defined basin topography. Macroscopic textural features in the evaporite section resemble those associated with modern sabkhas. Deposition of, or early diagenetic change to, anhydrite was followed by partial conversion to gypsum during Mississippian time and resulted in vertical expansion of approximately 33 percent where the conversion is complete.

Water seepage areas in one of the mines can be related to the distribution of the permeable sandstone facies of the Bethel Formation overlying the Paoli Limestone and to structural deformation after evaporite deposition. The occurrence of solution cavities above anhydrite in the gypsum-mining seam suggests that water movement to the mine level has been a relatively recent development.

Introduction

For many years anydrite and gypsum had been observed in well cuttings from the lower part of the St. Louis Limestone (Mississippian) in southwestern Indiana, but it was not until 1948 that major producers of gypsum inquired about the possibility of commercial development. On the basis of information supplied by the Indiana Geological Survey, interest in gypsum increased to the point that commercial exploration began in 1951. Four companies, Certain-Teed Products Co., National Gypsum Co., Ruberoid Co., and U.S. Gypsum Co., conducted extensive exploration programs during

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the early 1950's. By 1955 the U.S. Gypsum Co. and the National Gypsum Co. had opened mines and built fabrication plants near Shoals in Martin County.

The first published report on the evaporites in the lower St. Louis in southwestern Indiana was by McGregor (1954). He (p. 22-23) indicated that the St. Louis evaporites were deposited in restricted basins, a concept also employed, although modified in detail, by Pinsak (1957, p. 24) and French (1967, p. 320). The theory that the evaporites formed in basins has generally persisted, although in 1968 Rooney and French (p. 763) noted that the mosaic textures in the St. Louis evaporites were similar to those found in modern deposits of sabhka origin.

Outside of Indiana, Saxby and Lamar assembled well-drilling data and in 1957 reported on the occurrences of anhydrite and gypsum in Illinois. In a similar study McGrain and Helton (1964) reported on the occurrences of anhydrite and gypsum in Kentucky.

The objective of this study is to bring the regional aspects of evaportie sedimentation and the detailed view of the Shoals deposit together to obtain a better understanding of evaporite sedimentation in the Illinois Basin. Eleven diamond drill cores on file in the Indiana Geological Survey core library penetrated the St. Louis evaporite section and were useful in our regional

SYSTEM	SERIES	GROUP	FORMATION	MAIN LITHOLOGY
MISSISSIPPIAN	CHES-TERIAN	West Baden	Bethel Fm.	sandstone shale
		Blue River	Paoli Ls.	limestone
	VALMEYERAN		Ste. Genevieve Ls.	limestone
			St. Louis Ls.	limestone cherty limestone
				gypsum
				anhydrite
				silty dolomite
		Sanders	Salem Ls.	limestone

Figure 1. Chart showing stratigraphic relationships in Indiana.

study; cores from 161 holes drilled by the four companies and exposures of evaporites in the mines near Shoals provided the data for this detailed study.

Regional Setting

The St. Louis Limestone along the eastern shelf of the Illinois Basin is part of a thick middle Mississippian carbonate section (fig. 1). The St. Louis ranges in thickness from a thin edge along its northern limit in west-central Indiana and central Illinois to about 350 feet in the southeastern part of the basin in Indiana and Kentucky. Like most stratigraphic units of middle and late Mississippian age, the St. Louis thickens irregularly southward and southwestward in the basin.

Anhydrite and gypsum are found in the subsurface in the lower part of the St. Louis. These evaporite rocks occur along a broad belt that extends from north-central Kentucky through southwestern Indiana and across south-central Illinois (fig.2). Within this belt the St. Louis can be divided into two parts based on lithology: an upper part that consists mainly of fine-grained skeletal, pellet, and micritic limestones containing dense nodular chert, and a lower part that consists mainly of silty dolomite, fine-grained limestone, anhydrite, and gypsum.
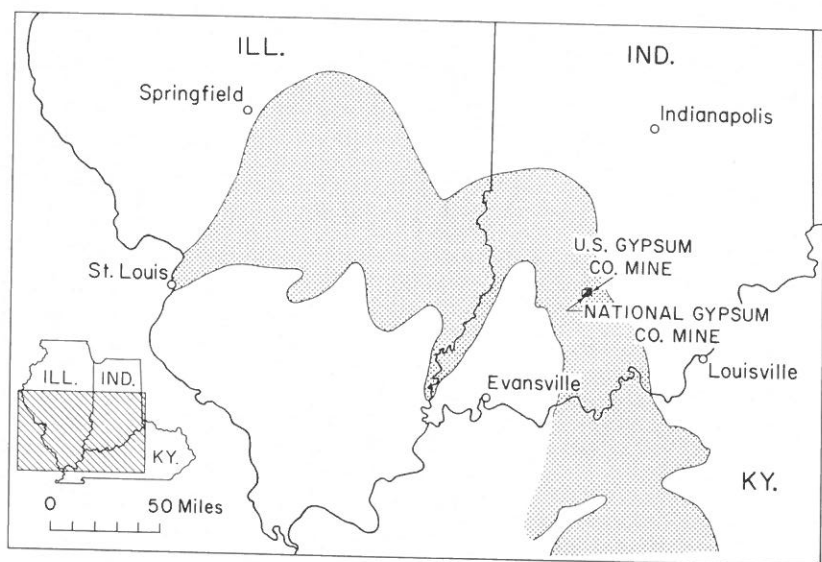
Figure 2. Distribution of anhydrite and gypsum in the St. Louis Limestone in the Illinois Basin. Illinois data from Saxby and Lamar, 1957, fig. 6. Kentucky data from McGrain and Helton, 1964, fig. 4.

Cyclic Deposition

A repetitive sequence of evaporite lithologies is characteristic of the lower St. Louis. In order to better understand this cyclicity of deposition, a detailed examination was made of a core from Indiana Geological Survey drill hole 208, which was drilled in Greene County. This core has very little loss and is well suited for this study because it contains a thick evaporite section, 163 feet thick, and lithologies that appear to be typical of those found in the evaporite section in other parts of the Illinois Basin.

Based on lithology, stratigraphic relationships, and sedimentary structures, 18 depositional cycles have been recognized in the lower St. Louis evaporite section in this core (fig. 3). Not all the cycles are complete, either because of nondeposition or erosion, but on the basis of our study, we believe that a complete or ideal depositional cycle consists of three characteristic lithologies, one of which is repeated (fig. 4). From the base upward, they consist of light brownish-gray mottled silty dolomite, dark-brown pellet-micritic limestone, a repetition of the silty dolomite, and nodular anhydrite.

Silty dolomite lithology. — The silty dolomite lithology amounts to about 42 percent of the evaporite section. It typically consists of light brownish-gray very finely crystalline dolomite containing from trace amounts to as much as 20 percent clay and medium and coarse quartz silt. This lithology has been found in several places to lie both above and below the pellet-micritic limestone lithology, and those parts that are adjacent to the limestone generally contain only trace amounts of noncarbonate material.

Some parts of the lithology, generally those parts that contain only small amounts of quartz silt, are mottled light and dark grayish-brown and contain structures that are believed to have originated from burrowing organisms. Other parts of the lithology that are low in noncarbonate material are commonly faintly laminated and consist of very finely crystalline dolomite. Sinuous subparallel laminae of dark-brown dolomite, interpreted as algal structures, are commonly found in parts of the lithology near the nodular anhydrite lithology, although they are also found elsewhere.

Pellet-micritic limestone lithology. — The pellet-micritic limestone lithology amounts to about 18 percent of the evaporite section. It is typically dark-brown pellet-micritic limestone. In many places it contains randomly scattered very dark-brown dolomite crystals that give a birdseye structure. The dolomite crystals are individual euhedral crystals as much as 2mm in diameter and composite masses of crystals as much as a centimeter in diameter. Skeletal and coated grains, generally 0.25 to 0.5 mm in diameter, and scattered small needlelike and platelike fragments that may have an algal origin are present in minor amounts, although in some places they may be the dominant constituent. Black shaly dolomite with dolomitic shale laminae and thin beds as much as 0.5 foot thick is present in this lithology in several of the cycles. Except in these thin beds, clay and quartz silt are present in only trace amounts.

Nodular anhydrite lithology. — The nodular anhydrite lithology amounts to about 40 percent of the evaporite section. It consists mainly of bluish-gray nodular anhydrite, but where gypsified, it consists of light-gray
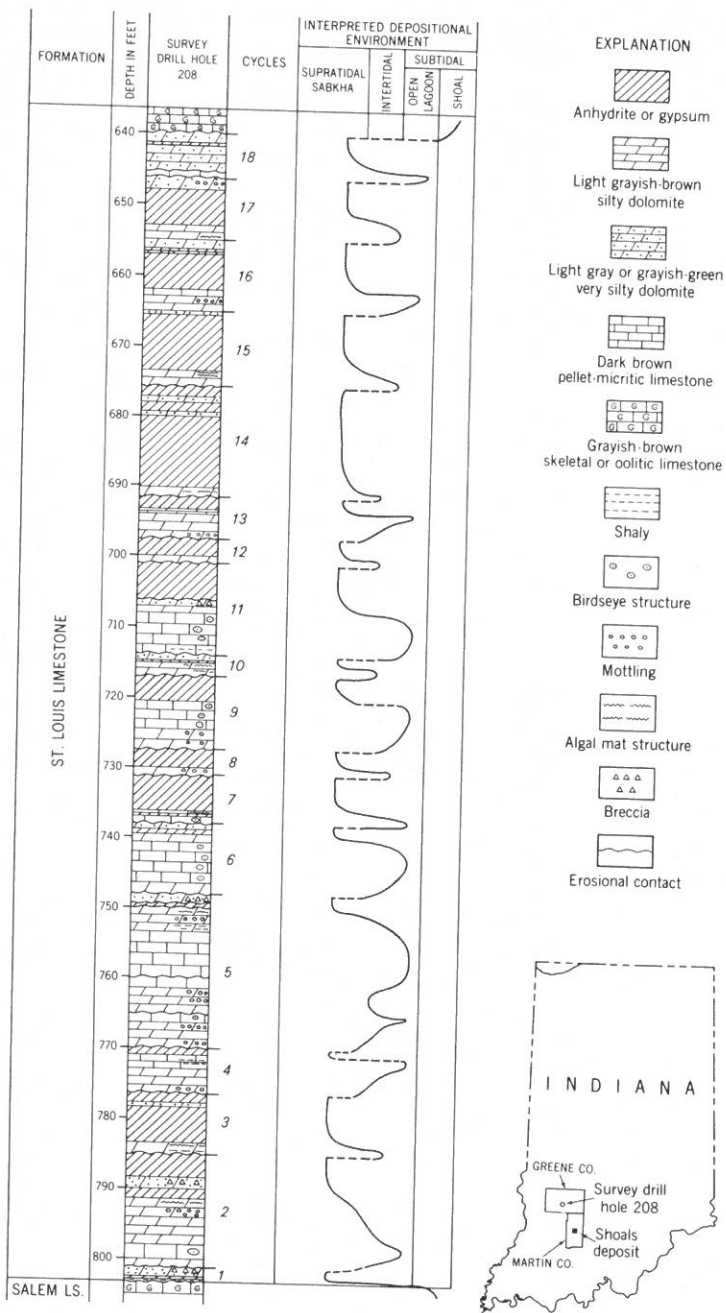
Figure 3. Detailed stratigraphy of core from Indiana Geological Survey drill hole 208 depicting lithologic cycles and interpreted environments.

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GENERALIZED SECTION	DESCRIPTION	ENVIRONMENT		
		SUPRATIDAL SABKHA OR RESTRICTED LAGOON	INTERTIDAL	SUBTIDAL OPEN LAGOON
	Anhydrite or gypsum; grayish-blue or white, nodular			
	Silty dolomite; light brownish-gray, mottled, algal mat structures			
	Limestone; dark brown, pellet-micritic, birdseye structures, black shaly beds in places			
	Silty dolomite; light brownish-gray, mottled, algal mat structures			

Figure 4. Generalized stratigraphic column showing lithologic sequence resulting from an ideal evaporite cycle. See fig. 3 for explanation of symbols.

and white gypsum. The anhydrite contains both mosaic and penemosaic textures in which the nodules are generally outlined by thin laminae of light-gray silty dolomite or light grayish-green argillaceous dolomite. Contorted laminae and thin beds of silty dolomite, similar in composition to the dolomite enclosing the adjacent nodules, are abundantly interbedded within the anhydrite lithology. Some of the beds, which may be as much as 0.2 foot thick, are brecciated and have clasts of argillaceous and silty dolomite with a very argillaceous dolomite matrix. In the upper part of the lower St. Louis evaporite section, mottled red and green very argillaceous dolomite and dolomitic claystone are present in the anhydrite lithology as laminae and thin beds.

Interpretation. — The original sediment that makes up the silty dolomite lithology is believed to have been deposited in an intertidal environment. The sinuously laminated algal-mat structures with medium and coarse quartz silt suggest intertidal conditions but the argillaceous and silty dolomite breccias may indicate that the sediments were exposed to supratidal conditions.

The character of the pellet-micritic limestone lithology suggests that original deposition took place in subtidal conditions. Although direct comparison of these limestones to modern deposits may not be conclusive, the textural characteristics of these limestones are very similar to the fine-grained pellet muds being deposited in modern Persian Gulf lagoons (Bramkamp and Powers, 1955; p. 139-140; Kinsman, 1966, p. 303-304).

The sedimentary associations, composition, and textures of the nodular anhydrite lithology are indeed convincing evidence for sabkha origin. The host sediments where the anhydrite nodules formed are generally brecciated silty dolomites and algal-matted silty dolomites, but the anhydrite nodules may also be found associated with the finely crystalline dolomites. Rarely are the anhydrite nodules found associated with the pellet-micritic limestones. Apparently the porosity of the host rock and the position of sabkha groundwater table were major controls governing where the anhydrite nodules occur. Butler (1969, p. 72-74) suggested that intermittent surface flooding of the sabkha replenished the groundwater brine supply, but Kinsman (1966, p. 304-305) referred to movement of lagoon brines through sabkha sediments to replenish the groundwater brine supply. Possibly both mechanisms, taken together, could account for differences in thickness and location of dolomites that accompany and normally enclose the anhydrite nodules.

The repetitive sequence of lithologies is interpreted as having been deposited during both the transgression and regression of a very shallow sea. On the basis of the textural framework of the limestones and the grain size of the noncarbonate components, we believe that the depositional energy level was low, although occasionally storm activity might have resulted in episodic higher energy level conditions. Gradual basin subsidence, either uniform or periodic, and possibly changes in sea level produced onlap and offlap conditions that resulted in a cyclic sequence of carbonate sediments. Permeation of the more porous carbonate sediments by brines under sabkha conditions and early diagenesis resulted in the beds of nodular anhydrite.

Although several ancient evaporite deposits have been attributed to a sabkha origin, little has been published on the cyclical sequence of lithologies in the evaporite cycle. Shearman (1966, p. B211) described three complete cycles in 17 feet of the Purbeck Beds (Jurassic) in southern England and attributed their origin to sabkha conditions. Wood and Wolfe (1969) described nine cycles that they believed represented sabkha deposits in 176 feet of core from the Arab/Darb Formation (Jurassic) in the Trucial States of Arabia. The lithologic types, sedimentary structures, and sequences of lithologies described in both of these studies are similar in many ways to those found in the St. Louis evaporite section.

The Shoals Deposit

Structure. — The Shoals deposit is near the center of the belt of evaporite-bearing lower St. Louis strata in Indiana (fig. 2). Currently two companies, the National Gypsum Co. and the U.S. Gypsum Co., have room-and-pillar underground mines developed in the deposit. The lower St. Louis is

approximately 150 feet thick in the Shoals area and contains at least 10 depositional cycles, the last two of which have the greatest economic importance. The sulfate horizons of the last two cycles are locally known as the anhydrite-pit bed and the gypsum-mining seam. The rocks overlying the gypsum-mining seam consist of 240 to 300 feet of Blue River limestones and from 20 to about 200 feet of West Baden sandstones, shales, and limestones. The gypsum-mining seam dips westward and southwestward, so that the depth from surface ranges from 300 feet along the east edge where the seam elevation is 200 feet above sea level to about 450 feet in the western part where the seam elevation is 50 feet above sea level.

Until recently it was generally believed that evaporites were deposited in basins or at least in a marine environment in which topography restricted the flow of sea water and caused hypersaline conditions. To gain a better understanding of the Shoals gypsum-mining seam and to try to define the margins of the presumed basin in which the evaporites were deposited, two maps have been constructed. These are a structure map of the floor of the gypsum-mining seam (fig. 5) and a map of the residual topography after a regional dip of 45 feet per mile, S. 83° W., was removed (fig. 6).

The floor structure map by itself only hints at the existence of a basin; there are only two small depressed areas, one in the NW¼ sec. 23 and the SW¼ sec. 14 and the other near the center of the E½ sec. 26. Areas of higher elevation are suggested between sections 23 and 24 and sections 22 and 23. Removal of the regional dip changes the appearance of the basin, so that a
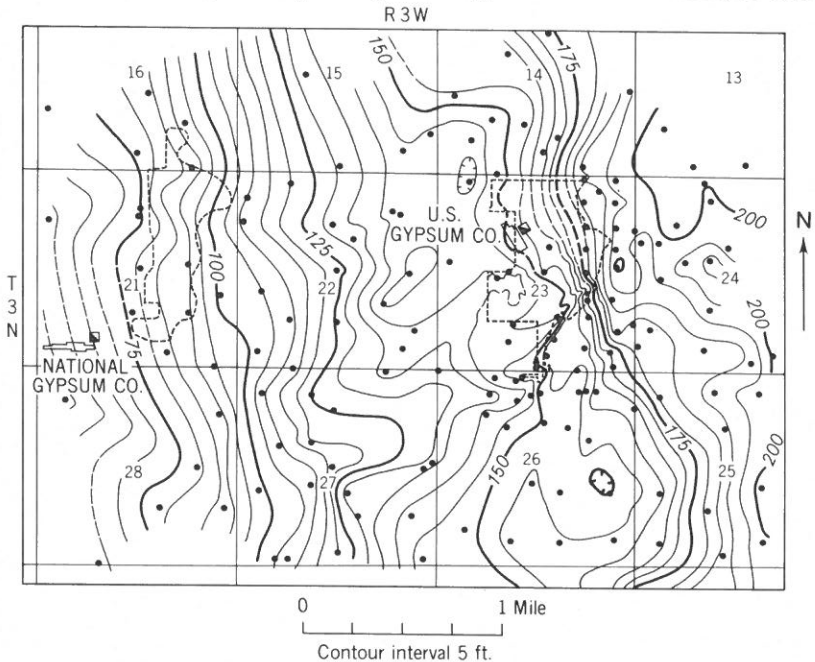
Figure 5. Map showing structure of the floor of the gypsum-mining seam at Shoals, Indiana. Dashed lines outline mined-out areas.
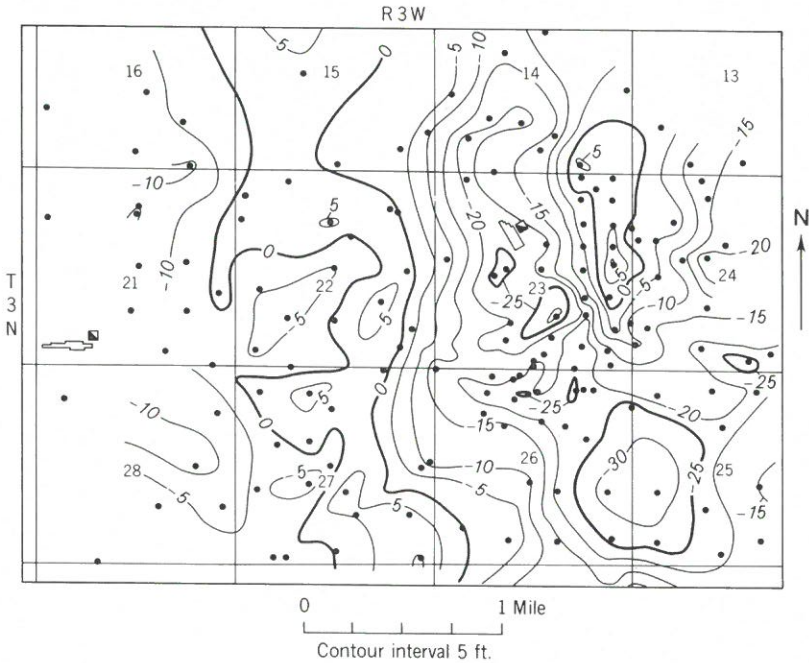
Figure 6. Map showing structure (regional dip removed) of the floor of the gypsum-mining seam at Shoals, Indiana.

partially defined basin appears to extend approximately NNW-SSE through sections 14, 23, 26, and 25. At the same time, however, the higher elevation features become more apparent. The positive area between sections 23 and 24 is accentuated and extended. Likewise, the high area between sections 22 and 23 is extended from the SW¼ sec. 27 through the NW¼ sec. 27, E½ sec. 22, and northward into section 15. This latter positive area is in the approximate center of the presumed basin.

A map of the gypsum-mining seam thickness has also been constructed (fig. 7). When this map is compared with the residual topography map of the floor of the gypsum-mining seam, other incompatibilities appear. A very notable contradictory relationship is the seam thickness in the NE¼ SE¼ sec. 26. Although this area is in the deepest part of the residual basin, less than 10 feet of gypsum is present. In addition, the large topographically high area between sections 23 and 24 and its northern extension should have little or no gypsum, yet it is covered with as much as 16 feet of gypsum. Contradictory relationships also occur near the margin of the presumed basin. For example, the residual topographically low area along the south edge of section 24 should be covered by the full seam thickness but contains very little gypsum. The residual topographically high area between sections 22 and 23, which is in the approximate center of the presumed basin, is also the general location of the thickest gypsum-mining seam. These occurrences suggest that the topographically high areas in a sabkha depositional environment favor the

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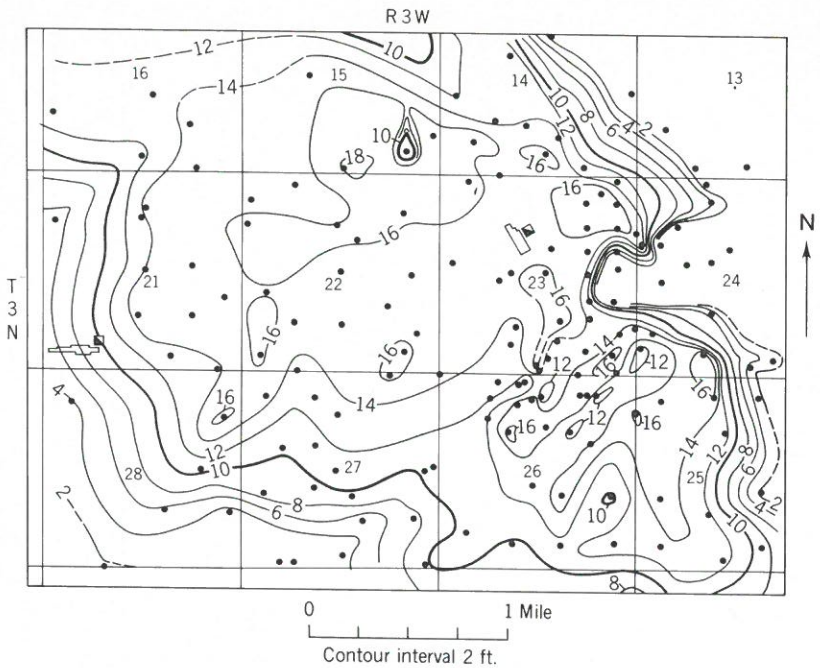
Figure 7. Map showing thickness of gypsum-mining seam at Shoals, Indiana.

maximum deposition of sulfate. The mining-seam thickness map reflects thinning by solution of the gypsum as well as original depositional thickness. The thinning of the gypsum-mining seam in sections 14 and 13 is known to be due to solution as is the thin area in the SE¼ sec. 15, and possibly the thin area near the south edge of section 24 may also represent solutional thinning.

Another comparison, one that shows a partial correlation between depositional thickness and residual topography, can be made between the thickness map of the limestones that overlie the gypsum-mining seam (fig. 8) and the residual topography map (fig. 6). This limestone section, consisting of the upper part of the St. Louis Limestone and the Ste. Genevieve and Paoli Limestones, thickens in the eastern half of the map area where the residual topography is negative; however, in the western half, in sections 15, 22, and 27, the thickest limestone sections cored overlie only shallow depressions or definite topographically high areas. Although some correlation appears to exist between the thickness of limestones that overlie the gypsum-mining seam and the residual topography, this correlation may be only coincidental. Porosity in modern sabkhas where anhydrite is being deposited ranges from 40 to possibly 80 percent (Kinsman, 1966, p. 312). If this range of porosity existed in the lower St. Louis evaporites that were deposited at Shoals, continuing compaction of the evaporites themselves could provide shallow depressions which would accumulate greater thicknesses of overlying sediments than would areas without evaporites.

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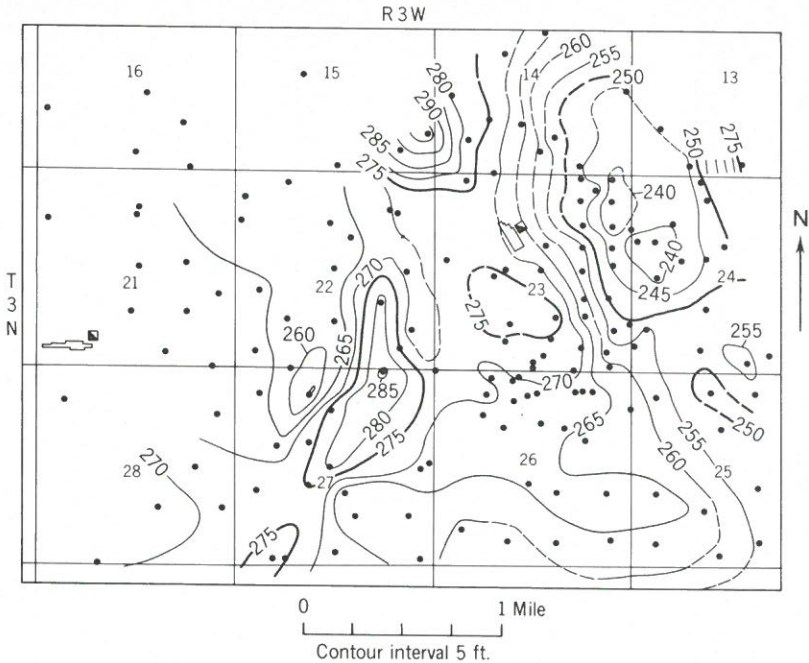
Figure 8. Map showing thickness of limestones of the Blue River Group overlying the gypsum-mining seam at Shoals, Indiana.

In summary, only part of the topographic features which should logically influence the depositional thickness of the gypsum-mining seam and the overlying limestones correlates positively. The remaining topographic and (or) structural features seem to have no effect or correlate negatively. Some of the structural or topographic features are certainly postdepositional and thus cannot be expected to correlate with depositional thicknesses. However, there is no evidence in the form of closely spaced jointing or obvious later structural deformation to indicate that the original topography has undergone any major change. The presumed basin is not well defined either before or after removal of the regional dip, and thus the presence of a well-defined basin does not appear to be a requirement for the deposition of the evaporites.

Stratigraphy. — Previously in this paper an idealized depositional evaporite cycle was described. It begins with deposition of fine-grained carbonate sediments in the open lagoon, continues with silty and laminated algal-matted carbonate sediment, in the tidal zone as water shallows, and ends with precipitation of nodular or crudely bedded gypsum or anhydrite and dolomitization of the enclosing sediments near the water table of the sabkha. It should be kept in mind that gypsum or anhydrite precipitates in the earlier host sediments, the actual location depending primarily on the location of the water table of the saturated brines and the characteristics of the host sediments.

Of the many evaporite beds in the lower St. Louis at Shoals, two are thick and pure enough to be mineable. These are the gypsum-mining seam that is the highest sulfate horizon in the sequence and is mined by both the U.S. Gypsum Co. and the National Gypsum Co. and the anhydrite-pit bed that occurs 5 to 7 feet below the gypsum-mining seam and is mined only by the National Gypsum Co. Although the anhydrite-pit bed occurs throughout the Shoals area, only in the western half of the area is it thick enough to be mined. In the eastern half it is thin or in a few places entirely absent.

The floor of the anhydrite-pit bed is a dark brownish-gray very finely crystalline dolomite. The anhydrite-pit sulfate bed, itself, can be subdivided into three units as follows:

(1) A lowermost unit, approximately 5 feet thick, is grayish-blue anhydrite containing scattered green dolomitic shale fragments in places abundant enough near the top of the unit to form a bed that encloses anhydrite nodules.

(2) A middle unit, generally 2 to 3 feet thick, is grayish-blue nodular anhydrite containing scattered fragments of light-brown argillaceous dolomite. At the top of the unit the dolomite may be several inches thick and faint laminations can be observed in it.

(3) The uppermost unit is similar to the lowermost unit except that the shale within it is more finely divided and slightly more dolomitic. The upper two-thirds of the unit is converted to gypsum in the area where it is being mined. In general, the anhydrite is partly converted to gypsum wherever the overlying gypsum-mining seam is wholly converted to gypsum.

A dark-brown crudely laminated dolomitic limestone layer about 1½ feet thick, believed to represent a fossil algal mat, overlies the uppermost unit of the anhydrite-pit bed, and it in turn is overlain by about 5 feet of very finely crystalline dark-brown dolomite containing ripple-marked shale partings, which also forms the floor of the gypsum-mining seam.

The gypsum-mining seam is here subdivided into five sulfate units based on the type of impurity contained and the competency of the host sediment (fig. 9a).

(1) The lowermost unit, 0 to 3 feet thick, contains irregular discontinuous fragments of light grayish-olive argillaceous dolomite. A discontinuous greenish-gray shale parting separates units 1 and 2.

(2) The second unit, 2 to 3 feet thick, is similar to the first except that the dolomite impurities are more argillaceous. The break between the second and third units is a discontinuous light-brown dolomite bed that averages about an inch thick.

(3) The third unit, about 3 feet thick, contains scattered light-brown dolomite laminae that are similar to the dolomite bed between the second and third units. The break between the third and fourth units, known as the "stone seam," ranges in thickness from a thin discontinuous shale parting in parts of the southeast quarter of the area to as much as 2 feet near the western margin of the deposit. The

Figure 9a. Photograph showing gypsum-mining seam units 1 to 4 in the U.S. Gypsum mine.

average thickness is about 10 inches. The lower half of the stone seam is a medium-crystalline light-brown dolomite. The upper half is an extremely finely crystalline argillaceous light-brown dolomite that contains contorted laminations that apparently represent algal-mat structures.

(4) The fourth unit, 2 to 4 feet thick, is similar to the third unit except that the impurities change from light-brown dolomites to green dolomitic shales about halfway up in the unit, with no discernible break in sulfate deposition. The unit becomes shalier toward the top and normally is gradational over a short distance into a shale break between the fourth and fifth units. Where there is a sharp distinction between the fourth unit and overlying shale the gypsum in places exhibits a "cumulous" structure recognizable only on mine pillar walls (fig. 9b). This break is green to greenish-gray dolomitic shale peppered with small gypsum nodules and spliced with satin spar seams. In a few areas the shale contains little or no gypsum and forms a definite bed.

(5) The uppermost unit, 0 to 4 feet thick, is the purest sulfate unit and is interlayered but not intermixed with laminated dark-to light-brown dolomite beds a few inches thick that apparently represent fossil algal mats. Overlying the unit is light-brown finely crystalline dolomite that is in places argillaceous and in a few areas contains birdseye structure with dolomite and gypsum crystals a few millimeters in diameter.

As might be expected, variations in the units occur laterally across the Shoals deposit. For example, the dolomite impurities in the gypsum-mining seam are more argillaceous in the eastern part of the deposit than in the western part. In the eastern part, along the east side of the U.S. Gypsum mine, all of unit 5 and part of unit 4 are absent and are replaced by a breccia consisting of light-brown to grayish-brown argillaceous dolomite. A similar breccia is found in cores at the gypsum-mining seam horizon east of the 2-foot isopach line, except where the gypsum seam has gone into solution and cavities are present in its place.

Textures — The dominant megascopic texture in the gypsum in the gypsum-mining seam is nodular, mosaic or penemosaic (Rooney and French, 1968, p. 755). The textures in about one-fourth of the strata are flocculent (Riley and Byrne, 1961, p. 555) or wispy (Holliday, 1971, p. B310). Enterolithic folding can be readily recognized in some areas. The nodular texture is not recognizable in unit 5, the highest purity sulfate horizon, except at the contacts with the interbedded dolomites and at the base of the unit at the shale break. The lower contact presents a crudely pock-marked surface that appears to have originated from the growth of the anhydrite nodules.

The floor of the gypsum-mining seam in both mines is pock-marked with small depressions previously thought to be irregular ripple marks. Close examination, however, showed that the depressions are not ripple marks but are displacement depressions that result from the impression of overlying nodules in a soft unconsolidated sediment. Likewise, the lower surface of the
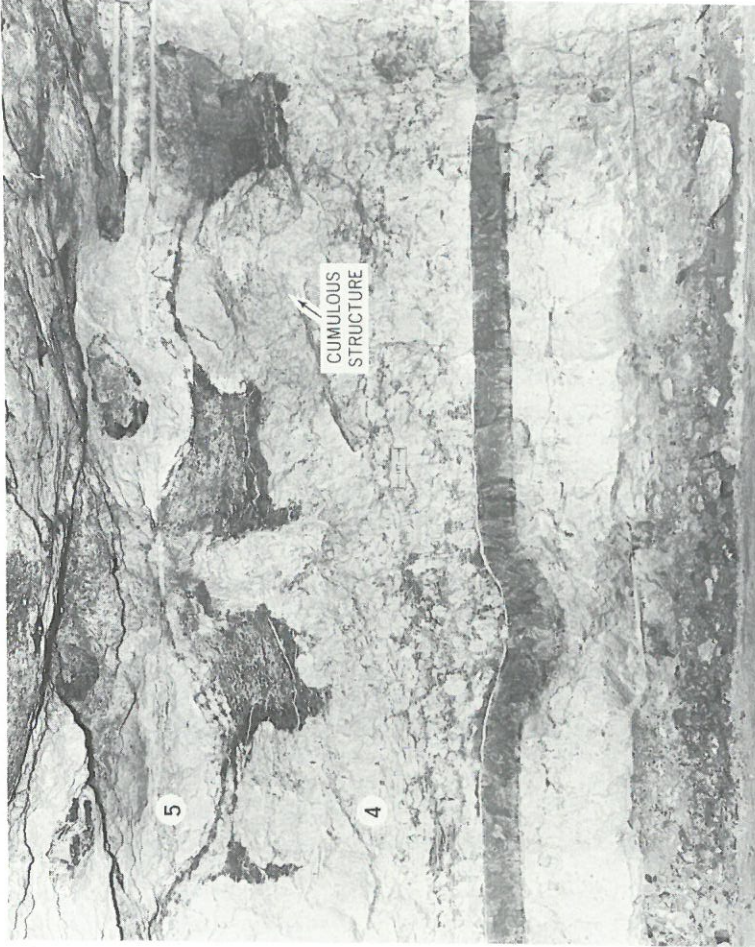
Figure 9b. Photograph showing gypsum-mining seam units 4 and 5 and cumulous structure at the top of unit 4 in the National Gypsum mine.

limestone bed above the uppermost unit of the anhydrite-pit bed shows similar displacement depressions. Both the mine floor and the top of the anhydrite-pit bed are faced with the thin bright-green chloritic shale partings and a satin spar layer varying in thickness but averaging about one-half inch. The contacts are sharp and well defined. There are no gradations of dolomite to sulfate and no evidence that the sulfate beds replaced some other original sediment.

Further evidence that suggests the sulfate beds displaced rather than replaced some other original sediments is the diversity of composition of the host sediments. It seems unlikely that the sulfate beds would be able to replace such diverse sediments as shale, siltstone, and dolomite with equal success.

The completeness of the nodular texture seems to depend on the lithologic character and mechanical properties of the surrounding or included impurities. This observation was also noted by Holliday (1969, p. 1256-1257). The nonnodular part of unit 3 and other high-purity sulfate horizons in the Shoals deposit almost universally are bordered by a thin chloritic shale lamina which is extremely easily separated parallel to stratification. When anhydrite or gypsum is precipitated within carbonate host rocks, mosaic and penemosaic textures form, depending primarily on the quantity of host rock available to enclose the nodules.

The carbonate host rocks in all the units of the gypsum-mining seam have been split roughly horizontally. Most of the resultant space is filled with a coarsely crystalline satin spar gypsum. These filled spaces have been referred to as veins (Bundy, 1956, p. 246). Less than 1 percent of the veins are incompletely filled and show growth of the satin spar inward from both walls. Most of the incompletely filled veins occur in the center part of the larger dolomitic impurities.

The conversion of anhydrite to gypsum and the growth of the satin spar veins in the deposits at Shoals were discussed by Bundy (1956, p. 246-249). The anhydrite-gypsum conversion is reported to result in a volume increase of 30 to 50 percent (Pettijohn, 1957, p. 479). Measurements along 200 vertical traverses across dolomitic impurities spliced with satin spar veins in the gypsum-mining seam indicate that a 33 percent expansion in volume has taken place — well within the expansion range reported by Pettijohn.

In addition to the vertical expansion described above, horizontal expansion of the deposit is indicated by the shearing exhibited in the gypsum-mining seam at its thinning edge in the eastern part of the U.S. Gypsum mine (fig. 10).

It may never be known with absolute certainty whether deposition of the sulfate was directly as gypsum or as anhydrite. If deposition occurred directly as gypsum, however, conversion to anhydrite must have taken place diagenetically very early, because there are no shrinkage or other deformation features in or around the gypsum-mining seam or anhydrite-pit bed.

In summary, the sequence of lithologies in the Shoals deposit compares very closely with the ideal evaporite cycle of the sabkha environment. The interval from the algal-matted limestone above the anhydrite-pit bed to the laminated dolomite at the top of the gypsum-mining seam represents one complete evaporite depositional cycle.

Figure 10. Photograph showing shearing at the thinning edge of the gypsum-mining seam in the U.S. Gypsum mine.

Anhydrite Gypsum Hydration Controls

Many gypsum deposits are reported in the literature to be the result of hydration of anhydrite, and the idealized gypsum deposit is pictured as being a near-surface phenomenon resulting from the hydration of anhydrite to gypsum as the overlying rock cover thins. Although the general correlation of increasing anhydrite with greater depth cannot be disputed, the detailed pattern of hydration in any particular deposit is often affected by other influences, such as the existence of aquifers or permeable horizons along which water can move laterally or paleotopographic features which may or may not conflict with present topography. In short, any feature that affects hydrology may also affect the change from anhydrite to gypsum. Because the gypsum-mining seam at Shoals contains much anhydrite, the present topographic surface and a paleotopographic surface were examined for correlation with hydration of the gypsum-mining seam.

The present land surface above the Shoals deposit is part of the Crawford Upland, a dissected upland with angular to flat-topped ridges, steep slopes, and narrow flat stream bottoms. The Bethel Formation underlies the stream valleys in the immediate area. Total relief in the area is 300 to 400 feet, but a deeper Pleistocene erosional surface is masked by later valley filling. The present surface topography has little if any influence on the occurrence of gypsum. Although the thickest anhydrite does occur beneath a topographic high, similar topography also covers the major part of the gypsum reserves. Other evidence indicating that recent hydrologic features have little influence on the present distribution of gypsum is the existence of water-filled cavities above anhydrite in the SE¼ sec. 15 and adjacent to anhydrite in the NE¼ sec. 23.

Other than the present topographic surface, one other well-developed surface, the horizon between the Paoli Limestone and the Bethel Formation, was mapped (fig. 11). This map also shows the areal distribution of anhydrite in the gypsum-mining seam. The interpreted mapped surface is the break between the deposition of Blue River limestones and the overlying West Baden sandstone, shale, and limestone sequence, and it is the topographic surface believed to correlate best with the hydration of the gypsum-mining seam. This interpreted paleotopographic surface shows that drainage was from northeast to southwest in the eastern half of the map area and generally ran east of a prominent topographically high area that has steep slopes. Beneath this prominent high and the steep slopes is the area of thickest anhydrite in the gypsum-mining seam. A higher area but with more gentle slopes is in the NE¼ sec. 23; it also overlies anhydrite in the gypsum-mining seam.

Because of the depth of the present erosion surface, other paleotopographic surfaces which are well-developed erosion surfaces, such as the Mississippian-Pennsylvanian unconformity, cannot be investigated. The West Baden shales which underlie these erosion breaks probably were effective barriers, however, and prevented the migration of water from Pennsylvanian sandstones to the gypsum-mining seam.

Figure 11. Map showing topographic interpretation of structure. Datum is top of the Paoli Limestone. Stippled pattern indicates areas of anhydrite in the gypsum-mining seam.

Water Problems

The U.S. Gypsum mine has been flooded twice by a large inflow of "pluto" or hydrogen sulfide-bearing water. During the time of inflow, pluto-water springs 5 to 7 miles northwest of the inflow point were drawn down, and there was, and still is, speculation that the mine had tapped into the entire underground drainage system of the karstic Mitchell Plain, which lies about 10 miles east of the Shoals deposit. The inflow during the first flood, which occurred in 1960, was estimated at 25,000 gpm. In 1965, in spite of precautionary measures taken against a similar occurrence and much activity during the time of inflow, the mine again flooded. The inflow was from the same location as in 1960 and the measured flow rate was about 10,000 gpm.

Because of its severity and economic importance, many aspects of the mine water problem have been investigated. The investigations have included geologic, geophysical, hydrologic, and rock mechanics studies along with core drilling on a regular basis. All the investigations have indicated that for a water problem to exist at the mine level, there must be a water reservoir, such as an aquifer or underground cavity system, and a conduit into the mine, such as a joint, bedding plane, permeable horizon, or extension of the cavity system. There must also be enough pressure difference to keep the water or fluid in the reservoir and conduit circulating, although it is possible that circulation in the cavity system at the gypsum-mining seam level may be

primarily an ion migration mechanism rather than a mass movement of water. Drill hole information indicates that a solution cavity produced by dissolving the top of the gypsum-mining seam in groundwater was the immediate reservoir and conduit that flooded the mine, but this information does not explain why the cavities are located where they are, nor does it give reasons for the locations of small water flows in the mines. Losses of drilling fluids during core drilling of the Blue River limestones were rarely experienced, which indicates a low bulk permeability for these rocks. Laboratory investigation of permeabilities of rocks overlying the gypsum-mining seam showed that permeable limestones and dolomites are not widespread and in fact the gypsum itself is nearly impermeable. In general, most of the limestones are very nearly impermeable and most of the dolomites have moderate radial permeabilities in the range of 0.1 to 10 millidarcies, but a few measurements are more than 50 millidarcies. East and northeast of the mine area, St. Louis silty dolomites may be permeable enough to transmit water in quantity, but the areal distribution of these dolomites is not well-known, and it is uncertain whether these dolomites have any relation to the developed cavity system.

Both mines have "drippers," that is, smallflows and drips of water coming from the mine roof through roof-bolt holes, joints, or bedding planes. Some of the drippers eventually dry, but others seemingly run eternally. It is apparent that isolated drippers in the mines must be fed through joints at one or more levels above the mine and that localized areas of several small drippers are also likely to be fed by a single joint or small number of joints as part of the path the water takes to get into the mine.

The Bethel Formation overlies the Blue River limestones and is composed of sandstones and shales that are believed to have been deposited in an alluvial-deltaic environment. During Pleistocene and Recent time, erosion exposed these sandstones, and they now underlie a thin alluvial fill in Beaver Creek and South Fork Beaver Creek on the east edge of the Shoals deposit. Radial permeabilities of the Bethel sandstones, which measured as high as 250 millidarcies, were found to be much higher than the carbonate rock permeabilities. These sandstones are permeable enough to supply water to a large number of joints that can feed and distribute water to lower levels or into the mine. Plotting the distribution of the sandstone portions of the lower 20 feet of the Bethel Formation (fig. 12) showed that the sandstones covered or surrounded the areas known to contain a cavity system at the gypsum-mining seam level and provided an explanation for almost all the dripping areas in the U.S. Gypsum mine. It also explained the general lack of dripping water in the National Gypsum mine.

Correlation between the sandstone-covered areas and water occurrence in the mine was demonstrated by advancing mining in the U.S. Gypsum mine in the SE¼sec. 23. As development entries progressed southward, the most severe structural deformation in the mine was encountered. Small water flows into the mine accompanied the initial advance into the structurally deformed area; however, as mining progressed through the area, even though structural deformation decreased in intensity, the quantity of water increased. The area of greatest inflow of water into the mine was found to be overlain by an
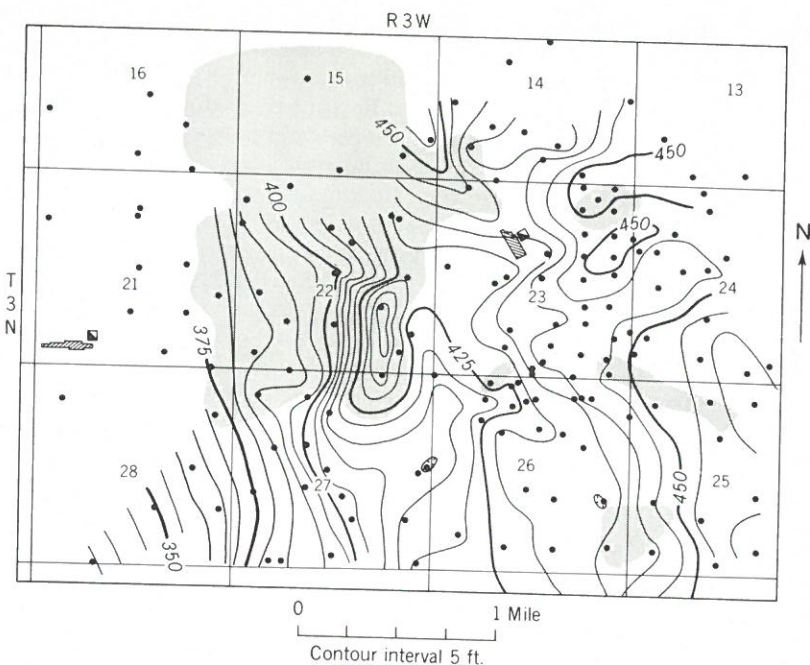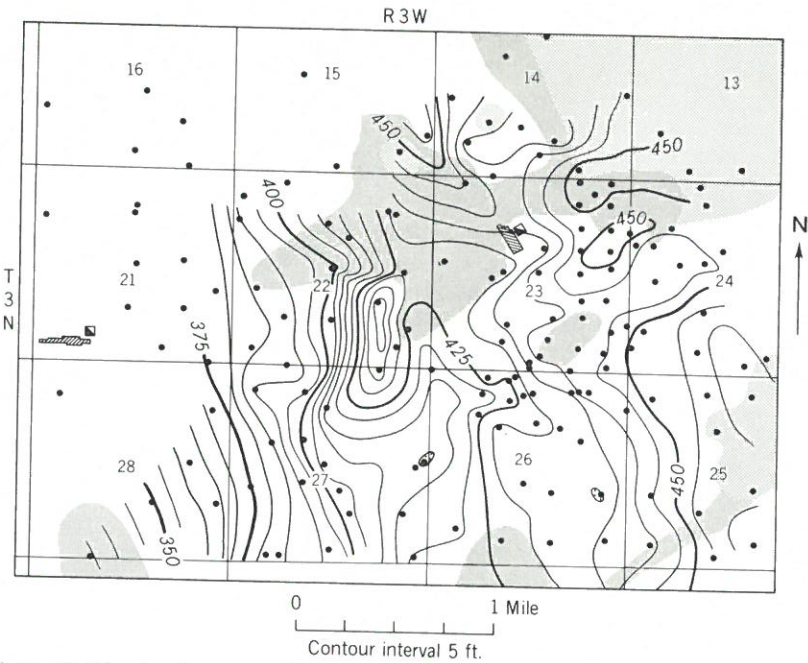
Figure 12. Map showing topographic interpretation of structure. Datum is top of the Paoli Limestone. Both stippled patterns indicate distribution of sandstone in the Bethel Formation. Light stippled pattern indicates areas where solutional activity is taking place in the gypsum-mining seam.

isolated sandstone body above the Blue River limestones.

The few dripping areas in the U.S. Gypsum mine that are not below the Bethel sandstones can be explained by fracturing resulting from structural deformation. The two largest of these dripping areas, with flows of 10 gpm and 4 gpm, both lie on the eastern margin of the Shoals deposit. Comparing the gypsum-mining seam isopach with the residual topography of the mining seam floor shows a thick gypsum seam where the residual topography indicates that none should have been deposited. The final structure, although believed to be little deformed, is postdepositional; thus, fractures which would allow water to reach the gypsum-mining seam could be created in the overlying strata. Also along this thinning edge of the deposit there is less gypsum available from hydration of anhydrite to possibly fill these fractures. One of these drippers, the 10 gpm one, does flow directly from a fracture that is incompletely filled with gypsum.

Examination of another area in Indiana lends further support to the theory that water problems in the gypsum-mining seam are related to the occurrence of a sandstone aquifer overlying the Blue River limestones. An area near Arney in Owen County, about 40 miles north of Shoals, contains a thick bed of gypsum in the lower St. Louis Limestone. Core drilling revealed a cavity system above the gypsum apparently resulting from the solution of the gypsum by groundwater. The extent of the cavity and its access to a water

source were indicated in 1969 in a water-pumping test through a well lined with 16-inch casing. Although more than 2 million gallons of water per day was pumped from the cavity for 15 days, the drawdown was only 6 inches. Cores drilled along the eastern margin of the deposit indicate that here as in the Shoals deposit a thick permeable sandstone lies directly on the Blue River limestones. This sandstone is cut by Fish Creek, a stream large enough to provide easy recharge to the aquifer.

In summary, water problems occur where permeable Bethel sandstones overlie the gypsum-mining seam and in areas that have been structurally disturbed, especially along the eastern margin of the Shoals deposit. The sandstone aquifers are exposed in the stream valleys and are easily recharged. Therefore, the potentially hazardous water areas can be reasonably well defined before actual mining by the use of a Bethel facies map to show areas of sandstone occurrence and by the use of a gypsum isopach map and a residual topography map of the mining seam floor to help define the structurally deformed areas.

Main Conclusions

1. The evaporite section in the lower part of the St. Louis Limestone consists of a distinctive sequence of lithologies in cyclic arrangement that appears to have been deposited in a low-energy environment by the transgression and regression of a shallow sea across a nearly featureless plain similar to modern sabkhas and associated shallow lagoons along the Trucial Coast of the Persian Gulf.

2. Although shallow lagoons accumulated carbonate sediments and may have been the source of brines that produced the evaporites, the evaporites show little evidence that they formed in basins.

3. The evaporites precipitated in previously deposited host sediments in a sabkha supratidal environment; the actual extent and thickness of the evaporites depend on the position of the brine water table and the characteristics of host sediments.

4. In the Shoals deposit, primary hydration of anhydrite to gypsum is believed to have occurred during Mississippian time, probably subsequent to the deposition of the Blue River limestones.

5. Water problem areas in the gypsum-mining seam in the Shoals deposit correlate with the distribution of the permeable sandstone facies of the Bethel Formation and with the structure of the deposit as defined by the topography of the gypsum-mining seam floor.

Acknowledgments

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GEOLOGY OF THE U.S. GYPSUM SPERRY, IOWA MINE

Devonian Gypsum of Iowa

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Abstract

Gypsum observed in a mine located eleven miles north of Burlington, Iowa, exhibits pseudo-folds heretofore undescribed in the literature. The pseudo-folds are approximately one meter in horizontal extent and three meters vertically. They have associated with them tabular dolomite bodies inclined approximately 60 degrees from horizontal. A mechanism of formation of the pseudo-folds is proposed and includes folding by a flexural mechanism and replacement of anhydrite by gypsum along arched planes assumed to be trajectories of maximum stress. The fold form produced by replacement is deformed by flexural slip or flexural flow folding.

General Geology

Since Keyes described the general geology in 1893, very little has been published on this area. A guide book compiled by the Kansas Geological Society in 1935 covers this area and includes stratigraphic descriptions, isopach maps and structure contour maps for the major formations present.

Surface Geology

Pleistocene till and alluvium comprise the major units exposed at the surface. Rocks which crop out in the area are Pennsylvanian in the northern portion of the county and Mississippian in the southern half. Several known outcrops of Devonian Maple Mill shale are also present. Outcrops of Mississippian strata occur along the bluffs of the Mississippi River, which borders the county on the east.

Subsurface Geology

Stratigraphy

Approximate stratigraphic thicknesses in the local area to the top of the Maquoketa shale are as follows:

Pleistocene till	30-95	meters
Mississippian	14.5	meters
Devonian Maple Mill	98	meters
Devonian Lime Creek	3.29	meters
Devonian Cedar Valley	39.4	meters
Devonian Wapsipinicon	24.6	meters

The buried bedrock surface is dissected by deep steep-walled valleys of probably pre-Pleistocene age. The bedrock on the buried upland surface is Mississippian: the Devonian Maple Mill shale and occasionally the Devonian Cedar Valley limestone constitute the bedrock surface in the deep buried valleys.

The thickness of the glacial till varies from a few feet to approximately 30 meters on the upland surfaces and up to 95 meters in the buried valleys.

The Mississippian limestones are part of the Kinderhook series. In places they have been removed by erosion during the formation of the buried valleys, and also thinned on the upland surface to an average thickness of 14.5 meters.

The Devonian Maple Mill shale has a thickness of 98 meters where overlain by Mississippian limestone. The shale is absent in isolated areas located beneath the bottom of deep valleys.

The Devonian Lime Creek dolomite and Cedar Valley limestone are generally present in full thickness.

The Wapsipinicon formation is composed of five members, of which only the upper three are present in this area. They are from youngest to oldest: Davenport limestone, Spring Grove dolomite, and Kenwood shale. The Otis and the Coggan members are absent.

The Spring Grove member has an overall thickness of approximately 11.5 meters. The gypsum is located near the middle of this member. The Spring Grove is fine-grained, thinly-laminated, saccharoidal, buff to brown dolomite, and contains abundant steeply-dipping, calcite-filled fractures. The top of the gypsum bed forms a sharp stratigraphic break with the dolomite and the lower contact is gradational with dolomite below. The contact of the Spring Grove member with the underlying Kenwood shale is also gradational.

Structure

The study area is located near the Mississippi arch (Howell, 1935) between the Forest City Basin to the southwest and the Illinois Basin to the east. The axis of the arch roughly parallels the Mississippi River (Howell, 1935). The regional dip to the west is 2 meters per mile and to the east is 4 meters per mile.

As a result of recent studies by Parker of the Iowa Geological Survey (personal communication) on a sub-regional basis and by the writer on a local scale, smaller folds have been found superimposed on the regional structure. These folds have a northwest-southeast trend and display an enechelon pattern of doubly plunging anticlines and synclines. The mine is situated near the crest of one of these anticlines.

Gypsum Bed

The gypsum bed occurs in the Spring Grove member approximately 3.5 meters below the top of the member. It is approximately 4.5 meters thick with the upper 3.0 meters exposed in the mine. Figure 1 represents diagramatically a composite face displaying the various units, all of which are not present at any one location.

The gypsum bed is composed of two distinct units separated by a thin carbonate lamina. The upper unit is thick bedded to massive and 1.5 meters thick; the lower unit measures 3.0 meters in thickness and displays thin bedding. Anhydrite lenses occurring in the upper and lower units exhibit differences in dolomite distribution and content, and crystal structure.

The upper gypsum has lenses of black dolomite, celestite, satinspar and anhydrite, and the lower gypsum contains anhydrite lenses. Where lenses of
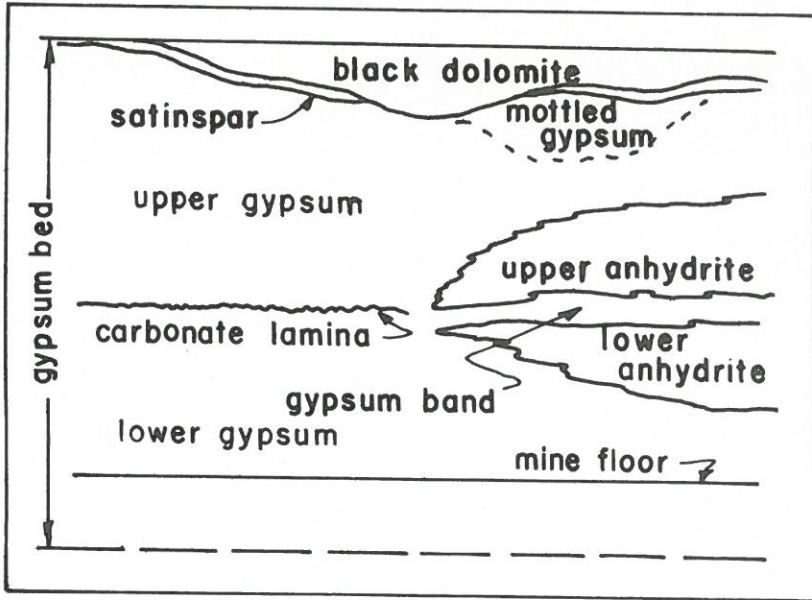
Figure 1. A diagrammatic sketch of the Gypsum Bed.

anhydrite in the upper and lower gypsum units are adjacent they are separated by an uneven band of gypsum which occurs at the same horizon and in place of the carbonate lamina. The occurrance of the gypsum band at this horizon points up the separation plane between the two gypsum units.

Upper Gypsum

The upper gypsum is white, fine-grained, thick bedded to massive, contains small amounts of brown dolomite, and has an average thickness of 1.5 meters. In some areas a fine-grained black dolomite occurs as non-oriented, intersecting veinlets near the top of this unit. This type of structure has been described as mottled by Adams (1904). The thickness of the mottled gypsum ranges from 30 to 90 centimeters with an average of 30 centimeters.

Microscopically the gypsum in this unit if fine to coarse-grained with several distinct types of crystals of various size and shape. They are as follows:

1. Anhedral crystals less than 0.035 mm. Generally appear as a matrix to larger crystals.
2. Anhedral equant crystals, 0.035 mm and greater
3. Anhedral bladed crystals, 0.8 x 0.09 mm.
4. Anhedral groups (crystalline groups) varying from 2.0 x 2.0 mm to 5.0 x 3.0 mm.
5. Euhedral to subhedral tabular crystals varying from 0.06 x 0.10 mm to 0.32 x 0.95 mm.
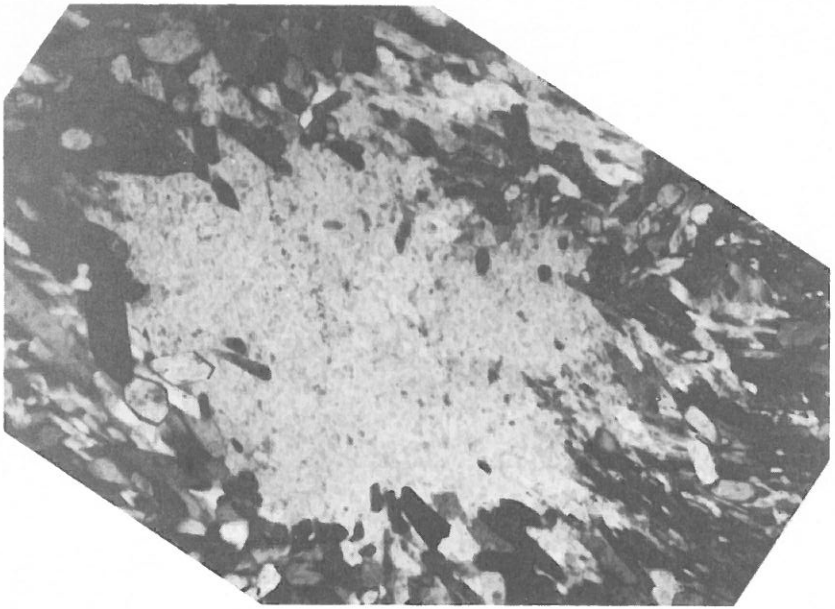
Figure 2. Photomicrograph of a crystalline group at maximum illumination. Enlarged 25X.

All of these occur together producing a non-oriented pattern. There is no descriptive term presently used in the literature which adequately described the observed texture.

Large anhedral groups (Figures 2 and 3), which will be referred to in this study as crystalline groups, have been called "superindividuals" by Ogniben (1957) and "integrated gypsum" by Goldman (1952).

In thin section a crystalline group exhibits an almost uniform color at maximum illumination giving the appearance of a single crystal. Upon rotation of the microscope stage the crystalline group exhibits random extinction and its multi-crystalline nature causes the appearance to change unevenly from the uniform white color to various shades of black and gray. To date no crystalline group has been observed with a uniform black color characteristic of extinction in a single crystal.

A preferred orientation of some crystal shapes exists locally within small areas. Small zones or clusters of bladed crystals commonly occur with their long dimensions parallel. In some instances these zones extend across the thin section, but generally they terminate within the thin section. A preferred orientation formed by alignment of bladed grains appears to exist around the periphery of some of the crystalline groups.

Euhedral to subhedral tabular crystals of gypsum occur randomly throughout the thin section. Their euhedral form and darker outline due to relief cause them to appear more prominent than other grains of similar size. Figure 4 shows these crystals within and penetrating the boundary of a crystalline group.
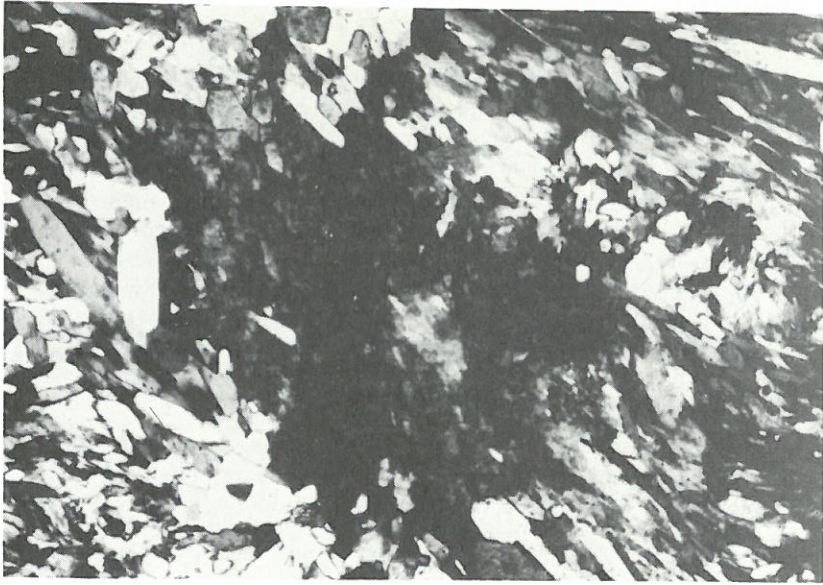
Figure 3. Photomicrograph of a crystalline group (the same one as in Figure 2) rotated slightly from maximum illumination. Enlarged 25X.
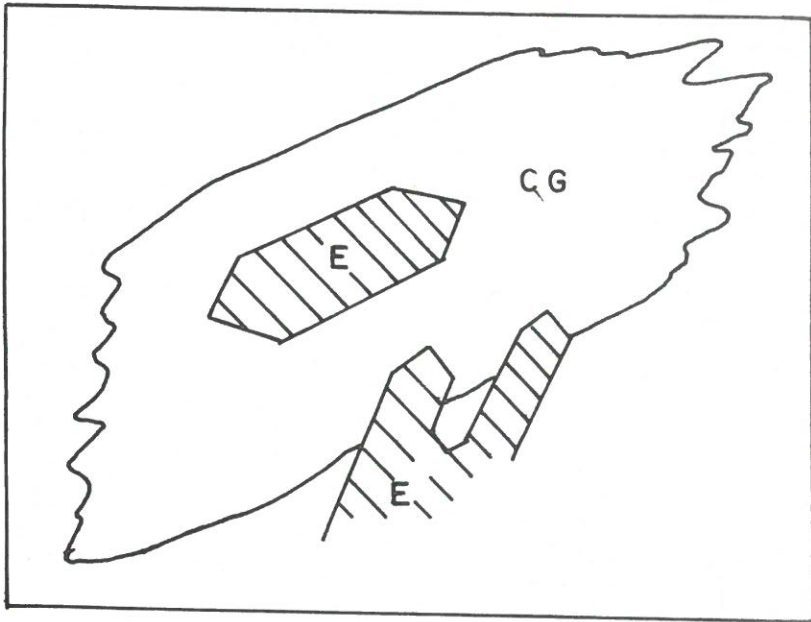
Figure 4. Euhedral gypsum crystal within and penetrating a crystalline group. C Crystalline group. E euhedral gypsum.

Dolomite occurs in this unit as very fine-grained equant (0.15 mm) to rectangular (0.14 x 0.09 mm) crystals or in a granular form which does not exhibit well-defined euhedra.

Veins of gypsum cutting the dolomite display characteristic comb structure, transverse structure, and a non-oriented structure.

Black dolomite lenses

The black dolomite lenses are composed of fine-grained, almost lithographic dolomite containing gypsum veins and averaging 30 centimeters in thickness. They range in thickness up to one meter and in some areas are absent. The upper surface of this unit is in contact with an overlying brown dolomite along a sharp undulating interface. The lower surface of the unit is a sharp contact with rock gypsum or a thin lens of satinspar.

Satinspar lenses

White to translucent satinspar occurs as lenses with a maximum thickness of two centimeters. They are absent in some areas of the mine but where present they show sharp contacts with the dolomite above and the gypsum below.

Upper anhydrite unit

The upper anhydrite is pale blue in color, fine-grained, massive and contains thin non-oriented veins of brown dolomite (Figure 5).
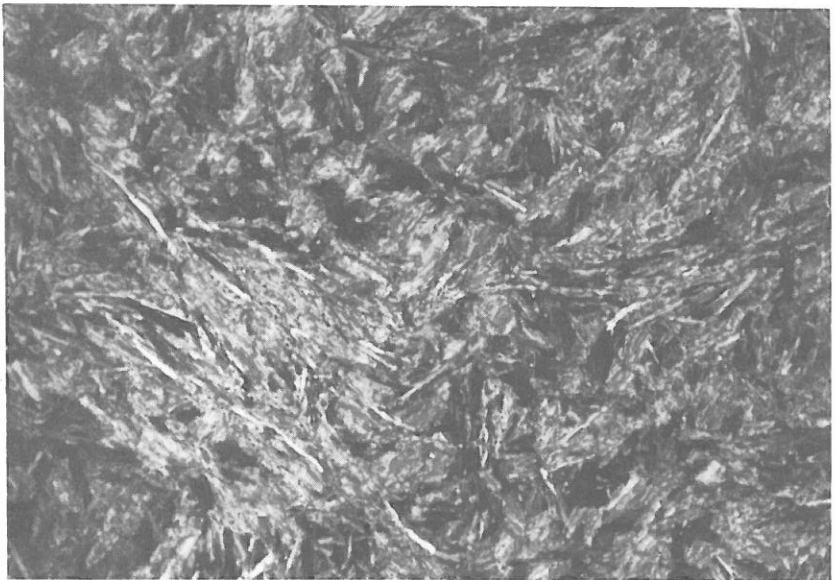
Figure 5. Photomicrograph of the upper anhydrite. Enlarged 25X.

The anhydrite crystals are present in two forms:
1. Euhedral bladed (0.61 x 0.03 mm).
2. Euhedral to subhedral equant (0.04 x 0.04 mm)

Gypsum is present as large subhedral crystals (1.85 x 2.12 mm). Euhedral dolomite crystals occur as rhombs throughout the unit with the concentration of dolomite increasing downward.

The texture of the upper anhydrite is characterized by two textural elements; one element is composed of slightly bent, bladed crystals occuring in spiral-like whirls, in a matrix of smaller equant crystals; the second element contains lathlike crystals oriented with their long axes sub-parallel. The oriented groups occur as bands. These two textural elements occur together in a pattern dominated by the first element which is difficult to describe with a common textural term.

Many of the bladed or lath-like crystals of anhydrite exhibit low birefringence, parallel extinction, and low relief which are properties similar to the optical characteristics displayed by gypsum. It was thought that these long lath-like crystals were either pseudmorphs of gypsum after anhydrite or anhydrite crystals oriented with their optic axes parallel to the axis of the microscope. In order to evaluate the above possibilities, thin sections were studied on the universal stage. The results indicated that the lath-like grains exhibiting the above mentioned properties were anhydrite.

Gypsum occurs randomly in the anhydrite matrix as large crystals (Figure 6) or along definite planes as bands or vein-like bodies ranging up to 3.5 mm in width and extending across the thin section. The vein-like bodies have been observed in hand specimens to be tabular with non-parallel sides and will therefore hereafter be referred to as veins.
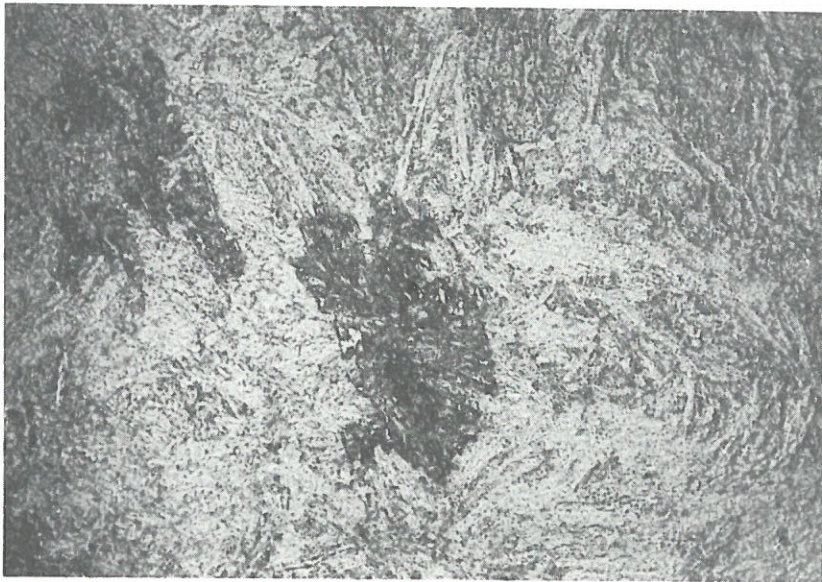
Figure 6. Photomicrograph of a subhedral gypsum crystal in anhydrite. Enlarged 25X.

The large subhedral crystals of gypsum contain segments of anhydrite crystals displaying optical continuity. The anhydrite segments are separated by the gypsum. The gypsum boundaries are generally irregular; however, some display sharp boundaries which cut individual anhydrite grains. Those gypsum crystals with irregular boundaries appear to have more anhydrite included within them than those which have well-defined faces. Bundy (1956) has reported these in anhydrite studied in Indiana and has used them as evidence of gypsum after anhydrite.

The gypsum which occurs in the veins is generally euhedral and in some a preferred orientation is observed. The veins are generally 2 mm or greater in width and extend completely across the sections. The boundaries of these bodies are irregular and can be described as jagged, with anhydrite and gypsum crystals interpenetrating along the boundary. The line of contact between gypsum and anhydrite varies with crystal orientation of the gypsum. In general gypsum occuring as large twinned crystals truncates anhydrite crystals as shown in Figure 7. Where the gypsum crystals are small the boundary is jagged following the contour of each crystal. In many instances the vein will split into two closely spaced parallel veins which can rejoin to form a larger vein with an anhydrite inclusion.

The dolomite is randomly distributed in this unit and is not abundant. Dolomite occurs in the following ways: as individual rhombs; as a granular texture composed of rhombs oriented in shapes sometimes suggesting relic tabular outlines. The rhombs vary in size from 0.01 to 0.05 mm. Some rhombs occur as rims of dolomite surrounding cores of anhydrite.
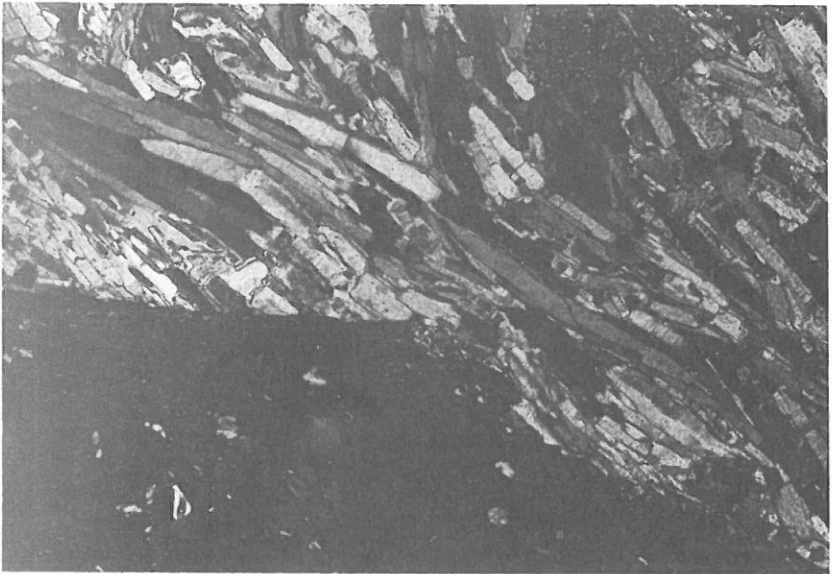
Figure 7. Photomicrograph of anhydrite crystals truncated by twinned gypsum. Enlarged 63X.

Carbonate lamina-gypsum band

The carbonate lamina, which separates the gypsum bed into two units, is present as a brown to black carbonate material of variable thickness (1.8 to 3.3 mm), and occurs at a horizon varying from four to five feet below the roof of the mine. The lamina is composed of a fine-grained granular material, considered to be carbonate because of its high birefringence, and occurs in thin veins cutting gypsum crystals or along the interface between crystals. Gypsum and traces of anhydrite crystals occur within some of the larger areas of the lamina.

Larger bladed crystals of gypsum above and below the carbonate lamina are oriented with their long dimensions parallel to each other and perpendicular to the lamina. This oriented texture does not extend more than eight centimeters above and below the lamina.

Anhydrite lenses occurring in the upper and lower gypsum units are generally adjacent but separated along a horizontal plane by a gypsum band which varies in thickness from a few millimeters up to several centimeters. The gypsum is similar to the upper and lower units except it does not contain dolomite. This gypsum is referred to as the gypsum band (Figure 1).

The carbonate lamina cuts the pseudo-folds with little or no vertical displacement (Figure 8). If displacement does occur the radius of the curved lamina is greater than the radius of the pseudo-fold.
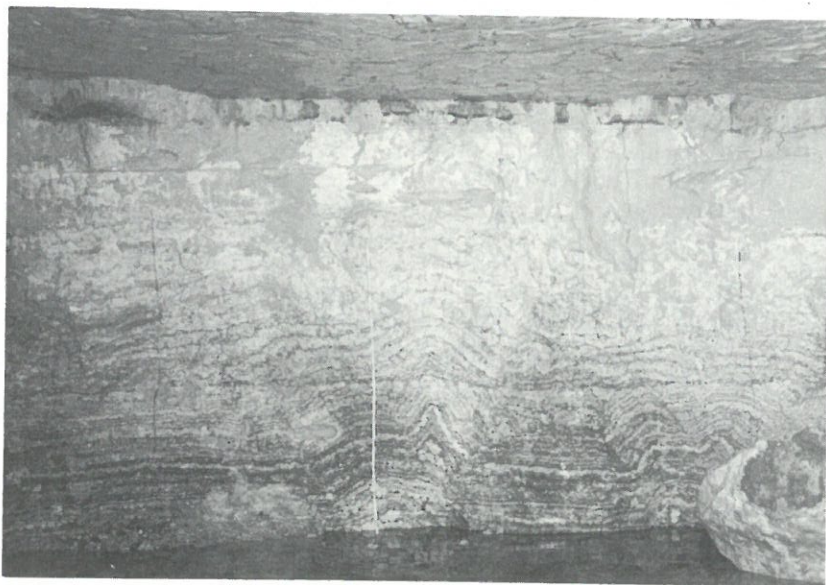
Figure 8. Asymmetric fold-form cut by nearly horizontal carbonate lamina.

Lower Gypsum

The lower gypsum is fine-grained, white, contains more brown dolomite than the upper gypsum, and averages 3 meters in thickness.

The brown dolomite occurs in thin, uneven laminations which range up to approximately 6 millimeters in thickness. The dolomite bands are separated by gypsum which ranges from 12 millimeters to 3.8 centimeters in thickness. The dolomite laminations are uneven and in some instances cut across the gypsum to give it a segmented appearance. This type of structure has been termed "pinch and swell" structure by many investigators and "boundinage" (sausage-like) by Rily and Bryne (1961). Both terms, as defined, connote a genetic mechanism which may or may not be responsible for the observed structures; however, pinch and swell adequately describes the appearance of the structure and thus will be used in this study for its descriptive value only.

In thin section the lower gypsum displays characteristics similar to the upper gypsum. They are as follows:

1. Anhedral crystals 0.04 mm and smaller
2. Anhedral bladed crystals, 0.92 x 0.06 mm.
3. Anhedral groups (crystalline groups) varying from 2.0 x 2.0 mm to 3.9 x 2.6 mm in size.
4. Euhedral to subhedral crystals 0.06 x 0.10 mm to 0.32 x 0.95 mm.

The texture is exactly the same as that described for the upper gypsum and therefore will not be rediscribed here. The major petrographic difference between the two units is the amount and   occurrence of dolomite.

The dolomite is composed of equant euhedral rhombs varying from 0.12 to 0.02 mm in size with the average around 0.04 mm. The dolomite is cut in places by veins of gypsum which exhibit comb. transverse and non-oriented structures. Many rhombs show a corroded external boundary and some exhibit a carbonate rim with a core of gypsum. There are other rhombs which exhibit zoning of the dolomite.

Another feature observed in many thin sections, not restricted to any one unit but common in the lower parts, is a preferred orientation of the dolomite crystals. This orientation is in the form of individual dolomite rhombs aligned to form subhedral six sided tabular bodies filled with gypsum or anhydrite, depending on the location. These tabular outlines are generally 1.2 x 0.8 mm in size. Brown (1931) observed carbonate present around individual anhydrite crystals in what he described as a "net". Stewart (1951a) shows the same features along crystal boundaries of anhydrite, however there is no regular shape.

Lower Anhydrite

The lower anhydrite is pale blue in color, fine-grained and banded with brown dolomite. Maximum thickness of the lenses ranges from 15 to 61 centimeters. The brown dolomite occurs as stringers and produces lamination similar to those previously described in the gypsum unit. There is one difference; the dolomite grains occuring in the bands are not as compact as in

the equivalent gypsum horizon, but are more dispersed and disseminated throughout the anhydrite.

Microscopically most anhydrite in the lower unit is composed of crystals which exhibit more of an equant or rectangular shape than the combination of lath and equant forms characteristic of the upper anhydrite lenses. This type of structure has been called "pile of bricks" structure by Brown (1931). There is more dolomite and gypsum present than in the upper anhydrite. Dolomite seems to be more abundant in the upper portion of the lens and gypsum dominates the lower portion. The anhydrite appears to differ from that found in the upper anhydrite in three ways:

1. Smaller size crystals dominate, 0.05 x 0.10 mm.
2. The crystals do not exhibit sharp faces or boundaries but instead are slightly rounded and seem to interpenetrate each other.
3. There are fewer lath-like crystals present and those that do occur show a low birefringence. Some exhibit undulatory extinction, and many are penetrated by other anhydrite crystals.

Much of the anhydrite occurs within gypsum as highly corroded and rounded crystals. Large anhedral crystals of anhydrite are present in anhydrite and dolomite.

Gypsum is found in this zone in veins or as random euhedral and anhedral crystals. This occurrence is similar to that described for the upper anhydrite and therefore will not be resdescribed here.

Differences between the upper and lower anhydrite lenses are characterized by the dolomite distribution and textural variations of the anhydrite. Dolomite in the upper anhydrite lenses is non-oriented, disseminated, and of a lower concentration than in the lower anhydrite. Dolomite in the lower anhydrite lenses is located along many horizons producing irregular laminations or a banded effect. Dolomite occurring in diffuse laminae in a disseminated manner has the appearance of a finely woven net. The laminae are separated by anhydrite; however, dolomite cuts across the anhydrite and commonly connects the laminae. Textural differences of the anhydrite lenses are characterized by the presence or absence of oriented lath-like grains. The occurrence of these grains in the upper anhydrite lenses produces a gneissic structure which is notably absent in the lower unit.

Dolomite in gypsum produces a bedded effect which has a slightly different appearance than the laminations produced by dolomite in anhydrite. The concentration of the dolomite into thinner laminae in the gypsum develops a sharper contact and a darker color than the similar relationship in anhydrite. This contrast is apparent when bedded gypsum and anhydrite are observed adjacent to each other.

Internal Structures

The gypsum bed contains several types of internal structures. They are pseudo-fold, dolomite bodies of uneven dimensions, and quartz nodules.

Pseudo-folds

The laminated gypsum, and occasionally anhydrite, does not always occur as horizontal planar features, but may be present in a knob or domical form. This structure has been called a pseudo-fold based on evidence that it is not completely formed by displacement of the laminations. The normal mechanism of fold formation requires that the components of the fold be displaced. The pseudo-folds will also be referred to as fold forms in the descriptive sense.

The shape of these forms approximates parallel or concentric folding, when observed in the mine walls, Figure 9. The fold measures approximately three feet horizontally and one foot displacement in the vertical direction (Figure 10). In the south end of the mine the lower part of the gypsum bed is exposed and the fold forms observed in this area exhibit a gradual decrease in the magnitude of the vertical dimension with depth. Figure 9 shows the lowermost dolomite lamination almost horizontal. The radius of curvature of the fold form increases in the upward direction creating a flatter or gentler fold form near the top of the bed; see Figure 8. The gypsum and dolomite occuring near the middle of the bed exhibit sharp fold forms which in some instances display a slightly deformed core. Deformation of this nature suggests folding by a flow mechanism; however, the laminations involved in the fold do not exhibit thinning on the limbs and thickening on the crest of the form. This type of intralayer folding would fit into the flexural-flow class defined by Donath and Parker (1964). Most folds are not symmetrical about a vertical axial plane, and some as in Figure 8 show extreme asymmetrical tendencies.
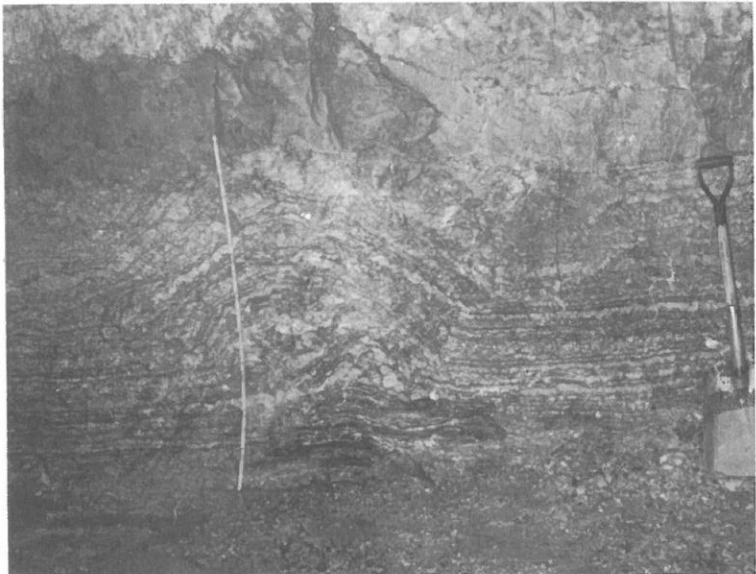
Figure 9. Fold-form illustrating decrease in vertical displacement with depth.
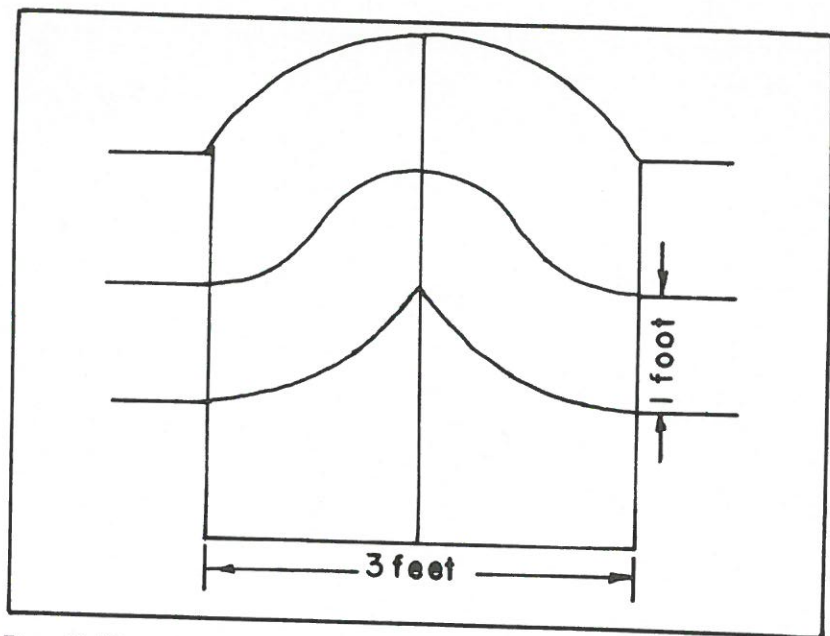
Figure 10. Diagrammatic sketch of fold-form observed in the mine.

Synclines are not associated with the pseudo-fold anticlinal form. The bedded gypsum between pseudo-folds is horizontal except when two fold forms are adjacent. In this situation the fold forms appear to interpenetrate and the base of the trough between them is an angular inflection point.

An axial trend may exist for the pseudo-folds but actual field evidence is scanty. Where observed in pillar corners the form appears domical. The fold form pattern may resemble the shapes produced by enechelon folding, with short linear features producing a knobby effect.

The fold form is very prominent in the lower portion of the gypsum bed where the dolomite content is high, but as the dolomite laminations become thinner toward the top of the bed the definition of the form decreases and in many areas is undetectable.

Anhydrite lenses which occur in the upper middle portion of the gypsum bed appear to truncate the fold forms: however, on closer inspection becomes apparent that veins of gypsum occur in the anhydrite and parallel the fold form in the gypsum below. See Figure 11. The curved gypsum veins cutting the essentially horizontal anhydrite lens clearly demonstrate that a fold form has been developed without displacing the anhydrite. A description of this feature could not be found in the literature and therefore it is assumed that this is the first time this relationship in gypsum and anhydrite has been described.
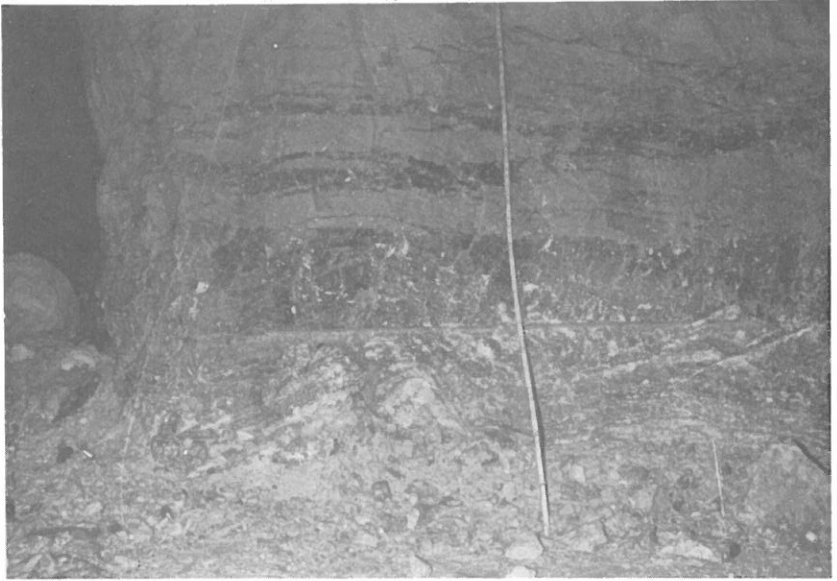
Figure 11. Fold-form developing into anhydrite lens.

Dolomite bodies

The dolomite bodies which occur in the mine have been grouped into two types, one of which is more abundant.

The more common type always occurs associated with the fold form. The dolomite accumulations are discordant, tabular, with their long dimension ranging from 0.3 to 3 meters and their short dimension generally less than eight centimeters (Figure 12). One edge of this tabular feature occurs near the core of the fold form and extends upward at an angle ranging from 12 to 35 degrees (an average of approximately 30 degrees) from the vertical. In one place this feature can be traced from one pillar to another: however, this is generally very difficult and if a trend does exist it is subtle. In places where this feature cuts across a lens of anhydrite, a zone of gypsum, two to eight centimeters in width, it is observed between the dolomite and the anhydrite. In one instance two such bodies, one on each side, were associated with one fold form.

The other type of dolomite accumulation occurs randomly throughout the mine. Most of these bodies are of irregular shape - less than 60 centimeters in width, 90 to 120 centimeters in vertical height (measured from the floor of the mine) - and contain small (5 x 1 cm) solution cavities which are lined with fiberous gypsum crystals with their long axis oriented perpendicular to the sides of the cavity. The dolomite is fine-grained, light brown, saccharoidal, and has as aappearance similar to the dolomite above and below the gypsum bed. Where the lower portion of these bodies occur in the unit of the laminated gypsum, laminations often carry through some parts of the

Figure 12. Tabular, inclined dolomite body.

dolomite body. The gypsum bands display a concave up form adjacent to the dolomite body which in appearance resembles a drag phenomenon.

The dolomite in these bodies is observed in thin section as granular fine-grained euhedral crystals and as disseminated rhombs surrounded by a matrix of gypsum. The dolomite rhombs are approximately equant and range from 0.03 to 0.07 mm in size. The granular dolomite is penetrated by vein-like bodies of gypsum which exhibit transverse and non-oriented structures. The preferred orientation of gypsum in veins is less oriented where these bodies extend into areas dominated by disseminated rhombs and gypsum matrix.

Quartz nodules

Quartz nodules which vary in size from 2.5 to 18 centimeters in diameter have been found at various localities in the mine. Only one complete nodule has been recovered intact, and this one was found on the floor of the mine after a face had been blasted. Many fragments of nodules have been observed in the walls. The nodule recovered is subspherical in shape and 18 centimeters in diameter. The nodules are composed of quartz veined with gypsum and generally occur at a horizon approximately 1.2 meters below the roof of the mine. From limited observations, it appears that they occur in small groups of two to four nodules with each separated from the adjacent nodule by gypsum. The distance between nodules in a group varies from 3 to 45 centimeters and the distances between groups is measured in several meters to hundreds of meters.

The nodules are composed of crystals of quartz which range in size from 0.03 mm to 0.45 mm, with the larger crystals being subhedral and the smaller

crystals anhedral. The texture varies from a mosaic for the larger crystals to granular for the smaller anhedral crystals. Euhedral shapes appear around some anhedral quartz grains as an overgrowth. Other euhedral shapes are surrounded by anhedral overgrowths of quartz. Some shapes are hexagonal and others are square and rectangular.

Gypsum occurs in the nodules in two ways: 1. as a matrix mineral between groups and individual quartz euhedra, and 2. as veins cutting through the larger quartz euhedra and fine-size granular quartz.

The gypsum which occurs as a matrix mineral appears to be filling voids because the quartz grains are idioblastic around the periphery of the gypsum.

The veins show what might be called a low-order of preferred orientation. The crystals do not show transverse structure but instead display larger more equant subhedral crystals in a mosaic pattern with an occasional lath-like crystal oriented perpendicular to the long axis of the vein.

Discussion

The nature, origin and history of the Sperry deposit comprises its petrology. From the data gathered in this study, the mode of formation of the original rock cannot be stated. Presently the deposit is gypsum with remnant anhydrite lenses.

Four minerals (gypsum, anhydrite, dolomite and quartz) have been observed to occur in the gypsum bed. Their apparent paragenetic relationship is summarized in Figure 13.

MINERAL	EARLY ⟶ LATE
Anhydrite	——————
Dolomite	——————
Gypsum	? — — — ——————
Quartz	— ? — — — ? — — — ? — — —
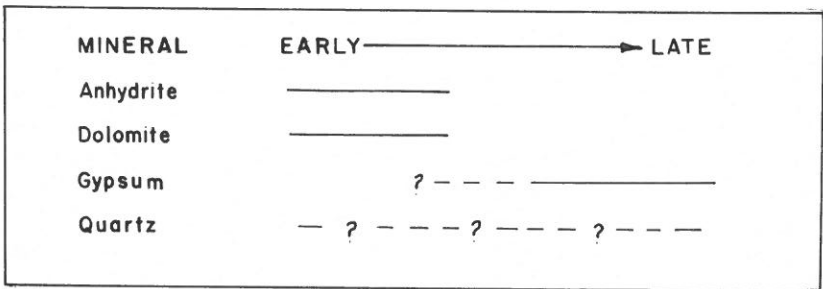
Figure 13. Paragenetic diagram of minerals observed in the gypsum bed.

Megascopic and microscopic evidence indicates the gypsum is replacing anhydrite. Replacement is taking place along the following interfaces: the upper and lower boundaries of the anhydrite lenses, the walls of the veins cutting the anhydrite lenses, and within the body of the lenses along the faces of large subhedral crystals of gypsum.

Hydration of the anhydrite bed probably commenced at the upper and lower contacts of the bed and proceeded along fronts toward the middle of the bed. Lens shaped anhydrite bodies present near the upper middle portion of the bed support this hypothesis.

Laminations are absent in the upper anhydrite, yet the upper gypsum at the same stratigraphic horizon is faintly bedded. The lower anhydrite lenses are laminated by diffuse dolomite laminae whereas the gypsum at this horizon is distinctly laminated. Assuming that the physical and chemical characteristics of the anhydrite bed prior to hydration were the same as those observed in lenses in the mine, the apparent concentration of dolomite or brown material (perhaps iron oxide) along definite planes may be the result of redistribution of these materials during hydration.

A statement supported by irrefutable evidence on the origin of the carbonate lamina cannot be made; however, there are two possible mechanisms of formation:

A. The anhydrite prior to hydration was divided into two units by a separation plane at the horizon presently occupied by the carbonate lamina. The differences in the dolomite content and distribution, and textural variations of the anhydrite in the upper and lower gypsum units indicate that two separate units were present prior to hydration. The absence of the carbonate lamina between anhydrite lenses is difficult to explain by this hypothesis.

B. The carbonate lamina may be a feature of late origin. If the "pseudo-folds" were formed by normal deformation the lamina would have had to form later than deformation. The absence of the lamina between anhydrite lenses supports a late origin, whereas, the displacement of the lamina by "pseudo-folds" refutes a late origin.

Other hypothesis can possibly be proposed on the origin of the carbonate lamina, but in light of present data it will be considered a feature controlled by the inherent differences in the two major units of the gypsum bed prior to hydration.

The origin of the fold-forms can only be postulated at this time. Interrelationships of the carbonate lamina, anhydrite lenses, gypsum veins, and the pseudo-folds suggest several possible mechanisms of formation. They are:

A. Expansion due to hydration of anhydrite produces stress fields along which replacement of anhydrite takes place.

B. Regional and local folding of the gypsum bed produces stress fields along which replacement of anhydrite occurs.

C. Regional or local folding produces deformation and folding as the result of a flexural mechanism.

Two of the above (A and B) introduce a new concept of fold formation.

Following is a description of each of the above mechanisms.

A. The following sequence is based on the assumption that hydration of anhydrite produces a volume expansion.

1. Hydration of anhydrite starts from the upper and lower boundaries of the anhydrite bed.

2. Certain local areas will have greater access to water along point or line sources, therefore hydration will proceed at a faster rate at these locations.

3. Hydration creates greater volume change in these areas and

therefore local stress fields will be developed as shown in Figure 14-b.

4. Regional bending has produced tension and compression in the upper and lower portions of the gypsum bed, respectively. Therefore, there is less confining stress at the top of the bed than at the bottom. This explains the presence of fold forms only at the bottom of the gypsum bed.

5. Planes of maximum stress are developed and replacement takes place along them in both the lower and upper anhydrite units.

6. A major shear plane occurs between 12 and 35 degrees from the vertical. Dolomite concentrates here to produce the inclined tabular bodies, Figure 12.

7. Hydration goes to completion and pseudo-fold forms develop.

B. The following hypothesis assumes that local bending of the gypsum bed has produced a stress field in the bed similar to that shown in Figure 14-b. Replacement of anhydrite occurs and the sequence of change will be the same as the mechanism above (A) except steps two and three which involve expansion are omitted.

C. Normal folding may be produced by deformation of the gypsum by a flexural mechanism. The cause of deformation may be the result of regional bending of the gypsum bed, expansion due to hydration of anhydrite or excess overburden pressure causing the gypsum to flow.

1. Hydration from top and bottom of the bed will produce two layers of gypsum separated by anhydrite. The gypsum will act as an incompetant member and the anhydrite and dolomite beds will act as competant members.

2. Gypsum, being incompetant, will yield by flexural-slip and flexural-flow and be displaced. Folds will be produced in the gypsum as hydration goes to completion.

Each of the above mechanisms may explain a part of the formation of the pseudo-folds. Replacement and deformational features are observed indicating that both mechanisms may occur; however, singly they cannot explain the formation of pseudo-folds.

Conclusions

The pseudo-folds described in this study are formed by a combination of mechanisms, including deformation and replacement.

Donath and Parker (1964) showed that the relative ductility (described as competency by most authors) can be related to fold form. By referring to this figure the deformational portion of the formation of the pseudo-folds can be explained. If one assumes that the mean ductility is low for anhydrite and moderate for gypsum, and the ductility contrast is moderate between the two, the changes which occur through hydration can be related to the change in the mechanism of folding. Therefore as hydration proceeds the volume of gypsum and the mean ductility of the bed increases and the mechanism of deformation

approaches flexural-flow is the asymmetrical form and the slightly deformed core of the fold forms, as shown in Figure 8.

The following sequence appears to be best supported by the available data. Expansion due to hydration of anhydrite is assumed.

--- σ max.
— σ min.

anhydrite ⬚ dolomite laminations ⬚ dolomite
gypsum ⬚ disseminated dolomite ⬚ gypsum
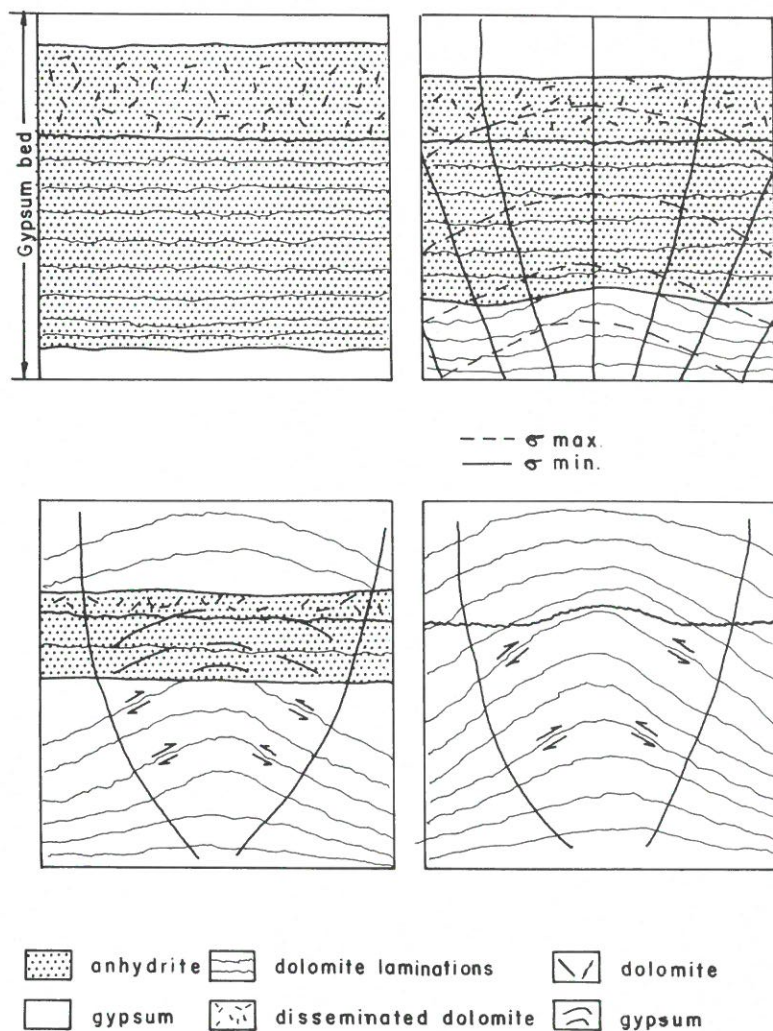
Figure 14. Hypothetical sequence of events for the hydration of the anhydrite bed and formation of the pseudo-folds.
(a) Anhydrite bed prior to hydration.
(b) Anhydrite bed partially hydrated showing maximum and minimum stress trajectories.
(c) Anhydrite almost completely hydrated. Veins of gypsum occur in the anhydrite paralleling the pseudo-folds in the gypsum below. Dolomite occurs along maximum shear planes in inclined position.
(d) Anhydrite bed completely hydrated to form the gypsum bed. The carbonate lamina is slightly displaced.

1. Hydration from outer boundaries of the bed toward the middle.
2. Higher rate of expansion occurs along point or line sources due to accelerated hydration.
3. The concentration of stress due to accelerated hydration produces a stress field as shown in Figure 14. Figure 14 shows the distribution of maximum and minimum stress trajectories.
4. Hydration occurring in areas of a uniform horizontal overburden stress produces horizontal laminations.
5. Expansion will produce lateral displacement of material. Movement takes place along shear planes according to the flexural-slip mechanism. The magnitude and intensity of deformation is such that the overlying anhydrite may be deformed into gentle folds by flexural-slip due to concentration of pressure as a fold form develops in the gypsum below.
6. Replacement continues along the front and also along planes of maximum stress extending into the anhydrite as shown in Figures 14-b and 14-c.
7. Major shear planes develop between 12 and 35 degrees from the vertical, and dolomite accumulates along them. Maximum shear planes would occur along trajectories bisecting the angle of intersection between the maximum and minimum stress trajectories (Figure 14-b). Figures 14-c and 14-d and the photo in Figure 12 illustrate this feature.
8. Hydration proceeds toward the middle producing pseudo-folds. The pseudo-folds later experience flexural-slip and flexural-flow folding producing shear in the limbs of the fold and a flow type deformation in the core of the fold form.
9. Hydration goes to completion and pseudo-folds continue to form.
10. The slight displacement of the carbonate lamina shown in Figure 8 can be explained by deformation due to either flexural-flow or flexural-slip after hydration is complete.

In summary, the pseudo-folds are formed partly by deformational folding and partly by replacement of anhydrite by gypsum along stress planes. Deformation may be the result of expansion upon hydration of anhydrite or regional folding with a flexural-slip mechanism.

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AVAILABILITY AND POTENTIAL UTILIZATION OF BYPRODUCT GYPSUM IN FLORIDA PHOSPHATE OPERATIONS

by

John W. Sweeney[1] and Bobby J. Timmons[2]

Abstract

The generation rate and availability of byproduct gypsum in Florida is assessed to determine the magnitude of the situation and to stimulate the utilization of this gypsum resource. Past trends are projected to determine the future availability of these materials.

Several new uses of byproduct gypsum could utilize large volumes of the material. The projected annual generation rates of byproduct gypsum from wet-process phosphoric acid manufactured in Florida far exceeds domestic gypsum demand.

Known, potential, and new uses of byproduct gypsum are reviewed and discussed in this paper.

Introduction

During the past two decades, there has been a constant shift in the United States toward using multinutrient and mixed fertilizer materials in place of single-nutrient materials. This trend has brought about the localization, especially along the Gulf Coast and in Florida, of large raw-materials-oriented chemical companies manufacturing wet-process phosphoric acid, which is the basic material needed to produce high-analysis multinutrient fertilizer. This manufacture of wet-process phosphoric acid results in the generation of large quantities of impure byproduct gypsum.

The objective of this paper is to stimulate thought toward the utilization of these vast amounts of byproduct gypsum, for the most part stacked on the surface and available at very low cost. More complete utilization of our mineral wastes would certainly improve the environmental picture and possibly solve some of our mineral resource problems. We would like to discuss the magnitude of the problem, review some of the past research, and try to move toward a solution to finding economic uses for these materials. Our objective is really twofold: to find a high-volume use for this material that would increase our resource base; and to solve an aesthetic problem by eliminating the huge mountains of materials — and they do look like mountains on the flat Florida terrain.

Availability

The availability of byproduct gypsum depends on the amount of phosphate rock used in the manufacture of wet-process phosphoric acid.

The principal reaction taking place in the manufacture of wet-process phosphoric acid is best represented by the following equation:

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \longrightarrow$$
$$10CaSO_4 \cdot 2H_2O + 6H_3PO_4 + 2HF$$
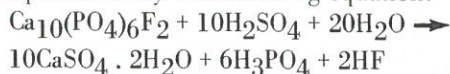
[1]U.S. Bureau of Mines Liaison Officer, Tallahassee, Fla.

[2]Economic Geologist, Florida Department of Natural Resources, Tallahassee, Fla.

The process is carried out in the digestion system over a period of about eight hours. The reaction itself is completed in a matter of minutes, but additional time is needed to allow for the proper formation of the gypsum crystals. Sulfuric acid (93 percent H_2SO_4) and finely ground phosphate rock are continuously added to a slurry consisting of reactants, products, and sufficient recycling weak phosphoric acid to maintain sufficient fluidity. The slurry is continually drawn off and filtered.

The gypsum filter cake is reslurried with water and usually discarded.[3] Large volumes of byproduct gypsum are available in Florida. For every ton of phosphate rock processed to phosphoric acid, approximately one and one-half tons of byproduct gypsum are generated.
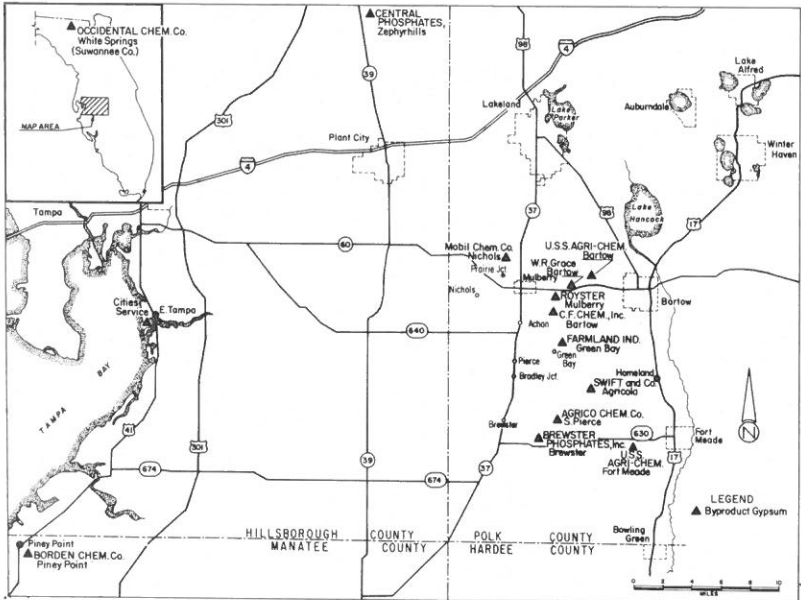
Figure 1. - Location of byproduct gypsum in Florida.

Let's look at the magnitude of the situation. Figure 1 shows the location of the phosphoric acid plants in Florida and the location of the stacked gypsum.

Table 1 lists the companies generating the gypsum, the acreage needed for storage, the annual generation rate, and current inventories of stacked gypsum.

[3]Bixby, David W., Delbert L. Rucker, and Samuel L. Tisdale. Phosphatic Fertilizers, Properties and Processes. Wet Process Phosphoric Acid. Sulphur Institute, October 1966, p. 9-11.

TABLE 1. - **By product gypsum inventory in Florida-1972**[1]

Company	Acres	Annual Generation Rate Tons/Year	Available Tons
Agrico Chemical Company, Pierce	250	1,000,000	6,000,000
Brewster Phosphates, Brewster	70		13,500,000
Borden, Piney Point	100	900,000	3,700,000
Cities Service, East Tampa	260	5,500,000	45,000,000
Central Phosphates, Zephyrhills	100	1,000,000	6,000,000
C. F. Chemicals, Inc. Bartow	200	2,500,000	24,000,000
Farmland Industries, Green Bay	60	2,300,000	6,000,000
W. R. Grace, Bartow	75	1,600,000	16,000,000
Mobil Chemical Company, [2] Nichols	300		9,000,000
Occidental, White Springs	100	1,000,000	4,000,000
Royster, Mulberry	48	3,000,000	5,000,000
Swift & Company, Agricola	50		3,500,00
U.S.S. Agri-Chemicals, Bartow	80	1,500,000	5,000,000
Ft. Meade	80	600,000	6,000,000
Totals	1,773	20,900,000	152,700,000

[1] Data obtained through personal communication with individual companies.
[2] Sold Harding Plant to Conserv, Inc., June 1971.

Summarizing, we see that there are over 152 million tons of gypsum currently available (1972), and the material is being generated at the rate of 21 million tons annually. Byproduct gypsum generated during 1971 was about one-half of the 1969 world production of primary gypsum, and almost three times that of the domestic production of natural gypsum.[4]

Without making any sophisticated projections, taking growth rates of the wet-process phosphoric acid industry and other factors into consideration, but just at the current growth rate, over the next ten years there will be over 200 million tons of byproduct gypsum generated in Florida, and that's more than doubling the amount of material that is already stacked on the ground.

Let's look at some of this material. Figure 2 shows an oblique aerial photograph showing the largest single amount of byproduct gypsum available in the central Florida area.

Figure 2. - Aerial view showing stacked byproduct gypsum.

[4]Ashizawa, Roy Y. Gypsum. BuMines Minerals Yearbook-1969, v. 1-2, 1971, p.547

Figure 3 is an aerial view showing stacked byproduct gypsum and the water retention areas.
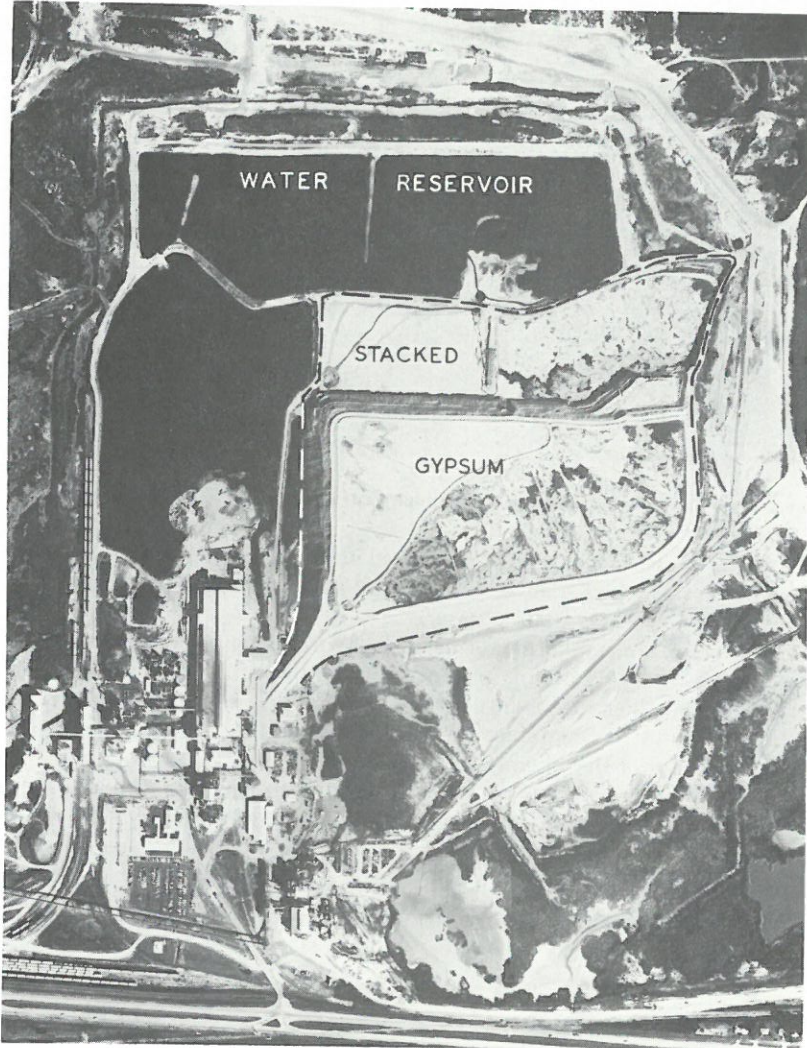
Figure 3. - Aerial view showing stacked gypsum waste, water reservoir, and acid plant.

Figure 4 is a panoramic view showing byproduct gypsum, the gypsum discharging in a mined area, and waste water return lines.
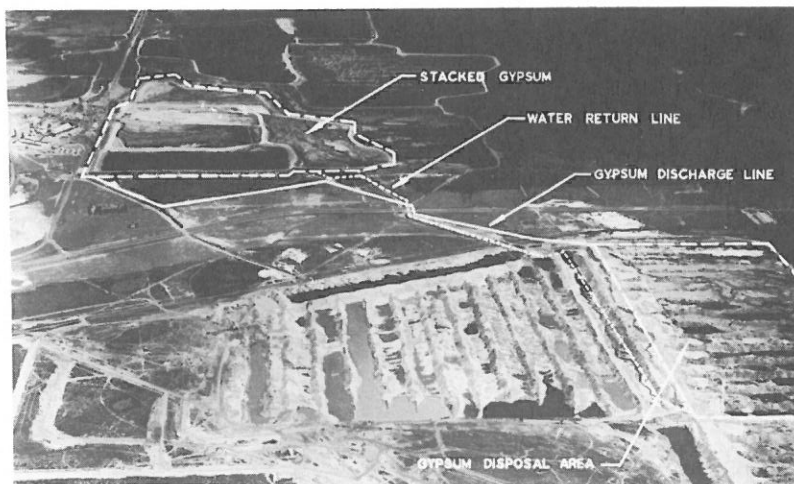
Figure 4. - Panoramic view showing stacked gypsum, waste acid plant, gypsum discharge pipeline, and waste disposal area.

Now that we have briefly examined the magnitude of the available byproduct, let's look at some of the physical and chemical characteristics of the material which may dictate its use.

Physically, the crystalline forms of the byproduct gypsum are unlike the gypsum used to make building products, which have flatsided crystals. The byproduct gypsum crystal is jagged and/or acicular, and therefore does not bond favorably in the manufacture of gypsum building products.

Table 2 shows the chemical analysis of a typical byproduct gypsum sample. The material has a lower calcium sulfate content than the naturally occurring material used for building products. However, by simple screening, much of the silica can be removed. That still leaves the deleterious fluorine and phosphoric acid, which limits the use of byproduct gypsum.

TABLE 2 - Analysis of Slurry of Byproduct Gypsum

Gypsum	Percent
Acid insoluble, incl. SiO_2	3.52
Acid soluble, P_2O_5	0.66
F as CaF_2	1.42
Calcium Sulfate ($CaSO_4$)	73.25
Combined water	18.21
R_2O_3 (Fe+Al oxides)	0.54
Chlorine as NaCl	0.03
Carbonate as $CaCO_3$	1.00

Uses

Current

Several companies in central Florida have mines adjacent to their phosphoric acid plant. In these cases, the companies utilize the mined-out areas as gypsum disposal areas putting 30 to 40 feet of the gypsum below the surface. These areas "can be" dressed off, when the gypsum is filled to grade, to create reclaimed land. Figure 4 is an example of this use. This type of disposal is limited, however, because the acid plant location is not always in close proximity to a mined-out area.

At the present time, in Florida, very small amounts of this byproduct gypsum are being sold and used as land plaster in the peanut growing areas of northern Florida and southern Georgia and Alabama. Minor amounts (10,000 to 15,000 tons annually) are also being used in the Tampa, Fla., area as road base stabilization material. It has also been reported that in Winnfield, La., natural gypsum and anhydrite is used extensively as road base stabilization material and as an asphalt filler (up to 30 percent).[5]

Potential

The potential uses for byproduct gypsum are the same as the uses of naturally occurring gypsum, but with the added problems of lower grade and impurities. Therefore, the material must be beneficiated in some manner before it can be used for normal applications. Some of the potential uses for this byproduct gypsum are as follows:

1. Utilization for agricultural pruposes - land plaster.
2. Converting to sulfur or sulfuric acid and cement.
3. Various calcined gypsum products.
4. Cement production (retarder).
5. Road base stabilization.
6. Asphalt filler.

What use can be made of this tremendous tonnage of gypsum derived from the production of wet-process phosphoric acid? Some of the current uses have been listed; each, however, with the possible exception of using the material as road-base stabilization, would only utilize minor amounts. Evaluating each of the listed uses, there is only a limited market for the gypsum for agricultural uses, about 20,000 tons per year. Converting the gypsum into sulfur or sulfuric acid and cement becomes less attractive as sulfur supplies become more abundant. Using the gypsum as a cement retarder would only have limited usage, and it would be expensive to remove the impurities.

The Japanese have developed a process to produce gypsum in a related wet-process phosphoric acid method; but rather than be in the business of

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[5]Personal communication from Dr. B. F. Buie, Geology Department, Fla. State University, Tallahassee, Fla.

producing phosphoric acid as we are in the United States, their process is designed to produce hemihydrate gypsum with phosphoric acid as the byproduct. The hemihydrate is then reslurried with cold water to recrystallize the gypsum into coarsely crystalline dihydrate gypsum. This material compares favorably with natural gypsum for the manufacture of the various gypsum products.

In Europe, gypsum is calcined at high temperatures along with coke, silica, and clay and is used to produce sulfuric acid and a cement clinker. [6] More recently, Gebr. Giulini Gmb H. of Ludwigshafen, West Germany, has developed a process that offers an attractive low-cost potential for byproduct gypsum from wet-process phosphoric acid.[7] The process converts the material into hemihydrate powder used to make building blocks. The end product is calcium sulfate hemihydrate in alpha form, which has more favorable properties than beta-hemihydrate produced by dry calcination. The process also substantially lowers the impurities of fluorine and phosphorus pentoxide, which are present in the gypsum feed, so that they present no problems in the final product. According to Giulini, the final product, either as powder or as a cast construction element, compares favorably with most products made from natural gypsum. For example, a plant at Ludwigshafen, West Germany, processes 165 tons per day of $CaSO_4.2H_2O$ at a total production cost of \$4.10 per ton of hemihydrate. The economics will vary between locations, but the figures presented are interesting and within an economically attractive range.

A plant to process gypsum for utilization of sulfur content was established in Texas but had to close because the lowering of sulfur prices due to the abundance of sulfur from natural gas made the plant operation uneconomical.

The U.S. Bureau of Mines has conducted considerable research to develop methods to economically convert the byproduct gypsum into gypsum products. Preliminary tests conducted at the Bureau's Salt Lake City Metallurgy Research Center, Salt Lake City, Utah, on gypsum from the Simplot operation near Pocatello, Idaho, indicates that byproduct gypsum can be calcined and used as various plaster products including floor and roof fillers, plaster board, Keen's cement, land plaster, and fiber-reinforced wall plaster for undercoats.

Gypsum waste from a Florida operation was also tested to determine the feasibility of processing the material into plaster of paris. The main impurities in the Florida byproduct gypsum was silica sand. The color of the final gypsum product was acceptable, but the plaster tended to crumble under minor loads. By repeated screening, the silica sand content (5 percent) was reduced to 2.5 percent. This fraction, however, was abundant enough (minus 250 mesh) to be detected by x-ray diffraction methods.

[6]Chemical Week. They're Moving Gypsum Mountains. August 3, 1968, v. 103, pp. 37-38.

[7]Ellwood, P. Turning Byproduct Gypsum Into a Valuable Asset. Chemical Engineering, March 24, 1969, v. 76, pp. 106-108.

Conclusions

Let's review what we have been talking about. There are 152 million tons of byproduct gypsum on the ground and it is being generated at the rate of 21 million tons per year — a staggering figure!

What can we do with this material that doesn't present an environmental threat or hazard as some mineral wastes do, yet it does present an aesthetic problem? In ten years, we will add 200 million tons to the stacks; in 30 years, we will add 600 million tons to the stacks. Where does it stop? We must advance technology, we must devise economic processes and uses for this material or methods to dispose of it economically. I know what you are thinking about now — we have enough gypsum being generated in Florida to plaster the earth and then some.

Our purpose in presenting this paper is to stimulate thought. Where can you find a low-grade ore containing two valuable coproducts (fluorine and phosphorus pentoxide) already mined and available for next to nothing and in some cases nothing. Yes, many processes have been developed and we know of minor uses but let's not be satisfied; let's keep hammering away until we can come up with answers. I'll leave you with that thought.

REMOTE SENSING A NEW TOOL
FOR
INDUSTRIAL MINERALS EXPLORATION

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Chief of Remote Sensing
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Abstract

Techniques for identifying soils, alluviums, and bedrock were first developed in the early 1940's with the advent of aerial photography as a mapping tool. At the close of World War II the declassification of color infrared photography extended our analysis ability beyond the limits of normal vision. Within the past 20 years geologists and engineers have been introduced to increasingly sophisticated tools which utilize portions of the electromagnetic spectrum from ultraviolet, through visible and infrared, to microwave. Investigators have found that by utilizing different portions of the electromagnetic spectrum additional information can be obtained concerning materials on the earth's surface. Advancements in data handling techniques, data enhancement techniques and data analysis have produced high resolution systems which can map sources of aggregate, the suitability of materials for construction, and can outline those areas of urban and industrial expansion which should be avoided for the development of aggregate plants.

Introduction

A generalized definition of remote sensing is the detection and/or evaluation of electromagnetic energy. Electromagnetic energy consists of electromagnetic waves and particles (photons) which travel at the speed of light, 186,000 miles per second. Visible light is a narrow band of electromagnetic energy that we detect with our eyes. This energy is produced by the sun, it travels through our atmosphere, interacts with earth materials, some of it is absorbed, and some of it is reflected. With our eyes we detect only a portion of what is reflected. That which is absorbed is reradiated back to the atmosphere and eventually to free space at wavelengths far beyond human vision and beyond the capabilities of photography.

The technology of remote sensing first developed to detect and record reflected energy in the visible range, then as photographic technology evolved we were even able to photograph beyond the limits of human vision in the reflected infrared. Military reconnaissance systems developed in the late 1940's and early 1950's were released to the civilian community in the 1960's. These systems consisted of thermal mappers capable of mapping radiation emitting from the earth at wavelengths beyond photographic capabilities and side looking airborne radars capable of mapping soils, rocks and cultural features through clouds and dense vegetation.

When the military furnished remote sensing systems to the scientific community, these systems became tools looking for applications and in the early 1960's often the tools fell short of our needs. Early investigators often flew as many sensors as possible to see what they would detect. The usual result was an abundance of imagery, but not much understanding of what phenomena were being mapped.

In the last decade investigators and applicators using the remote sensing approach have examined earth materials and their associated spectro-
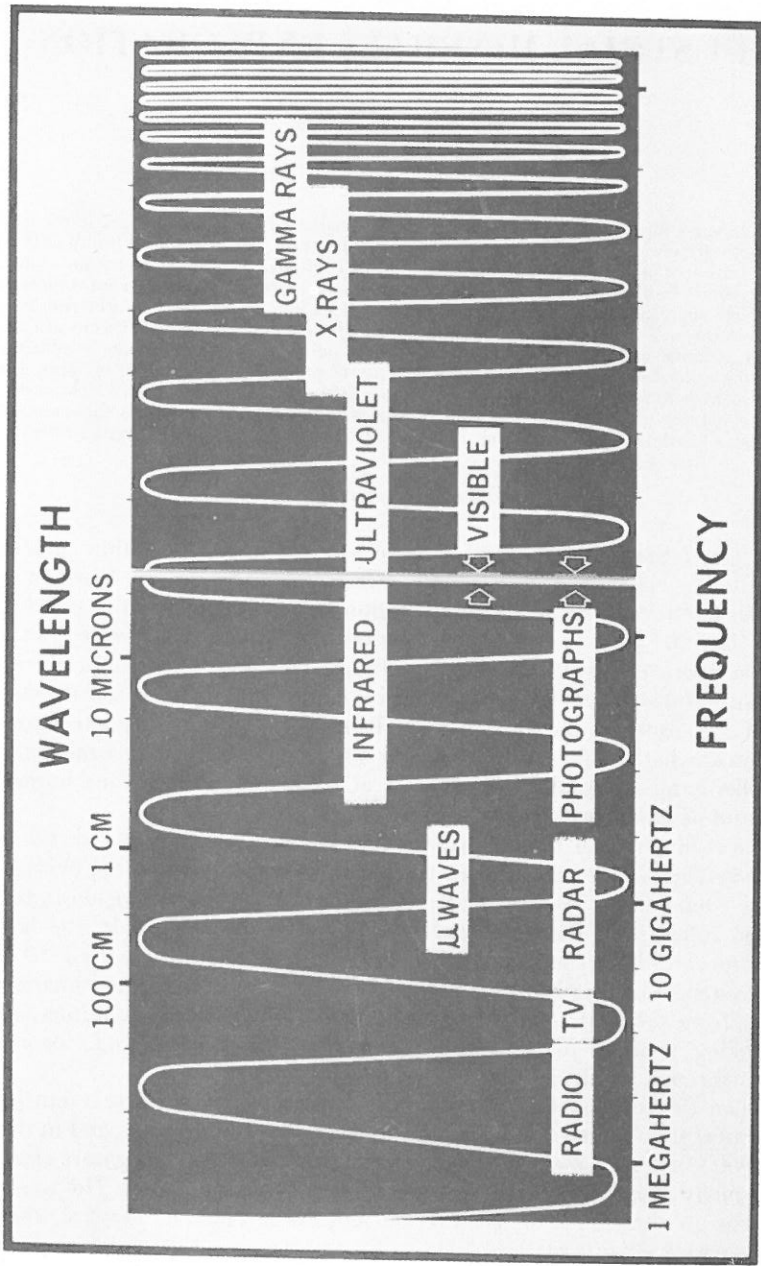
Figure 1
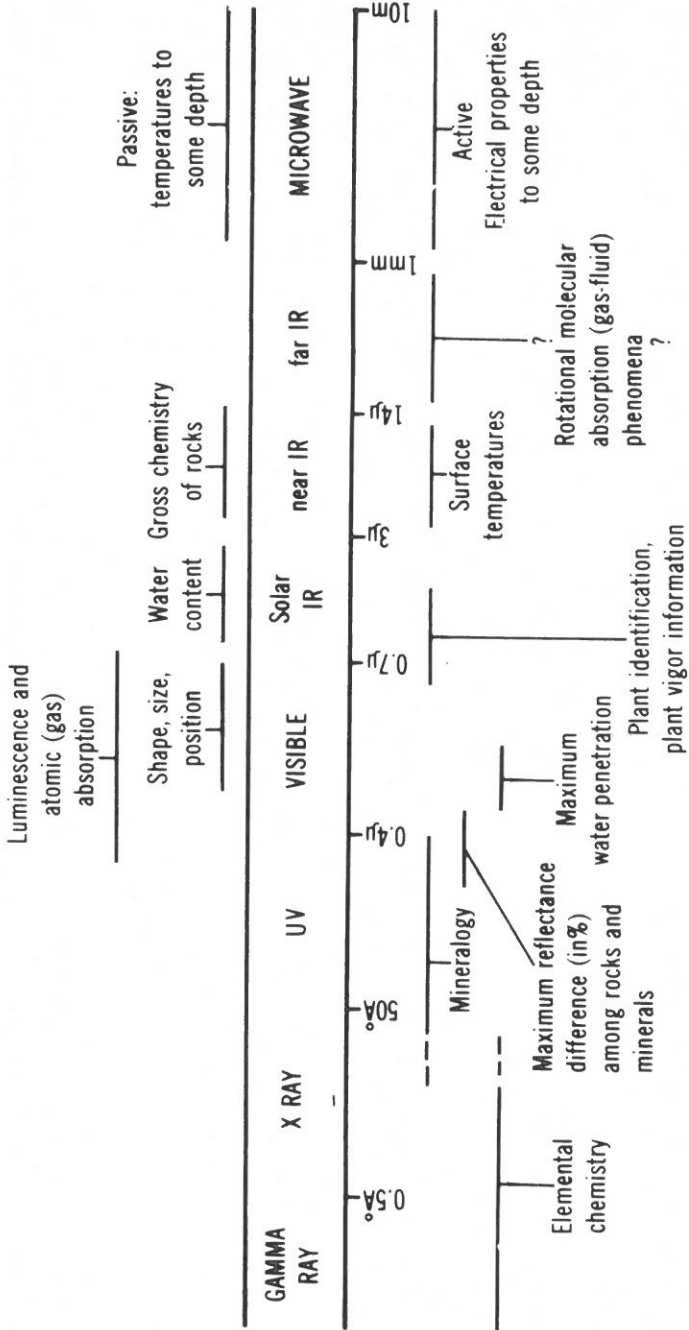
Figure 2. Summary of types of information and/or properties of materials that may be interpreted from observations of various parts of the electromagnetic spectrum.
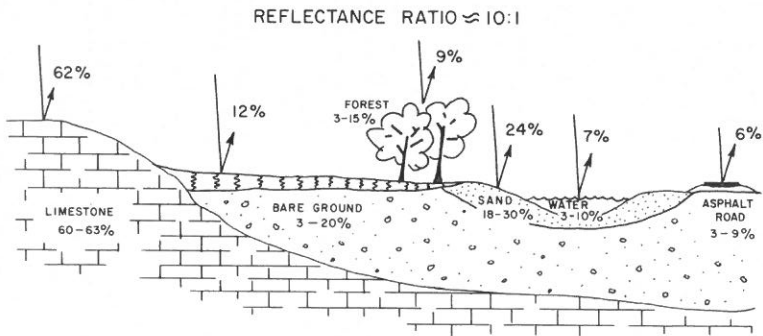
Figure 4 : REFLECTANCE OF MATERIALS IN VISIBLE
AND PHOTOGRAPHIC INFRARED PORTION OF SPECTRUM

Figure 3. Reflectance of materials in visible and photographic infrared portion of spectrum.

radiometric phenomena, then designed overflights to map electromagnetic parameters of earth materials. This rational phase in the evolution of remote sensing technology has produced applications beyond those of conventional aerial photography and more applications are becoming evident every year.

Remote Sensing as Applied to Construction Materials

Remote sensing permits the acquisition of a large amount of information over a short period of time. A single 9 x 9-inch image taken from 65,000 feet can cover areas 20 miles square, while space acquired data can cover areas over 10,000 square miles with a single frame. A photointerpreter can rapidly map areas that look promising for construction materials and delineate those areas which appear less promising using such synoptic coverage. Remotely sensed imagery can tell you where to make your detailed ground studies eliminating expensive ground studies in potentially unproductive areas. Generally, cost-effectiveness of the remote sensing approach becomes greater as sites become more remote.

The U.S. Army Corps of Engineers in Vietnam were involved in the search for engineering construction materials using the remote sensing approach and was able to locate construction materials rapidly in a variety of landscapes. In the Mekong Delta the only hope for suitable materials was sand. These sand deposits were found in abandoned river channels, point bars, and in the coastal plain of the delta as stranded beach ridges (cheniers). They found that the vegetation growing on these features reflected more infrared radiation on to color infrared film than surrounding vegetation growing on fine grained silts and clays. The vegetation growing on silts and clays was stressed due to high soil moisture and thus reflected more in red and less in the infrared. Vegetation growing over marsh and swamp appeared green.

In the Mekong terrace they were concerned with locating bedrock near the surface or laterite. Identification of soil moisture patterns and drainage patterns was possible using black and white photography with a Wratten 25

LIGHT REFLECTANCE OF SURFACE
REFLECTANCE, %
GRASS
CEMENT
SOIL
ASPHALT

LIGHT SENSITIVITY OF FILMS
LOG SENSITIVITY
Supper XX - Aero Panchromatic Film
Infrared Aero Film

LIGHT SCATTERING BY ATMOSPHERIC HAZE
SCATTERED LIGHT INTENSITY %

LIGHT TRANSMISSION BY FILTERS
TRANSMISSION, %
Wratten 25A (light red filter)
Wratten 89A (deep red filter)
WAVE LENGTH, millimicrons

TYPE OF SURFACE	PREDICTED TONE ON POSITIVE PRINTS			
	PAN FILM	25A FILTER	I.R. FILM	89A FILTER
GRASS	DARK		LIGHT	
CEMENT	LIGHT		LIGHT	
ASPHALT	DARK		DARK	
SOIL	LIGHT		DARK	

Courtesy of R.N. Colwell   Figure 4.

VEGETATION LIGHT REFLECTANCE CURVES

Monterey Pine ———————— A
Calif. Bay — — — — — — — — — — B
Poison Oak ·············· C
Coyote Brush —— -- —— -- ——D

From Lauer, School of Forestry
University of California
In cooperation with U.S. Dept.
of Agriculture
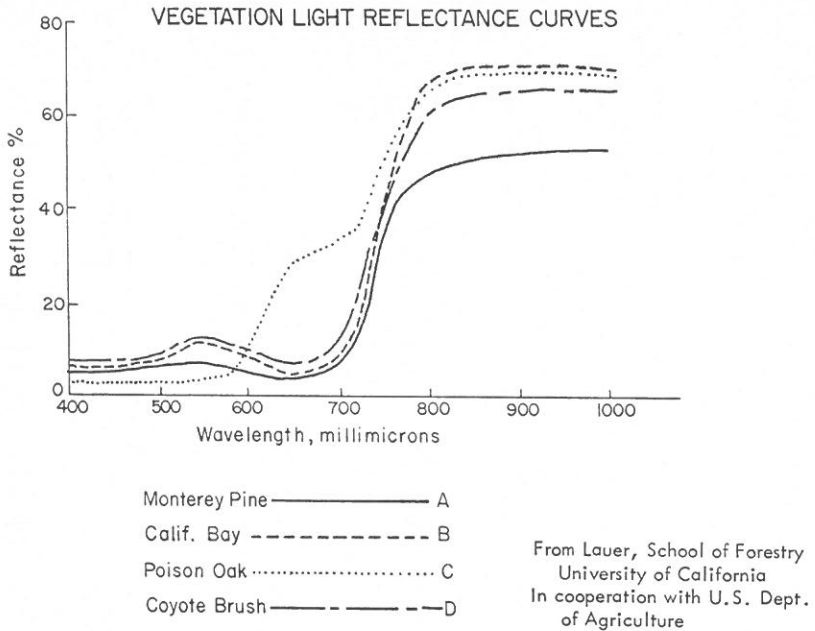
Figure 5.

(red) filter. Areas of high soil moisture appeared darker, while well drained areas appeared lighter in color, and bedrock as dark patches surrounded by light colored well drained soil. In some cases, even though bedrock was several feet below the surface, sufficient float was present to assist in its detection.

Side Looking Airborne Radar was used to some success in locating materials concealed by vegetation and for mapping large areas with a single pass.

Remote sensing for construction materials and industrial minerals in the midwest is not an easy task. Here in the midwest a mantle of wind blown loess covers fine grained till which in turn covers bedrock. So, often instead of mapping materials directly we must use indicators of materials, like vegetation and geomorphology. Vegetation which taps shallow aquifers is likely to show high reflectance in the infrared, and if the aquifers are shallow sands we may pick up their geometry by tracing healthy vegetation across the landscape.

Perhaps most important of all in the search for industrial minerals, the remote sensing approach offers synoptic coverage of possible sites and allows companies to assess growth potential for a region. Therefore, impact of probable materials sites on the local environments can be assessed as well as the expansion and development of these local communities into potential operational areas. Remote sensing methods, since they detect a spectrum of radiation reflecting from, or emitting from earth materials, can map materials based on their spectroradiometric properties. As we develop better tools we may be able to map those unique spectroradiometric properties associated

-104-
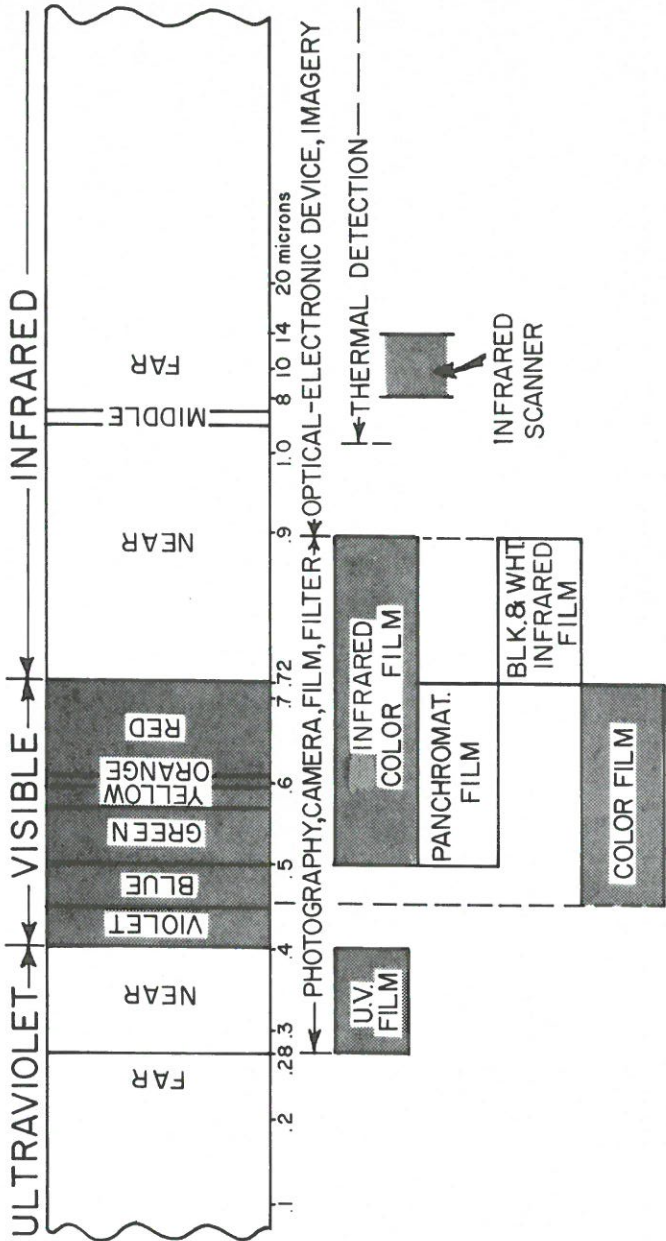
Figure 6.

with a particular material. By being organized and aware of potential remote sensing applications, companies engaged in exploration for industrial minerals can be ready to apply these tools, as they are made available and as new analysis techniques are applied.

BARITE ORE POTENTIAL OF THE TAILINGS PONDS IN THE WASHINGTON COUNTY BARITE DISTRICT IN SOUTHEASTERN MISSOURI

by

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Missouri Geological Survey and Water Resources

Abstract

The Missouri Geological Survey recently made a study of four tailings ponds in the Washington County barite district. The residual ores, mined here since 1850, are derived from the Upper Cambrian Eminence and Potosi Dolomites. The bedrock occurrences are stratiform, Mississippi Valley type deposits related to the important lead deposits of the Southeast Missouri district. Hand mining for barite by shallow shafts and pits gradually gave way to large-scale strip mines and washer (jig) plants during the 1930's and early 1940's. The district is the leading barite producer in the United States. Production averaged about 285,000 tons per year in the last decade. At present, about 50 percent of the output is sold for use as a weighting agent in drilling muds. The balance is chemical-grade material used in the manufacture of glass, paint, barium chemicals, and for fillers in rubber and a host of other products.

The purpose of the Survey's study was to focus attention on the barite ore potential of the nearly 70 ponds present in the district. Four ponds were test-drilled using Shelby tubes. The drill samples were assayed for barite, and tonnage-grade estimates were calculated for each pond. Screen tests were run on composite samples.

The Bottom pond near Cadet is the largest and most economically attractive of the four tested. It has a 52-acre surface area and is estimated to contain about 1,090,000 tons of tailings grading 7 percent barite, or about 82,000 tons of the mineral. The high-grade portion of this pond contains about 86,000 tons of tailings grading 18 percent barite.

There may be as much as 40 million tons of tailings in the nearly 70 ponds in the district, and they would contain at least 2 million tons of barite if an average grade of 5 percent is assumed. This is over 10 years' supply at the present production rate. However, screen tests indicate that around 50 percent of the barite is in minus 400-mesh sizes. Economically feasible techniques and equipment for recovering the barite fines will have to be developed.

Introduction

The Missouri Geological Survey recently conducted an investigation of four large tailings ponds in the Washington County barite district. The purpose was to evaluate their potential as an added source of barite. The investigation was partly funded by a special appropriation of the State Legislature. Analytical work was done at the U.S. Bureau of Mines Rolla Metallurgy Research Center under a cooperative agreement.

Location and Mining History

The Washington County district is about 50 miles southwest of St. Louis and centers around the town of Potosi, the county seat (Figure 1). The barite producing area lies within the Southeast Missouri lead district, one of the great metal-mining centers. Today, the mines are producing about 75 percent
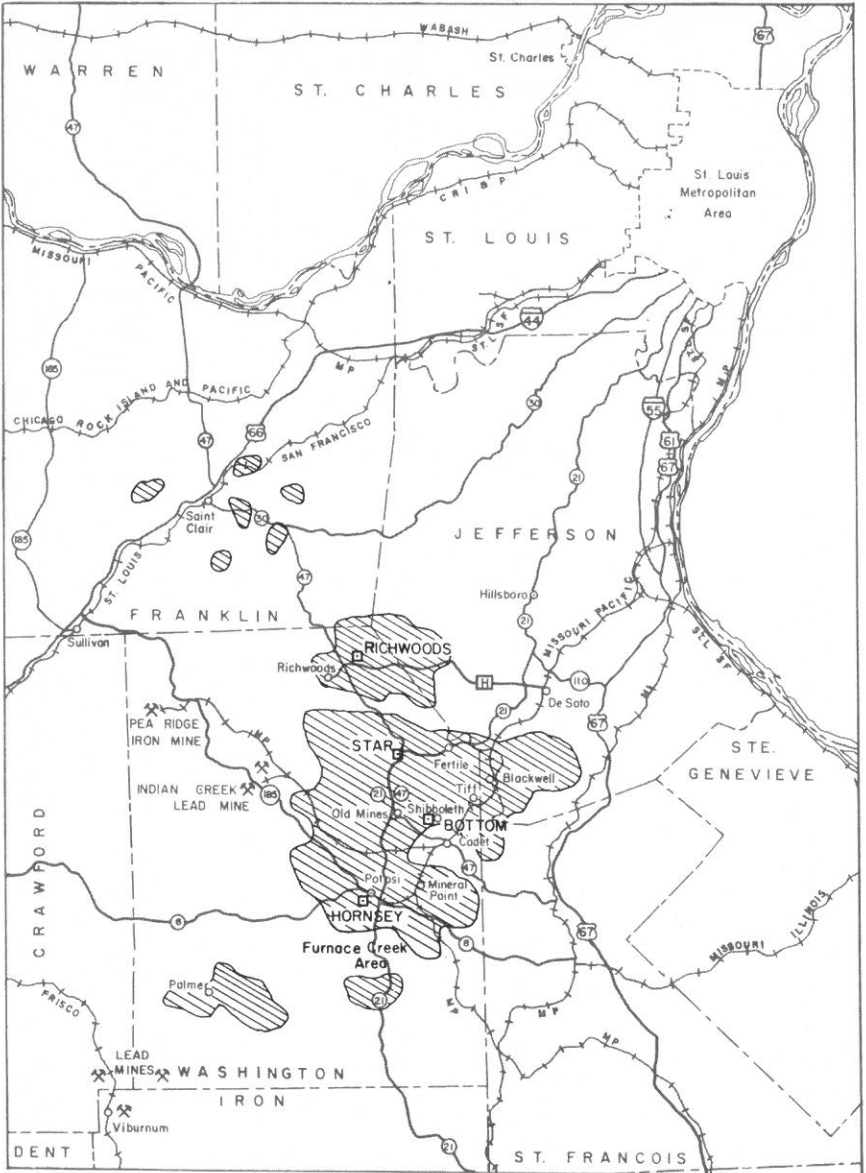
Figure 1. Washington County barite district in southeastern Missouri with locations of the four tailings ponds test-drilled by the Missouri Geological Survey.

of the lead output in the United States. Mines around Potosi were for many years the principal lead producers in the state. Barite, traditionally called "tiff" by the miners, nearly always accompanied galena in the Washington
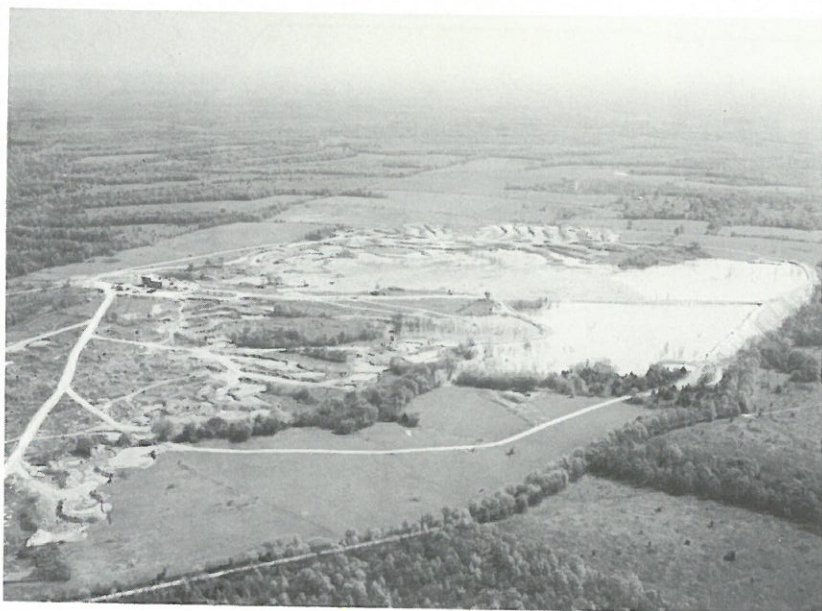
Figure 2. Active washer plant, tailings pond and nearby strip mine area near Richwoods.

County lead ores, and was discarded as useless at the time. Tiff mining was initiated in 1850, at about the time that lead mining began its decline in the area (Sackett, 1958).

In the early days, lead and barite mining usually consisted of sinking shallow pits and shafts in the residual surface clays. Fragments of galena and barite were picked out of the clay and were cleaned by hand. Hand digging for barite continued as an important industry in Washington County until 1942. Large strip mines and washer plants have been in use since then (Figure 2). Most of the production today comes from remaining hand diggings and earlier strip mine areas.

Mine-plant Operations and Tailings Ponds

The washer plants are equipped with rotary breakers, log washers, trommel screens and jigs. The largest plants can treat about 120 cubic yards of ore per hour and require up to 5,000 gallons of water per minute. They are rock-em sock-em affairs in which barite recovery is sacrificed for throughput. This aspect of the washers is discussed on page 109.

The eight companies now active in the district operate 15 mines and washer plants. An inventory of all known tailings ponds by the Missouri Survey is the basis for figure 3. Nearly 70 ponds were identified. Over 40 of them are classified as large in size — each believed to contain at least half a million tons of tailings.
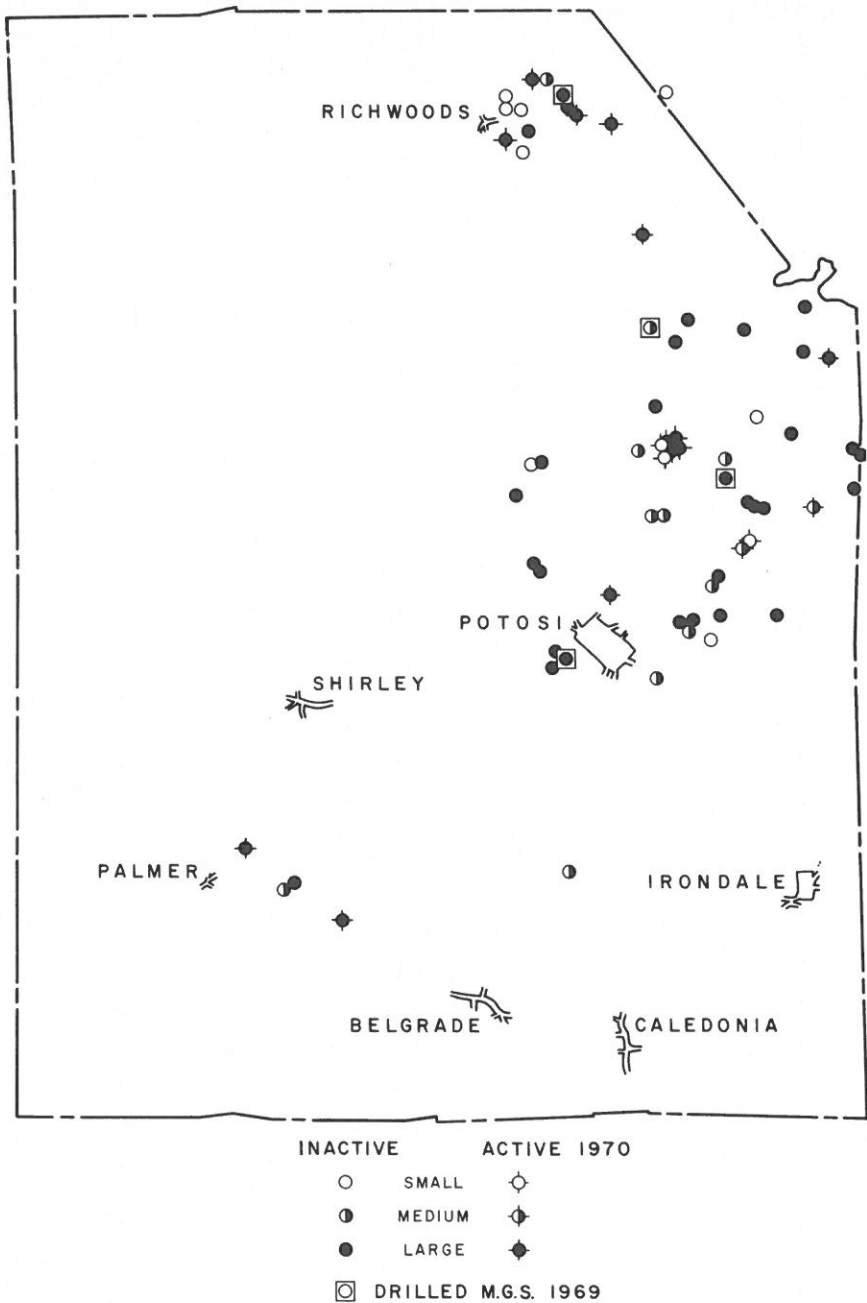
Figure 3. Locations and size estimates of the barite tailings ponds in Washington County, Missouri.

Production, Uses and Value

The Washington County barite district is the largest producer in the United States, usually contributing about a third of the domestic output (Brobst, 1970). To date, over 11½ million tons of concentrates have been marketed from Missouri ores. Arkansas, Georgia, Nevada and Tennessee follow Missouri in that order in all-time total production. Missouri's output averaged slightly over 285,000 tons of concentrates per year during the 1960's. In 1970 and 1971, about 50 percent was sold for use as a weighting agent in drilling muds. The balance, chemical-grade concentrates, was used in the manufacture of glass, paint, barium chemicals, and for fillers in rubber and a host of other products.

Barite is a relatively low-value commodity. Unground concentrates for the drilling mud market are valued at about $12.50 a ton in Missouri. Chemical-grade material may be valued as high as $24.50 per ton. Fluctuations in the drilling mud market quickly affect local and regional production levels. Transportation costs and competition from foreign imports also have an important bearing on sales.

Geology and Ore Deposits

The barite ores are of the residual type. Fragments of the mineral occur in red and brown surface clays that have accumulated from weathering of the Upper Cambrian Potosi and Eminence Dolomites. These are the uppermost formations in the Upper Cambrian Series (Figure 4). Fresh bedrock exposures in roadcuts and strip pits often show barite filling fractures and other openings in the dolomites. The porous horizons that are mineralized appear to result from solution activity. The residual ores average about 10 feet thick, ranging from a few feet up to 25 or 30 feet.

The lead deposits being mined today are all found in the Cambrian Bonneterre Formation, the lowest carbonate unit in the section (Figure 4). The nearest mines, at Indian Creek and Viburnum, are shown in the southwest part of figure 1. Barite is absent in all the Bonneterre lead deposits, but it is the major constituent in the barite-galena deposits related to the Potosi and Eminence formations. The Washington County districts are on the north flank of the Ozark uplift (McCracken, 1971) and some major faults transect the area.

Both the lead and the bedrock barite-lead occurrences are stratiform, and are usually considered to be Mississippi Valley type deposits. Detailed studies in the barite district by Wagner (1970) suggest that fault and fracture systems have acted as channelways for the mineralized solutions. The solutions have then migrated laterally into preferred, porous and permeable horizons where mineral deposition has taken place. Ore is formed at the surface when the soluble constituents in these horizons have been removed by weathering.

				LITHOLOGIC DESCRIPTION	MINERAL COMMODITIES
PALEOZOIC ERA	**ORDOVICIAN SYSTEM**	**CANADIAN SERIES**	Chert residuum		
			Jefferson City Dol. (200'-300')	Dolomite, fine- to medium-grained, argill-aceous, cherty,"cotton rock"variety locally abundant.	Crushed stone
			Roubidoux Fm. (125'-200')	Dolomite, light gray to brown, fine-grained, cherty Sandstone, quartose.	Building stone / Ground water
			Gasconade Dol. (250'-300')	Dolomite,light gray to buff, fine - to coarse-grained, cherty ; contains beds and lenses of Cryptzoon.	Crushed stone
			Gunter Mbr. (20'-40')	Dolomite, arenaceous, rounded- frosted quartz grains.	Ground water
CAMBRIAN SYSTEM	**UPPER CAMBRIAN SERIES**		Eminence Dol. (150'-300')	Dolomite, light gray, medium- to coarse-grained, medium to massively bedded, cherty.	Barite Crushed stone
			Potosi Dol. (250'-300')	Dolomite, brown to gray, fine- to medium-grained, massively bedded, contains abundant quartz druse.	Barite Lead Zinc Ground water
		Elvins Group	Derby-Doerun Dol. (100'-200')	Dolomite, tan to buff, fine to medium-grained, argillaceous, silty.	
			Davis Fm. (125'-225')	Shale, dolomitic, thin- bedded; contains edgewise conglomerate. Eoorthis zone 30 to 35 feet below top."Marble boulder bed"60 to 70 feet below top.	
			Bonneterre Fm. (200'-450')	Dolomite, light gray, fine- to medium-grained, glauconitic in places, contains some dark green to black, thin shale beds. Lenses of gray to pink limestone are referred to as "Taum Sauk marble".	Lead Zinc Copper Cobalt Nickel Crushed stone High Ca lime
			Lamotte Sandstone (0'-500')	Sandstone and conglomerate, quartzose, arkosic; contains interbedded red-brown shale.	Building stone Ground water
PRECAMBRIAN ROCKS				Basic intrusives Bevos group Musco group Van East group Middlebrook group Granite and granite porphyry intrusives. Extrusive felsite flows and tuffs.	Crushed stone Iron

Figure 4. Generalized stratigraphic column of southeastern Missouri.

Drilling Project

Four older ponds with stabilized surfaces were selected for test-drilling (Figure 1). A skid-mounted drill and 3-inch diameter Shelby tubes were used to collect samples. A 30-inch extension was connected above the sampling tube to prevent contamination by caved and squeezed-in material.

The Bottom pond near Cadet is the largest and most economically attractive of the four tailings ponds that were drilled. It has a 52-acre surface area and 77 holes were drilled to test it (Figure 5). The holes averaged about 15 feet deep and maximum depth was 30 feet. In the other ponds, maximum depths ranged between 50 and 65 feet.
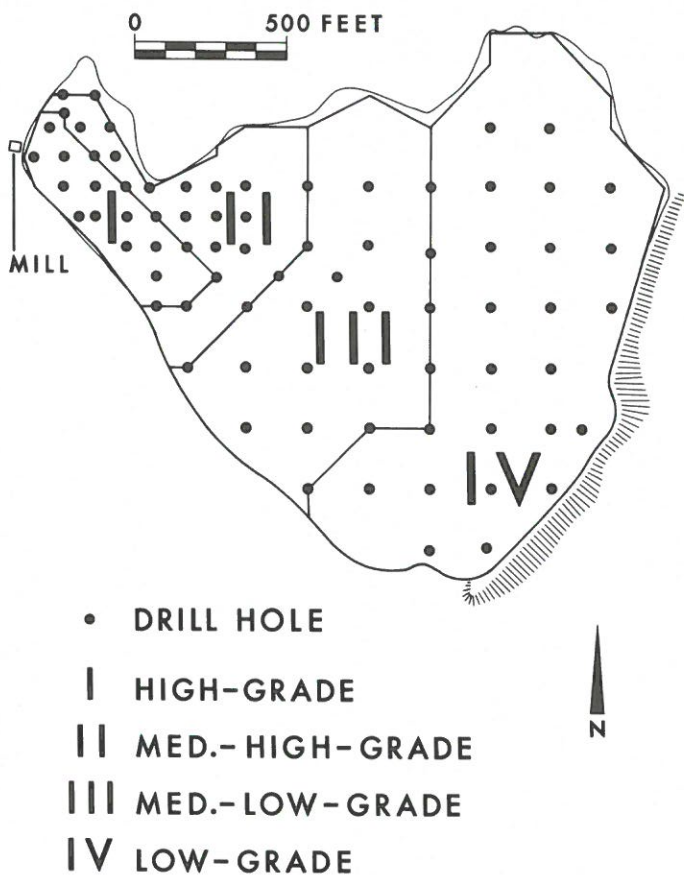
Figure 5. Drill pattern and grade zones on the Bottom pond.

Grade Zones in the Bottom Pond

The specific gravity of barite is about 4.5, exceptionally high for a nonmetallic mineral. As expected, the barite grades determined from the drill samples fall off systematically with distance away from the washer discharge. The location of the mill and the 4 grades zones in the Bottom pond are shown in figure 5.

AREA I

18 %

16,000

86,000

AREA II

11%

15,000

133,000

AREA III

8%

27,000

353,000

AREA IV

5%

24,000

518,000

TOTAL POND

7%

82,000

1,090,000

LEGEND

% BaSO₄

Tons Barite
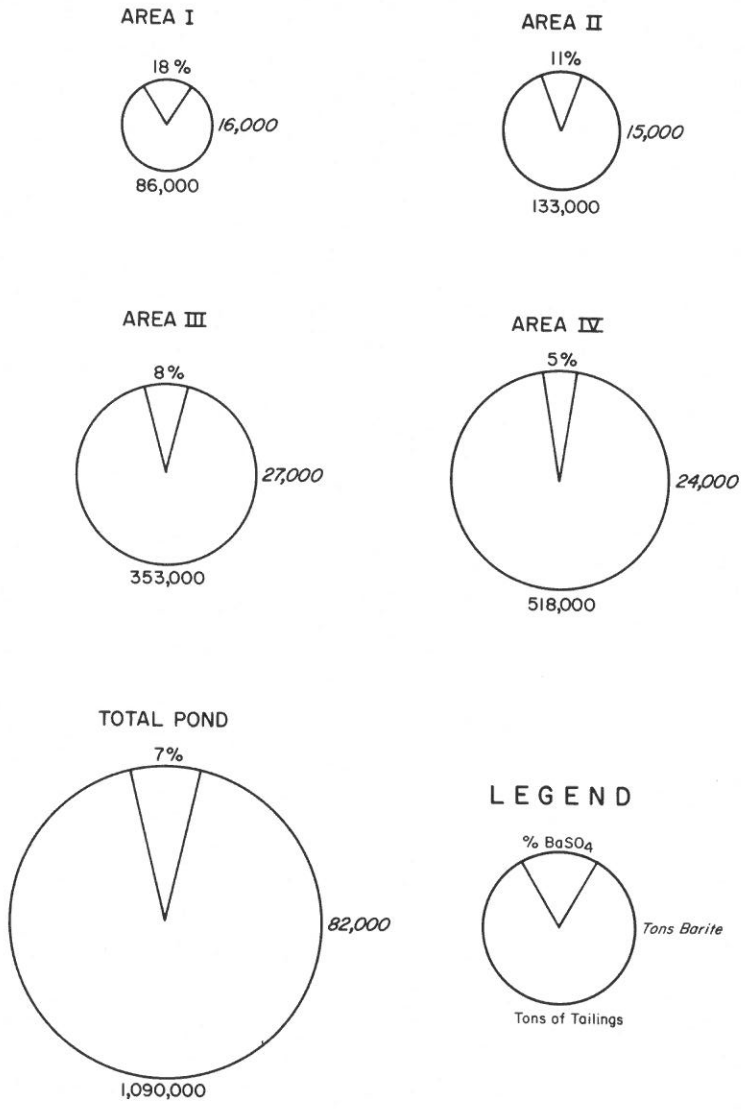
Tons of Tailings

Figure 6. Tonnage-grade estimates for the Bottom pond.

A total of 1,090,000 tons of tailings was calculated for the entire content of the Bottom pond. An estimate of 86,000 tons grading 18 percent barite was made for Area I; 133,000 tons grading 11 percent for Area II; 353,000 tons grading 8 percent for Area III; and 518,000 tons grading about 5 percent for Area IV. Average grade for the pond as a whole was 7.2 percent barite, equivalent to nearly 82,000 tons of the mineral. Estimates of barite contents by grade zones are: 16,000 tons in Area I; 15,000 tons in Area II; 27,000 tons in Area III; and 24,000 tons in Area IV. The tonnage-grade estimates for the pond are summarized in figure 6. The 572,000 tons of tailings in Areas I, II and III combined, have an average grade of 10.2 percent $BaSO_4$ and contain about 58,000 tons of barite. This material is generally higher-grade than average mine-run ore in the district, estimated at 9 or 10 percent barite.

Table 1	
SUMMARY INFORMATION ON THE BOTTOM WASHER PLANT OPERATIONS	
Operating Data	
Years in Operation	15:1945-1959
Crude Ore Treated, Estimated Tons	4,500,000
Barite Concentrates Produced, Estimated Tons	300,000
Calculated Ratio of Ore to Concentrates	15:1
Calculated Average Recoverable Ore Grade, Percent $BaSO_4$	6.7%
Calculated Average Annual Production, Tons of Concentrates	20,000
Tailings Pond Data	
Tailings, Estimated Tons	1,090,000
Average Barite Grade, Percent $BaSO_4$	7.2%
Barite in Pond, Estimated Tons	82,000
Plant Production Equivalent, Years	4
Pond Barite Percentage of Total (Concentrates + Pond Barite)	27%
*Plant Recovery Estimate	70%
Estimated Percent of Total Barite Lost in Pond	20%

*Assumes that about 1/3 of the barite losses are in the gravels and coarser waste rock; the remaining 2/3 in the tailings pond.

Summary Information on the Bottom Plant and Pond

Over a 15-year period, the Bottom washer plant treated about 4½ million tons of ore and produced roughly 300,000 tons of barite concentrates (Table 1). The ratio of ore to concentrates was 15 to 1, and recoverable ore grade about 6.7 percent barite for the lifetime of the operations. Plant capacity averaged around 20,000 tons of concentrates per year.

Several pertinent estimates for the Bottom pond are listed in the second entry in table 1. The tonnage-grade estimates given earlier in the text are repeated. The roughly 82,000 tons of barite calculated for the pond are equivalent to about 4 years' output of the plant. The metallurgical recovery is estimated at 70 percent. It follows that about 20 percent of the barite originally present in the ore now resides in the tailings pond, and the remaining 10 percent is assumed to have been lost with the gravels and coarser waste rock.

	Table 2			
	SCREEN ANALYSES, COMPOSITE SAMPLES OF THE BOTTOM POND			
Mesh	Area I High-Grade	Area II Medium-Grade	Area III Med-Low-Grade	Area IV Low-Grade
+10	1.42%	0.65%	0.10%	0.02%
-10 +14	.89	.61	.13	.03
-14 +20	1.34	1.00	.18	.04
-20 +28	2.05	1.61	.28	.06
-28 +35	3.16	2.61	.59	.08
-35 +48	5.53	4.40	1.38	.18
-48 +65	7.56	5.65	2.49	.48
-65 +100	5.71	4.69	2.94	.90
-100 +150	5.15	3.92	2.84	1.27
-150 +200	2.65	2.17	2.01	1.01
-200 +270	2.42	1.77	1.97	1.31
-270 +325	1.80	1.47	1.77	1.37
-325 +400	.62	.53	.61	.36
-400	59.70	68.93	82.71	92.89
	100.00%	100.00%	100.00%	100.00%

Size and Grade Information on the Composite Samples

Thirty or more drill samples from each grade zone in the Bottom pond were composited to make up representative samples of the tailings for metallurgical testing. Screen test results for each of the area samples are given in table 2. The composite sample assays agree closely with the barite grades calculated for each area in the tonnage estimates, as indicated in table 3. Weight percentages (from Table 2) and barite assays of the plus and minus 400-mesh fractions of the composite samples are shown in the upper entry in table 3. The fall off in grain sizes and barite contents with distance from the washer discharge are well illustrated. The uniformly low-grade assays of the minus 400-mesh fractions are also noteworthy. The latter fraction was calculated to comprise about 84 percent of the tailings in the pond as a whole.

Barite separates were prepared from each composite sample using a heavy media. Screen tests were then made on the separates to determine the weight percentages of the barite grains from each area in the plus 65-mesh, minus 65 plus 400-mesh, and minus 400-mesh size fractions (Table 3). The 65-mesh break was chosen because it is near the lower size limit for tabling and the upper size limit for froth flotation. Once again there is a marked decline in grain size, and in effect of grade, with distance from the plant discharge. There is practically no plus 65-mesh barite in Areas III and IV, which include about 80 percent of the total tons of tailings. In Areas I and II combined, less than 20 percent of the barite is plus 65-mesh. For the pond as a whole, only about 4 percent of the barite grains are plus 65-mesh while 43 percent are minus 65 plus 400-mesh and about 52 percent are minus 400-mesh.

In the final entry, the pounds of barite per cubic yard of tailings are given for each grade zone and for the pond as a whole. These values are based on the assays and density determinations developed in the tonnage-grade estimates as explained in the footnote. The approximate cutoff grade in the district of 100 lbs. per cubic yard was exceeded in all but Area IV.

Conclusions

Superficially, Areas I, II and III of the Bottom pond look like a bonanza for remining. Average barite assays in Areas I and II are more than double the 100 lb. per cubic yard cutoff used in the district (Table 3). However, the fine sizes of the barite, also shown in the table, present serious recovery problems. Over 80 percent of the barite grains in Areas I and II are less than 65-mesh in size. In the pond as a whole, about 52 percent of the barite is minus 400-mesh. This would seem to rule out the use of any simple, inexpensive gravity recovery methods. Froth flotation or some sort of cyclone-type separator will probably be needed for effective recovery.

A total of 40 million tons of tailings is estimated to be contained in the nearly 70 ponds counted in the Washington County barite district. The ponds would contain at least 2 million tons of barite if an average grade of 5 percent is assumed. This is over 10 years' supply at the current production rate. It might

Table 3

SIZE-GRADE INFORMATION FOR THE COMPOSITE TAILINGS SAMPLES AND FOR THE HEAVY MEDIA BARITE SEPARATES

Barite Assays of Composite Samples and Plus & Minus 400 mesh-Fractions

	Area I	Area II	Area III	Area IV	Pond Total Calculated
Tonnage Estimate Assays:	18.2% BaSO$_4$	11.3% BaSO$_4$	7.7% BaSO$_4$	4.6% BaSO$_4$	7.2% BaSO$_4$
Composite Sample Assays:	20.1% BaSO$_4$	11.2% BaSO$_4$	6.7% BaSO$_4$	4.9% BaSO$_4$	7.5% BaSO$_4$

Mesh	(Wt.%) Assays	(Wt.%) Assays	(Wt.%) Assays	(Wt.%) Assays	(Wt.%) Assays
+400	(40) 42% BaSO$_4$	(31) 28% BaSO$_4$	(17) 21% BaSO$_4$	(7) 20% BaSO$_4$	(16) 27.5% BaSO$_4$
-400	(60) 5.3%	(69) 3.7%	(83) 3.7%	(93) 3.7%	(84) 3.7%
	(100)	(100)	(100)	(100)	(100)

Weight Percentages of Total Barite by Sizes in the HMS Samples

Mesh	Area I	Area II	Area III	Area IV	Pond Total Calculated
+65	25.3%	14.7%	1.1%	0.3%	4.3%
-65 +400	59.0	62.6	53.4	28.9	43.3%
-400	15.7	22.7	45.5	70.8	52.4%
	100.0%	100.0%	100.0%	100.0%	100.0%

*Pounds of Barite Per Cubic Yard of Tailings:	491	260	160	90	149

*Based on the density determinations and barite assays developed in the tonnage-grade estimates.

be valued at as much as $80 million, since little or no grinding of the recovered product would be required.

The study by the Missouri Geological Survey has demonstrated that the ponds contain very large amounts of barite. The potential of this resource would seem to justify the time and expense of intensive research on practical recovery techniques. In fact, equipment and reagent suppliers have already shown definite interest. It is probably only a matter of time before the richer tailings are profitably exploited. When this occurs, it will initiate the third major mining cycle in this remarkable district.

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SUBSURFACE PUMPED STORAGE AND ENVIRONMENT*

R. L. Loofbourow**

Abstract

Thermal plants generate most of our power. They reach intended efficiency only when working steadily at designed load. They need time to be brought on line. Power demand, however, fluctuates continuously. Large difference between daily and weekly highs and lows is common. Pumped storage is a prime regulator, using surplus power and retrieving much of it to meet peak demand. It does this with a high degree of flexibility. It can also provide power during limited emergencies.

Conventional pumped storage consists of an upper and a lower reservoir with a powerhouse to generate power as water is dropped through it or, when surplus power is available, to return the water to the upper reservoir. Elements of proposed subsurface hydro pumped storage are entirely similar but the powerhouse and the lower reservoir are deep underground.

For practical reasons the lower reservoir must be in competent, tight rock. Special site testing is needed. Sites for subsurface hydro pumped storage should have a body of water or a convenient place to impound one, for the upper reservoir. Another form of regulator in which compressed air is accumulated underground to be fed to a gas turbine-generator, could be designed without an upper reservoir. Generally the best sites are near sizable markets for both power and stone, i.e., populated areas. This enhances the intrinsic usefulness of the pumped storage and helps reduce the capital cost of the power-delivering system. Freedoms inherent in subsurface design tend to reduce operating costs. Finally, subsurface pumped storage, in comparison with most conventional plants, promises half a dozen environmental advantages. It can be built in many places which are not obvious. Where extra capacity to meet peak demand is needed, it merits informed consideration.

Subsurface pumped storage can be combined with some other elements of power systems, e.g., the upper reservoir can double as a cooling pond for a thermal plant.

Subsurface pumped storage is one example of the application of deep underground construction to serve two purposes with advantages in both and to the environment as well.

Introduction

Power companies are squeezed between increasing demand and clamor to preserve natural surroundings. Pumped storage could help carry peak demands yet certain projects, with most or all planned elements at the earth's surface, have encountered determined opposition because of their environmental consequences. Subsurface pumped storage could minimize the basis for the objections and be eminently practical in other ways.

Subsurface concepts are by no means new. In 1949 a Swedish patent was issued on the accumulation of compressed air in underground excavations for later use in gas turbines.[1] In 1964 Bauer and Harza proposed to combine a hydro pumped storage with the Chicago Flood Water Control Project.[2] In 1968 three Swedish civil engineers made an excellent case for the general application of subsurface hydro pumped storage, on its own merits, at the World Power Conference.[3]

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[1] References are shown at the end of the article.

Types of Pumped Storage

Many of the pumped storages in Italy, Spain, Austria and Switzerland are at alpine sites illustrated by the upper sketch of Figure 1. In these heavily glaciated, high mountains, lakes differing greatly in elevation can be close horizontally. These are "natural" sites. The lakes can be the upper and lower reservoirs and the powerhouse is likely to be underground. If the lakes are sizable, even the water level fluctuation, which is minimized by high head, may be inconspicuous. The environmental effect is slight indeed.

Pumped storage is being built on the Salt River east of Phoenix, just below one dam and at the head of the lake formed by the next dam downstream, as illustrated by the lower sketch, Figure 1. Here also the pumped storage facility is inconspicuous.

Neither of these two natural types of site is necessarily advantageous in all other respects nor is either to be found near many large cities in North America. Most of the sites which can be developed here are more like those of Figure 2. The upper sketch illustrates a surface hydro pumped storage with an upper reservoir built on or near the top of the highest, steepest hill available. In some cases an existing body of water can be used for the lower reservoir. At many of these sites the available head is less than optimum and the combined length of penstock and tailrace is likely to be several times the head. This increases capital cost and inertia problems.

A subsurface hydro pumped storage is indicated at the lower left in Figure 2. The upper reservoir, which may be a natural lake, an existing storage reservoir or the sea, is in a natural depression of the surface and the lower reservoir is space excavated deep underground. The available head is very nearly equal to the combined length of penstock and tailrace. At many sites the most favorable head can be selected. With high head less water is moved to generate the required energy and most elements of the facility are smaller and simpler.

The sketch at the lower right of Figure 2 illustrates a gas turbine prime mover with a deep underground compressed air storage excavation. The basis for this type is that about two thirds of the power developed by the usual gas turbine is consumed in compressing air fed to the combustion chamber. In this case air is compressed with off-peak power and stored so that the full power developed by the turbine can be used to help carry the peak demand. Calculations show advantage in using pressure which would call for storage excavations about 1,000 to 1,500 feet below the surface. This is based on a conservative ratio of pressure to depth. For equal generating capacity the volume of this storage can be as little as one fifth of that which would be needed for subsurface hydro. This volume can be reduced further by providing an upper reservoir connected to the storage so that water replaces the air consumed, maintaining an even, hydrostatic pressure on the remaining air. This water is displaced back to the upper reservoir by charging air at slightly more than hydrostatic pressure. Exhaust of gas turbines is understood to be comparatively clean but it is a factor in the choice between the subsurface types. Factors favorable to gas turbine-compressed air plants

Legend

1 Upper Reservoir
2 Penstock
3 Powerhouse
4 Tailrace
5 Lower Reservoir
6 Service Access

ALPINE TYPE SITE

Characteristics

Use of existing lakes is common

Good ratio, head : combined length of penstock and tailrace

Head may be high enough to require special powerhouse but needing less water movement; most elements are smaller or simpler

Little effect on environment

BETWEEN RESERVOIRS

Between even large reservoirs, head may be less than preferred

Levels of reservoirs, especially the lower, must be maintained

Powerhouse is below water table

Good ratio, head : combined length of penstock and tailrace

Pumped storage installation itself has little effect on environment

Figure 1

TWO "NATURAL" SITES FOR SURFACE HYDRO PUMPED STORAGE
not to scale

COMMON SITUATION OF CONVENTIONAL HYDRO PUMPED STORAGE
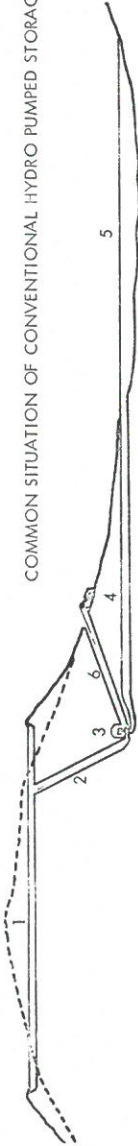
At many sites elevation difference less than ideal with reservoir on hilltop far above natural water table
Limited head calls for larger units to move more water, for more land and larger range of water levels
Construction of upper reservoir may be difficult and must be done well
Ratio of head to combined length of penstock and tailrace adds to cost and inertial problems

GAS TURBINE WITH SUBSURFACE COMPRESSED AIR STORAGE

Upper reservoir not essential
Powerhouse on surface
Least excavation, no large shafts
Depth likely to be 300 to 500m
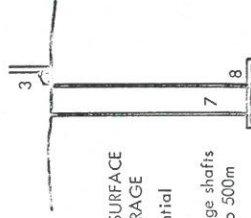
LEGEND
1 Upper Reservoir
2 Penstock
3 Powerhouse
4 Tailrace
5 Lower reservoir
6 Service Access Shaft
7 Mining, Vent Shafts
8 Compressed Air Chamber

Figure 2

SUBSURFACE HYDRO PUMPED STORAGE

Upper reservoir may be a natural body of water or built in a valley
At most sites head can be 400 to 550m or considerably more if preferable
Ideal ratio, head : penstock + tailrace
Less land needed

COMPARISON OF CONVENTIONAL PUMPED STORAGE AND TWO SUBSURFACE TYPES
not to scale

include location where an upper reservoir would be difficult, where salt is the only stable rock, where market for stone is limited and the required capacity is moderate. The turbine-compresser must have special features; units are not known to be available now.

Choice of Sites for Subsurface Pumped Storage

Site requirements for excavated pumped storage include (a) a sizable mass of competent, tight rock at appropriate depth, and (b) a market for the rock excavated. Use of stone can make subsurface pumped storage eminently practical. It avoids piling up an unsightly dump, and stone credit can pay a substantial part of the day-to-day excavating cost. The possibility of using stone is best near cities which are also load centers in the power network. Prices of crushed stone in most North American cities have risen sharply partly because of the greater cost of stripping, depletion of good stone, tighter zoning and similar restrictions.

Strong stone is an ideal medium in which to make large, stable underground openings. Generally it also makes the best concrete aggregate, surfacing stone and filler for bituminous mixes. Limestones of suitable chemical composition might serve as flux, chemical lime, aglime and cement rock.

Rock in which the lower reservoir is to be excavated should be uniformly competent but it need not extend to the surface. Improvements in boring and casing shafts of small and medium diameter, and in chemical grouting and other methods for building larger shafts, reduce the problems of working through weaker ground.

The shape, spacing and arrangements of the chambers making up the lower reservoir are preferably chosen for safety, stability and least mining cost. The extent of the reservoir must be essentially horizontal but the plan can be made to fit any reasonable property or geological boundaries. The water level in the lower reservoir can fluctuate within the full height of the space, hence excavations can be kept within a comparatively small area.

At and near the land surface, shale and sandstone are the most common bedrocks. As a rule they are unsuitable for aggregate, but in many places there are beds of strong dolomite and limestone between the softer beds. In other places the cover of sedimentary rock is thin enough that the lower reservoir could be excavated conveniently in crystalline rock. Figure 3 shows an example. In southeastern Nebraska and southwestern Iowa good quarry stone is scarse. The Mississippian or Devonian dolomites might serve in places. The buried basement ridges seem more inviting.

Strong basement rocks outcrop along the North Atlantic Coast generally through the Maritime Provinces and New England. To the south an increasing thickness of soft sediments is found at the coast but through Virginia, estuaries extend inland to locations where strong rock should be found in the desired range of depth. Still farther south the increasing thickness of the soft sediments directs search inland. There are no strong rocks near the surface on or near the Gulf Coast but in places there are salt domes. Compressed air could
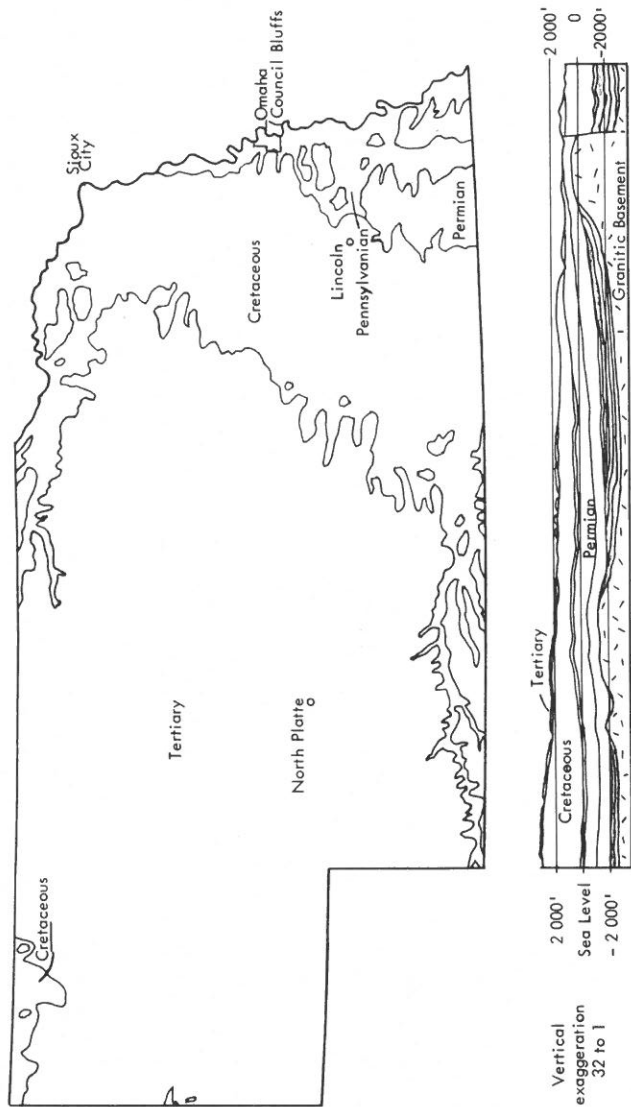
Figure 3

BEDROCK GEOLOGY OF NEBRASKA AND CROSS SECTION ALONG NEBRASKA-KANSAS BORDER

Rock at surface is shale, sandstone, chalk, shaly limestone and similar with very few beds of stronger limestone but note "granitic" basement rock in the east at 700 feet and south central to northwest at 2 000 to 3 000 feet

after Nebraska Geological Survey, 1969

be stored in some. Masses of competent rock are not common on the West Coast but there are good prospects in and near several cities.

Upper Reservoirs

In many places where pumped storage would be useful, topographic relief is altogether insufficient or less than would be desired for conventional surface reservoirs. At some possible sites opposition has developed. In most cases it attacks the upper reservoir. The compressed air-gas turbine plant does not require an upper reservoir. At some sites an existing reservoir, lake or an arm of the sea could serve as an upper reservoir for subsurface hydro pumped storage. If an upper reservoir is to be built, it can generally be smaller and it can always be located in a naturally low area which is more secure in itself and presents less hazard to people downstream than a reservoir on a hilltop.

Hilltops are uncomfortable places to build lakes.
1. Resulting change in the appearance of the hill may in some cases be visible only from the air but where the top is truncated and spoil dumped around the flanks of the hill, the change is drastic from any point of view. In any case a substantial area is flooded.
2. Gravity tends to close steep rock fractures in valleys, and to open those on hills.
3. In many places, rock on hilltops is more deeply weathered and fractured than in valley bottoms. Hilltop reservoirs have given trouble.[4,5,6] Some sites have been abandoned after testing.
4. Hilltop reservoirs are more vulnerable to failure by seismic movement, subsidence, under-mining of slopes by floodwater and slides, unnatural increase in porewater pressure, tendency of clays to soften or go thixotropic and to damage from any sort of attack by man. Long circumferential dikes are more difficult to inspect, maintain and protect than comparatively small dams.
5. Recent history in southern California demonstrates that failure of hilltop reservoirs can be sudden and is always a threat to life and property downstream.

Choice of Head

A prime advantage of subsurface pumped storage plants is that at many sites, probably at most, head can be chosen for the best balance of many factors and conditions which govern design and in turn affect capital and operating costs and construction time. The least complicated reversible Francis pump-turbines can be designed for efficient performance at heads to 400 m. The maximum design head of reversible units is now 550 m[7,8]. With separate turbine and pump units, which cost more and require more powerhouse space, much greater heads can be used. The San Fiorano pumped storage in Italy works at 1,432m[9].

Reservoir Volumes

The importance of being able to market stone at a rate which agrees reasonably with the desired schedule is indicated by approximate calculation of the quantities. To generate 800 MW continuously for 4 hours with a head of 400 m, at 80% efficiency, would call for movement of 3.7 million cubic meters of water (130 million cubic feet). With allowance made for excavations other than the lower reservoir the total would probably be about 11.5 million tons.

The amount of excavation can of course be reduced by designing for higher head. In many cases there could be benefit in completing a first stage, subsequently enlarging the lower reservoir and adding power units as needed.

Security from Damage by Seismic Movement

Evidence[10] leads to the conclusion that excavations properly located in sound rock are more secure from earthquake shock than alternative structures built on the surface. Underground excavations should not cross faults on which there is movement, though in one case where a curved tunnel crossed the active fault in two places, structural damage extended only a few yards from the fault.[10a] In sound rock, faults are easier to recognize and classify; it is easier to keep work away from these hazards. However, the fall of a few tons of rock would not impair the usefulness of a lower reservoir.

Summary of Environmental Effects

The two types of subsurface peaking power facility promise the following environmental advantages in comparison with the usual type of surface pumped storage.

1. The compressed air-gas turbine type requires no upper reservoir; it requires little land but consumes fuel. The gas turbines which would be used are typically noisy.
2. At typical sites, choice of head allows subsurface hydro pumped storage to provide needed capacity with less water, improving chances of using an existing water body and reducing the size of most plant elements.
3. If an upper reservoir is built, it is least vulnerable to damage from the half dozen causes identified.
4. If an upper reservoir is built, it can be in the most natural place, be smallest and least conspicuous, and present least hazard to people and property downstream.
5. Evaporation loss will be reduced to less than 50%, in some cases, eliminated.
6. Subsurface plants occupy least land.
7. Subsurface plants are easier to inspect, maintain and protect.
8. Greater freedom of location generally makes it possible to use shorter power lines crossing less land; they would be more easily put out of sight.

9. During construction the excavated stone furnishes a needed material usually obtained from quarries or pits.

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THE ROLE OF THE GEOLOGIST
IN
ENVIRONMENTAL POLLUTION CONTROL

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Martin Marietta Corporation

Abstract

The advent of stricter controls on environmental pollution including; air pollution, water pollution and "visual" pollution have opened a broad field for geologists whether employed as consultants or within the company framework.

The geologist is uniquely qualified to work in the field of environmental pollution, because of his type of training which always incorporates the examination of several viewpoints before reaching a conclusion.

The extent of background requirements is discussed dealing with overburden, water, vegetation, type of material mined, and legal implications.

The geologist's role is examined with respect to how he can help solve company problems dealing with environment either from within as an employee or from without as a consultant.

Introduction

The time is past when an individual or a company can leave land in any shape they want without regard for others. It is also past time for people in the extractive industry, and I refer to all industries which extract minerals from the ground, to ignore their effects on pollution. The old concept that land is an inexhaustible resource was once thought to be true. Hence it was used without regard to after uses or as to how its use for mining would effect others.

Discussion

Geology is a valuable tool to any industry that has to operate under the watchful eye of an environmentally conscious public. I would like to show you what a valuable contribution a geologist can make, primarily by citing my own experiences in the field. My work is not unique. Geological principles can be applied to all phases of industrial activity where environmental changes will occur. In the limestone industry there are three types of pollution that may occur; air pollution, water pollution and visual pollution.

My work is primarily with limestone and because of the nature of this material, there is no serious water pollution problem, and air pollution is basically dust which is more of a nuisance than a harmful material. The third, visual pollution is of considerable importance, and had always been one of the biggest objections people have to quarry operations.

Air Pollution

First we have air pollution. Any of you who have been around an operating limestone quarry know how dusty it can get. In Kansas we have the added factor of high winds which can transport fugitive dust great distances. My role in air pollution thus is primarily one of dust control, and this involves

maintaining monitoring systems, and public relations when our dust control systems fail. There has been dust control via bag houses etc. on stationary plants for many years, but we are dealing with portable plants with many dust producing transfer points and little has been done to solve this problem. However we are testing control equipment and will solve the problem. There are many people in the limestone business who have no knowledge of how to set up an effective monitoring system to provide useful information. The analytical training of a geologist helps in setting up a program, and while you don't usually have to worry about plant design you should be aware of their operating principles to set up preliminary monitoring programs. Such monitoring systems might include any of the dust fall bucket systems or power aid sampling devices depending on how sophistic you need to get. You also must be able to explain to a farmer who says your limestone dust is damaging his crops, yet feeds his cattle fine grind lime, and uses ag-lime on his fields for better crops.

Water Pollution

Water pollution problems for our industry are even less than for air, because all we are doing is to wash fine limestone and clay from the products. In fact in properly set up wash systems we actually return cleaner water to the streams than we take out. My role in water pollution control is primarily to be familiar with water pollution regulations and see that they are brought to the attention of our operating people.

Visual Pollution

Visual pollution for our industry is a different story, because where you might not actually see some types of air and water pollution you certainly can see where limestone has been worked by open pit methods. There are other points which give the quarry industry a bad name; blasting, dust, traffic, safety, noise, but the main thing is —— what will it look like after we have finished. Let's face facts, we have not been the world's best housekeepers, and much of our trouble has been brought about by our own work habits.

You must realize one thing about the operation of the extractive industry —— as each ton of material is removed, we are that much closer to being finished with the property. When we have removed the mineral resource the land must be left in a suitable manner so it can be used for other purposes.

We realize that you can't take something from the ground and leave the area like it was before, but we must be able to look far enough into the future to some projected uses when we are finished. The land therefore fulfills a dual role, the primary one being to provide a vital construction material, and after that provides a continuing usefulness either in production, recreation or in some other way.

We all know some of the classic after uses for depleted quarries such as: sanitary land fills, lakes, and maybe game refuges. But how about:

1. Mobile home sites — In windy areas like Kansas a properly reclaimed quarry provides an excellent protected location for these fragile structures.

2. Fish farming ponds — With very little work after a property is depleted shallow ponds serve well as fish farms. One such farm in Kansas is producing more income from raising catfish for the table than they did from raising beef on a 300 acre farm.

3. Feed lots with sewage lagoons — The closed circulation of a quarry pit provides an excellent system for slot floor hog feeder operations. This type of operation is becoming more and more popular and provides a higher grade pork than the old style methods.

4. Row cropland — corn, soybeans, milo, wheat.

5. Home sites — Some very expensive, exclusive homes have been built in and around old quarries in the Kansas City, Missouri area.

6. Tree farming — Especially the "cut your own" Christmas tree type. Christmas trees do well on poor soil.

7. Industrial sites — Particularly those who might want a close land fill for reject and waste products.

8. Parks

9. Orchards

10. Pasture

Actually the list could be almost endless, and all it takes is some preplanning, which could include complete investigation of the site for any proposed use which might be a safety or pollution hazard.

The role of the geologist in a proper restoration program is pretty well self evident, as we are dealing with geologic materials and geologic settings. For example, no proper lake or pond could be built without knowledge of whether the site will hold water or not. There is also the consideration of slides due to placement of overburden which must be taken into account.

To give you an idea of what can be done we can take a look at our Kansas operations, and while they will differ from other areas in some respects, the same need for pre-planning exists in all operations.

In Kansas we quarry limestone from as little as 18" to as thick as 100 feet and our overburden which consists of shale, dirt, and rock varies from a few inches to over thirty-five feet. This variability makes each location different, however, the principles of our program remain the same.

Our reclamation program begins when we start our prospecting on the property. This program includes core drillings, auger drillings, and a stadia map of the property. The completed map tells us where the best spot is to open a quarry, what the overburden will be, and what direction the quarry should advance from the initial opening.

After I have gone over the map with the production manager we go over the property in the field and discuss the best way to make the opening and where the most advantageous place is to put the first dirt. Some properties lend themselves well to cut and fill methods, where the old pit is backfilled and

a small hole left when finished. Some are best suited to no backfilling but which can be left as a nice lake.

At the time the lease is made the landowner suggests the type of after use he would best like to have and we try to accommodate him. If we see a better potential use than does the owner we show him the reasons why. Reclamation which proceeds as the property is worked is constantly monitored and adjustments made when needed. We have found that by moving the dirt where we want it the first time, reclamation becomes a continuing process and adds little or nothing to the cost.

Whenever possible we take the black dirt from new stripping and place it on the old backfill and our superintendents carry the same seed mixture as used by the Kansas Highway Commission to seed the ground back to prevent unsightly erosion.

We have done several experimental projects dealing with plantings of various types of trees as well as grass seeding and have found most overburden well suited to growing vegetation.

Our company is a leader in the field of restoration and reclamation in Kansas and we feel that if all the extractive industries, not only in Kansas but everywhere, would give some real thought to after use planning, the whole industry would benefit. Gone are the days when people were only interested in making a buck from the land, they now want to know how it will look when the minerals have been extracted.

The geologist is uniquely qualified to work in the field of environmental control, as he is trained in one of the only disciplines that I know of where he is required to look at several viewpoints before reaching a conclusion. You should, in addition to normal training and background, be familiar with government rules and regulations dealing with pollution etc. as you will be called upon to interpret them at times. Whether it be in the field of air, water, or visual pollution we are dealing with geologic processes and can be of tremendous value in recommending or carrying out a program.

The field is wide open both within a company structure, or the consultant to use his geologic knowledge in application to today's biggest problem environmental protection.

HUMIC ACID COMPLEXES
FROM NATURALLY OXIDIZED LIGNITE:
THEIR GENESIS,
CHEMISTRY AND UTILIZATION

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Abstract

Leonardite is a naturally oxidized lignite which occurs principally in western North Dakota and southeastern Saskatchewan. Lignite undergoes slow oxidation in the shallow subsurface by air penetration or by oxidizing ground water circulation. Lignite weathering processes result in a complex mixture of alkali-soluble humic and fulvic acids. This solubility is due to the COOH, phenolic OH and alcoholic OH groups which characterize altered lignite.

Infra-red spectra studies denote the great intensity of the 5.8 micron band in leonardite. This reflects the high carbonyl concentration during oxidation of lignins. The principal bands in the spectrum are phenolic and carboxylic OH, aliphatic CH, carbonyl, conjugated carbonyl and aromatics, CH_2 and/or CH_3 and/or ionic carbonyl, ethers and condensed aromatics or substitutions in the benzene ring. Low-angle X-ray scattering studies correlate the greater concentration of aromatic structures with the higher intensity of the lignite peak, reflecting those structures which have not been altered by the weathering processes which produced leonardite from lignite. The transformation of lignin degradation products, through demethylation and hydroxylation, shorten the side chain linkages and permit further oxidation. This results in humic and fulvic acid complexes. Leonardites have variable oxygen contents ranging from 25 to 60 per cent, whereas that of lignites contain less than 25 per cent.

Differential thermal analyses conducted quantitize the undesirability of leonardite presence in lignite mining tonnage when used as a fossil fuel. Leonardite is considerably more endothermic, and requires higher combustion temperatures than lignite. However, the heavy metal elemental adsorptive properties of humic acid complexes in leonardite, as well as the characteristically high clay content, suggest successful commercial utilization as a plant growth stimulant. More than thirty trace element metals were detected in leonardite and humic acid ash samples. These include Al, Sb, Be, B, Ca, Cr, Cu, Gd, Ga, Au, Fe, Lu, Mg, Mn, Mo, Ni, Nb, K, Sc, Si, Ag, Na, Sr, Ti, V, Yb, Y, and Zr.

Between 60 and 80,000 tons of leonardite are annually produced from the Peerless Mine, Gascoyne, North Dakota. Most of this production is mixed with caustic soda and sold as a drilling mud viscosity thinner. About 3,000 tons are annually sold as a water conditioner. Saskatchewan measured reserves of leonardite are limited when compared to the extensive North Dakota deposits, but renewed exploration is in progress.

Introduction

Leonardite is a naturally oxidized lignite which occurs principally in western North Dakota and southeastern Saskatchewan. Lignite undergoes slow oxidation in the shallow subsurface by air penetration or by oxidizing ground water. Deposits vary in thickness from thin films to in excess of ten feet.

Leonardite has been used to manufacture brown dyestuffs, as a water-softening and conditioning agent, as a drilling mud additive and as a plant fertilizer.

This paper is divided into sections on the geology and genesis of leonardite deposits, organic and geochemistry, and industrial applications, both present and potential.

The Saskatchewan Research Council and the Department of Mineral Resources have established (R. O'Donnell, personal communication 1972) a

guideline for considering leonardite to be that lignite alteration having a soluble humic and fulvic acid content of at least 40 per cent spectro-photometric transmission. This is the property of a mixture of 20 per cent pure leonardite and 80 per cent lignite, and is comparable to a minimum calorific value of 6300 BTU/lb.

Acknowledgments

Geology of Lignite Oxidation

The term leonardite was originally applied by Dove (1926) to the alkali-soluble fraction of raw, earthy lignite. This fraction is essentially a complex mixture of humic and fulvic acids. It is generally accepted that leonardite is generated from lignite oxidation, although Kohanowski (1957) proposed that it is not always a direct oxidation effect. He proposed that alkaline waters leached humic acids from soils of gumbo type, transferred these to the subsurface, and precipitated them whenever the pH value fell below 6.5. Likewise, leonardite deposits may form, it was proposed, by the transportation and precipitation of humic acids from pre-existing oxidized zones of lignite seams. It is admitted by this writer that these two "transported" mechanisms are possible, but considers them unlikely to permit a sufficient concentration to produce a readily recognizable humic acid deposit. Nevertheless, Cooley (1954) has reported a few small patches of this leached and transported type at the site of certain artesian springs in the northwestern corner of North Dakota. Here the well and spring waters commonly have a content of 1500-2000 ppm of sodium bicarbonate with very little calcium. A thorough field examination of Saskatchewan leonardite and lignite deposits, accompanied by a reconnaisance examination of the extensive North Dakota deposits, supports this writer's contention that leonardite forms essentially in situ in the upper oxidized portions of lignite seams. Leonardite zones are usually irregular and gradational in character, which is attributed to the variable effects of oxidation from gound water circulation in the shallow subsurface. Entire lignite seams may have oxidized to leonardite, but they usually grade downward into lignite below the water table. Consequently, the most lignite oxidation from vadose water effects occurs at and immediately above the water table.

The borehole stratigraphic section (Figure 1) was taken at the site of Saskatchewan's largest leonardite deposit in the Utility Mine, Estevan, and is representative of leonardite associations in the Province. Research is
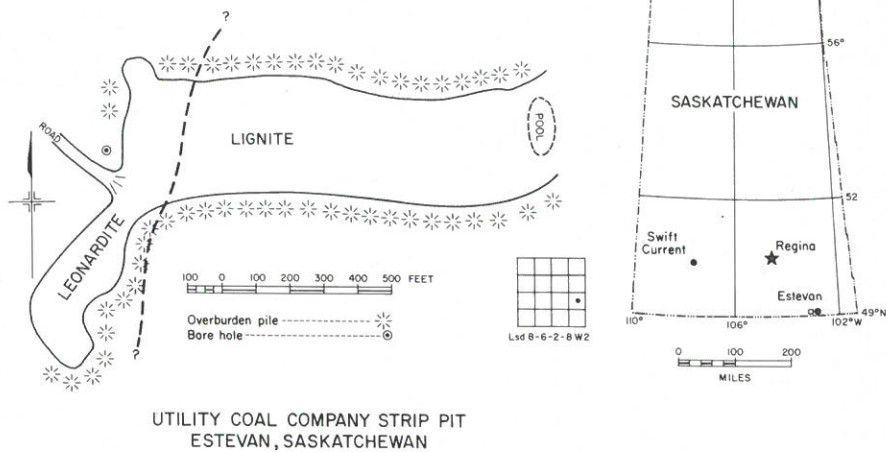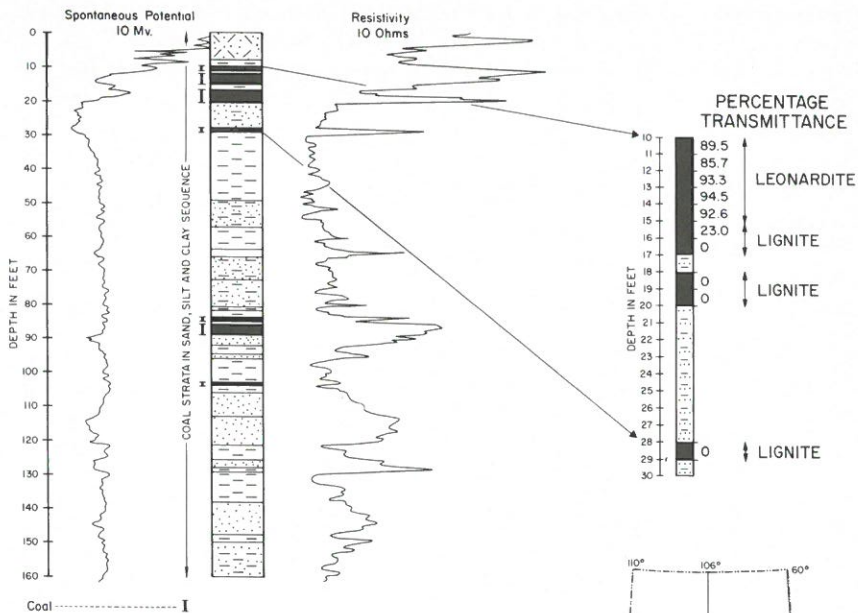
Figure 1. Leonardite and lignite stratigraphy at the Utility Coal Company Mine, Estevan, Saskatchewan.

currently in progress by this writer and his colleagues in the Saskatchewan Research Council on developing satisfactory borehole geophysical techniques for distinguishing leonardite from lignite in the shallow subsurface.

Leonardite deposits are intimately associated with the distribution of near surface lignite seams in the Williston Basin of southern Saskatchewan.

western North Dakota and eastern Montana. Appreciable leonardite deposits in Saskatchewan are limited to the Estevan coalfield (Figure 2) in the Ravenscrag Formation (Paleocene). The two largest Saskatchewan leonardite deposits are on the property of the Utility Coal Mining Company, southwest of Estevan. Commercial production from Saskatchewan deposits has so far proved to be marginal or uneconomical, particularly because of their low tonnage when compared to the extensive North Dakota deposits. Leonardite occurs throughout Bowman and Slope Counties, North Dakota in the Ravenscrag equivalent Fort Union Formation. It is presently commercially mined from the upper most bench of the Harmon bed in the Peerless Mine, owned by the Knife River Coal Mining Company, Gascoyne, Bowman County. This leonardite bench is about 6 feet thick and is separated from 2 lower benches of unaltered lignite by 12 feet of clay. The leonardite in the Peerless mine is at depths varying from 8 to 35 feet below the surface. In Saskatchewan the leonardite varies from essentially at surface elevation down to about 20 feet.

The Peerless Mine annually produces about 60-70,000 tons of leonardite for the drilling well additive market. In 1971 some 80,000 tons (unprocessed) were sold for 2 to 3 dollars per ton. About 3,000 tons per year are also sold as a chemical for water conditioning. North Dakota leonardite reserves are virtually unlimited.

Organic and Geochemistry

Leonardite is defined as oxidized lignite and characterized by a high fraction of alkali-soluble, acid insoluble, humic acid complexes. Fulvic acid complexes, which are alkali and acid soluble, are intimately associated. The chemical and structural characteristics, however, of humic acids are still poorly defined.

Leonardites have variable oxygen contents ranging from 25 to 60 per cent, whereas that of lignites contain less than 25 per cent. Leonardite invariably has a high ash content. Proximate and ultimate analyses for leonardite and lignite are given in Table 1.

The humic acids of leonardite are believed to be largely as insoluble calcium salts (Youngs and Frost, 1963). When leonardite presence is tested by solubility in alkaline sodium hydroxide, the soluble sodium humic salt complexes result. A variety of functional groups are present in lignite and leonardite, as determined by the following infra-red spectroscopic observations.

Infra-red Spectroscopic Characteristics

Infra-red spectroscopy studies on the Saskatchewan lignites provided useful data relating to the chemical and structural distinctions between the macerals. Infra-red absorption is also useful to ascertain the differences between lignite and its oxidized variety, leonardite. Coals of the same rank from various parts of the world have the same general properties and infra-red spectra, as do their maceral components have their own distinctive spectra. This experiment was designed to provide spectral patterns which would be

TABLE 1

CHEMICAL ANALYSES

	LIGNITE	LEONARDITE	HUMIC ACIDS	FULVIC ACIDS
ASH	10.0	18.7	. . . .	. . . .

ULTIMATE (MOISTURE AND ASH FREE, PERCENTAGE BY WEIGHT)

	LIGNITE	LEONARDITE	HUMIC ACIDS	FULVIC ACIDS
Carbon	73.8	63.9	57-69	50.9
Hydrogen	5.1	4.0	2.5-5.0	3.4
Oxygen	19.9	28.4	25-38	44.8
Nitrogen	1.2	1.2	0.5-1.7	0.8
Sulphur	1.0	2.5	0.5-1.0	0.2
Humic Acids Extracted	5.0	84.3	. . . . .	. . . . . .

PROXIMATE (PERCENTAGE BY WEIGHT) OF LIGNITE

Moisture	33.2
Ash	8.8
Volatile	32.0
Fixed Carbon	26.0
Sulphur	0.4
B. T. U./lb.	6911.0

PETROGRAPHIC ANALYSIS OF LIGNITE BY VOLUME

Structured Vitrinite	62
Structureless Vitrinite	6
Groundmass Vitrinite	11
Fusinite	8
Exinite	7
Micrinite	1
Inorganics	5

Adapted from Broughton.(1972b), O'Donnell (1970a, b, 1971).

COALFIELDS IN SOUTHERN SASKATCHEWAN

Compiled by P Broughton after McKay (1947), Broughton (1971) and unpublished data in the files of Industrial Minerals Division, Department of Mineral Resources.

Zone of concentrated strip and underground coal mines in the Ravenscrag Formation lignite

Leonardite outcrop in the Ravenscrag Formation

CENOZOIC
- Wood Mountain Formation (Miocene)
- Ravenscrag Formation (Palaeocene) Cypress Hills Formation (Oligocene) in part

MESOZOIC
- Whitemud Formation, Frenchman Formation, Eastend Formation (Upper Cretaceous)
- Bearpaw Formation (Upper Cretaceous)
- Oldman Formation

Figure 2. Coalfields of southern Saskatchewan.

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TABLE I

CHEMICAL ANALYSES

	LIGNITE	LEONARDITE	HUMIC ACIDS	FULVIC ACIDS
ASH	10.0	18.7	....	....

ULTIMATE (MOISTURE AND ASH FREE, PERCENTAGE BY WEIGHT)

Carbon	73.8	63.9	57-69	50.9
Hydrogen	5.1	4.0	2.5-5.0	3.4
Oxygen	19.9	28.4	25-38	44.8
Nitrogen	1.2	1.2	0.5-1.7	0.8
Sulphur	1.0	2.5	0.5-1.0	0.2
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PETROGRAPHIC ANALYSIS OF LIGNITE BY VOLUME

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Fusinite	8
Exinite	7
Micrinite	1
Inorganics	5

Adapted from Broughton (1972b), O'Donnell (1970a,b, 1971).

useful for a rapid identification of the individual macerals without resorting to the more time-consuming thin and polished section petrographic techniques, and to provide understanding of basic molecular processes during lignite oxidation. A Perkin-Elmer Model 621 Grating Infra-red Spectro-photometer was used with equally weighed samples in KBr pellets. A thorough mixing in a vibratory shaker was employed to avoid the formation of false water peaks from grinding hydroscopic potassium bromide. These false peaks are normally at 2.95, 4.90 and 6.12 microns. A series of samples were dried at 100°C. in a vacuum oven for four hours, and quickly transferred to the mulling agent to minimize effects of oxidation and moisture absorptions. The spectral patterns obtained from macerals using this treatment differed insignificantly from the non-treated.

Spectral information on the structure of coal is obtained by reference to spectra-structure correlations. The assignment of specific bands to structures is often controversial, but is detailed in a number of references. Friedel (1966), Francis (1961) and Roy (1965) are particularly useful. A discussion of the individual spectral bands of Ravenscrag lignite (Estevan No. 3 seam), and their structural correlation follows (See Figures 3 and 4):

2.72 micron band. Assignment of this weak band is uncertain, but probably is free OH. It is most pronounced in lignite and more so in leonardite, but essentially absent in the individual macerals. It is very faint in the attrital mixtures of vitrinite and exinite.

WAVELENGTH (MICRONS)

TRANSMITTANCE (PERCENT)

LIGNITE

LEONARDITE

LIGNITE ASH

FREQUENCY (cm⁻¹)
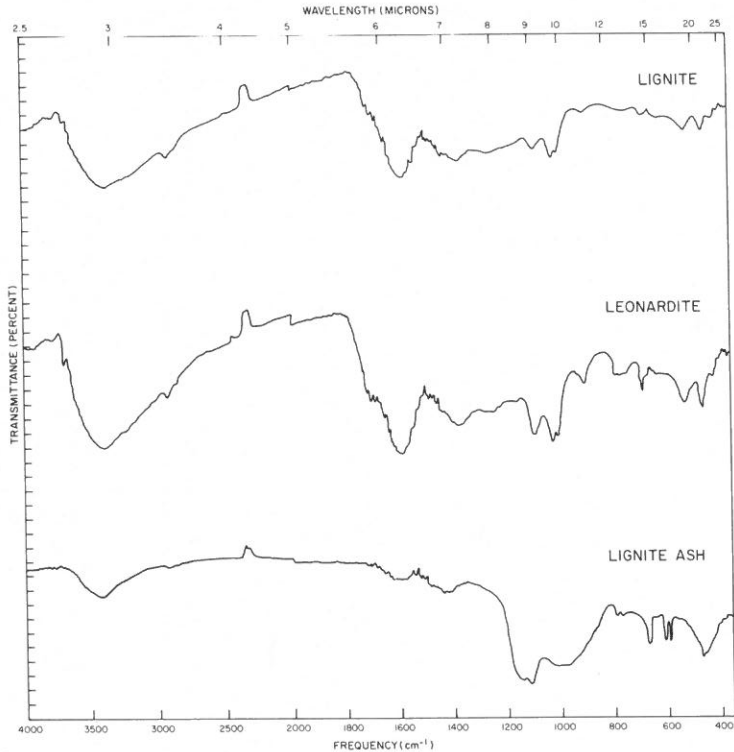
Figure 3. Infra-red spectra of lignite and leonardite.

2.8-4.0 micron band with 2.95 micron peak. Due to the apparent lack of aliphatic C-O absorption at 9.0 and 9.5 microns, and the presence of phenolic C-O absorption in the 8 micron region, the OH group band is usually assigned to phenols. As pointed out above, the vacuum drying treatment does not substantially affect this peak, except in the leonardite samples. This intense and broad peak is assigned to phenolic and carboxylic OH and is present in all the macerals, as well as lignite and leonardite. The band in this range is skewed to the higher frequency, from 3.0-4.0 microns. This broad absorption from 3.0 to about 4.0 microns is apparently due to -OH groups that are more strongly hydrogen-bonded than the -OH groups contributing to the 3.0 band. It is very weak in fusinite.

3.42 micron band. This weak band is superimposed on the skewed broad phenolic OH band above. It is present with about the same intensity in all the macerals, as well as in the lignite and leonardite. In resinite it is the characteristic intense band, and is assigned to the aliphatic CH group. The intensity of this band may constitute a practical semi-quantitative estimate of the exinite percentage present in a sample.

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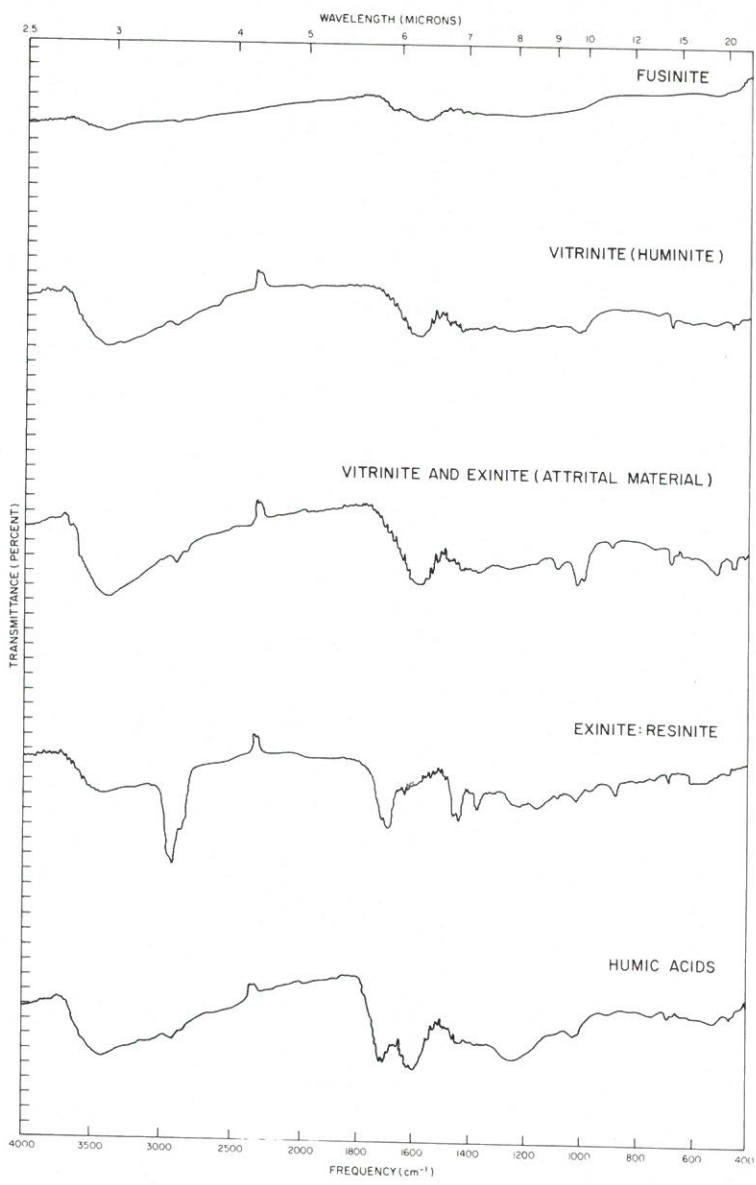
Figure 4. Infra-red spectra of macerals.

3.5 micron band. A very weak band is superimposed on the 3.42 band. Like the above, it is interpreted as an aliphatic CH structure, and is most pronounced in resinite. It is not present in fusinite.

5.8-5.9 micron band. This band is assigned to carbonyl groups, and is very weak to absent in medium to high rank coals. It is a strong distinct peak in resinite and in the humic acid extraction of leonardite. In leonardite it is present, but largely overlapped by a broad 6.25 micron peak. It is completely overlapped by the 6.25 micron peak of lignite. The peak is weak in all other macerals, and is usually hidden by the broad base of the 6.25 micron band. The presence and intensity of this peak serves as an indicator of coal oxidation, thus easily identifying leonarditic compositions. The presence of a strong peak in this position indicates a natural humic acid concentration. The peak is weak in fusinite.

6.25 micron band. This intense and relatively broad peak remains controversial in assignment. The band is due either to aromatic structures and/or a chelated and conjugated carbonyl structures. This band is intense in vitrain, lignite, leonardite and humic acids. It is absent to very weak in fusinite and resinite. Pronounced shoulders of 6.3-6.7 microns are assignable to aromatics.

6.9 micron band. This band appears as a minor shoulder on the 7.2 micron band in all the macerals of lignite and leonardite. Only in resinite is it an intense peak, representing a CH_2 and CH_3 structure assignment, as well as aromatic CC or ionic carbonate. Considering that carbonate frequency bands in the ash are apparent at this wavelength, the effect of ionic carbonate on this intensity is prominent.

7.27 micron band. A broad, intermediate intensity band from 7.2-7.3 microns is assigned to CH_3 groups. It is present in all the macerals, lignite and leonardite at about two-thirds the intensity of the 6.9 micron band. The intensity is slightly higher in resinite, and weaker in the fusinite. It is weakest in the humic acids. In several of the resinite samples the peak intensity increased to intermediate strength.

7.5-10.5 micron bands. This region is assigned to aromatic ethers and phenols. A very low intensity curve, with indistinct peak positions, is characteristic of the vitrinite; attrital mixture of vitrinite, exinite and inertite; leonardite and lignite. The curve is distinctly more intense in the humic acids, approaching intermediate intensity, and absent in fusinite. The curve becomes biomodal in the resinite with peaks at 8.1 and 8.5 microns. A minor peak at 9.7 microns with a shoulder at 9.9 microns is present in all of the lignite macerals, though very weak in fusinite. In leonardite the 9.7 and 9.9 bands are intense, but considerably weaker in the humic acid extraction. This intensity, likewise, is reflected in lignite, but when broken down into macerals, it is considerably weaker. The upper wavelength area of this range may also be due to the presence of kaolinite and other silicates. The higher ash content of leonardite is probably responsible for the strong intensity bands in this wavelength region.

11.0-11.1 micron band. A small but sharp band of this wavelength may be attributed to peroxides. The band is strong in leonardite, but

considerably weaker in the humic acid extraction, and appears to reflect a high silica contamination. It is absent in relatively silica-free vitrinite but intermediate strength in silica-free resinite. The attrital mixture of vitrinite and exinite reflects the intermediate strength and composition between these two extremes. It is likely that the band represents an overlap of silica and peroxide structures. It is absent in the silica-rich fusinite structures, however, indicating the dominant peroxide influence.

13.0 micron band. A low intensity broad peak extends from 12.0 to 14.2 microns, with an indistinct peak at 13.0 microns. Assignment of the weak overlapping peaks in this area is uncertain, but is probably due to condensed aromatics or substitution in the benzene ring. This region is also strongly reflected by the inorganic constituents, and strongest in the intermediate strength band of leonardite, when compared to the same wavelength in the humic acid extraction. The lignite and its macerals only have very weak to absent bands. It is absent in the fusinite samples studied.

Higher wavelengths than the above are attributed to inorganics. An infrared examination of the lignite ash (Figure 3) was used to interpret the influence of mineral contamination on the analyses above. The fusinite has variable ash contamination, reflecting the degree of cellular void filling. The ash content of the lignite column sample was usually between 8 and 9 per cent, but leonardite often contains up to 18 per cent ash. An examination of the lignite ash spectra disclosed the degree of possible contamination. Water absorption is apparent at the 2.9 micron bands. An unknown inorganic peak is present at 3.4 microns. The 6.25 micron band is assignable to silicates. Carbonate is apparent at the 7.0 micron band, sulphate at 8.9 microns, and carbonate again at 14.9 microns. Silicate bands are present at 10.0, 12.6, 16.4 and 21.0 microns. The weak peak at 3.4 microns is usually assigned to aliphatic CH structures, and is persistant in all lignite macerals studied. Its presence in the spectra of the inorganic contamination-free resinite clearly demonstrates its organic composition. However, the writer is unable to assign the band's presence in the lignite ash.

In summary, the infra-red spectra of leonardite and lignite have the same general characteristics, as was first noted by Fowkes and Frost (1960) in their study of American leonardites. The characteristic difference is the greater intensity of the 5.8 micron band in leonardite, reflecting an oxidation state. Sharp intensities of several inorganic bands in frequencies higher than 8 microns also characterize leonardite. The lignite macerals have similar spectral patterns, but distinct differences are apparent. The prominent aliphatic CH group band in resinite is notable. H-bonded (OH) is greatest in vitrinite, less in resinite and least in fusinite. The presence of H-bonded (C-O) or polycyclic extended quinones is prominent in vitrinite, leonardite and humic acids, but less so in fusinite and resinite

The alkali solubility of humic acids is due to the COOH, phenolic OH and alcoholic OH groups which comprise better than 20 per cent of the molecule (Berkowitz, Moschopedis and Wood, 1963; O'Donnell, 1970a).

Flaig (1966) proposed the following mechanism for formation of natural humic acids from lignin degradation (Figure 5). Many of the functional

Figure 5. Adapted from Flaig (1966), O'Donnell (1971a), and Haider and Martin (1967).

groups examined by infra-red absorption are present in this mechanism. The lignin-cellulose linkages, particularly in vitrinite, are broken by oxidative splitting to form primary structural units. These units have side chains which are then further oxidized followed by demethylation. The demethylation is responsible for gallic acid derivation from syringic acid and protocatechuic acid from vanillic acid. It appears that protocatechuic acid is involved in the aromatic to aliphatic transformation that takes place during humification (O'Donnell, 1971a). In this instance P-hydroxyl-benzoic acid is hydroxylated to protocatechuic acid and this in turn to gallic acid (Haider and Martin, 1967). These polyphenols are than converted to quinones by oxidative decarboxylation. Quinones can be generated by oxidation from phenolic derivatives with hydroxyl groups in the 1,2,3- or in the 1,2,4-position. The newly formed quinones react with nitrogenous compounds to form dark colored polymers broadly referred to as humic acid complexes.

Relative concentrations of humic acid complexes are subject to varying interpretations. Recently, low-angle X-ray scattering studies of leonardite, humic acids and lignite macerals were undertaken to examine certain aspects of this problem (Broughton, 1972a). It is apparent that as the carbon increases and oxygen content decreases between leonardite and lignite the position of the primary sub-peak (Figure 6) is shifted to slightly higher d-spacings. The shift from 3.37 angstroms for leonardite to 3.44-3.58 angstroms for lignite and vitrinite was determined to be consistent in all specimens examined. These differences undoubtedly reflect changes in aromatic structures, whereas the secondary sub-peak around 4.30-4.50 angstroms does not change consistently. The latter bond distances can be attributed to alicyclic structures. Leonardite and lignite can also be distinguished by examining the relative intensities of the 3.1-3.7 angstrom subpeak. Apparently, the high intensity of the lignite peak and the lower intensity of the leonardite peak correlates with the greater concentration of aromatic structures which have not been altered by oxidative weathering.

Differential Thermal Analyses

Differential thermal analysis consists of heating simultaneously the material to be analyzed and a thermally inert comparison material which does not undergo a chemical phase change through the temperature range selected, as the temperature between the standard and the test material is measured and recorded. An exothermic reaction is when the temperature of the test sample is higher than that of the inert material, and the deflection of the thermal curve is upward. In endothermic reactions the temperature is lower and the thermal curve is downwards.

The study of coal differential thermal curves was first attempted by Hollings and Cobb (1923) using a nitrogen atmosphere about the samples. Since this initial work various atmospheric conditions, including a vacuum, have been experimented with.

The experimental procedure in this study utilized a closed tube sample holder in air, forming a slightly reducing atmosphere. The use of closed tube apparatus overcomes the masking effects of a broad exothermic curve when
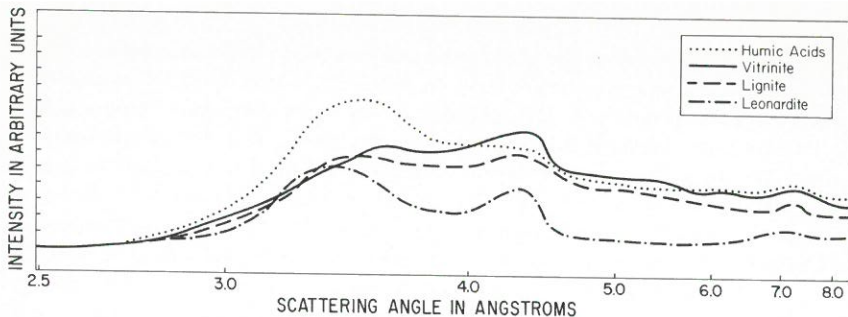
Figure 6. Low-angle X-ray scattering characteristics of leonardite and lignite.

coals are burned in open tubes. The closed tube system inhibits the escape of gas from the coal and the entry of air. Built-up volatile partial pressures result and oxidation is prevented. The test samples of Ravenscrag Formation lignite and leonardite (Estevan No. 3 seam) were analysed at ten degrees per minute from room temperature to 1000°C. A photographic recorder was utilized. Size of the air dried samples was 400 mg., with an alumina standard. The resinite sample, however, was 118 mg.

The purpose of the study was to differentiate the Saskatchewan lignite macerals, lignite and leonardite, on their thermal properties. This is believed to be the first differential thermal analysis of leonardite.

All test samples start loosing volatiles (water vapor) at around 100°C. The lignite macerals, lignite and leonardite samples generally each have one large exothermic peak and one large endothermic peak. The endothermic peak varies between 270° and 325°C., and the exothermic peak between 175° and 225°C.

A comparison between the lignite column sample and the leonardite thermal curves shows several distinctive trends, particularly in the location and intensity of the broad endothermic peak of the 200°C. range. The lignite sample peak at 200°C. shifts to 225°C. in leonardite, with minor subpeak at 150°C. on this lignite major peak. An important difference is the intensity of the bonded OH loss peak of 200-225°C. A shift to the higher temperature is noted in the leonardite, as well as an endothermic reaction intense enough that the curve goes off scale (Figure 7), reflecting the breakdown of the phenolic and carbonyl acid OH groups which have their highest concentration in the leonardite. This high concentration is confirmed by the oxidation effects in the infra-red spectral studies. Likewise, the major combustion peak at 350°C. in leonardite is less intense and shifted to higher temperatures than the similar peak of lignite at 325°C. The weathering-oxidation effects on the lignite are also pronounced in the shift of the endothermic peak of lignite at 560°C. to 575°C. in leonardite, accompanied by a substantial increase in intensity. Minor peaks, forming shoulders on the 325°-350°C. exothermic peak are present. The fundamental causes of such changes in the oxidation of coal are not fully understood, but the correlation with infra-red data is useful. The structural breakdown by thermal conditions of the high concentrations of humic acids, including concentrated phenolic and carbonyl OH groups, in the leonardite may be causitive.
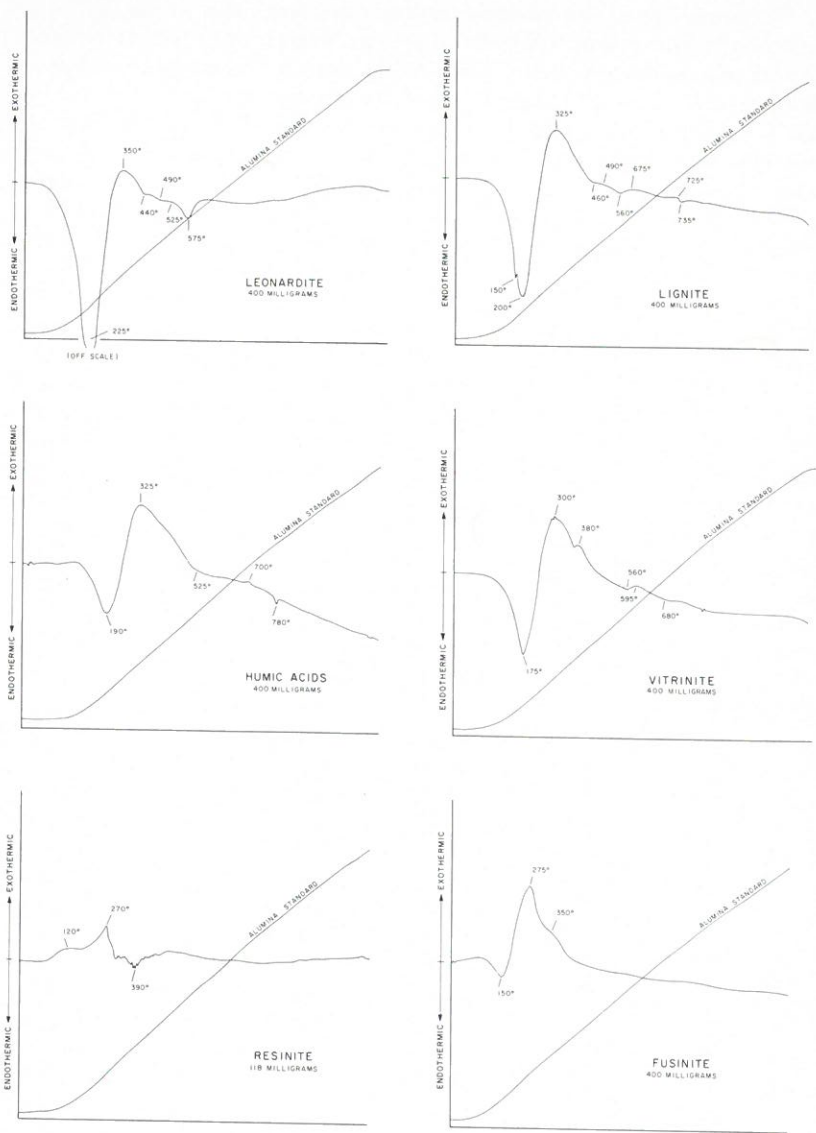
Figure 7. Differential thermal analyses.

A weak exothermic (725°C.) and endothermic (735°C.) thermal peak occurs in the relatively high temperature ranges of lignite samples. They are not readily detectable in any of the maceral curves, but may be related to the 700°C. exothermic peak and/or the stronger 780°C. endothermic peak in the humic acids curve. These high temperature peaks can only be assigned to inorganic thermal decompositions.

A comparison of the vitrinite maceral curve with that of the lignite (79 per cent vitrinite, petrographically) is similar, except for the displacement of the peak temperature positions. The low temperature endothermic peak of the vitrinite (175°C.) is at a slightly lower temperature range than the lignite (200°C.). These are probably assignable to the H_2O and bonded OH molecules, and the smaller peak area of the vitrinite is indicative of lower hydroxyl group percentages. Nevertheless, the degree of combustion is virtually the same, as determined by the area of the exothermic 300-325°C. curve. A distinct exothermic shoulder at 380°C. is notable on the vitrinite curve, but not on the lignite. This may be related to a higher concentration of resinite in the vitrinite, than would be in the lignite column sample. The 560°C. endothermic peak retains its temperature position and intensity between the lignite and vitrinite samples.

The fusinite maceral thermal curve indicates that there are organic structures still present in the maceral. It is apparent that what may appear to be relatively pure petrographic carbon (charcoal) still contains an appreciable percentage of vitrinite volatiles. The phenolic OH groups apparently are destroyed in the charcoaling process, such that only the secondary absorbed water remains. The fusinite looses a small percentage of absorbed water at 150°C. Combustion of the remaining volatile material in the fusinite is sharp and occurs over a narrower temperature range than vitrinite, peaking at 275°C. No peaks occur above 450°C. The influence of inorganic contamination is uncertain in this thermal curve and is assumed to be negligible because of the selection of petrographically inorganic-free samples for this experiment. The thermal curve of resinite does not have any endothermic peak in the 100° and 300°C. temperature range, as do all other macerals. The major exothermic combustion peak is at 270°C. with a minor hump at 120°C. The resinite is characterized by a jagged-line melting endothermic curve at 390°C. No reactions are apparent at higher temperatures.

In summary, the liberation of volatile matter from organic compound disintegration is between 120 and 350°C. (peaks). These are predominantly structural groups rich in hydroxyl and other oxygen containing functional groups in this experimental non-oxidizing atmosphere. The lowest temperature range is observed in resinite, and the highest in leonardite, and thus indicates desirable and undesirable influences for economic industrial combustion utilization. Bonded OH content is relatively dominant in leonardite, less in lignite and small but variable in the individual macerals. In lignite and leonardite secondary decomposition of the above generated products is between 500 and 600°C. Burning of elemental carbon is essentially prevented by the non-oxidizing atmosphere.

Geochemistry

Semi-quantitative trace element analyses of five samples of lignite and leonardite are in Table 2. The samples represent continuous columns removed from the working face in the Utility Coal Company strip pits. The lignite and

leonardite samples were ashed at 700°C. for 24 hours. The humic acid extract of leonardite was ashed for 30 hours at 650°C. The 60 element semi-quantitative spectrographic analyses were obtained using a Jarrell Ash 3.4 meter with Ebert Grating applied to a direct current arc. Input voltage was 220, and discharge current was 1-50 amperes. A thoroughly mixed pulverized sample of 5 milligrams was mixed with 10 milligrams of carbon buffer and transferred quantitatively to a graphite electrode. This electrode was then placed in the arc stand of the instrument and an arc was formed between the sample electrode and a counter electrode. The current, was gradually increased until the complete sample was burned off in approximately three minutes. The spectrum was permanently recorded on glass plates, from which the intensities of the resulting lines at various wave-lengths of the elements are measured. Standard samples with relatively the same matrix as the unknown sample are analyzed simultaneously. The intensities of the elements in the sample spectrum are compared to the intensities in the standard spectrum and the resulting figures are calculated to obtain the concentration of the various elements in the sample. The results are estimated to be accurate within thirty per cent (semi-quantitative). Detection limits are given adjacent to the sample analyses, which are expressed as percentages.

The lignite column sample ashes to 8.6 per cent by weight. Leonardite invariably has higher percentages of inorganics, and is 15.2 per cent in the sample used. Leonardite from this area was dissolved in concentrated sodium hydroxide, and then neutralized with hydrochloric acid. The resulting precipitate of sodic humic acid salts was then ashed to 9.7 per cent by weight at 650°C.

The trace and minor element analyses of Table 2 represent whole seam sampling. Coal seams generally have higher minor and trace element content in the margins of the seam, particularly the basal zone. This indicates that elements were immobilized and were not available for accumulation by subsequent plant growth. In a developing peat bog accumulation, the initial vegetation has its roots in the subsoil, and is dependent upon this zone for its nutrients. With continued peat deposition, subsequent root systems are above the seam underclays. Subsequent plants depend upon the release of elements from the peat humis and from the influx of elements from erosional cycles adjacent to the depositional basin. Element concentration in the coal seam is also influenced by absorption or chemical reaction with ground water during the coalification process, as well as concentration of the elements in mineral matter deposited along with the plant material in the pre-coal accumulation. Ground water alteration after coalification may be important, and indeed is in this seam.

The literature on distribution of trace elements with respect to petro-graphic lithotype, position in the seam and association with organic or inorganic fractions is extensive. Nicholls (1968) presents a particularly comprehensive summary.

Primary biological concentration in pre- and early peatification is usually responsible for the high percentages of boron, as well as some nickel and copper in the coals. Boron has an affinity for illite lattice structures, and

TABLE 2

SEMI-QUANTITATIVE

CHEMICAL ANALYSES

(Percentages)

ELEMENT	TOTAL LIGNITE	LIGNITE ASH	TOTAL LEONARDITE	LEONARDITE ASH	HUMIC ACIDS ASH	ELEMENT	DETECTION LIMIT
Aluminum	0.5	Major	1.0	Major	Major	Aluminum	-
Antinmony	ND	ND	ND	ND	Detected	Antinmony	0.01
Arsenic	ND	ND	ND	ND	ND	Arsenic	0.1
Barium	0.07	*	0.1	*	*	Barium	0.01
Beryllium	<0.001	<0.001	<0.001	<0.001	<0.001	Beryllium	0.001
Bismuth	ND	ND	ND	ND	ND	Bismuth	0.001
Boron	0.003	0.08	0.001	0.003	0.001	Boron	0.001
Cadmium	ND	ND	ND	ND	ND	Cadmium	0.01
Calcium	Major	Major	Major	Major	0.5	Calcium	-
Cerium	ND	ND	ND	ND	ND	Cerium	0.001
Cesium	ND	0.005	ND	ND	ND	Cesium	-
Chromium	<0.001	0.001	<0.001	<0.001	*	Chromium	0.001
Cobalt	ND	<0.001	ND	ND	ND	Cobalt	0.001
Copper	<0.001	0.001	<0.001	0.003	0.03	Copper	0.001
Gadolinium	ND	<0.001	ND	0.001	0.001	Gadolinium	0.001
Gallium	ND	ND	0.001	0.002	0.002	Gallium	0.001
Gold	ND	Trace	Trace	Trace	Trace	Gold	-
Hafnium	ND	ND	ND	ND	ND	Hafnium	0.1
Indium	ND	ND	ND	ND	ND	Indium	0.01
Iridium	ND	ND	ND	ND	ND	Iridium	0.01
Iron	0.01	Major	0.1	0.5	0.7	Iron	-
Lanthanum	ND	ND	ND	ND	ND	Lanthanum	0.01
Lead	ND	0.02	ND	<0.01	ND	Lead	0.01
Lithium	ND	ND	ND	ND	ND	Lithium	0.01
Lutetium	ND	<0.001	ND	<0.001	<0.001	Lutetium	0.001
Magnesium	0.5	Major	0.5	1.0	0.3	Magnesium	-
Manganese	ND	0.05	ND	0.005	0.01	Manganese	0.001
Mercury	ND	ND	ND	ND	ND	Mercury	0.01
Molybdenum	ND	<0.001	<0.001	<0.001	0.04	Molybdenum	0.001
Neodymium	ND	ND	ND	ND	ND	Neodymium	-
Nickel	<0.001	0.003	<0.001	<0.001	0.02	Nickel	0.001
Niobium	ND	ND	ND	ND	<0.1	Niobium	0.01
Osmium	ND	ND	ND	ND	ND	Osmium	0.1
Palladium	ND	ND	ND	ND	ND	Palladium	0.001
Phosphorus	ND	<0.1	ND	ND	ND	Phosphorus	0.1
Potassium	<0.1	<0.1	<0.1	<0.1	0.1	Potassium	-
Platinum	ND	ND	ND	ND	ND	Platinum	0.01
Rhodium	ND	ND	ND	ND	ND	Rhodium	0.001
Ruthenium	ND	ND	ND	ND	ND	Ruthenium	0.1
Scandium	ND	0.003	ND	0.001	0.003	Scandium	0.001
Silicon	1.0	Major	Major	Major	Major	Silicon	-
Silver	<0.001	<0.001	<0.001	0.001	0.003	Silver	0.001
Sodium	<0.1	*	<0.1	<0.1	*	Sodium	-
Strontium	0.08	*	0.06	*	0.01	Strontium	0.001
Tantalum	ND	ND	ND	ND	ND	Tantalum	-
Tellurium	ND	ND	ND	ND	ND	Tellurium	-
Thallium	ND	ND	ND	ND	ND	Thallium	0.1
Thorium	ND	ND	ND	ND	ND	Thorium	0.1
Thulium	ND	ND	ND	ND	ND	Thulium	0.01
Tin	ND	<0.01	ND	ND	ND	Tin	0.01
Titanium	0.1	>0.7	0.5	0.7	>0.7	Titanium	0.1
Tungsten	ND	ND	ND	ND	ND	Tungsten	0.1
Uranium	ND	ND	ND	ND	ND	Uranium	0.1
Vanadium	0.001	0.005	0.001	0.005	0.007	Vanadium	0.1
Ytterbium	<0.001	<0.001	<0.001	<0.001	<0.001	Ytterbium	0.001
Yttrium	0.001	0.003	<0.001	0.001	<0.001	Yttrium	0.001
Zinc	ND	ND	ND	ND	<0.1	Zinc	0.1
Zirconium	0.002	0.03	0.03	0.04	0.06	Zirconium	0.001

Major - Above normal spectrographic range
* - Greater than 0.1 %
ND - Not detected
< - Less than
> - More than
Detected - Antimony suffers from chromium interference and because of the high level of chromium present in the sample a chemical analysis is necessary to determine the actual amount of antimony in the sample.

consequently may also be concentrated in the inorganic fraction, as in the lignite of this study. Post-burial adsorption by organic matter affects germanium and molybdenum concentrations. Molybdenum concentration is high in the leonardite sample, and apparently is concentrated in the humic acid fraction. Considering the post-coalification diagenesis of lignite, the influence of ground water is critical in the concentration of this element. The leonardite and humic acids also concentrated copper, manganese and nickel

from ground water in the samples studied. The elemental adsorptive and moisture-retaining properties of leonardite and humic acids are well recognized by Kristeva et. al., 1954; Laatch, 1950; Swaby, 1950; and O'Donnell, 1970. Adsorption by clay minerals at an early coalification stage incorporates gallium, some chromium and vanadium present in the samples. Post-coalification ground water circulation is primarily responsible for the oxidation of the lignite into leonardite and is accompanied by significant concentration of clay minerals. Inspection of the higher element concentrations in the leonardite and humic acids may then be attributed to both the influx of mineralized ground water in contact with an adsorptive medium and the concentration of adsorptive clay minerals. Post-coalification mineralization is evident petrographically. Kaolinite, gypsum and calcite in thin section are largely introduced by ground water movements after the lignification. Primary, detrital veinlets of kaolinite, montmorillonite, illite, calcite, gypsum and quartz are confirmed by X-ray diffraction and optical examination. These contemporaneous inorganic accumulations are primarily responsible for the major percentages of silicon, aluminum, magnesium, iron (also from biologically fixed pyrite), sodium and calcium.

X-ray and optical studies of the distribution of mineral species within the lignite and leonardite seams have been completed, though the trace element distribution is currently in progress. The highest inorganic concentration is the basal carbargillite zone of the seam, and thus contains the highest percentage of detrital clay, quartz and trace minerals. Above this zone the mineral concentration is largely correlative with petrographic component distribution. The presence of lithotype fusite is particularly important for the concentration of clay minerals, gypsum and calcite. These secondary minerals are trapped in the cellular voids of fusinite by circulating ground waters and often fill up to 70 per cent of the available space. The more soluble gypsum is usually the dominant species present. Higher concentrations of kaolinite, montmorillonite, illite and quartz are generally found in the clarodurite, duro-clarite and clarite lithotypes. The lowest inorganic percentages are associated with vitrite, and is predominantly the most soluble species thenardite, as well as secondary calcite and gypsum. Consequently, relative concentrations of inorganic particles is dependent upon distribution of petrographic macerals, (see Broughton, 1972b). No bromoform heavy fraction minerals other than limonite, pyrite and traces of marcasite were observed. The presence of natro-jarosite in this seam has been confirmed by R. O'Donnell of the Saskatchewan Research Council. This petrographic maceral distribution also would control the trace element distribution, although the experimental work to confirm this has not yet been completed. Goldschmidt (1935) found that beryllium, vanadium, cobalt, nickel, gallium, zinc, and yttrium were more abundant in the ashes of forest and swamp humus. The paleo-environmental analysis of this seam (see Broughton, 1972b) regards this time interval as a dominating forest-moor influence associated with periodic reed-moor influences. Consequently, the distribution of these trace elements would be largely dependent upon the inherent environmental influences expressed in the petrography.

Industrial Applications

Naturally oxidized lignite has several properties that can be utilized in a variety of non-fuel industrial manners. Leonardite can disperse and stabilize solid suspensions in liquids, making it useful when added to borehole drilling muds as a viscosity and gel strength inhibitor, reduces the plastic viscosity and pH., and has virtually no effect on the filtration properties of the fluid. An apparent viscosity of about 40 centipoises is initially achieved, increasing to about 180 after 30 minutes. Higher concentrations than 3 lbs. per barrel seem to enhance the viscosity thinning effects only slightly.

A leonardite-caustic soda mixture is commercially prepared at the Peerless Mine, North Dakota for the borehole drilling mud market. The caustic additive promotes the greatest reduction in apparent viscosity at a leonardite-caustic weight ratio of 2:1, with initial values of about 200 centipoises. The results indicate that effective use of leonardite-caustic addition is best when the ratio is between 4:1 and 1:1. Odenbaugh and Ellman (1967) note that application rates of 4 lbs. of leonardite per barrel of drilling fluid in combination with caustic soda (weight ratio of 3:1) gave minimum plastic viscosity and least change with aging at higher temperatures, simulating bottom-hole conditions.

Leonardite as a drilling fluid additive, however, is not beneficial when the borehole has salt contamination, a condition that may be common in some well fields. The effect of sodium chloride contamination is to reduce the filter-loss rate, but at the expense of increasing the gel strength; the overall effect being essentially detrimental.

As previously pointed out leonardite currently is being utilized commercially only as a drilling mud additive with minor uses as a water softener. However, utilization of humic acid extracts have significant potential. They make agreeable wood stains, or solutions for coloring cellulose products, such as paper, fiber, for paint, graining colors, frescoes, inks, etc. The use of leonardite extracts as wood stains is enhanced by the fact that strong exposures, long duration to sunlight do not decompose the organic structures to cause fading. In the 1920's leonardite humic acid extracts were commercially marketed as a wood stain under the trade name of **Dakalite** by Dakalite Products Company of Burlington, North Dakota (Dove, 1926). Modern synthetic dyes have since displaced leonardite extracts in this market.

The use of leonardite and its humic acids as a plant growth conditioner is the current direction of many research efforts (Freeman and Fowkes, 1968; Youngs and Frost, 1963; Frost, Hoeppner and Fowkes, 1959; O'Donnell, 1970a, 1970b, 1971).

The effect of humic acids on plant growth is due to the important role of phenols and carbonyl structures in metabolic processes. Acceleration of the plant dimensions and weight results from humic material promoting respiration and photosynthesis. O'Donnell (1971) notes that the quinone and polyphenolic groups stimulate the metabolism such that respiratory intensity, coupled by higher absorption of nutrients, is increased. Likewise, the nitrogenous compounds (proteins and amino acids) of the humic acid complexes induce catalytic reactions on the photosynthesis process.

Humic substances tend to form chelate complexes with iron, aluminum, copper and other poly-valent ions. Affinity to form iron chelates directly stimulates root initiation of tomato plants in the experiments of Freeman and Fowkes (1968). Humic acid complexes also have the property to decrease the loss of moisture from the soil and thereby increase its workability. Agricultural applications of leonardite represent the greatest potential use for oxidized low rank coals.

A major problem related to industrial application of humic acid complexes is developing a commercially viable system of humic acid preparation. A technique to remove the sand, silt and clay and chemically alter the insoluble calcium ion must be utilized. The most common laboratory technique for separation of humic acids is to use an alkali (i.e. sodium hydroxide) extraction process. However, on a commercial scale this method would be disadvantageous because of (1) large volumes of water needed to obtain a low ash product, (2) difficulties in separation of fulvic acids from humic acids, and (3) the requirement of fresh alkali, which is consumed in the process, for each lot of humic acids preparation.

Youngs and Frost (1963) and Fowkes and Frost (1960) concluded that the most economical and commercially applicable solvent process for extraction of humic acids is a mixture of acetone and water. In this process the leonardite is first treated with a dilute acid, proportional to the amount of humic acid recovery. These authors recommend a ratio of one liter of 80-20 acetone-water mixture by volume, to be applied to 10 grams of HCl per 100 grams of moisture-free leonardite. See the flow chart in Figure 8. The acetone is recovered by low temperature distillation and recycled for the next batch of raw leonardite. The humic acids are easily filtered once the acetone is removed.

ORGANIC SOLVENT EXTRACTION
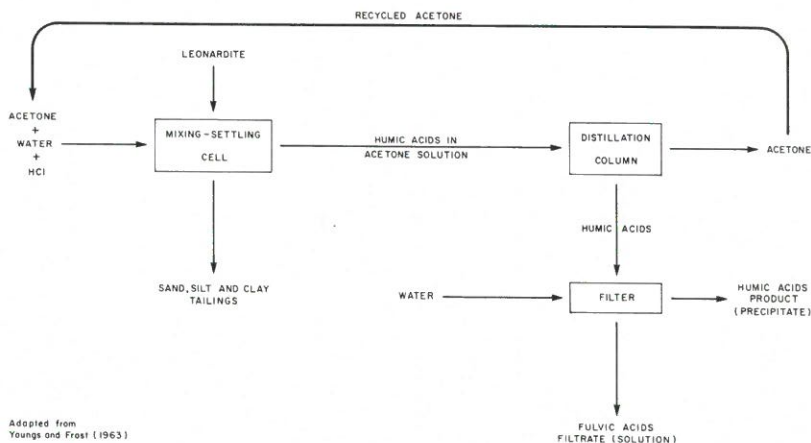
Figure 8.

Summary and Conclusions

Humic acid complexes are generated during oxidation of lignite strata. The following observations characterize their genesis:

1. Leonardite deposits are correlative with near surface distribution of lignite seams in the Williston Basin.

2. Lignite undergoes slow oxidation in the shallow subsurface by air penetration or by oxidizing ground waters at or just above the water table.

3. Leonardites have variable oxygen contents, ranging from 25 to 60 per cent, whereas lignites contain less than 25 per cent.

4. Functional groups present in lignite are essentially the same as those in its oxidized state. Only the percentages of each vary considerably. Leonardite is characterized by a strong carbonyl concentration. X-ray studies have demonstrated concentration changes during oxidation for aromatic but not alicyclic structures.

5. A shift to higher combustion temperatures is a characteristic oxidation effect, reflecting the breakdown of phenolic and carbonyl OH functional groups. These have their highest concentration in leonardite.

6. Leonardite has elemental adsorptive and moisture-retaining properties. Off-scale endothermic thermal reactions result from the loss of OH structures in thermal analyses.

7. Leonardite has the useful property of being able to disperse and stabilize solid suspensions in liquids when added to borehole drilling muds as a viscosity control agent. The adhesive properties of humic acids lend themselves to utilization as wood stains. The use of leonardite and its humic acids as a plant growth conditioner is the current direction of many research efforts. The effect of humic acids on plant growth is due to the important role of phenols and carbonyl structures in the metabolic process, supplemented by the humic acids' adsorptive properties for trace and minor element nutrients.

8. The most commercially efficient process for concentration of humic acids is utilization of acetone as an organic solvent.

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MINERAL RESOURCES DEVELOPMENT IN THE PUBLIC DOMAIN- AN UNFINISHED CASE HISTORY

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Abstract

Investigation of a large phosphate deposit in Southern California has been actively carried on since its' discovery in 1963. The deposit is situated on public lands within a National Forest, with prospecting and ultimate acquisition of mining rights regulated by Federal leasing laws.

New Federal legislation dealing with environmental quality, together with the recent wave of public awareness and concern for the environment, has necessitated in-depth ecologic studies to be made which in turn have led to almost continual review and modification of proposed mining plans. A public hearing was held in order to discern any environmental problems prior to issuance of a mineral lease on the deposit.

This paper summarizes the development history and geology of the deposit, and outlines the various eco-system investigations. Pertinent regulations are reviewed together with a discussion of the numerous governmental agencies involved. Strategies utilized by conservation groups against the proposed mine development are described and comments are offered regarding general trends in mineral resources development on public lands.

Introduction - Historical Background

In 1962, United States Gypsum Company obtained an option to purchase a group of gypsum mining claims in north-central Ventura County, California. This gypsum deposit was located on public lands within the limits of Los Padres National Forest. After 18 months of intensive investigation, including geologic mapping, core drilling, outcrop sampling and sample analysis, the company exercised its' option and purchased the mining claims in April, 1964.

During the gypsum investigation, a series of phosphatic beds were recognized in the study area, and whose economic potential warranted a thorough and separate investigation. Although the phosphatic units were outcropping within the boundaries of the gypsum mining claims, the phosphate could not be included in the mining claims since it is a "leasing" mineral and does not fall under the mining laws of the United States but is instead covered by the Mineral Leasing Act of 1920. Consequently, the company made application to the U.S. Bureau of Land Management for a phosphate prospecting permit on 2433.81 acres, and a prospecting permit was issued by that agency effective 1 November, 1964.

The original two-year prospecting permit was subsequently extended for an additional three years in order to allow a complete evaluation of the deposit and, consistent with federal regulations, application was made for a Preference Right Phosphate Lease in April, 1969. As of the date of

presentation of this paper, no lease has been issued. Instead, there has been a three year period of delay during which numerous agencies have made studies of the project, the various environmental and ecologic factors have been investigated in depth, a public hearing has been held to allow the development of factual information concerning the possible effects the proposed mining operation would have on the environment, and an environmental impact statement is being drafted by the Federal Government.

The investigation of the phosphate deposit in the period from 1964 to the present time is the subject of this paper, together with a discussion of the environmental and eco-systems studies made, the role of the various governmental agencies involved, and a review of the opposition to the development of the deposit.

Description of the Area

The general area in which the phosphate deposit is located (Figure 1) lies on the south slope of Pine Mountain in the headwaters of Sespe Creek in north-central Ventura County, California. This places the deposit some 90 air miles west-northwest of Los Angeles, 35 air miles north of Ventura, and about 25 road miles from Ojai, California. Primary access to the mining area is via California State Highway 33, a black top paved road which runs from Ventura on the south to the San Joaquin Valley to the north.

The general area is quite mountainous, the rugged topography having been sculptured by geologic faulting and continuing erosion brought on by heavy rain storms. The dominant feature is Pine Mountain ridge, averaging 6,000 to 7,000 feet in elevation and reaching 7,510 feet maximum elevation at Reyes Peak. The mineral property lies along the south flank of Pine Mountain to the southwest of Reyes Peak and averages about 5,000 feet in elevation.

An average of 23 inches of moisture falls per year, mostly as rain, during the period from November to April. Rainfalls of from 2 to 5 inches in a 24 hour period are not uncommon. Precipitation is insignificant from May through October. Temperatures range from a high of about 100 degrees F. during the summer months to well below freezing in the winter. Occasional snowfalls occur during the winter months, but the snow seldom persists for more than a few days.

The principal drainage of this mountainous area is Sespe Creek, which is an intermittent stream in its upper reaches adjacent to the phosphate study area. As shown in Figure 2, the Sespe is about 50 miles in length, flowing in an east to south direction and joining the Santa Clara river near the town of Fillmore, California. The total watershed drained by the Sespe is approximately 260 square miles in area.

The phosphate lease area parallels the main course of Sespe Creek and lies from 1.5 to 2 miles to the north. Four canyon systems cut across the phosphate outcrop zone from north to south, but only one — Chorro Grande Canyon — has year around flow, although very restricted in the summer months. There are several natural springs near the headwaters of these canyons which flow year around, but at very low volumes during the dry summer months.

Figure I.
Location maps,
Pine Mountain Phosphate
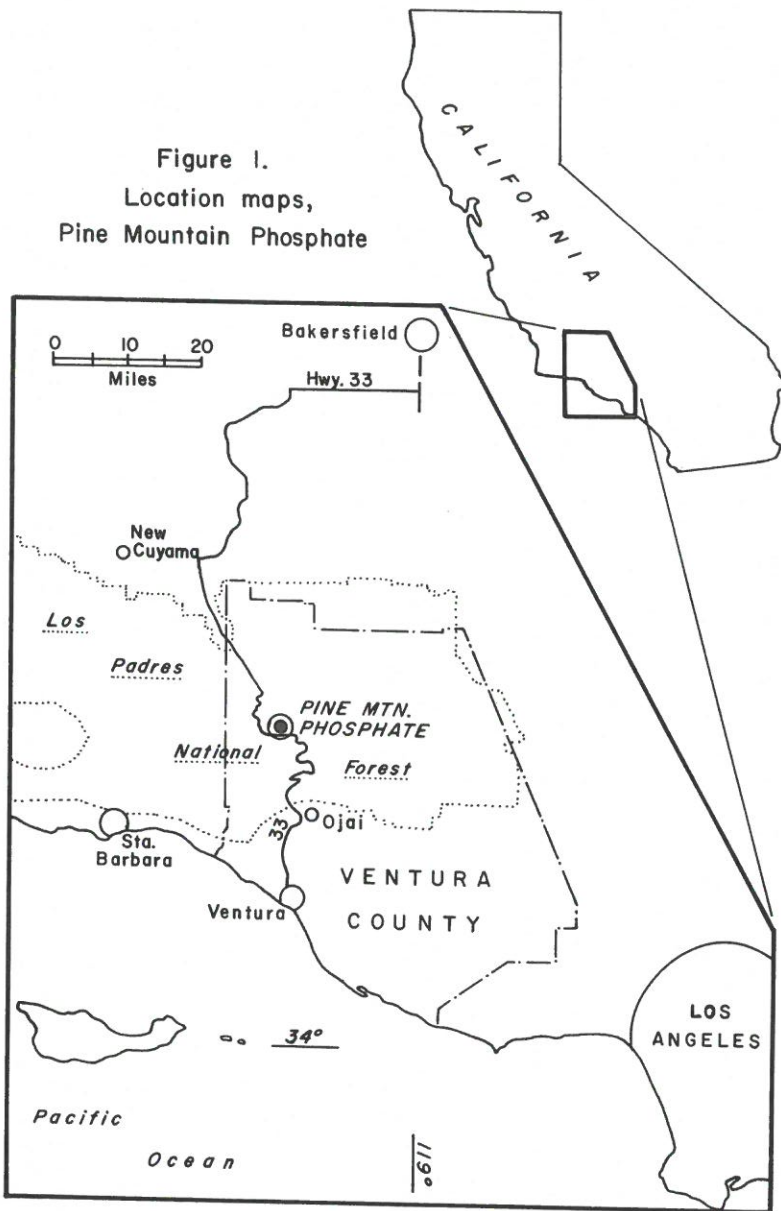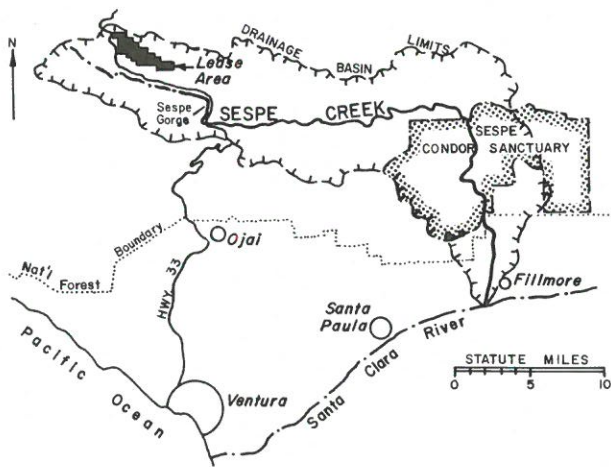
Fig. 2-A Sespe Creek drainage basin.
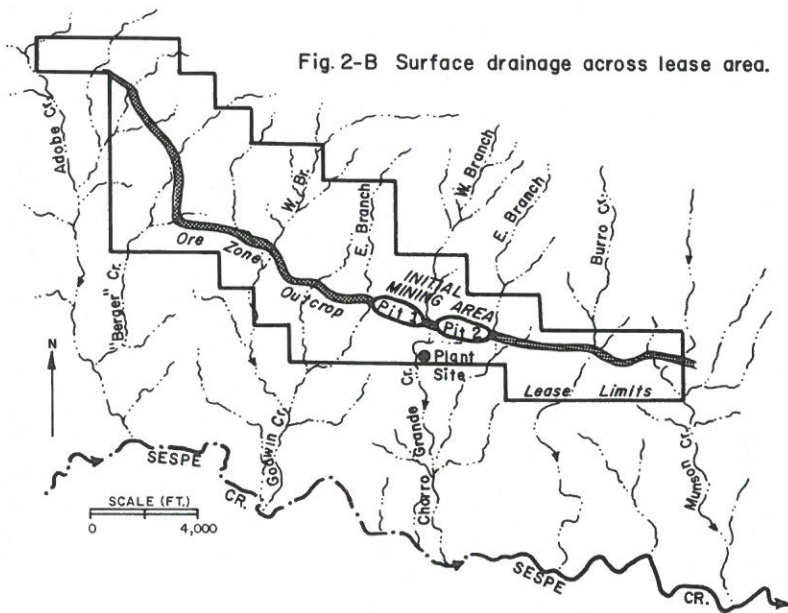
Fig. 2-B Surface drainage across lease area.

Most of the lease area has a southerly exposure and is subjected to severe drying conditions in the summer months. Soil cover is thin to non-esixtant and when combined with the steep topography these factors result in a sparse to medium-heavy vegetative cover consisting of chaparral (California scrub oak, chamise, buck brush, manzanita, yucca and mountain mahogany), numerous annual plants, and minor grasses. A few small to medium-sized Piñon pine trees are found within the lease area, but there are no large individual trees or groves which will actually be disturbed by mining. Big cone Douglas fir, sugar pine and Jeffery pine are found in abundance on the top and north slope of Pine Mountain Ridge, outside the phosphate lease area — and it is from these large trees that Pine Mountain derives its name. A few of these large conifers are found in the uppermost reaches of the major north to south oriented canyons on the south flank of Pine Mountain but at a much higher elevation than the phosphate, and outside the proposed mining area.

There are no game fish in the vicinity of the proposed mining site, and only limited aquatic life (invertebrates characteristic of ephemeral streams) is found in the upper reaches of Sespe Creek and its tributaries. Downstream from Sespe Gorge, which is located some six miles down the Sespe from Chorro Grande Canyon, there is fair to good sport fishing since the stream is stocked with trout by the California Fish and Game Division.

The principal species of animal life found in the lease area are mule deer, coyotes, and a few gray fox and bobcat. Small mammals include cottontail and jackrabbits, ground squirrels, chipmunks, gophers, deer mice and wood rats. Several types of reptiles are found in the area, particularly gopher snakes and rattlesnakes. Bird life is typical of chaparral communities throughout southern California and includes quail, jays, towhees and other songbirds.

The study area and proposed lease is located along a flyway of the California Condor — which has been officially designated as an "endangered species" — and is situated some 16 miles from the Sespe Condor Sanctuary. That Sanctuary is the principal nesting area of the Condor, which ranges over a large "U" shaped area in San Benito, Monterrey, San Luis Obispo, Santa Barbara, Ventura, Los Angeles, Kern, and Tulare counties of southern California as shown in Figure 3. Recent information indicates that this range, or foraging area, may extend southward to Baja California. The proposed lease area of just under four square miles is located in the southern portion of this several tens of thousands square mile range.

The area surrounding the proposed mining site is very sparsely settled, there being only from 4 to 6 year around residents living on private lands within the National Forest and which lands were originally acquired under the Homestead Act. The closest towns are Meiners Oaks and Ojai, 25 miles to the south, and New Cuyama about 35 miles to the north.

The only agricultural activity in this area is a minor amount of grazing. This grazing is limited principally to the several parcels of private land described above, and to some small open grassy areas adjacent to these private parcels which are leased from the U.S. Forest Service for that purpose.

There is no marketable timber in the region, either as saw timber or for pulpwood. The nearest crop raising activity is located in the Ojai Valley (25 miles south) where citrus is the principal crop, or the Cuyama Valley (20 to 35
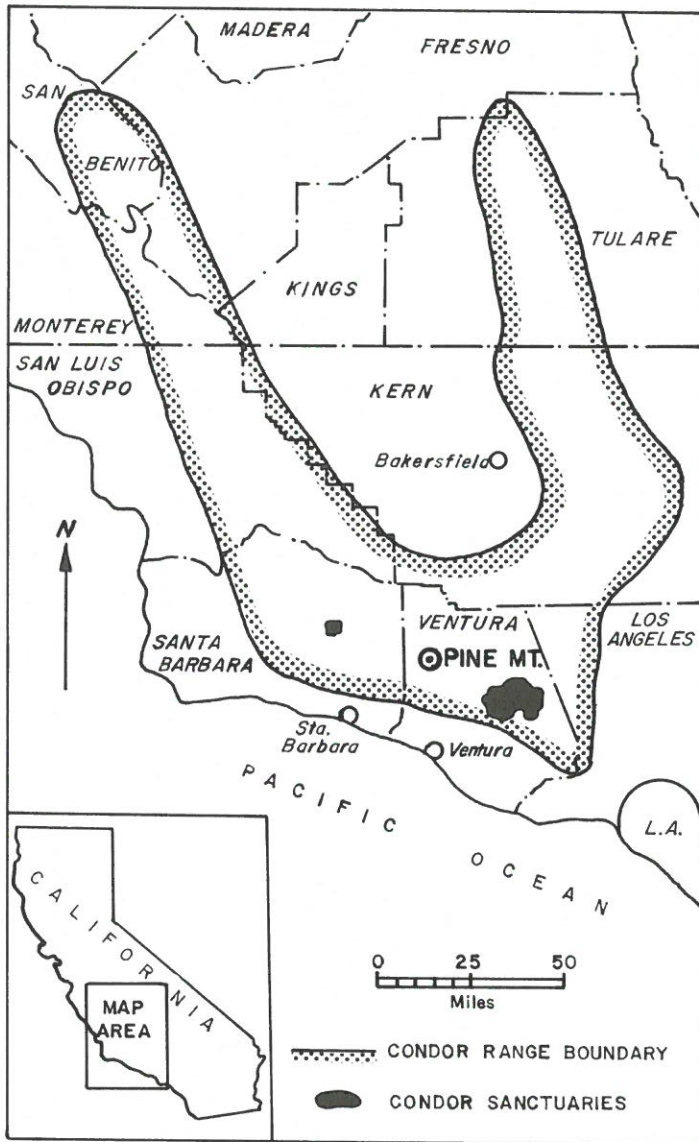
Fig. 3 California Condor Range (after Mallette & Borneman, 1966)

miles north) where alfalfa and grains predominate.

Geology of the Area

The geology of this general area had not been studied or mapped in any detail prior to 1962 when United States Gypsum optioned a group of gypsum mining claims. Detailed mapping of economic units by United States Gypsum has been carried on from 1962 to date. Additional areal mapping has been done by the Geology Department of Stanford University summer field camps during 1963, 1964 and again in 1968 at a scale of 1" = 2,000' using USGS 7½ minute topographic quadrangle maps as a base.

The rock formations at or near the surface range in age from Middle Eocene to Upper Miocene, and consist of marine sands, silts, shales and conglomerates together with minor amounts of carbonate-sulfate units which were deposited in a shallow marine environment. The lithology and stratigraphy of the area have been described by Dickenson and Lowe, and a general stratigraphic column is shown by Figure 4, which illustrates the relationship of the various rock units found in the area. A general geologic map of the area is shown in Figure 5.

Extensive faulting occurs throughout the entire Transverse Ranges, of which the study area is a part. Major faulting and concomitant folding are indicative of the entire region, with such well known features as the San Andreas fault, the Big Pine fault and the Santa Ynez fault being located only a few miles from the study area. Structurally, the immediate area is dominated by the Pine Mountain Thrust Fault which lies immediately north of the phosphate outcrop zone and can be traced for approximately 15 miles in a generally east-west direction.

The only minerals of economic potential known to exist in this region are gypsum and phosphate, both of which are found in the Santa Margarita formation of Upper Miocene Age.

The gypsum occurs as relatively pure beds ranging from 20 to 30 feet in thickness, which are overlain by a variable thickness of interbedded sands, thin mudstones and siltstones. These uppermost, poorly consolidated beds are very late Miocene and possibly even Pliocene in age, and are of probable continental origin.

The phosphatic member of the Santa Margarita formation lies approximately 100 feet below the base of the massive gypsum beds, and ranges in thickness from 100 to more than 300 feet in thickness within the bounds of the lease application. This phosphatic unit consists of dark brown to dark gray interbedded mudstone, phosphatic mudstone, phosphatic sandstone, phosphorite and phosphatic bentonite, all thought to have been deposited in a shallow, brackish environment. The phosphate mineralization occurs as a carbonate-fluorapatite (francolite or collophane) and most commonly takes the form of small pellets, pebbles, and phosphatized bones, teeth or shells. In excess of 80 percent of all the phosphate is made up of rounded or ovulitic pellets less than 2 mm in diameter.

AGE	FEET THICK	MAP SYMBOL	LITHOLOGY	ROCK UNITS	
MIOCENE	500	Tsg		gypsiferous member	SANTA MARGARITA FORMATION
	200	Tsp	Angular Unconformity	phosphatic mem.	
	200-300	Tsw		white mem.	
	250	Tms		silty mem.	MONTEREY FORMATION
	200-500	Tmb		sandy mem.	
	500-700	Tmm		muddy mem.	
	100-700	Tv	disconformity or diastem	VAQUEROS FORMATION	
OLIGOCENE	1250-1500	Tsu		SESPE FORMATION	
	200-300	Tsb	local disconformity	basal member	
EOCENE	250-500	Tcw		COLDWATER SANDSTONE	
	5000	Tt		TOPATOPA GROUP	
	?	Tj	FAULT→	JUNCAL FORMATION	

(thickness brackets: 1000; 1000-1250; 1500-1750)

(after Dickinson & Lowe, 1966)

Fig. 4 Stratigraphic column, Pine Mtn. area, Ventura County, Calif.

EXPLANATION

Preference Right Lease Limits

Tsg	Gypsiferous mem. SANTA
Tsp	Phosphatic mem. MARGARITA
Tsw	White ss & sil mem. FM

Tms	silty phase MONTEREY FM
Tmb	sandy phase (and Branch Can P ss)
Tmm	muddy phase

| Tv | VAQUEROS FM |

| Tsu | undifferentiated SESPE FM. |
| Tsp | basal cg & ss |

| Tcw | COLDWATER SS |

| Tt | TOPATOPA GP |

| Tj | JUNCAL FM |

E O C E N E   O L I G O   M I O C E N E

-167-
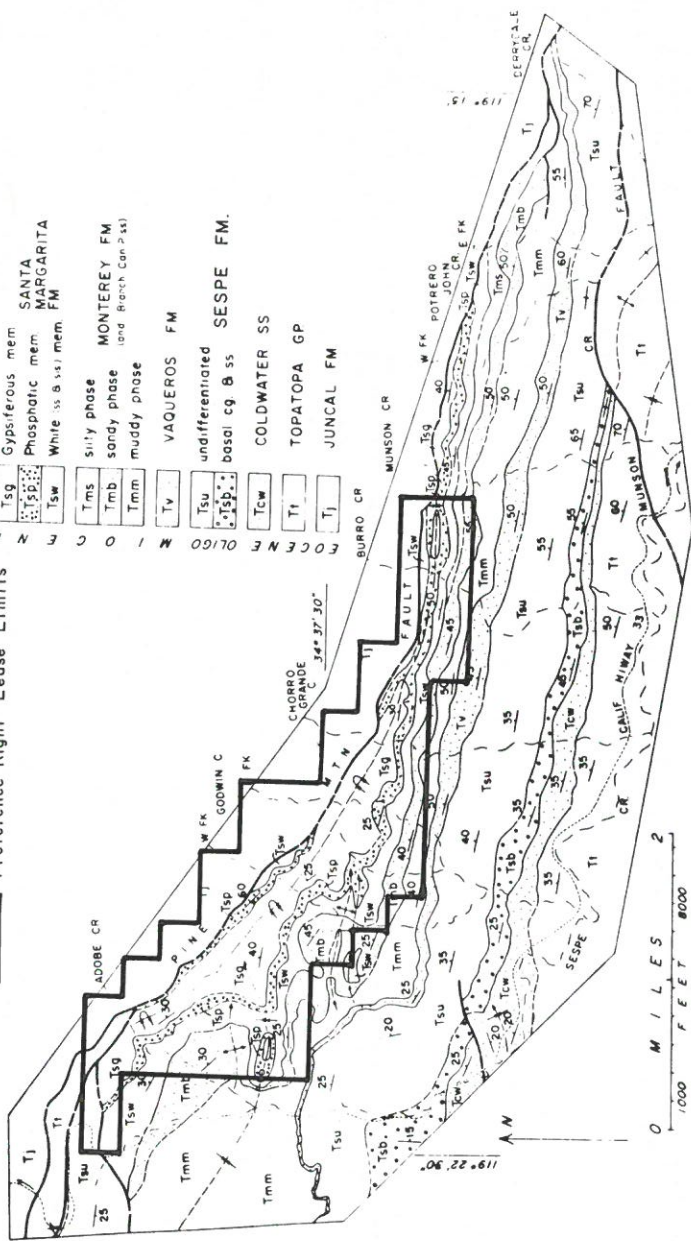
Pellets and pebbles of phosphorite are black when viewed in an unweathered state, primarily due to included carbonaceous material, but rapidly weather to a warm light reddish-brown when exposed to the atmosphere for relatively short periods of time. The distinctive coloration of weathered phosphatic rocks at outcrop is an excellent field guide during mapping and exploration since it contrasts sharply with the much lighter-colored adjacent sandstone beds.

Detailed study of the phosphatic zone shows a series of individually distinct beds which vary from a few tenths of a foot to several feet in thickness, each bed carrying a phosphate content which is remarkably uniform along strike and down dip, but which is highly variable across the beds. Phosphate content of various individual beds ranges from a "trace" to over 28 percent P_2O_5 (phosphorous pentoxide).

The phosphatic zone, and the overlying gypsum unit, outcrops more or less continuously along a strike length of some five miles. The Miocene rocks have been folded into an asymetric, or "overturned", syncline due to the thrusting action along the Pine Mountain Thrust Fault. This overturning is reflected by a repetition of phosphatic unit outcrop along much of the strike length, but with the various beds in reversed sequence. The phosphatic beds on the normal side of the syncline — and which are at the lowest elevation — dip from 30 to 35 degrees northward into Pine Mountain, but reappear in an overturned mode near the thrust fault where they exhibit attitudes ranging from vertical to nearly horizontal.

The outcrop zone of the phosphatic unit is cut off on the east by the Pine Mountain Thrust Fault, which over-rides successively older Miocene beds, and on the west, by a minor normal fault. For this reason, the upper Miocene beds considered here are the youngest found in the entire area. Bedrock surfaces are masked at several locations along the strike by landslide debris, terrace gravels, and other forms of colluvium, but only to a minor degree.

It should be pointed out that the entire thickness of phosphatic rocks is not considered economic due to the occurrence to non-phosphatic intervals or thicknessess containing only traces of phosphate. From a mining point of view, such beds must be considered waste. The economic interval, or "ore zone", is approximately 90 feet thick and lies near the center of the phosphatic unit (see Figure 6). The grade of the ore zone averages about 8.3% P_2O_5. Overlying the mineable reserves of ore are 50 feet of phosphatic mudstone and soft sandstones, succeeded by 90 feet of very loosely consolidated sandstone, ten to twelve feet of fairly hard shell hash and coquina, 20 to 30 feet of gypsum, and up to 150 feet of gypsiferous sands, mudstones and siltstones. Colluvial cover may also overlie portions of the mineable reserves.

As is the case with any ore, the 90 feet "ore zone" is made up of a combination of several minerals, which are identified in Figure 7. A typical chemical analysis of the ore is also included.

Prospecting & Evaluation

After the initial identification of the phosphate interval in 1963, no
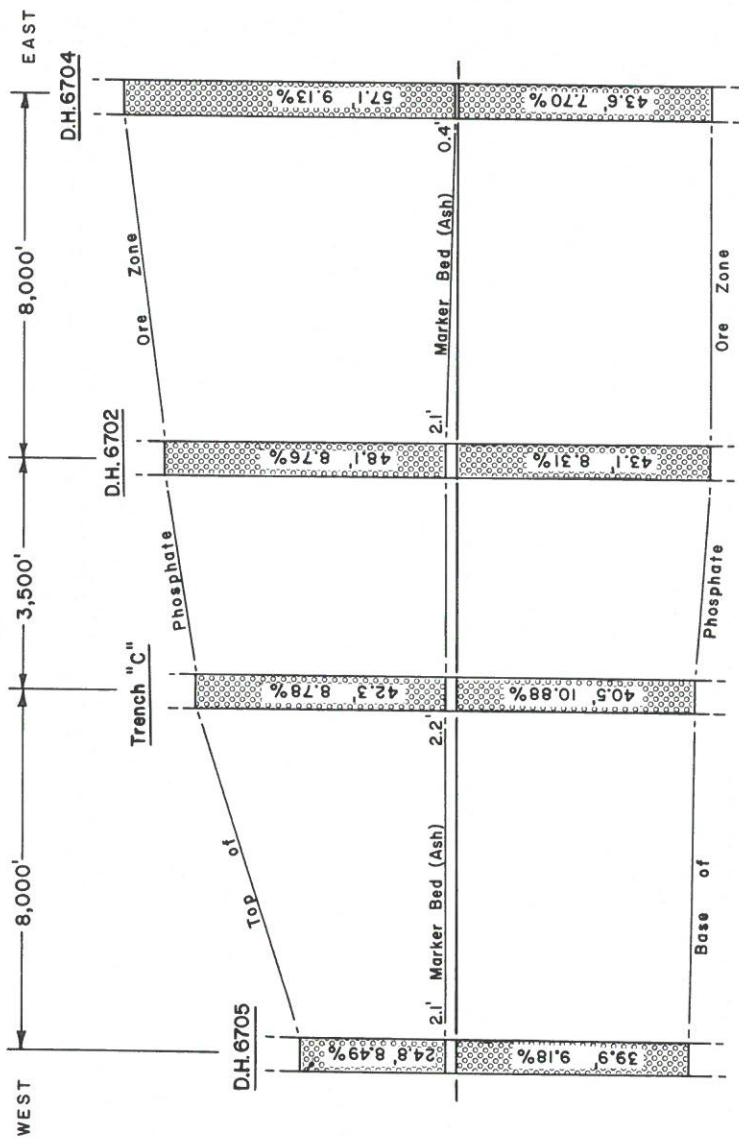
Fig. 6 Phosphate ore zone correlation showing thickness (ft.) and grade (% P_2O_5)

FIGURE 7

"Ore Zone Mineralogy"

Quartz	52.0
Apatite	21.5
Clay Minerals	13.0
Carbonate	6.0
Gypsum	2.0
Organic Material	4.5
Minor Occurrences	1.0
	100.00%

Typical Chemical Analysis of Ore Zone

Phosphorous as	P_2O_5	8.70%
Calcium as	CaO	14.01
Magnesium as	MgO	1.28
Iron as	Fe_2O_3	1.96
Aluminum	Al_2O_3	11.14
Silica	SiO_2	52.00
Sulphur as	SO_3	0.81
Titanium as	TiO_2	0.50
Organic Material		4.44
Carbon Dioxide	CO_2	2.86
Combined Water	H_2O	0.33
Chlorine	Cl	0.07
Fluorine as	F	0.85
Sodium as	Na_2O	0.27
Potassium as	K_2O	0.28
Minor Elements*		0.50
		100.00%

* Includes Arsenic - 2 ppm

Mercury - 0.4 ppm

prospecting was possible until such time as the Prospecting Permit was obtained. Once permission was secured, the prospecting and evaluation of the deposit was carried out using the normal tools of the exploration geologist; i.e. field mapping, painstakingly detailed outcrop description and sampling, preliminary trenching and sampling, core drilling, and additional, more complete trenching and sampling, followed by bulk sampling of the ore zone for use in process testing by a pilot plant. Throughout the entire period the myriad samples obtained by field parties were carefully prepared and forwarded to contract analytical laboratories for determination of phosphate values.

Geologic mapping was performed using a 1″ = 400′ topographic map prepared by photogrammetric techniques and was augmented by more detailed mapping on 1″=100′ base maps covering the initial mining area. Later in the program, a new set of topographic base maps was made covering a total of nearly 25 square miles, which include not only the phosphate outcrop zone and potential mining area but large segments of the surrounding terrain. This latest mapping serves as a base reference for various eco-system studies, mine-plant layout and planning, access road design, ground and surface water studies, and planning for revegetation and land reclamation.

The company supported an investigation of the petrology and origin of the phosphatic member by Gary Player, which was performed as a part of the requirements of a master of arts degree in geology at the University of California at Los Angeles. Other detailed field work and sampling was made by Gower and later by Lowe, of the United States Geological Survey.

Mining Plans

Many varied factors must be considered for use in winning mineral values from the earth. The two primary considerations are A) the shape or configuration of the deposit and B) the rock types which make up the deposit or are adjacent to it. There are basic questions which must be answered in order to select the proper mining methods. Are the rocks competent? Are economic ore limits sharp and clearly defined? What is the depth of the deposit below the surface? How much waste must be moved per ton of ore recovered? Is the deposit uniform in grade, or are there wide variations in quality? Are there any structural complications? What about water problems, or contamination by waste rocks?

Field investigations showed that the deposit is some five miles long, 90 feet thick and, due to the dip of the beds, could be considered 1,000 to 2,000 feet wide. Several minor cross faults were noted along strike which would affect mining operations unless carefully considered in any plans. It was also apparent that the rocks of both the ore zone and over-lying units are generally soft and lacking in structural competency.

Studies of drill cores and excavations along the outcrop of the deposit established that the rock units involved are too weak to safely allow underground mining, and so forced the decision that the deposit must be worked by open pit methods. A study of all factors shows that a substantial

quantity of ore may be recovered by stripping away a reasonable amount of overlying strata, with stripping limits established at a ratio of about 2½ tons of overburden per ton of ore.

Also of primary concern are the several major canyons, or watercourses, which cut directly across the deposit every 2000 to 3000 feet along strike. The integrity of these canyons is essential to the preservation of the water-shed and so no mining will take place in them. As a result of these conditions, the mining operation will consist of a *series* of open pits along the strike of the deposit rather than one continuous 5-mile long excavation. (Refer to Figure 2-B.)

The dimensions of each open pit will be controlled by A) the strike length between the canyons, B) the limits of economic overburden removal which in turn determines the distance downdip that mining can take place, and C) the highly variable topography overlying a mining area. Within these criteria it is estimated that maximum pit dimensions could approximate 3000 feet in length, 900 feet in dip-slope distance and 400 feet depth below original land surface.

A cross-section of a proposed pit (Figure 8) shows its' configuration to be "Vee" shaped. One side of the "Vee" will follow the footwall contact of the ore zone, dipping 30° to 35° away from the outcrop. The other limb, or high wall, is planned to be established at 45° or a 1:1 slope and would be worked as a series of 20-foot wide by 20-foot high benches running parallel to the strike.

The mining operation will be designed so as to remove the first waste material overlying the ore zone and emplace it in carefully selected areas, which will be terraced and revegetated to avoid erosion problems. The ore will then be removed, and, after a period of about five years when all the ore had been taken from one end of the first open pit, the subsequent stripped material will be emplaced in the mined-out portion of the pit. From this point forward, the operation will require that mined-out areas be backfilled with the overburden as stripping advances, and that there be no further surface emplacement of waste.

It is projected that a total of about 400 acres would be disturbed by mining over the life of the operation, or an average of 8 acres per year for the estimated 50-year life of the deposit. As soon as backfilling of a mine area is completed, it will be revegetated. At any one time, there would be no more than 40 acres of backfilled area on which revegetation had not been initiated.

The mining will begin with the development of an open pit near the center of the deposit and situated between Chorro Grande Canyon and the next canyon to the west, a strike distance of about 2000 feet. The second pit to be developed would lie immediately to the east of Chorro Grande and would also have a length of about 2000 feet. These two sites are termed the "initial mining area" and would provide ore production for the first 15 to 20 years of life at the present planned rate of production. (See Fig. 2-B.)

Principal equipment used in the mining operation will be all diesel powered and will consist of bulldozers with rippers, rubber-tired self-loading scrapers, and rubber-tired front end loaders. The relatively soft, semi-consolidated nature of the ore zone and most of the overlying waste beds allows the effective use of this type of equipment. The harder gypsum beds
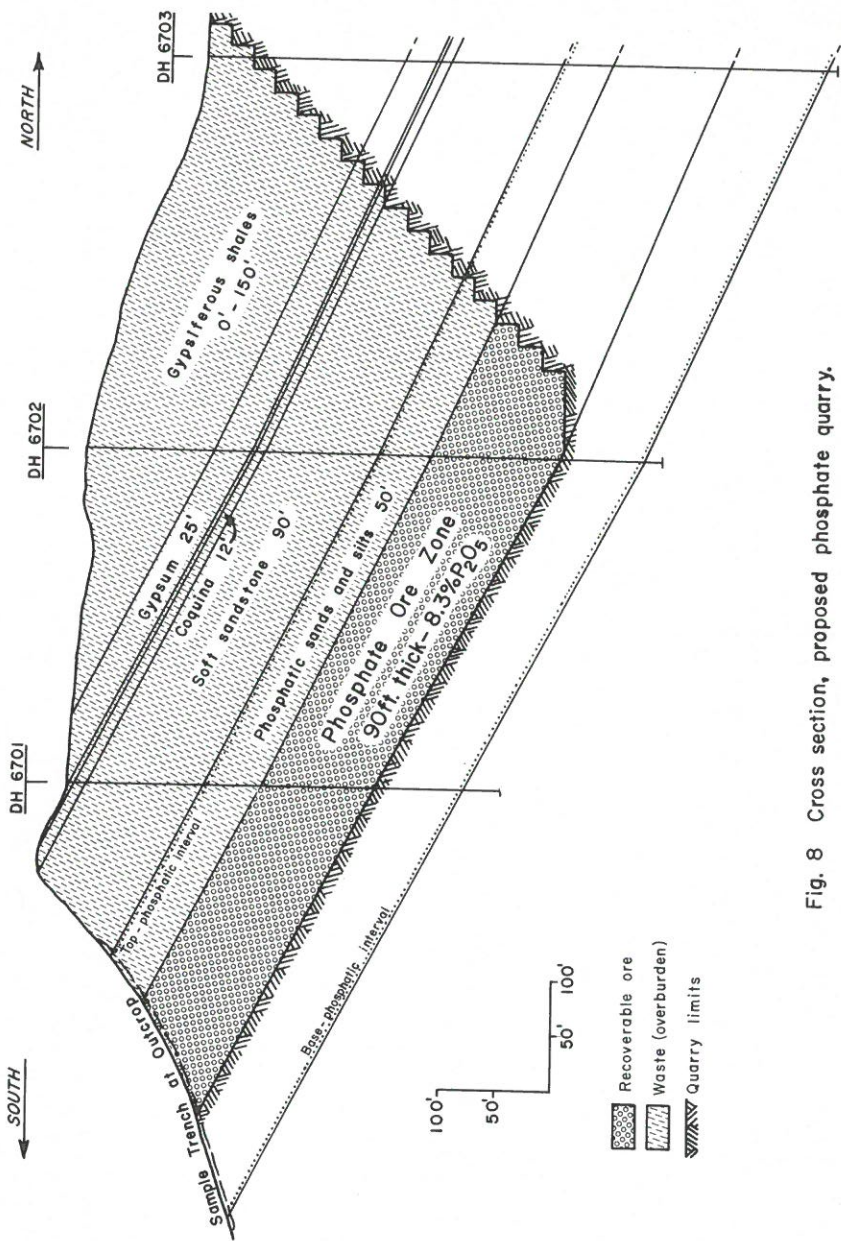
Fig. 8   Cross section, proposed phosphate quarry.

and thin coquina, where they are present within stripping limits, will be drilled with rotary drills and small individual blasts are planned for every second or third day. Thus there will be no daily, sustained heavy blasting pattern. Current estimates are that annual mine production will approach 650,000 tons of ore and about 1,500,000 tons of overburden.

Total ore production from the mine will be treated in a processing plant located adjacent to the initial mining area. Finished products from this plant will include dicalcium phosphate and phosphoric acid, which will be marketed in California and several adjacent western states. Although details of the processing of ore into finished products are not presented here, it should be noted that a novel, pollution-free technique will be utilized which should minimize or eliminate environmental concerns.

Other factors involved in mine development and processing were studied in great detail. Consideration has been given to the location of access roads, availability of utilities (power, fuel, water), transportation of required raw material and shipment of finished products to market, manning, and the like. Time will not allow a discussion of all these factors in this paper, but it should be pointed out that these elements have not been overlooked.

Environmental Considerations

From the very inception of the project it was realized that environmental considerations should play an important part during the exploration steps as well as in development planning. This was of particular importance since Federal Lands are involved and in view of a growing public concern for maintenance and improvement of the environment.

Basic environmental data has been acquired by company personnel and includes geologic information, data on climatology, surface water and spring flow, and ground water levels in area wells. The U . S. Forest Service proved to be of invaluable assistance in gaining a knowledge of the non-mineral resources of the area. In 1970, an outside group — Thorne Ecological Institute of Boulder, Colorado — was retained by the company to act as consultants regarding the ecological aspects of the proposed mining operation. Thorne immediately began a series of studies designed to develop a complete inventory of the major features of the natural environment of the area and to assess possible impact on the environment which might result from anticipated actions associated with project development. The Thorne group also thoroughly investigated environmental controls and/or alternate methods of accomplishing the various objectives, so as to lessen or eliminate environmental impact. Project plans have continually been altered to incorporate the recommendations of the Thorne group in order to minimize any adverse effects.

Listed on the following chart (Figure 9) are various major environmental factors studied in depth by consultants and company personnel. These factors are classified into two main groupings. Given on one side of the chart are the natural factors inventoried and referenced against any possible environmental changes in the future. On the opposite side of the chart are

FIGURE 9

NATURAL ENVIRONMENTAL INVENTORY FACTORS		PROPOSED ACTION CONCERN AREAS
Geology		Erosion
Climate		Surface Restoration
Soils		Revegetation
Water		Surface Water Quality and Availability
Vegetation		Ground Water Quality and Availability
Fauna	} IMPACT* {	Air Quality (Gases and Particulates)
Aquatic Biology		Noise
Archeology		Vibration
Recreation		Fire Hazards
Scenery — Esthetics		Roads — Transportation
Regional Land Use		People

* Short term impact can usually be tolerated or accepted providing the intensity is minimized. On the other hand, long term impact is undesirable, regardless of its intensity and the greatest challenge for planners lies in this area.

listed the factors which would be involved in the proposed mine development and for which detailed advance plans and programs have been formulated in order to minimize or eliminate adverse effects.

It must be emphasized that this chart is a simplification of the interplay between the various factors cited. However, the various categories are general in scope and could be applied to any proposed development at any location. Another point to stress is that the acquisition of additional basic environmental data is an on-going program, with new information continually fed into development planning to facilitate any required modifications.

A detailed scale model of the initial mining area and processing plant location was constructed to assist in development planning and to aid in the close study of environmental factors of the area. This 1" = 80' true scale model proved invaluable to company engineers and served additionally to assist in illustrating the planned action to other interested parties.

Pertinent Mining Laws and Regulations

As mentioned earlier in this paper, phosphate does not fall under the General Mining Laws of the United States. In 1920, certain minerals which were considered essential to life were withdrawn from mineral entry on Public Lands and were designated as leaseable minerals, with ownership vested in the People of the United States. Included in this category were the mineral fuels, fertilizer minerals, salt, and others. The Mineral Leasing Act of 1920 made provision, however, for the orderly development of such minerals within a framework of regulations and conditions which must be followed. Under these regulations, after the initial discovery of a leasing mineral, an application for a prospecting permit must be made to the Bureau of Land Management. After an investigation by B.L.M. to determine if the application covers an area which is open to such action, a field check is made of the application area by the U.S. Geological Survey to confirm that a discovery of the leasing mineral has been made and that the application is valid. B.L.M. then consults with other agencies which may have physical control of the area to determine what restrictions or conditions should be placed on the permittee during the prospecting period. In the case of the Pine Mountain phosphate deposit this other agency was the U.S. Forest Service, a part of the Department of Agriculture.

U.S. Gypsum Company made its original application for a phosphate prospecting permit February 27, 1964. After the steps described above had been followed by B.L.M., a prospecting permit was issued for a standard two year term, effective November 1, 1964. On August 16, 1966 the company made application for an extension to the permit period and on October 17, 1966, a three year extension was approved which expired October 31, 1969.

Evidence was established by the company during the 5 year prospecting permit period that a valuable phosphate deposit did occur within the permit area. Subsequently, an application for a preference right phosphate lease was filed for these lands on April 14, 1969. An examination of the site and all prospecting data was then conducted by the U.S. Geological Survey as required by the regulations. In July, 1969, the Geological Survey certified that

a discovery of valuable phosphate had been made and stated that U.S. Gypsum Company was entitled to a preference right phosphate lease*.

During the exploration of the deposit, all plans for work required the approval of the Regional Mining Supervisor of U.S.G.S. In addition, close cooperation with the U.S. Forest Service was mandatory since the prospecting permit was issued subject to stipulations of the U.S. Department of Agriculture and a bond posted by the company to assure proper performance under those stipulations.

Since all applicable laws and regulations have been complied with and since the existence of a valuable deposit has been proven, the question then arises as to the issuance of the preference right lease. As a result of new laws and regulations, issuance of a lease had been delayed.

In January, 1969, 43 CFR 23 was issued which covered "Surface Exploration, Mining and Reclamation of Lands". Under this rule, a technical examination was required which would "formulate the general requirements which the applicant (for a permit, lease or contract) must meet for the protection of nonmineral resources". Such requirements would then be incorporated into the permit, lease or contract. The burden of preparation of the technical examination under this regulation fell on U.S. Forest Service personnel. Numerous meetings were held with the Forest Service and other interested agencies, and the company was deeply involved in developing and presenting pertinent data to aid in the technical examination report. Several major revisions were made to this Forest Service report as more data was obtained, but the report has yet to be released after some 2½ years.

To further complicate the picture, we must now include Public Law 91-190, which became effective January 1, 1970, and is better known as the "National Environmental Policy Act". Under this law, and particularly in Section 102 (2) (C), all agencies of the Federal government were given the responsibility of preparing a detailed environmental statement which would be included in recommendations or reports on major Federal actions which would significantly affect the quality of the human environment. This detailed statement should cover the following points:

1) The environmental impact of the proposed action,
2) Any adverse environmental effects which cannot be avoided should the proposal be implemented,
3) Alternatives to the proposed action,
4) The relationship between local short-term uses of man's environment and the maintenance and enhancement of long term productivity, and
5) Any irreversible or irretrievable commitments or resources which would be involved in the proposed action should it be implemented.

The National Environmental Policy Act is necessarily very broad in concept and lacks specific rules or guidelines for its implementation or application to a particular condition. Therefore, there was a period of inaction

*See 30 USC 211-214, as amended, relative to issuance of a prospecting permit and preference right lease. This is in turn supplemented by regulations set forth in CFR 3500-3509.

during which the several involved Federal agencies deliberated on the question of how best to meet the requirements of N.E.P.A. in an assessment of the Pine Mountain lease application.

Recognizing this problem, the company offered to cooperate with U.S.G.S. in attempting to define the general guidelines which might be applicable to mineral development — among other uses of the land — using the Pine Mountain phosphate project as specific example of mineral resources development. After several months of effort by the Geological Survey, and with the company's assistance and cooperation in furnishing basic data, U.S. Geological Survey Circular 645, "A Procedure For Evaluating Environmental Impact" was issued in May, 1971. In this publication a method was outlined which, when properly applied, would act as a practical tool for resolving the all too often divergent viewpoints held by industry, conservationists and governmental agencies as regards the details of environmental impact of a proposed action.

Consistent with the new regulations, a Public Hearing was held in Ventura, California on July 27-28, 1971. The purpose of this hearing was to develop factual information concerning the possible effects the proposed mining operation and the construction of the necessary facilities, such as access roads, to support it, would have on the environment, including the California Condor. The hearing was held under the direction of the B.L.M., and interested parties were given the opportunity of making statements. The company, with a background of seven years investigation by company personnel and scientists of several disciplines, and using the approach outlined in Circular 645, presented a statement of the factual information concerning possible environmental impact of the project. This was augmented by detailed statements of the various consulting scientists, together with recommendations for controls which should be taken to assure the environmental integrity of the proposed mining area.

Opposition to the proposed mining operation was voiced at the Public Hearing by many conservation organizations, citizens committees, local governmental agencies and political factions. Regretably, this opposition tended to be less than factual and reached conclusions which were based on inference, allegation, or sophistic thinking. In the few cases where an attempt was made to present factual data, there were errors and/or incorrect assumptions. It is interesting to note that from all of those opposed to the project — including not only the statements made at the Public Hearing, but from numerous letters received by the Hearing Officer from those persons or groups who could not attend the hearing — there was not a single suggestion made as to alternatives or improved methods of conducting the proposed operation with a view toward minimizing environmental impact. The over-riding theme of the opposition was, instead, one of questioning the right of private industry to use mineral resources from the Public Domain to make a profit.

Several Federal agencies prepared studies of the project which dealt with environmental factors and concerns. The U.S. Department of Agriculture — Forest Service published a "Situation Statement" prior to the Public Hearing

(in January, 1971) and struck a note of deep concern for the effect the project would have on the non-mineral resources of the area. On July 12, 1971, another report entitled "Draft Environmental Impact Statement" was issued by the Bureau of Land Management, and drew heavily from the Forest Service report. The purpose of the B.L.M. "Draft Environmental Impact Statement" was to "solicit comments, suggestions, analyses, and additional data from Federal and State agencies, from local governmental and private entities and from interested members of the general public". It was also stated that a final environmental statement would be prepared and sent to the Council on Environmental Quality following a thorough analysis of the comments generated as a result of that statement.

Nature of the Opposition

In view of the current National wave of environmental consciousness it is not surprising that the Pine Mountain Phosphate Project has been the object of strong opposition by conservation-oriented groups. These groups are composed to both large, nation-wide organizations as well as local, citizens groups of very limited membership. The chart in Figure 10 gives a listing of organizations appearing at the Public Hearing in opposition to the pending lease. In addition to these organizations, opposition was also expressed by numerous private citizens and elected officials.

Details of the various concerns of those in opposition could not possibly be enumerated here, but the major points of contention included:

Protection of the California Condor
Erosion, watershed protection
Destruction of forest lands
Loss of recreational opportunities & facilities
Dust and noise
Fumes and gases
Hazards from fire, accidental spills
Increased highway traffic, resultant damage to state roads
Loss of aesthetic values
Non-economic nature of a deposit too low grade to mine

The tactics used by these various parties are well covered in the Sierra Club publication entitled "Eco-Tactics". This book is a *must* primer for conservation activists and should also be carefully studied by those of us in the mineral industry as well, in order to gain insight into what to expect when considering future mineral development. The same background is essential when considering existing operations which may draw the scrutiny of the conservationist movement.

The tactics used are — or should be — familiar to us all. Of prime requisite is *publicity*, and the opposition has kept the issue before the public by periodic news releases and television appearances. A concerted effort is made to broaden the coverage of the media so as to make the issue more than merely local in nature. National coverage by the magazines, bulletins and

FIGURE 10

List of organizations appearing in Opposition To U.S. Gypsum Phosphate Lease Application At Public Hearing July 27 — 28, Ventura, California

1. Sierra Club, National Organization
2. Sierra Club, Sespe Chapter, Ventura, California
3. Sierra Club, Los Padres Chapter, Santa Barbara, California
4. National Audubon Society
5. Santa Barbara Chapter, Audubon Society
6. Environmental Coalition of Ventura County
7. American Association of University Women, Ventura County Chapter
8. Comprehensive Health Planning Association
9. Concerned Citizens of Ojai
10. Friends of the Earth, California Branch
11. American Institute of Architects, So. California Branch
12. Oxnard Gem and Mineral Society
13. Committee to Save the Ojai
14. Ventura County Air Pollution Control District
15. East Ojai Valley Associates
16. California Outdoor Recreation League
17. League of Women Voters, Ventura, California
18. Santa Barbara Trails Advisory Committee
19. Committee for Open Space in Ventura County

periodicals published by the major conservation organizations is an excellent example of this trend. Environmental "walk-ins" to the proposed mining site, public meetings held to "discuss" the project, the circulation of petitions against the proposed operation, letters to the editors of numerous local and regional newspapers are other tactics used to exert pressure on the thinking of the general public.

The anti-mining, special interest groups also use *political pressure* to further implement their opposition. Write-in campaigns generated many letters to elected public officials and those in appointive positions within regulatory governmental agencies. This "flood" of letters gives the impression of a wave of great public interest and concern when, in actuality, only a very minute segment of the population is involved. The company itself is also the target of such letter writing campaigns.

Threats of *legal action* against both the company and the Federal government have been made. Three of the speakers at the Public Hearing went on record to this effect and then followed-up with a 13 page letter to the company — with copies to appropriate governmental agencies — in order to emphasize the point. The thinking which is used to support such threats is that the National Environmental Policy Act takes precedence over all other laws, such as the General Mining Laws and the Mineral Leasing Act, and provides a basis for rejecting any legal obligations established by those laws.

The *boycott* of U.S. Gypsum Company products has been threatened. The subject of *economics* and the questioning of the "valuable" nature of the deposit has been raised repeatedly. In addition, the need for more phosphate at this time is also questioned.

The hew and cry raised by the opposition has been generated only in the past several years, and was not heard during the initial 4 or 5 years of prospecting. During the later period company personnel have attempted to dispel the fears of the various opposition forces by meeting with them countless times, both in private as well as at public meetings and in panel discussions. Information developed by the company through on-site studies and process testing has been made available to such groups. No attempt has been made, however, for any type of concerted public relations programs by the company. Instead, our thinking is that such a program is unwarranted since the best interests of the public are being protected through the fair and equitable administration of existing laws and regulations by the appropriate governmental agencies. Since the inception of the project and the issuance of the phosphate prospecting permit in 1964, the company has been guided by and has complied with all applicable laws and regulations. But the opposition would have us believe that prior laws and regulations are no longer applicable following the enactment of the National Environmental Policy Act of 1969.

Current Status of Project

At the present time, the status of the project can be described in one word — "waiting". We are *waiting* for an environmental impact statement to be issued by the Department of the Interior. This statement would include the

technical examination of the project, together with the discussion of environmental factors and possible alternatives to the proposal, as well as a cost-benefit analysis.

We are *waiting* for the environmental impact statement to be forwarded to the Council on Environmental Quality for a critical review as required by the National Environmental Policy Act. The Council on Environmental Quality would also make recommendations as to what stipulations should be attached to the lease in order to protect the environment from long term damage.

And finally, we are *waiting* for the issuance of the lease, which must be a foregone conclusion based on many precedents in law and fact. To quote from the July 12, 1971, Bureau of Land Management Draft Environmental Impact Statement, page 2: The Mineral Leasing Act of February 25, 1920 (41 Stat: 437.440), as amended by the act of March 18, 1960 (PL 86-391) provides that, if the "the permittee shows to the Secretary of the Interior that valuable deposits of phosphate have been discovered within the area covered by his permit, the permittee shall be entitled to a lease for any or all of the land embraced in the prospecting permit"

Conclusion

This paper has summarized the development history and current status of a single mineral resource development on the Public Lands of the United States and under the laws and regulations which provide for such development. The decisions made in connection with the project will undoubtedly be a landmark which will set precedents as regards the extraction of solid minerals with respect to recent environmental legislation. It becomes important, then, for all factions concerned to calmly and thoroughly pursue a fair and realistic solution.

It is also imperative that all of you in the mineral industry — whether you are involved in the earth sciences, engineering, operating, or at the management level — become aware of the current trend in environmental concern in our nation and to prepare for its ramifications. As you review current operations or look toward future development of resources you must be aware of the concerns that will create opposition to each and every project — whether it is on private or public lands. You must be able to anticipate these concerns, plan for the tactics of the opposition, and, most of all, honestly and critically evaluate each and every step you propose in order to develop the best methods with the least possible environmental impact. And lastly, do your homework — that is, be sure you have thoroughly investigated all of the environmental factors and established a background of basic data against which you may judge your future actions.

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A MATRIX CLASSIFICATION FOR INDUSTRIAL MINERALS AND ROCKS

by

James R. Dunn

Abstract

Current classifications of industrial minerals and rocks tend to be inconsistent and are of limited value. A classification based on uses and process alone tends to obscure the importance of rock types. A classification based on rock types obscures the importance of processes and uses. Yet the essence of the understanding of the geology of industrial minerals and rocks is the interrelating of these difficultly-related areas. A modified matrix diagram with one coordinate dovoted to uses and processes and the other devoted to rock types clarifies the relationships. A special column is devoted to minerals which are referred to by numbers within appropriate matrix squares.

The Classification Problem

Industrial minerals and rocks have largely defied classification. Part of the reason is that both end uses and the characteristics of the raw materials are critical. In trying to show the importance of both, classifications tend to become hybridized.

Scanning the titles of the 1960 edition of "Industrial Minerals and Rocks" (Gilson, 1960) defines part of the problem. Chapter eight is called "The Carbonate Rocks" and includes such things as the chemical characteristics and chemical uses of carbonate rocks along with the physical characteristics and physical uses. Chapter nine is called "Cement Materials," most of which are carbonate rocks, and Chapter ten is called "Chalk and Whiting" which again is carbonate material. So also is the raw material for lime (Chapter 23) and magnesite materials (Chapter 25). And most crushed stone (Chapter 13) is carbonate rock as is the most common dimension stone (Chapter 15). Thus there is not only a chapter of the book devoted solely to carbonate rocks but also the better part of six other chapters is devoted largely to carbonate materials.

If we look further, we find that Chapters 13, on Crushed Stone; 19, on Granules; 22, on Lightweight Aggregates; and 41, on Sand and Gravel; are all devoted essentially to aggregate materials. These materials — along with dimension stone (Chapter 15) — have, or should have, many physical characteristics in common; yet they are treated in many parts of the book, and much repetition has resulted.

In addition, going back to carbonate rocks, carbonate rocks which are used for crushed stone must meet competitively the physical characteristics of such materials as gravel or crushed trap rock. Used as aggregate, carbonate rocks have much more in common with gravel and trap than they do, for

instance, with a chemical grade carbonate rock.

A classification which is internally consistent is obviously very difficult to make. Dr. Robert L. Bates (Bates, 1960), noting many of the above problems, devised a classification which was geologically significant. (This classification essentially into igneous, metamorphic, and sedimentary rocks and minerals, with some modifications, is used in part of my proposed matrix.) Yet such a classification does not clearly direct attention to uses.

Ideally a classification should direct the attention of users and processors to the alternate kinds of materials which are available for particular uses or processes. And a classification should direct the geologist's attention to potential uses for materials with which he is familiar.

But, most important, speaking parochially as a geologist, the present hybrid classifications tend to obscure the geological factors which are so critical in industrial mineral exploration and evaluation. For instance, hybridizing a chapter devoted to sand and gravel so that it covers both uses and occurrences (as in the 1960 volume of "Industrial Minerals and Rocks") creates the practical problem of who should write such a chapter — producer, engineer, or geologist? If it is written by a non-geologist, many critical geologic points may be missed. Unanswered might be such things as: (1) How do gradations vary with origin? (2) How does soundness vary with origin, with weathering, with regional bedrock lithologies, with elevation? (3) How is topography used in exploration? (4) How is sampling done? (5) When is there enough drilling? and so on. Conversely, a *geologist* writing such a chapter is likely to be equally uninformed on details of plant design, production, transportation, environmental controls, and so on. The problem is created largely because of the hybridization of a classification.

An Alternative

A common way to interrelate different areas is to use a matrix chart. The Gross National Product matrix interrelating industrial outputs is a well known example, and more recently the Environmental Matrix (Leopold etal, 1971) by members of the United States Geological Survey are excellent examples. A matrix, with industrial minerals and rocks plotted against processes and uses, would seem to be an ideal way to relate the critical pieces of knowledge required for precise thinking about industrial earth materials. In a sense, such a matrix is really two classifications cross-correlated for convenience.

The matrix should consist of a grid containing separate boxes with each box at the intersection of a final product and a geologic raw material. When the final product requires a certain geologic material, a check or number is put into the appropriate box.

Construction of the Matrix*

The basic layout-uses and processes:

* Chart in pocket.

In the column along the left side are placed the two broadest divisions of industrial mineral and rock material uses; that is, those materials whose ultimate use is primarily physical and those materials whose ultimate use is primarily chemical are grouped separately.

Under physical uses are first the broad use categories such as abrasives, aggregates, and fillers. The next subdivision is into the major processes which are used to make the end product, such as crushing, screening, or burning. The last grouping on the left side is the end product.

As an example of an end product which is important because of its physical characteristics we can take natural fine aggregate. Clearly the requirements are largely physical and it is in the broad category of aggregates. The major process is sizing or screening. If manufactured fine aggregate were the end product, the major processes would be crushing and sizing.

For chemical materials the broad categories are such things as raw materials for cement manufacture, chemical raw materials, and fluxes. The major processes may be thermal (for portland cement for example) or simply concentration as in the case of mineral concentrates for the production of chemicals. In the latter case, the final product might be something such as a "litium mineral concentrate." The concentrate may actually be several mineral materials; such as spodumene, lepidolite, or brine.

Many judgements have been made in such things as the processes selected, the groupings, and even the products. Some judgements were difficult and would have been made differently by someone else. For instance, what is the final product — how final? Is the final product a chemical raw material such as spodumene or is it lithia or lithium? I considered the final product to be a mineral concentrate.

Or is the final product a mineral abrasive powder or is it the concentrate? I chose the powder. But if that is true, is the final product of a thermally manufactured abrasive taken as SiO_2 and carbon or is it silicon carbide? And is this a chemical process? I chose the manufactured abrasive as the final product with a thermal processing. And then to deep the abrasives together I put this into the physical section with the other abrasives even though a chemical reaction is involved in the manufacture.

In every judgement, the overriding criterion was that the matrix be useful. Therefore, any poetic license which has been exercised has had the intent of maximizing potential value.

Basic layout, geologic materials:

The top of the matrix is devoted to a classification of earth materials which have potential value to industry. Again, some poetic license has been taken and some groupings are compromises between a more standard geologic classification and a classification of value to industry.

The first grouping is for igneous rocks. The categories are somewhat hybrid in that trap rock — which is not precisely defined geologically — is mixed in with more precisely defined rock types. The use of the term is dictated for maximum value.

The second category is for metamorphic materials. Most of the categories are regionally metamorphosed products. The talc materials, of course, are probably metasomatic. The gneissic granitic rocks are not included here but are considered to be with the granitic textured rocks. Again poetic license is taken because by use they group better with the granitic types.

Sedimentary materials have their own problems. For instance, how consolidated is consolidated? Some chalks, coquinas, marls, and guanos are certainly not very consolidated. Diatomite is included with the unconsolidated sedimentary materials. It might be asked: Why should this not be considered to be consolidated? Or if diatomite is unconsolidated, why should chalk not also be in the same category to be consistent? The judgement made was based on the fact that some diatomites actually are unconsolidated and diatomaceous material is mostly used in the unconsolidated state. Chalk, however, is more likely to be used in a consolidated state.

In the minerals section on the right top, hydrothermal and metasomatic are placed together because of the frequent gradational character of such deposits.

The industrial minerals are alphabetically listed and numbered at the right side of the matrix and the number of each mineral used is placed in the appropriate box by use and genetic environment. All minerals used are not necessarily listed. The major omission is that many potential gemstones are not on the list. It was felt that inclusion of all gems would make the list unwieldy.

The uses which are checked in the matrix for the various geologic materials have been taken primarily as the current uses. Some past uses have been eliminated and future potential uses are mostly not considered.

Concluding Statement

For any such categorization there should be a disclaimers. It is not possible to have all uses of industrial minerals on such a matrix, although most major uses are covered. Some minerals or rocks may be missing. For instance, coal has been left out; although it may be argued that coal may be used in the manufacture of silicon carbide and thus is, in that case, an industrial mineral. And some things such as fill and topsoil are included which are not normally considered to be industrial rocks. Yet at a time of potential growing shortages of virtually everything, common fill and topsoil become important locally critical industrial commodities. And they have certain limiting physical and chemical properties which make them valuable. Further, if we use economic criteria, these materials are sold locally for high royalty

payments in some areas of shortage. Anything which is expensive would seem to deserve a place among the more exotic materials.

In conclusion, at a time of looming shortages and increasing man-made stresses on our earth, the matching of materials available with need is even more critical. Perhaps a matrix of this type might be helpful.

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INDUSTRIAL ROCK- MINERIAL: PROCESS- USE MATRIX

ROCK MATERIAL

GENERAL USE CATEGORIES	CRITICAL MANUFACTURING PROCESSES	PRODUCTS

Rock material columns:

IGNEOUS — DEEP INTRUSIVE (GRANITIC, APLITIC TEXTURED ROCKS); EXTRUSIVE TO SHALLOW INTRUSIVE (TUFF, PUMICE, PERLITE, DIABASE TRAPROCK ANDESITE BASALT)

METAMORPHIC — GREENSTONE; STEATITE SOAPSTONE TALC ROCK; EMERY; MARBLE; SLATE; QUARTZITE

SEDIMENTARY — CONSOLIDATED — SANDSTONE (including GRAYWACKE); SHALE; DOLOMITE; LIMESTONE; ONYX TRAVERTINE; CHALK; COQUINA MARL; PHOSPHATE ROCK GUANO; BEDDED SILICA DEPOSITS

SEDIMENTARY — UNCONSOLIDATED — CLAY (MARINE LACUSTRINE); SAND & GRAVEL; TRIPOLI (ROTTENSTONE); DIATOMITE; OOLITE (PISOLITE); SHELLS; NATURAL WATERS (THERMAL, COLD)

MINERIAL MATERIAL CATEGORIES

IGNEOUS — PEGMATITE; GRANITIC (APLITIC); MAGMATIC DIFFERENTIATES
METAMORPHIC & METASOMATIC
HYDROTHERMAL & PNEUMATOLYTIC
SEDIMENTARY — CLASTIC; CHEMICAL (MISCELLANEOUS PRECIPITATES, EVAPORITES); MISCELLANEOUS
WEATHERING PRODUCTS

PRODUCTS DESIRABLE BECAUSE OF PHYSICAL CHARACTER

General use categories include: Abrasives; Absorbents; Art-objects; Bondants; Catalysts; Construction Materials; Dielectrics; Fillers and coatings; Filters; Glass raw materials; Hydrofracturing material; Insulating materials; Lubricants; Muds for drilling; Optical materials, natural; Pigments, mineral; Refractory-raw materials.

PRODUCTS DESIRABLE BECAUSE OF CHEMICAL CHARACTER

General use categories include: Cement materials; Chemical raw materials; Neutralizing, alkalizing agents; Fertilizers; Fluxing agents.

MINERIAL LIST

#	Mineral
1	Actinolite
2	Albertite
3	Alexandrite
4	Allophane
5	Alum
6	Alunite
7	Amber
8	Amblygonite
9	Amosite
10	Anatase
11	Andalusite
12	Anhydrite
13	Anthophyllite
14	Apatite
15	Aphrodite
16	Aragonite
17	Asbestos
18	Asphalt
19	Attapulgite
20	Beidellite
21	Barite
22	Bastnaesite
23	Bauxite
24	Bentonite
25	Biotite
26	Boehmite
28	Borax, borates
29	Brookite
30	Brucite
31	Calcite
32	Carnallite
33	Cat's eye gemstones
34	Celestite
35	Ceresine
36	Chalcocite
37	Chromite
38	Chrysotile
39	Clay
40	Cristobalite
41	Cryolite
42	Diamonds
43	Diaspore
44	Dickite
45	Dolomite
46	Dumortierite
47	Elaterite
48	Emerald
49	Endellite
50	Epsomite
51	Feldspar
52	Fluorite
53	Forsterite
54	Fuller's earth
55	Galena
56	Garnet
57	Gibbsite
59	Glauberite
60	Glauber's salt
61	Grahamite
62	Graphite
63	Gypsum
64	Halite
65	Halloysite
66	Hectorite
67	Hematite
68	Ilmenite
69	Imogonite
70	Jade
71	Kainite
72	Kaolinite
73	Kieserite
74	Kyanite
75	Langbeinite
76	Lazurite
77	Lepidolite
78	Magnesite
79	Marcasite
80	Meerschaum
81	Metahalloysite
82	Mica
83	Mirabilite
84	Molybdenite
85	Monazite
86	Montmorillonite
87	Mullite
88	Muscovite
89	Nepheline
90	Nitrates
91	Nontronite
92	Olivine
93	Onyx
94	Opal
95	Pearls
96	Periclase
97	Perovskite
98	Perlite
99	Petalite
100	Polyhalite
101	Pyrite
102	Pyroxene
103	Pyrophyllite
104	Pyrrhotite
105	Quartz
106	Rhinestone
107	Ruby
108	Rutile
109	Salt
110	Saponite
111	Sapphire
112	Selenite
113	Sepiolite
114	Sericite
115	Siderite
116	Sillimanite
117	Sodium carbonate
118	Sodium nitrate
119	Sodium sulfate
120	Sphalerite
121	Sphene
122	Spinel
123	Spodumene
124	Staurolite
125	Steatite
126	Strontianite
127	Sulfur
128	Sylvite
129	Talc
130	Titanite
131	Tobermorite
132	Topaz
133	Tourmaline
134	Tremolite
135	Tripoli
136	Trona
137	Vaughanite
138	Vermiculite
139	Witherite
140	Wollastonite
141	Wurtzite
142	Zircon

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