THE GEOLOGY OF THE PALEN MOUNTAINS GYPSUM DEPOSIT, RIVERSIDE COUNTY, CALIFORNIA

Thesis by

Richard A. Hoppin

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California
June, 1951

ACKNOWLEDGEMENTS

I wish to express my appreciation to Mr. Remington Stone, consulting mining engineer, who first brought the deposit to my attention and who acquainted me with the area and with some of its problems; to Mr. John Webb and Mr. Fleetwood Lawton, owners of the property, for their cooperation and their many kindnesses; to Mr. Arthur Kintano and Mr. Harmon Speaker for their companionship and their aid during the times that I was on the property; to Miss Ellen Powelson for drafting the index map; and finally to Professor Ian Campbell of the California Institute of Technology whose guidance and encouragement has been a great source of inspiration.

ABSTRACT

A large deposit of gypsum 5 square miles in area is located at the north end of the Palen Mountains. Interbedded gypsum, marble, quartzite, feldspathic quartzite, and lime silicate rocks, together with metamorphosed intrusives, are arranged in bands trending east-west. The rocks are intensely deformed and metamorphosed. Intense folding, faulting, brecciation, and shearing occurred as a result of strong deformation. These structures vary in magnitude from the large mappable units down to those microscopic in size. Along with the extreme deformation, the area has been subjected to regional, contact, and metasomatic and hydrothermal metamorphism in that order.

The gypsum occurs as massive beds of finely crystalline material of very high grade interbedded with marble or as thinly laminated gypsiferous epidotic schists. Little anhydrite is found at the surface and its presence at depth cannot be ascertained for no drilling has been done. Although the gypsum is of high quality, its value is lessened by the presence of large and small fragments of marble which are literally "floating" in the gypsum beds. These "Tectonic" impurities will increase the cost of mining.

The deposits have been variously dated as Precambrian and as Paleozoic. The lack of fossils and the small amount of geologic work done in the southeastern Mojave desert make dating and correlation difficult. The deposits are similar to those in the Little Maria and Maria Mountains to the east with an upper Paleozoic age designation probably the better alternative. The possibility should be considered that these gypsum, marble, schist, and quartzite beds are the deformed and metamorphosed equivalents of the gypsum, limestone, shale and sandstone of the Kaibab and Moenkopi (Permian and Triassic) formations in Southern Nevada.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

PAGE

FIGURES

INTRODUCTION

PURPOSE AND NATURE OF THE STUDY

The Palen Mountains gypsum deposit covers a small portion (five square miles in area) of the interior of one of the typical isolated mountain ranges of the Basin and Range province. The study of the area was undertaken with the view of bringing forth, in some detail, the internal structures of a part of one of these ranges. In addition, the gypsum deposit is rather unique in that it is associated with intensely deformed metamorphic rocks and is cut by one large, irregularly shaped igneous mass and by several small, sill-like igneous intrusions. The main features to be emphasized in this report are, the structure; the intensity of deformation, its effect on the gypsum and the various other rocks; the kinds of metamorphism and their relative ages; the effect of intrusion upon the gypsum; and, finally, a discussion of the geologic history with an attempt to correlate the deposits with other possibly contemporaneous sections in southeastern California and in Nevada and Arizona.

The latest topographic map available is the Palen Mountains quadrangle made by the United States Army Corps of Engineers during the war, scale, 1:48,000. This map was assembled from aerial photographs and though of excellent construction is nevertheless too small in scale for the purposes of mapping the geology of the gypsum deposit. To facilitate the geologic mapping, the gypsum area was photographed at a scale of 800 ft.

to the inch and a semicontrolled mosaic constructed at a scale of 400 feet to the inch by Pacific Air Industries of Long Beach, California. The contours were constructed by use of the stereoscope. Two United States Geological Survey benchmarks, check points obtained with a Paulin altimeter, and elevations of prominent peaks on the quadrangle map were used to provide vertical control. The contours give a fairly accurate picture of the topography, but are not quite accurate enough for detailed economic work. However, they are sufficient for the purpose of constructing topographic and geologic profiles.

A total of 35 days was spent mapping the deposit in the spring, fall, and winter months of 1950. The field work was supplemented by laboratory examination of 122 thin sections of significant rock samples.

PREVIOUS GEOLOGIC WORK IN THE REGION

Published geological work in the southeastern Mojave desert country, with the exception of the Eagle Mountains iron district, has been of only a reconnaissance nature. Little detailed work has been done and age determinations of the various Pre-Tertiary rocks have been only tentative. The one report on the gypsum deposits of the Palen Mountains is that of Harder (1909). His study, too, was only a reconnaissance and, although it is an excellent description of the deposit in general terms, it nevertheless does not cover the details of structure and metamorphism. Similar studies have been made on the gypsum deposits in the Maria Mountains to the east by Surr (1911). Brief descriptions of these deposits and also of those in the Little Maria Mountains can be found in Hess (1920), Tucker and Sampson (1929), and Jenkins, et. al. (1950). Much more detailed work has been done in the Eagle Mountains twenty five miles to the west by Harder (1912) and by Hadley (1945). The rocks in which the iron ore occurs are similar in a broad way to those in the Palen Mountains gypsum deposit. Very general reports in which the geology of the southeastern Mojave region is discussed can be found in Darton (1907), Brown (1923), Hazzard, et. al. (1937), and Miller (1945).

Almost all the rocks in this region older than Tertiary are metamorphosed. For this reason most geologists have been inclined to date them as Pre-Cambrian. Practically all admit, however, that their dating is rather tenuous owing to the almost complete lack of fossil discoveries.

GENERAL GEOGRAPHY

LOCATION

The Palen Mountains gypsum deposit is located in northern Riverside County, thirty miles northeast of Desert Center and about fifty miles northwest of Blythe. The deposit is readily accessible by a well maintained dirt road branching eastward from the Parker highway 17 miles north of Desert Center. The location of the deposit is shown on the index map (Fig. 1).

THE CLIMATE AND VEGETATION

The climate is hot and dry. In the summer daytime temperatures are often above 120°F and night temperatures seldom drop below 60°F. During the winter the climate is ideal, the temperature seldom going below freezing or above 80°F. Strong winds prevail for several days at a time during and after frontal passages, but the winds in this area are nowhere as severe or of as long duration as in the desert farther north. The rainfall is, of course, light and sporadic. Convective showers occur during the summer from July through September with less frequent frontal showers occurring spasmodically in the winter. The annual rainfall varies between one and five inches, rarely exceeding the latter figure. The rain, when it occurs, comes as very strong showers and creates great torrents in the washes. During these showers, owing to the lack of vegetation and of good soil, erosion is extremely rapid and great quantities of debris are moved in a very short time.

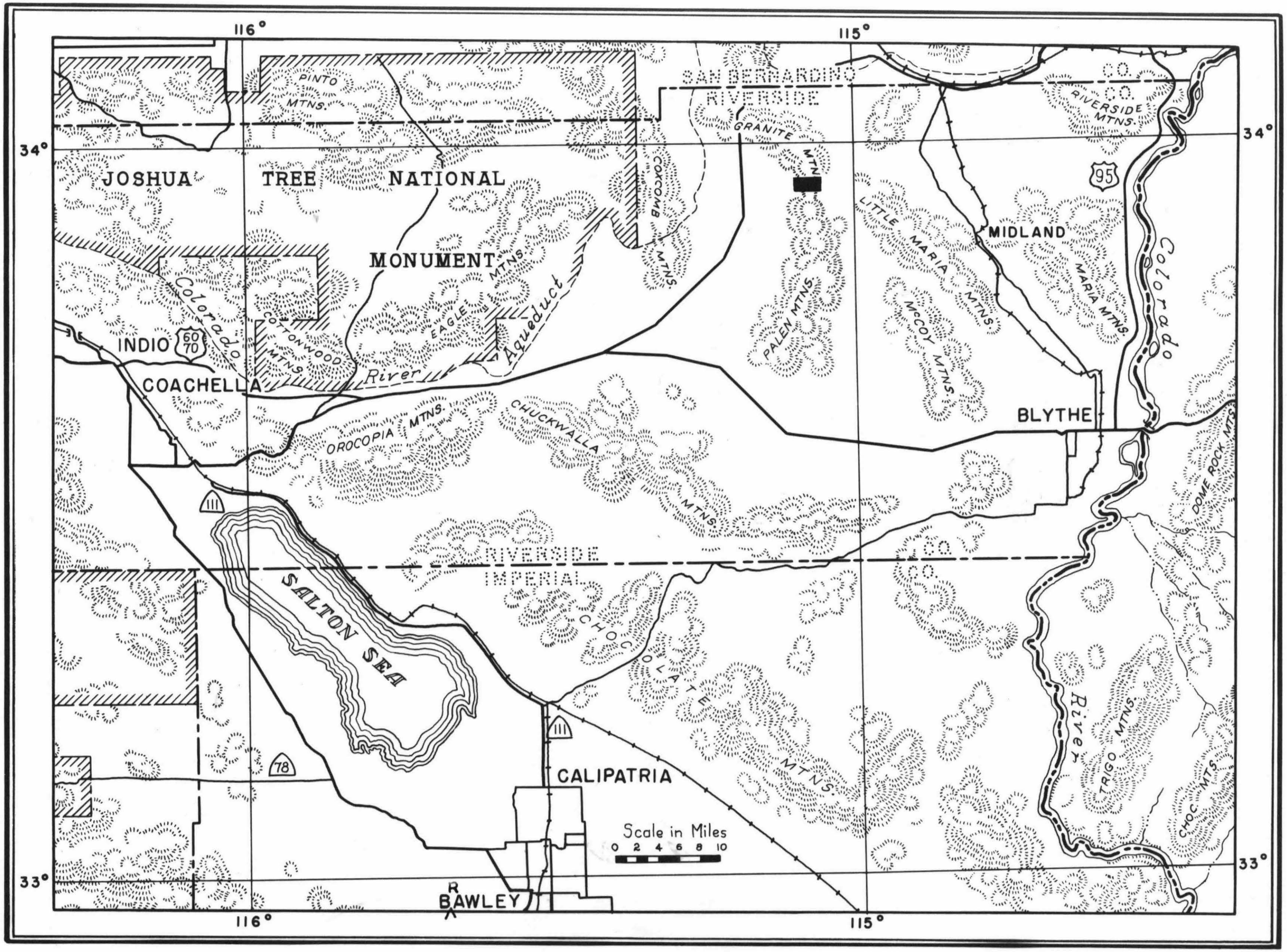


Figure 1. Index map of the southeastern Mojave desert, California. The dark, rectangular block marks the location of the gypsum deposits.

The area is devoid of trees except along the bordering outwash aprons, where locally there are small stunted growths of ironwood and paloverde. The rest of the area is covered by scattered clumps of creosote bush, ocotillo, cacti, and a few varieties of sagebrush. The dry washes also contain catsclaw, porcupine bush and other bushes, and, in favorable spots, a few trees.

TOPOGRAPHY

The Palen Mountains have a general north-south trend. They are about fifteen miles long and vary considerably in width. They rise precipitously from the surrounding broad, flat desert areas. Older accounts of the area include Granite Mountains to the north with the Palens. I shall follow the present usage limiting the Palens to the mountains south of the low pediment pass between the gypsum deposits and Granite Mountains.

The Palen Mountains have a maximum altitude of about 4000 feet; the Granite Mountains to the north rise to about 4500 feet. The gypsum area ranges in altitude from about 1250 feet to a maximum of 2000 feet.

The topography to the north and south of the deposits is extremely rugged and is very difficult of access. Within the gypsum area the relief is much more subdued except where recent gullying has opened deep, straight sided cuts as much as twenty or thirty feet in depth.

ROCK EXPOSURES

Characteristically, a considerable amount of bed rock is exposed in the desert mountains. However, mapping in some of the rocks is sometimes much more difficult than one would expect, because much of the bed rock area, rather than cropping out as clean, massive ledges, is merely a mass of rubble. For example, the marbles are massive, even on the surface, but the quartzites and the meta-igneous rocks are more commonly a disintegrated litter of broken blocks in which it is very difficult to map anything other than the general lithology and structure. Feldspathic zones, quartz veins, and dikes are very difficult to map and interpret because their contacts are concealed.

Considerable parts of the area are covered with gravel and talus to such a degree that fresh outcrops are difficult to find. Fortunately, recent gullying in these gravels has cut down to bedrock in some places, so that the structures can be mapped.

Slumping of the gypsum creates additional difficulties of interpretation, especially where capped by marble, or where intimately interlayered with schist.

At the west end of the deposit low outcrops of bedrock project through the gravel cover beyond the mountain front. The gravel cover appears to be rather thin for a distance of a quarter mile out on the outwash apron. This portion, therefore, apparently is a pediment rather than an alluvial fan. Similarly, the east end of Palen Pass has only a thin cover of gravel on a hummocky surface of bedrock.

GENERAL STATEMENT OF THE GEOLOGY

Although the Palen Mountains gypsum deposit is complex geologically, it is possible, nevertheless, to describe rather simply the broader geologic features. Therefore, it would be well to preface the detailed discussions of lithology, metamorphism, intrusion, and deformation with a general statement of the geology.

Interbedded gypsum and marble, quartzite, feldspathic quartzites, and lime silicate rocks together with metamorphosed intrusives are arranged roughly in bands trending east-west. Dips are predominantly to the north at moderate angles except where there may be reversals in the vicinity of minor warps.

The main deposits of gypsum are located in the southern part of the area and are completely isolated from the smaller, disconnected gypsum and marble masses in the northern section by metamorphosed igneous rock. This dark gray rock, probably once a quartz diorite, was intruded as a very irregular sill. The footwall, or south contact dips northward and is fairly regular, though modified by later faulting, but the hanging wall is extremely complex. In fact the whole north half of the area appears to be the cupola-roof pendant zone of the intrusive. The intrusive varies considerably in texture and appearance throughout its extent. Some portions of the intrusive are very small; many irregular masses one or two feet in diameter were punched into the meta-sediments and others were intruded as narrow, ramifying dikes or thin sills an inch or even less in width. The intrusive-metasedimentary relations become so complex in the northwest part of the area that a portion was mapped only as a meta-igneous and meta-sedimentary complex. Within the large meta-igneous masses themselves, small blocks of contact metamorphosed marbles and quartzite, and irregular patches of gypsum and gypsiferous schist are scattered.

Trending east-west across the center of the area is a series of sharp pointed peaks consisting mainly of dense, fine-grained lime-silicate rock and quartzite. The beds do not, however, strike east-west. Each peak is a rotated or offset fault block in which the beds strike northeast and dip 45° to 50° northwest. The contact between these rocks and the meta-igneous rock is very complex. Skarns are present in many places in the intruded beds in the contact zone.

The original sediments have been subjected to intense folding and faulting with the result that they are now considerably deformed. Finally, the whole area was subjected to metasomatic activity which was probably related to the intrusion of the granite to the north.

Miller (1944, p. 35) proposed the name, Maria, for this gypsum bearing meta-sedimentary formation.

The deposits are bordered on the south by a series of interbedded green conglomerates, phyllites, argillites, and grits which, for the present, are tentatively assigned to the McCoy Mountains formation (Miller, 1944, p. 32).

Because of the extreme complexity resulting from deformation and intrusion, it is very difficult to construct a stratigraphic column which can be carried across the whole area.

Therefore, several significant cross sections have been drawn, and from these a lithologic column has been constructed.

Plate 1 is a general view of the gypsum deposit. Plate 2 is a close up aerial photograph of the southern gypsum-bearing series.

GRAVELS

Approximately a quarter of the area is covered by talus or by a red, calcareous, stratified gravel varying from a few inches to over thirty feet in thickness. Recent gullying has in some places cut deeply enough to expose the gravel-bedrock contact. This contact is sharp and is essentially a horizontal surface with little relief (Fig. 5). One or two terraces are present along some of the washes.

In the middle and west portions of Palen Pass these gravels lie upon a series of white, calcareous, stratified gravels. These lower gravels are cut by northwest trending steep faults dipping either to the north or the south. The displacements along these faults are mainly of the normal type. These white gravels have an average dip of about 15° to the north, but in some of the fault blocks the dips are very steep or may be toward the south. The contact between the two gravel series is sharp. The elevation of the contact is not consistent from one spot to another and in several places the upper gravels are missing. A part of this difference in elevation is due to the very

Plate 1

Plate 1

Oblique aerial photograph looking northeast. The gypsum deposit is outlined in black. A portion of the Granite Mountains appears in the left center of the picture. The main part of the Palen Mountains extends south beyond the lower right margin. The mountains on the horizon are in Arizona. The deposit is about three miles long in the east-west direction.

Plate 2


Southeast boundary (fault)
Marble gypsum
Gypsiferous schist, quartzite, grit, and marble (highly epidotic)
McCoy Mountains (?) Formation
Gypsum
Highly deformed complex of laminated marble and siliceous marble and gypsum
Lime-silicate marble
Northeastern gypsum-bearing series
Porphyroblastic meta-igneous
Impure gypsum beds
Metaigneous

Plate 2

Oblique aerial photograph looking east-northeast along the southern gypsum-bearing series. A few of the main features of the geology are indicated in order that the picture may be tied into the geologic map.

recent faulting which has displaced the contact several inches or even several feet. Some of these recent breaks are renewals of earlier movements along faults in the lower gravels; others are new and show the same amount of displacement in both gravel series.

No attempt is made here to date these gravels except to suggest that the upper red gravels are probably Recent and that the lower gravels are Pleistocene or perhaps Tertiary in age.

THE STRATIGRAPHIC SUCCESSION IN THE MARIA FORMATION

The construction of a continuous stratigraphic column for the Maria formation is probably impossible. There are three distinct, isolated gypsiferous sections, none of which shows a similarity in succession when compared with either of the others. It is assumed, therefore, that these are all different units. It is doubtful that these represent all the original units of the formation, but it is difficult even to hazard a guess as to the thickness of the stratigraphic section that is missing because of intrusion and faulting. Furthermore, the thicknesses of the lithologic units vary considerably from place to place. The gypsum beds and to a lesser extent the marbles have been so contorted that the beds now visible probably bear little resemblance to the original series. The gypsum pinches and swells rapidly over short distances. A thick bed may pinch out completely within a distance of a few hundred feet. In a few spots, however, there are blocks in which the bedding and laminae of epidotic material are still visible. Marble lenses and individual large blocks and smaller fragments appear to be present everywhere in the gypsum. Although the gypsum is of high grade, difficulty will probably be encountered in mining because of the presence of these impurities.

Three geologic sections have been constructed. Section A-A' (Fig. 2) includes the south-central portion of the area, section B-B' (Fig. 3) crosses the northeastern gypsum-bearing series, and section C-C' (Fig. 4) intersects the northwestern gypsiferous group. The sections do not include all of the rock units present in the area owing to intrusion, faulting, and lateral changes in facies.

In the construction and interpre~~s~~tation of the cross sections the oldest beds are assumed to lie to the south. This requires that the section be right side up. Naturally, no sedimentary criteria remain that would be of aid to prove normal succession. Two lines of evidence support the assertion that the beds are not overturned. First, the attitudes of the drag folds are those that would be expected along the limbs of a normal anticline. Second, the roof zone of the meta-igneous sill-like intrusive is located in the northern part of the area. Contact metamorphic effects are much stronger here than in xenoliths farther south in the lower part of the mass.

Dip and strike determinations are often only approximate because bedding planes are highly distorted or obliterated. The attitudes shown are mainly those of lithologic boundaries. These boundaries, in turn, are usually very irregular, commonly

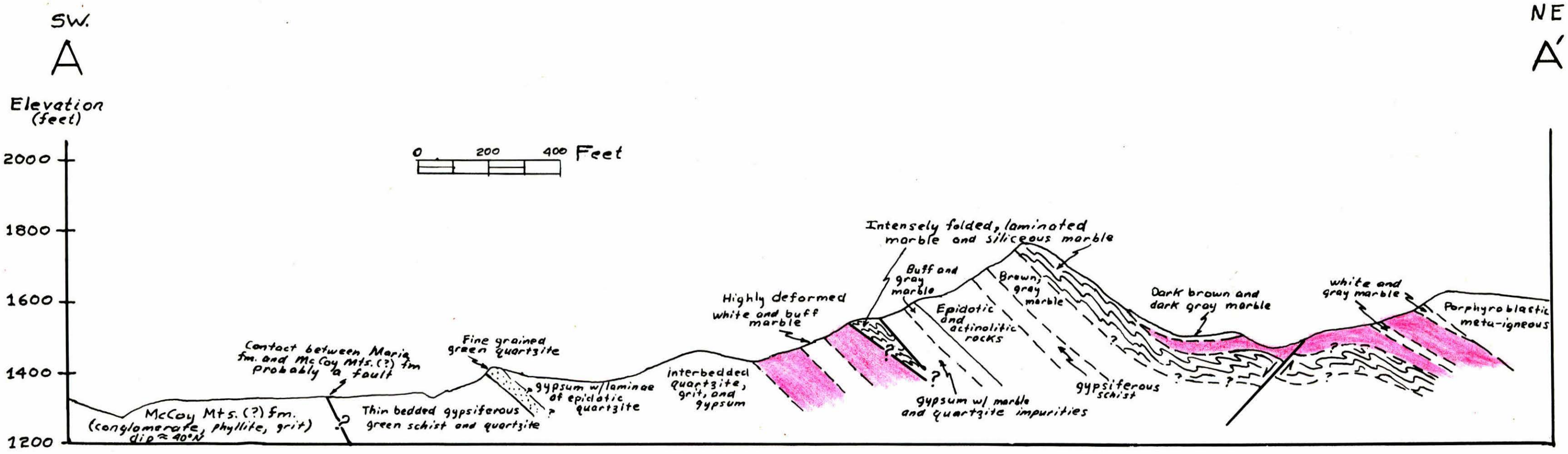


Fig. 2 Geologic section, A-A, across the southern gypsum bearing series. (Gypsum shown in red)

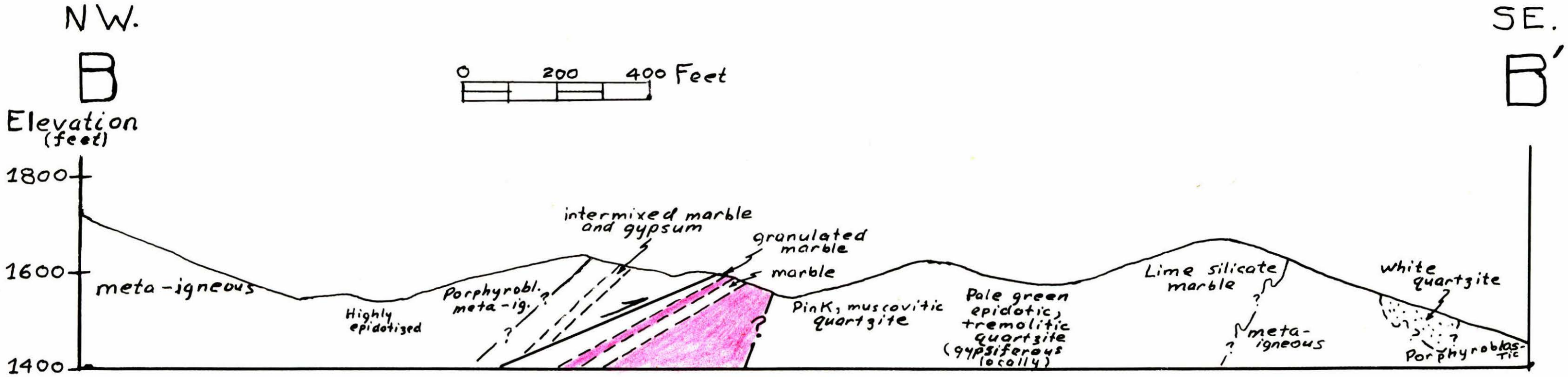


Fig. 3 Geologic section, B-B', across the northeastern gypsum-bearing series. (Gypsum shown in red)

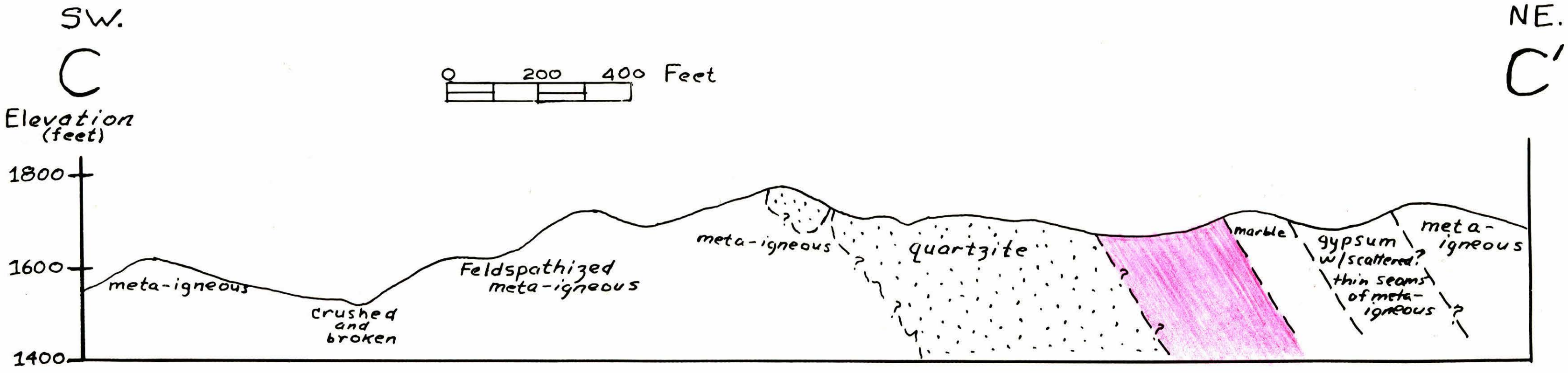


Fig. 4 Geologic section, C-C', across the northwestern gypsum-bearing series. (Gypsum shown in red)

blocky.

The cross sections, therefore, though giving a good picture of the structure, nevertheless must be viewed with the realization that the true detail can only barely be approximated. The general lithologies are indicated on the sections.

Table 1 shows the stratigraphic succession in the Maria formation as accurately as it could be determined in spite of the lack of continuity. It should be emphasized again that the thickness figures represent only relative orders of magnitude and that all the rocks show the ~~a~~effects of intense deformation. The youngest beds are placed at the top of the table. The major gypsum-bearing series are separated by faults or by intrusive rocks.

TABLE 1

STRATIGRAPHIC SUCCESSION IN THE MARIA FORMATION

	Description of unit	Thickness (feet)
	(gravel)	
	Pink, gray, white, and brown marble	100++
northwestern gypsum-bearing series	Gypsum; a few thin lamina of meta-igneous rock	25-200
	Marble; locally tremolitic; minor interbedded gypsum; extremely irregular in thickness	25-200
	Gypsum; contains irregular masses of marble	200-300
	Quartzite; white and pink, fine-grained, slightly feldspathic, variably micaceous	????
	(meta-igneous)	
	Marble xenoliths with small masses of tremolite-actinolite rock and iron ore. One large area contains about 300 feet of gypsiferous schist and a small amount of marble and fine-grained epidotic quartzite.	
	(meta-igneous, fault)	
northeastern gypsum-bearing series	Gypsum, marble, interbedded gypsum and marble; a small amount of quartzite as laminae in marble; probably three main beds of gypsum 25-100 feet thick, but these change abruptly in thickness laterally; this group is considerably faulted	400+
	(fault)	
	Quartzite; pink, fine-grained, hematitic, micaceous	200-300
	Quartzite; pale green, fine-grained, epidotic, tremolitic, feldspathic; locally gypsiferous	100-200
	Lime-silicate marble; very fine-grained, white, wollastonitic, slightly diopsidic	300

TABLE 1 (cont.)

--------------------(meta-igneous)--------------------

Quartzite, marble, and tremolitic marble in large and small masses completely surrounded by meta-igneous rock; small concentrations of iron ore. Total exposed thickness probably not more than 100 feet.

--------------------(meta-igneous)--------------------

Section at east end of area. Position with respect to the units above and below in this column not definitely known.	Tan marble	50
	Gypsum	25
	Marble; pink, brown, gray, and white; a few lenses of epidote-actinolite rock	50-100
	Gypsum	0-100

---------(thrust fault to west, reverse fault to south)---------

--------------------(meta-igneous)--------------------

southern gypsum-bearing series	Gypsiferous, green schist	0-200
	Marble; dark brown and dark gray; locally with interbedded quartzite; buff marble at base, white, gray, and buff marble at top	100
	Gypsum; large area exposed owing to stripping of overlying marble; pinches out locally	0-150
	Laminated marble and siliceous marble; intensely folded	100
	Brown and gray marble	100
	Quartzite; green, feldspathic; contains epidote, actinolite, and chlorite, gypsiferous locally in top 50 feet	200
	Gypsum; contains some marble and quartzite	50
	White and buff marble	75
	Gypsum; contains intermixed marble and quartzite	125

TABLE 1 (cont.)

Interbedded gypsum, quartzite, and quartz and feldspathic grit; marble at top	275
Gypsum with laminae of fine-grained and medium-fine-grained epidotic quartzite	250
Quartzite; green, very fine-grained, epidotic, with scattered grains of limonite	30
Thin-bedded, highly gypsiferous green schist and quartzite	500+
Total (3380+)-(4530+)	

------------------------(fault)------------------------------

(McCoy Mountains (?) formation)

STRUCTURE

GENERAL STATEMENT

The deformation of the rocks of the Maria formation has been profound. Folding, faulting, crushing, brecciation, shearing, and jointing are present ranging in scale from the large, mappable features down to those microscopic in size. Only the most significant structural features are included in the map. Most, if not all, of the lithologic boundaries mark loci of movement. Very few bedding planes and depositional contacts remain.

The most intense deformation occurred before the intrusion of the quartz-diorite. Therefore, the discussion will be divided into two parts, deformation prior to the emplacement of the quartz diorite and deformation later than the intrusion.

PRE-INTRUSION DEFORMATION

All of the folding, most of the internal deformation, and a good share of the faulting in the Maria Formation took place before the period of intrusion. These folds and faults are truncated by the metamorphosed quartz diorite (Fig. 6).

Folding has modified the northerly dipping east-west trend of the lithologic bands. The gypsum and marble area in the northwest corner of the deposit is a northwesterly plunging anticline further complicated by small cross warps and by elongate furrows. Similar small scale warping is present at the southeast end of the deposit. The reconstruction of these folds is based on the attitudes of lithologic contacts.

Deformation within the various rock types is so severe that bedding is now obscured. The marbles are intensely folded, broken, and sheared. Folds within a series of marbles have amplitudes ranging from twenty feet down to fractions of a foot. These folds are tight, often isoclinal and the axial planes vary in dip from vertical to almost horizontal. These planes dip to the north in general although in some places they too have been cross folded. This incompetent, plastic folding is strikingly revealed in the thinly laminated marble-siliceous marble series which makes up the north side of the

Fig. 5

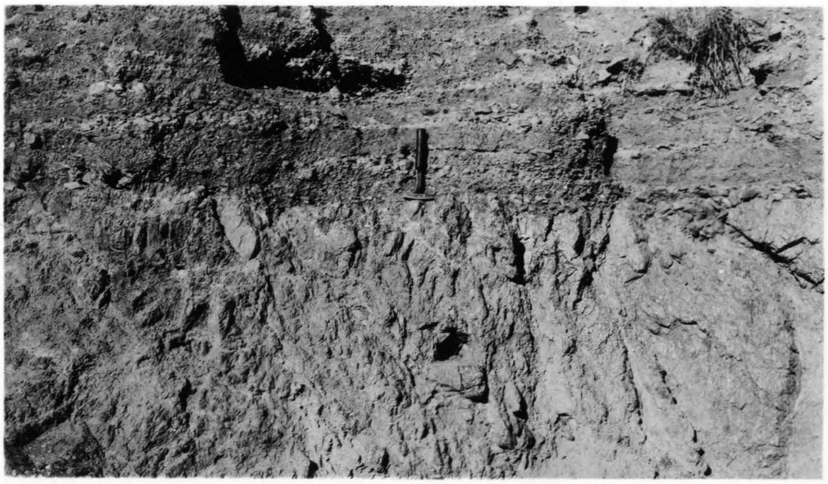


Fig. 6

Fig. 7

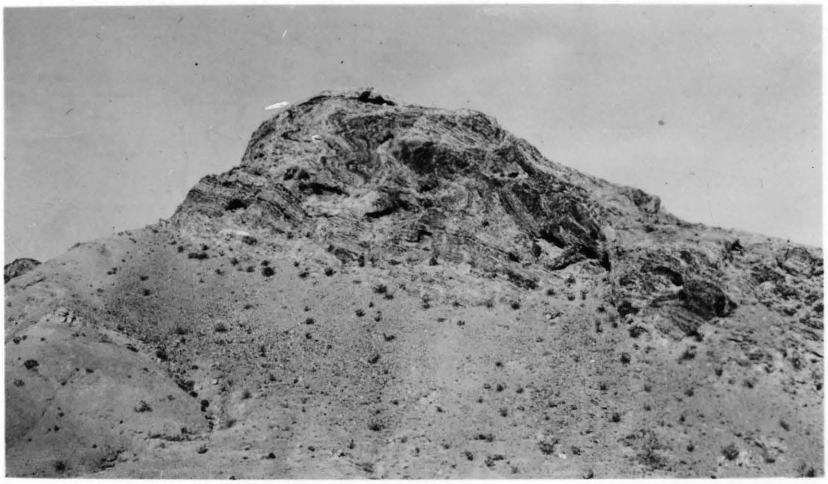


Figure 5. Stratified Recent gravels overlying sheared prophyroblastic meta-igneous rock.

Figure 6. Intrusive contact between porphyroblastic meta-igneous rock on the left and west dipping marble and gypsum beds. (Height from base of picture to top of hill is 50 feet).

Figure 7. Intensely folded beds of laminated marble and siliceous marble lying on gypsum. (Height from base of picture to top of hill is about 100 feet).

high east-west ridge in the southeast part of the deposit. Fig. 7 shows highly contorted beds of this series lying on gypsum in the western part of the area.

Probably closely associated in time with the folding and internal deformation was considerable faulting along bedding planes along with higher angle thrusting. The bedding plane movements and thrusting are marked by zones of brecciation (Fig. 8) and drag folding. The contorted marble-siliceous marble series may thus represent drag due to faulting rather than simple drag folding of an incompetent bed due to minor adjustments and slipping of competent strata during folding. Small scale incompetent folding in a thin layer of fine-grained actinolite between layers of granular epidote and quartzite is illustrated in Fig. 9.

Two thrusts can be definitely mapped. The first is indicated at the southeast border of the area. This fault strikes N. 22° W and dips 30° to the west. The sole of the thrust is marked by a tectonic breccia containing broken blocks of marble up to three feet in diameter. The rocks to the east of the thrust consist only of marble and gypsum in contrast to the much more varied section to the west. The thrust is terminated at its north end by the intrusive and at the south end by a steep reverse fault. The direction of movement of the upper plate was probably north to south as indicated by the east-west, northerly dipping imbricate faults. North-south compression is further suggested by steep, north-south tear faults and by steep NE- SW and NW - SE strike-slip faults.

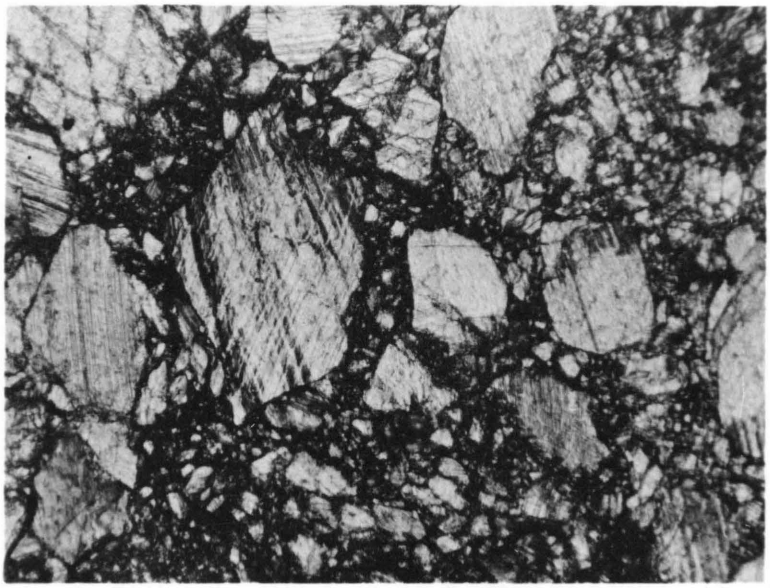


Figure 8.

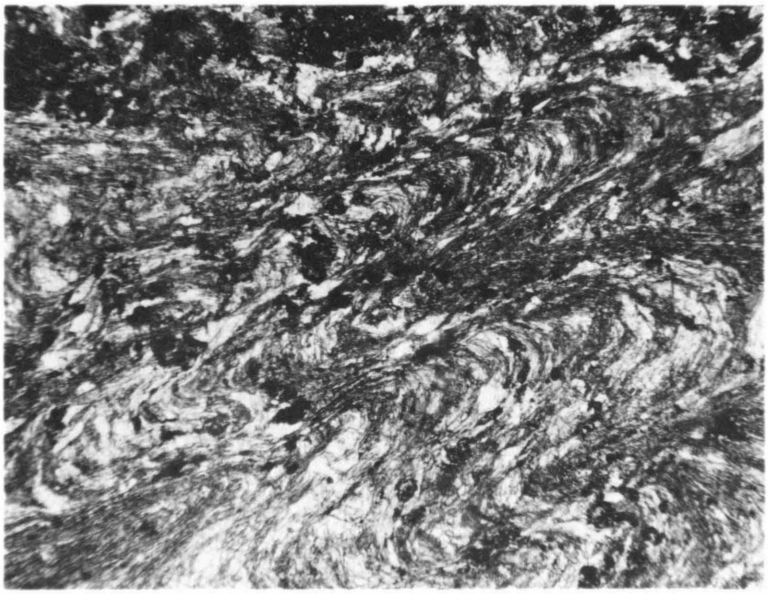


Figure 9.

TWO TYPES OF DEFORMATION IN ROCKS OF THE MARIA FORMATION

Figure 8. Cataclastic deformation in marble. Broken calcite fragments of all sizes down to the dark, extremely fine-grained, crushed matrix, Plane polarized light. X40.

Figure 9. Flowage folds in a band of fine-grained actinolite and minor quartz, chlorite, and green biotite. The needles flow around the bends of the folds. The top part of the photograph is granular epidote and quartz. x-nicols. X40.

The irregular northerly trending trace, therefore, is not the frontal margin of the thrust plate but rather is the eroded east end of the overthrust. The westerly dip probably is part of an undulation on a thrust surface dipping to the north. It could not be determined whether the undulation developed during thrusting or represents later warping of the thrust surface. The frontal margin of the thrust is cut out by the steep fault to the southeast.

Another thrust is indicated on section B-B' in the northeast section of the area. The base of the thrust is marked by a zone of coarse, granulated marble (Fig. 8). The thrust dips approximately 30° to the north. Just to the southwest of the crossection an imbricate fault in the upper plate dips 50° to the north.

Unfortunately these thrusts are traceable only over a very short distance because they are truncated by the later intrusive rock. As nearly as can be ascertained, these thrust traces have not been offset, suggesting that thrusting culminated this period of the deformation.

In summary, the pre-intrusion period of deformation was marked by intense folding and faulting along with contemporaneou~~t~~s extreme internal folding, crushing, shearing and brecciation. The period was ended by thrusting.

POST-INTRUSION DEFORMATION

Faulting apparently has taken place repeatedly since intrusion of the quartz diorite. Folding does not seem to have recurred since the early period of deformation.

The south contact of the intrusive has been considerably modified by faulting. The contact dips north at angles of 45° to nearly 90°. The porphyroblastic rock is intensely sheared and broken all along its south boundary to distances of 20 feet to as much as five hundred feet away from the contact. Along the western end of this contact the porphyroblastic rock is strongly stained by red iron oxide in zones of intense crushing up to 12 feet wide. This contact is displaced by cross faults in at least three places with the displacements along the fault traces amounting to 100-200 feet.

The northeast section of the area is extensively faulted. East-west faults are cut by several north and northwesterly striking cross faults. The strike slip displacement of the meta-igneous contact along the NW - SE fault is 500 feet. At the NW end of the same fault, the fault surface is exposed. The surface dips 45° to the north. Ill formed, horizontal grooves are still visible on the gypsum hanging wall. These indicate that the resultant relative movement was almost wholly strike-slip in nature.

The fault at the southeast border of the area separating the Maria formation and the McCoy Mountains (?) formation dips steeply to the northwest. The marble along the fault is intensely brecciated. In several places the marbles appear to be dragged down near the fault zone indicating a reverse component of movement. This fault is offset short distances at several places.

The extensions of known faults into the meta-igneous rock are difficult to follow. Further, although there are no doubt many faults within the meta-igneous series as indicated by the many shear zones and by the sudden changes in attitude of foliation suggesting rotation of blocks, it is not feasible to attempt to trace these.

The nature of the forces causing this period of deformation is less readily understood but it appears that they were vertically, rather than horizontally, directed forces. It is suggested that a good share of the deformation, therefore, may be the result of upward and outward directed components of forces due to the emplacement of igneous magma below and mainly to the north of the gypsum deposits.

Displacements in the Recent gravels in Palen Pass indicate that some of the faulting is very recent.

DISCUSSION

The entire western half of the southern gypsum belt was mapped as a highly deformed complex of gypsum, marble, laminated marble, and siliceous marble, and gypsiferous schists. This area is so highly deformed that trends can no longer be traced without extremely detailed work and even then a coherent picture may not be attained. The northward dip is still visible, however.

Many of the fractures are marked by quartz veins. Jasper breccias in several places give evidence that movement has occurred more than once in these zones.

Deformation locally produced well developed shear foliation in the marbles. Granulation of marble in several spots has already been mentioned. Crush breccias, flaser structure, and mylonites are also present. These structures were formed during all the periods of deformation.

Obviously the unraveling of the nature and the history of the deformation was only begun. It is believed, however, that the relative age of the different periods of deformation have been established. In a later section, an attempt will be made to fit these into the other events affecting the area with the hope of establishing a logical historical sequence.

PETROLOGY

MARIA FORMATION

General Statement

The textures and mineralogical compositions of the rock types comprising the Maria formation represent the ~~a~~effects of several periods and types of metamorphism on the original sedimentary series. Five kinds of metamorphism are distinguished: 1) Regional, 2) Contact, 3) Metasomatic, 4) Hydrothermal, and 5) Dynamic.

Regional metamorphism was the earliest and most widespread and took place during the pre-intrusion period of deformation. The regionally metamorphosed rocks were later locally contact metamorphosed during intrusion. A second, less intense regional metamorphism may have occurred after intrusion. Later metasomatic and hydrothermal activity further modified the rocks. Dynamic metamorphism, represented by local cataclastic structures and textures, recurred throughout the entire interval since the onset of the first period of deformation.

Although the mineralogy is not very complex, some minerals or mineral groups were formed during two or perhaps three of the different metamorphic epochs. Therefore in some of the rocks it is difficult to determine both the relative importance of the various metamorphic types and the paragenesis of the minerals making up these rocks as they now exist. The rock types of the Maria formation can be divided into five groups: 1) Gypsum and gypsiferous schists and quartzites, 2) Marble, 3) Quartzite, 4) Lime-silicate marble, and 5) Grits.

Gypsum

The gypsum occurs in massive beds of white, finely crystalline rock of very high grade interbedded with marble or in thinly laminated gypsiferous epidotic schists and quartzites. The average size of the gypsum grains is 0.2 mm. and their shapes are anhedral. Scattered grains of calcite and epidote are present in almost all samples (Fig. 10). Little anhydrite has been found and its presence at depth cannot be ascertained for no drilling has been done.

Marble occurs in the gypsum in masses of all sizes ranging from small fragments an inch or two in diameter up to large isolated blocks and lenses several tens of feet in thick-

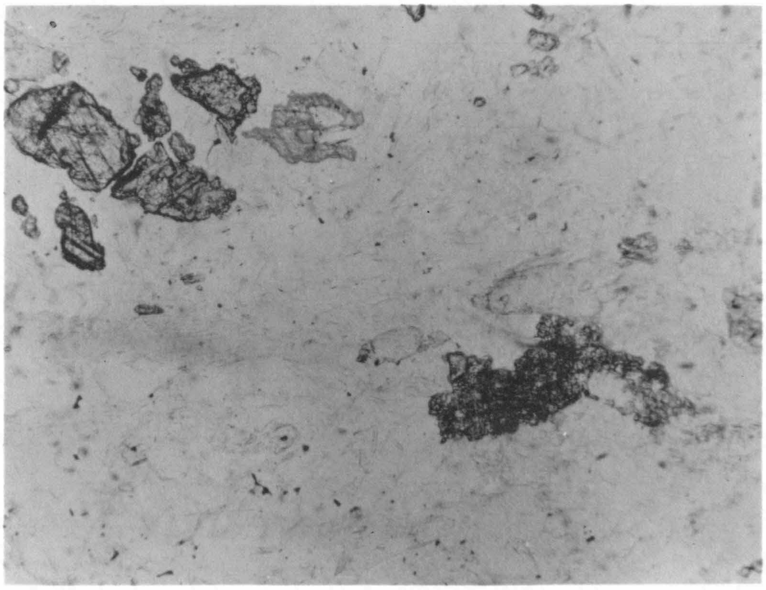


Figure 10.

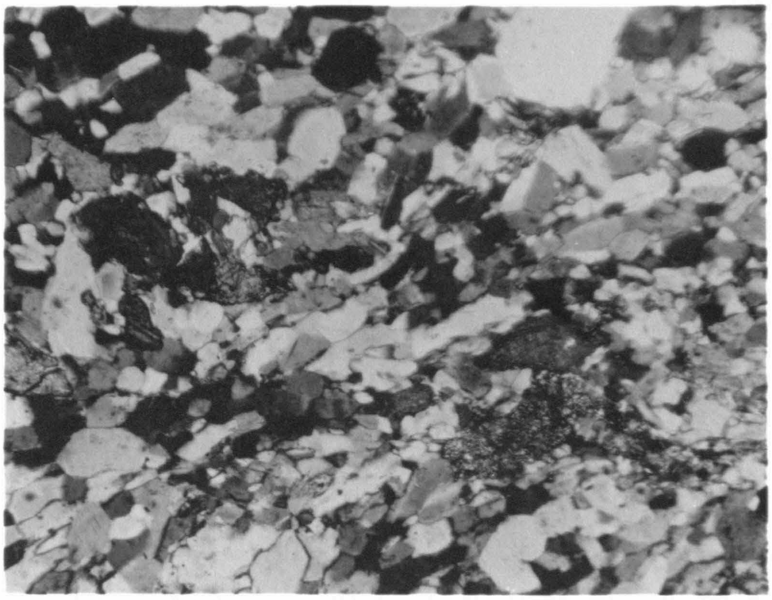


Figure 11.

MARIA FORMATION

Figure 10. Fine-grained gypsum. Calcite grains in upper left and an aggregate of granular epidote in lower right. Plane polarized light. X40.

Figure 11. Same field with x-nicols.

ness. Undoubtedly the original sedimentary series contained zones in which limestone and gypsum (or anhydrite) interfingered or had beds of gypsum (or anhydrite) enclosing thin beds or lenses of limestone. Several areas on the map suggest such possibilities. However, deformation has been so intense that much of the wedging out or pinching and swelling of the gypsum beds is of tectonic origin. Furthermore, the large marble blocks not only are chaotically distributed throughout the gypsum beds, but also are randomly oriented as indicated by the sharp difference in attitude of bedding from block to block. Many of the small fragments of marble are intensely sheared; coarse calcite grains are elongated and quartz grains are stretched and fractured and show wavy extinction. These blocks and fragments of marble (and minor quartzite) are called "tectonic" impurities.

Schist and quartzite laminae are present to a varying degree in the gypsum from occasional thin streaks to closely spaced layers separated by a thin bed of gypsum an inch or two thick. These laminae are green in color and consist of fine-grained epidote, green biotite, chlorite, and a variable amount of quartz. Few good outcrops of gypsiferous schist and quartzite were found. The beds slump easily. The gypsum is washed away leaving a slope covered by a lag gravel of flat, green fragments.

Origin of the Gypsum

The bedded deposits of the Palen Mountains were formed through sedimentary processes of deposition. Whether the calcium sulphate was deposited as gypsum or as anhydrite is a difficult problem to solve. Almost all geologists agree that the large bedded deposits of calcium sulphate were formed by precipation during evaporation from sea water. One of the most perplexing problems is the question of which sulphate was deposited originally, gypsum or anhydrite.

Posnjak (1938, 1940) restudied the relations between anhydrite and gypsum and showed that Van't Hoff and his associates were somewhat in error. He determined that saturated solutions of NaCl are not necessary in order that anhydrite form. Above 42°C only anhydrite can form even in the absence of any other salt and in very dilute solutions. Posnjak writes as follows (1940, p. 559):

> "At 30°C the solubility of gypsum and anhydrite first increases rapidly in the presence of increasing amounts of sea salts, goes through a maximum of about twice the usual salinity of sea water, and then gradually decreases. However, the decrease is more rapid for anhydrite and an intersection of the two curves takes place at about 4.8 times the usual salinity, the point at which anhydrite becomes the stable phase.
>
> Sea water is unsaturated with respect to $CaSO_4$ and only after its salt content has increased by evaporation to 3.35 times the usual salinity can deposition take place. Between this concentration and the one required for stable deposition of anhydrite nearly one half the total $CaSO_4$ in sea water will be deposited at 30°C as gypsum. Since at a somewhat lower temperature at which evaporation of a marine basin may be assumed to have taken place the conditions in all probability will not be greatly modified, a large proportion of $CaSO_4$ may always be expected to be deposited as gypsum. Sedimentary marine deposits of pure anhydrite must therefore either be at least partly derived from originally deposited gypsum or have been formed close to or above 42°C, the transition point of the two minerals."

These results indicate that the first-formed product will always be gypsum because most evaporites probably were deposited at temperatures below 42°C. Only when the volume of the sea water is reduced to about one fifth the initial volume is direct precipitation of anhydrite possible.

Gypsum is currently being deposited in the Gulf of Karabugas on the eastern side of the Caspian Sea and in the Great Bitter lake of Suez.

Because most gypsum deposits grade into anhydrite at depth, the tendency of most geologists is to regard the anhydrite as the original material to be precipitated. Anhydrite is found at depth in the Maria formation in the Little Maria Mountains just east of the Palen Mountains. It is probable that drilling in the Palen deposits will also reach anhydrite.

At this point we seem to have arrived at a somewhat paradoxical situation: The research of Posnjak and the occurrence of current deposition of gypsum are convincing arguments for primary deposition of gypsum; on the other hand, the gradation of gypsum to anhydrite at depth suggests that the original material was anhydrite. In order to reconcile these views it is necessary to show that anhydrite can be derived initially from gypsum. The anhydrite is then reconverted to gypsum by ordinary weathering.

The United States Bureau of Mines (Farnsworth, 1924) conducted some experiments on the stability relations of gypsum and anhydrite. It was found that anhydrite placed in pyrex glass bombs with water was unchanged under a temperature of 210°C and a pressure of 19 atmospheres. Gypsum similarly treated changed over to anhydrite at a temperature of about 160°C. It was concluded that anhydrite is the stable form of $CaSO_4$ under conditions of high temperature accompanied by pressure.

Posnjak (1938, pp. 257-258) was able to form a small amount of anhydrite by prolonged heating of gypsum at less than 200°C. The rate of formation of anhydrite gradually increased with increasing temperature. He made no reference to the possible ~~a~~effect of pressure.

Bowles and Farnsworth (1925, p. 742) pointed out that the combined volume of anhydrite and water is more than the volume of the gypsum; therefore, unless the water is immediately removed from the system, gypsum subjected to uniform pressure will remain gypsum. However, they indicate that under conditions of high temperature and pressure, temperature is the controlling factor as it overcomes entirely the retarding ~~a~~effect of pressure.

Extrapolating from a surface temperature of 20°C using an average geothermal gradient of 1°C per 30 meters, a gypsum bed would have to be at a depth of 5400 meters in order to reach a temperature of 200°C. The effective temperature in the transformation of gypsum to anhydrite will probably be ~~a~~slightly lower as the time factor increases. Much more experimental work on this problem is needed, especially with respect to the ~~a~~effect of stress.

Unfortunately, geologic evidence supporting the conversion of gypsum to anhydrite is lacking. With regard to the Palen

Mountains deposit, the extreme deformation and absence of drilling data make it difficult to answer the problem. The sample of gypsum pictured in Figure 11 shows a fair preferred orientation. The significance of orientation in gypsum must be viewed with caution. Fairbairn (1949, p. 291) advanced the possibility of reorientation of gypsum grains owing to grinding in preparation of the thin section. In each of three diagrams prepared from mutually perpendicular sections of a foliated gypsum rock he found an identical orientation. Megascopic examination of the gypsum beds in the Palen deposit reveals that deformation fabrics do exist. It is improbable that a tectonite fabric in anhydrite would be maintained in gypsum forming by hydration because of the large increase in volume. This means that the gypsum itself must have been deformed, Furthermore, it seems more likely that blocks and fragments of marble now occurring as isolated masses could be jostled about more easily in gypsum than in the more competent anhydrite.

Taking into account the compelling evidence for the initial deposition of $CaSO_4$ as gypsum and the strong probability that anhydrite occurs at depth, the following history of the gypsum is suggested:

(In order of decreasing age)

1. Deposition of gypsum
2. Deep burial allowing anhydrite to form under conditions of high temperature. (The period of pre-intrusion regional metamorphism and deformation).
3. Erosion prior to the deposition of the McCoy Mountains(?) formation. As the anhydrite was now in the zone of weathering, some gypsum again formed.

4. Burial followed by igneous intrusion. It is difficult to determine whether this burial was deep enough to allow a second conversion of anhydrite to gypsum. The low degree of regional metamorphism of the McCoy beds suggests that the conversion may not have taken place. Furthermore, the strong deformation now visible in the gypsum probably dates from the beginning of the post-intrusion period of deformation rather than being limited to only the very recent faulting. There was probably some local dehydration next to intrusive contacts.

5. Present period of erosion. Any anhydrite near the intrusive has been rehydrated.

This hypothesis requires that most of the gypsum of this deposit, though secondary, is older than the intrusive rock, or pre-Nevadan, as indicated by Table 5.

In conclusion, the work of King (1947, pp. 470-477) should be mentioned. He studied the Castile formation in West Texas and New Mexico. The formation consists principally of laminated anhydrite with some small lenses of calcite and some halite. The anhydrite averages 1,250 feet in thickness. Halite locally reaches a maximum thickness of 900 feet. He convincingly shows that the anhydrite is primary. The presence of halite indicates that the high salinity required for the precipitation of anhydrite must have been reached. Also, the laminae are undisturbed. There is no doubt, therefore, that here is a good example of initial anhydrite deposition. This thick, almost continuous section of anhydrite with some halite contrasts greatly with the interbedded marble and gypsum of the Maria formation. It does not seem likely that water from which $CaCO_3$ and $CaSO_4$ were being alternately precipitated would reach the necessary concentration for deposition of anhydrite. Furthermore, the Palen deposits contain no halite, nor are there any chloride minerals present that could have been derived from halite through metamorphism.

Marble

The marbles are predominantly white or buff colored, finely crystalline rocks. A smaller proportion are pink, dark brown, or gray. There are no dolomitic phases. The calcite grains are anhedral in shape and generally have an interlocking texture. The grain size averages 0.5 mm. in diameter. Minor impurities are quartz and tremolite.

In the northeastern gypsum-bearing area thermal metamorphism was superimposed upon the already regionally metamorphosed rocks. Marble containing magnesium was changed to periclase marble. By hydration of the periclase, the rocks were changed to brucite marble, or predazzite (Fig. 12). Marble with potash, silica, magnesia, and alumina was recrystallized to granular calcite and minor white mica. This white mica is being replaced by a white chlorite (Fig. 13) which is probably the iron-free variety, leuchtenbergite. In those marbles containing a white mica with some iron, the replacing chlorite is green.

Quartzite

Quartzite occurs as thick beds, as thin laminae several inches thick interlayered with marble, and as narrow partings in gypsiferous beds. They are pink, white, and green in color and are fine-grained, the average grain size ranging from 0.1 mm. to 0.5 mm. in diameter. There are many mineralogical varieties. Epidote-tremolite feldspathic quartzite (Fig. 14) is

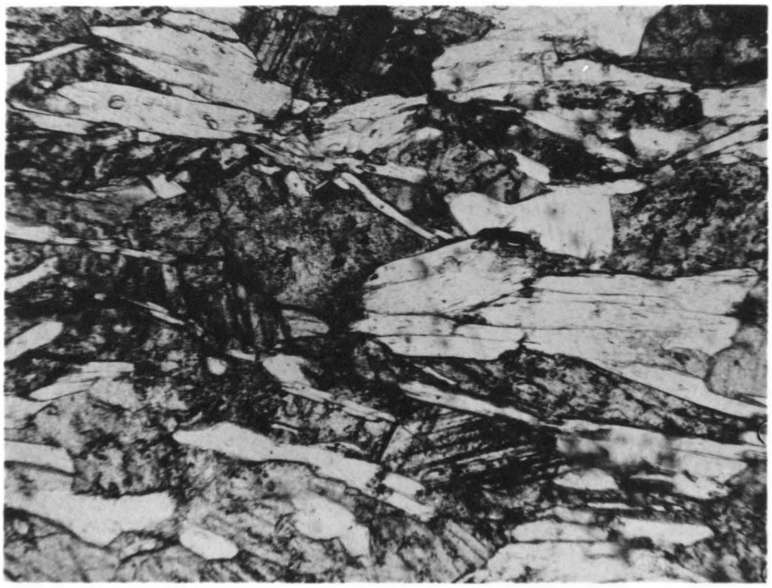


Figure 12.

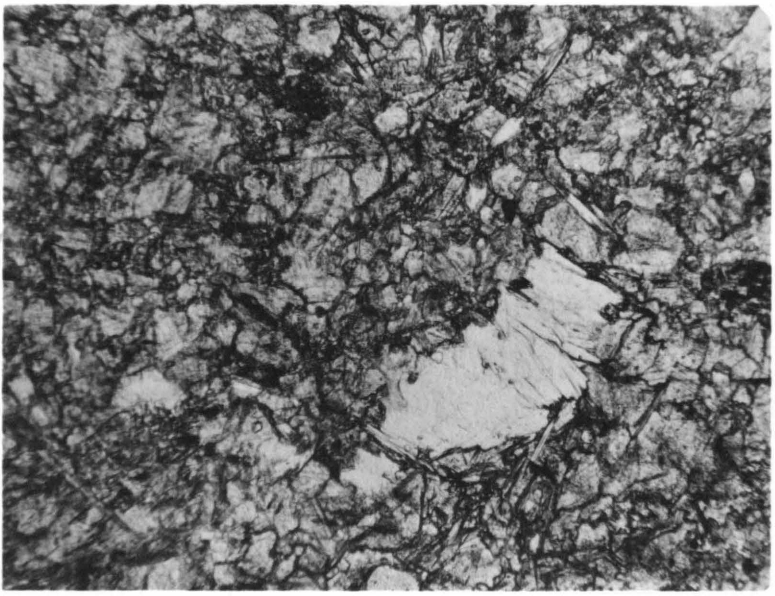


Figure 13.

MARIA FORMATION

Figure 12. Predazzite. White blades are brucite; gray, twinned grains are calcite. Plane polarized light. X40.

Figure 13. Fine-grained, granular marble. The aggregate of white blades and the scattered small blades are a white chlorite (leuchtenbergite?). One or two of the blades ~~is~~ are white mica. In other parts of the slide not pictured here, the chlorite is replacing the mica. Plane polarized light. X40.

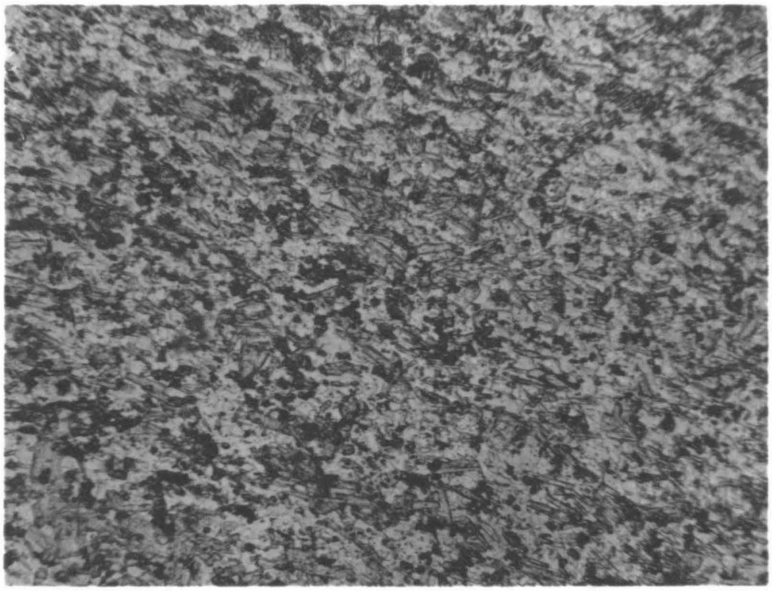


Figure 14.

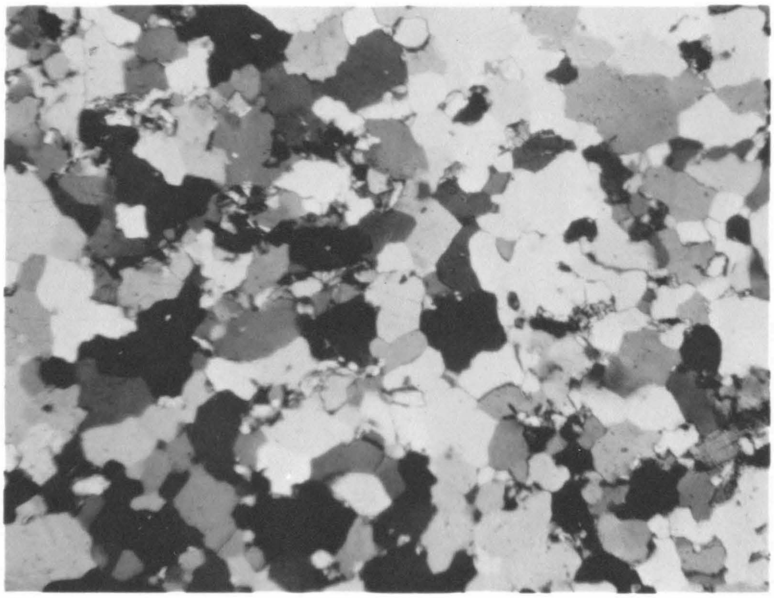


Figure 15.

MARIA FORMATION

Figure 14. Green, fine-grained epidote-tremolite feldspathic quartzite. Tremolite (gray blades) shows good preferred orientation. Dark granules are epidote. White matrix consists of granular quartz and feldspar (albite or orthoclase). Plane polarized light. X40.

Figure 15. Pink quartzite with white mica. Contains scattered euhedra of hematite which give the rock its characteristic pink color. x-nicols. X40.

but one example of the types found. Figure 15 is a microphotograph of a relatively pure quartz variety containing white mica and scattered euhedra of hematite. These samples are from the two distinctive quartzite beds lying stratigraphically above the lime-silicate marble series (section B-B', Fig. 3).

The quartzites generally show a planar structure which is due to the parallel orientation of mica plates and tremolite-actinolite blades or fibers. The thick beds are cut by closely spaced joints which divide the rock into rectangular blocks whose greatest dimensions are seldom more than three inches long.

In contrast to the blocky quartzite is the incompetently folded, laminated marble and siliceous marble series in the southern gypsum-bearing belt. The laminae are only an inch or two thick and consist of marble, tremolite marble, quartzose marble, and calcareous quartzite.

Lime-Silicate Marble

These dense, fine-grained, white rocks (Fig. 16) form the series of sharp peaks extending east-west across the middle of the area. The rocks lie directly above the meta-igneous rocks. They are strongly thermally metamorphosed. Their texture is granoblastic; the grains average 0.1 mm. in diameter. They consist mainly of calcite with smaller amounts of wollastonite and diopside. A minor amount of clear, granular alkali-feldspar is present. Locally, scattered aggregates, 1-2 mm. in diameter, of pale yellowish green epidote are developed.

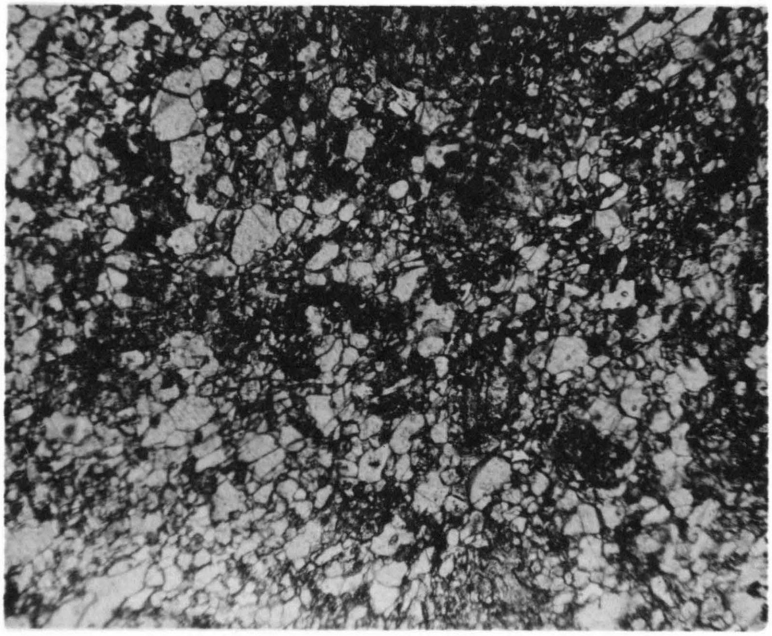


Figure 16.

Figure 17.

MARIA FORMATION

Figure 16. Lime-silicate marble. Very fine-granular calcite (gray), with granular wollastonite (dark) and minor diopside. Plane polarized light. X40.

Figure 17. Actinolite-feldspathic grit. Microcline, albite, and quartz in an extremely fine-grained matrix of these same minerals. The actinolite and minor green biotite, epidote, and sphene are interstitial to the larger, subrounded grains. x-nicols. X40.

Grit

This term is used to distinguish a group of rocks which are characterized by a marked hiatus in grain size. Grains of feldspar and quartz 0.2-0.3 mm. in diameter are surrounded by an extremely fine-grained matrix of actinolite, biotite, sericite, epidote, sphene, feldspar, and quartz (Fig. 17). The larger, subrounded feldspar and quartz grains are etched to a slight extent by the matrix minerals. There are all gradations between typical grit and equigranular quartzite.

Minor rock types

No large beds of paraschist are present in the Maria formation. The main occurrence of schist is as thin laminae in gypsiferous sections.

Within the marble are scattered, irregular lenses of tremolite-actinolite amphibolite. It is not known whether these are sedimentary or igneous in origin.

The unusual contact metamorphic types are discussed in the section on contact metamorphism.

Environment of Sedimentation

The original sedimentary section consisted mainly of limestone, gypsum, gypsiferous shale and sandstone, sandstone, feldspathic sandstone, and argillaceous, feldspathic sandstone (grit). Some of the limestone was dolomitic; however, dolomite does not seem to have been an abundant mineral in this area. The laminated marble and siliceous marble probably is the metamorphosed equivalent of a slightly dolomitic thinly layered limestone and chert sequence.

Such a group of sediments was probably deposited in a broad, shallow basin on a continental platform. At times the basin was partially or even wholly isolated. During these periods gypsum was deposited. The climate must have been arid or semi-arid in order that sufficient evaporation of the water could take place to allow the precipitation of calcium sulphate. From time to time the basin was replenished by fresh supplies of sea water; the salt concentration of the basin water was lowered enough such that limestone was deposited instead of gypsum. The presence of some detrital material indicates that there were periods when the normally dry streams entering the basin were filled with sediment-bearing water.

The sediments deposited in such an environment belong to the Foreland, or Platform, facies (Pettijohn, 1949, pp. 451-460) consisting of the aerobic and saline subfacies.

Many geologists have attempted to define a process by which thick deposits of $CaSO_4$ were formed, in spite of the fact that the salt comprises only 3.6% of the total salts in the sea. The numerous theories, many very ingeneous, will not be reviewed here. For an excellent summary the reader is referred to Pettijohn (1949, pp. 354-362).

Intensity of Metamorphism

An evaluation of the metamorphic rocks in terms of the facies concept is difficult because the area has been subjected to several periods and kinds of metamorphism. Furthermore, the area was not uniformly influenced. For example, the southern gypsum belt was little if at all affected by the intrusion of the igneous rock. The mineralogical and physical character of these rocks reflect the period (or possibly periods) of regional metamorphism with some modification by late hydrothermal activity. On the other hand, the rocks in the hanging wall zone of the intrusion were completely reconstituted by thermal metamorphism.

Only a few broad generalizations can be stated because the main goal of the work to this date has been to construct, for a highly complex area geologically, a fundamental framework which will serve as a basis for a detailed and logical petrographic study supplemented by significant chemical analyses.

The feldspathic quartzites and grits of the southern gypsum series are probably the best indicators of the grade of regional metamorphism. These rocks have an assemblage consisting of quartz-albite-microcline-biotite-epidote-actinolite-chlorite. This assemblage belongs to the biotite-chlorite subfacies of the greenschist facies (Turner, 1948, p. 94). To this subfacies belong the rocks of the biotite zone as defined for pelitic schists. This is a low-grade regional metamorphism.

The lime-silicate marble is an excellent example of a contact metamorphic rock. The calcite-wollastonite-diopside assemblage is stable in high-temperature facies (pyroxene hornfels facies) in general, including the high-temperature subfacies of the amphibolite facies (Turner, 1948, p. 73).

McCOY MOUNTAINS (?) FORMATION

This formation constitutes the entire area of the Palen Mountains south of the gypsum deposits. It was examined only in the immediate vicinity of its contact with the Maria formation. It consists of slightly regional metamorphosed grit (Fig. 18), phyllite, argillite, conglomerate, quartzite, and porphyritic quartz latite (Fig. 19). The rocks are highly altered, probably by hydrothermal solutions which found easy access in the highly sheared and broken rock typical of the contact zone. Several examples are shown in Figures 20 and 21.

Because these rocks are so strongly hydrothermally altered it is difficult to compare their degree of metamorphism with that of similar rocks in the Maria formation. The general impression gained was that the McCoy formation shows a lower grade of regional metamorphism. The pebbles in the conglomerates are undeformed (although quartzite pebbles can probably survive a fairly high grade of metamorphism); a phyllite which was thin-sectioned revealed that it was just beginning to recrystallize from the original shale.

The age relations of the McCoy Mountains formation and the Maria formation are not too clearly established in this area. For this reason the beds south of the gypsum deposit are designated as questionable McCoy Mountains formation. Further reflections on the problem are presented in a later section.

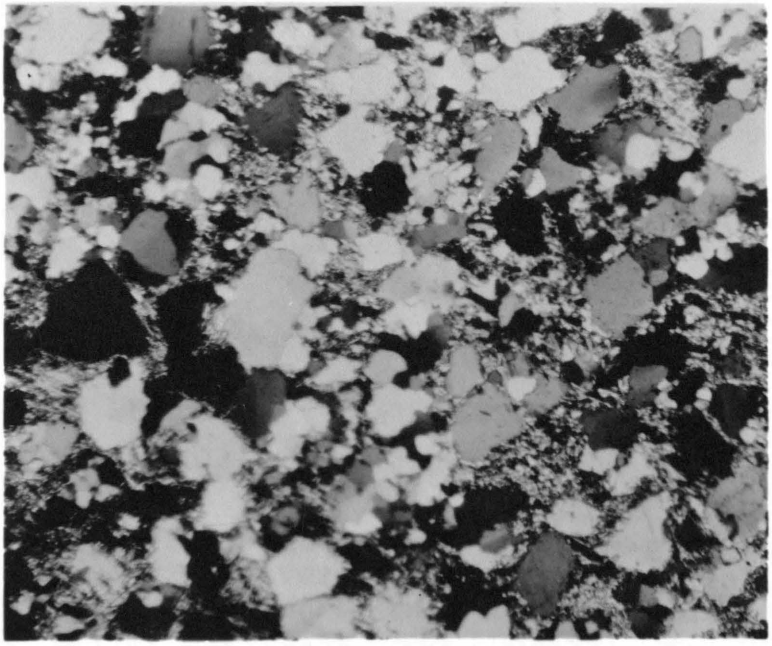


Figure 18.

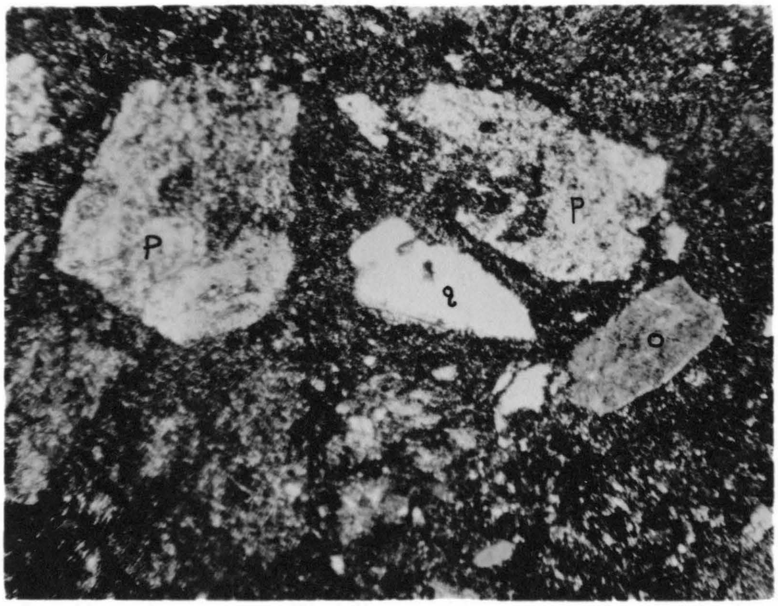


Figure 19.

McCOY MOUNTAINS (?) FORMATION

Figure 18. Quartz grit. Sub-rounded, medium-grained quartz in a matrix of very fine-grained quartz, pale green sericite, and epidote with minor magnetite, chlorite, muscovite, and apatite. x-nicols. X40.

Figure 19. Porphyritic quartz latite. Embayed quartz (q), altered plagioclase (p)-oligoclase?, and slightly altered orthoclase (o) in a microcrystalline groundmass of sericite, biotite, epidote, calcite, and sphene. x-nicols. X40.

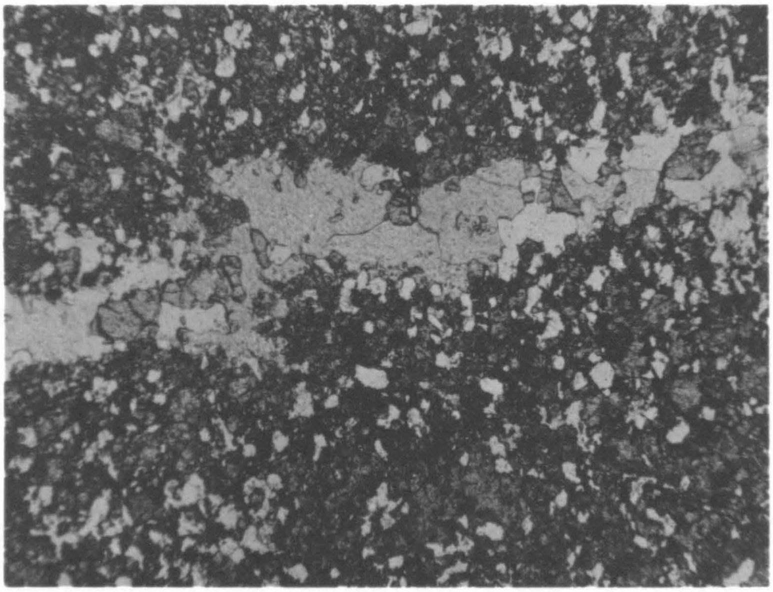


Figure 20.

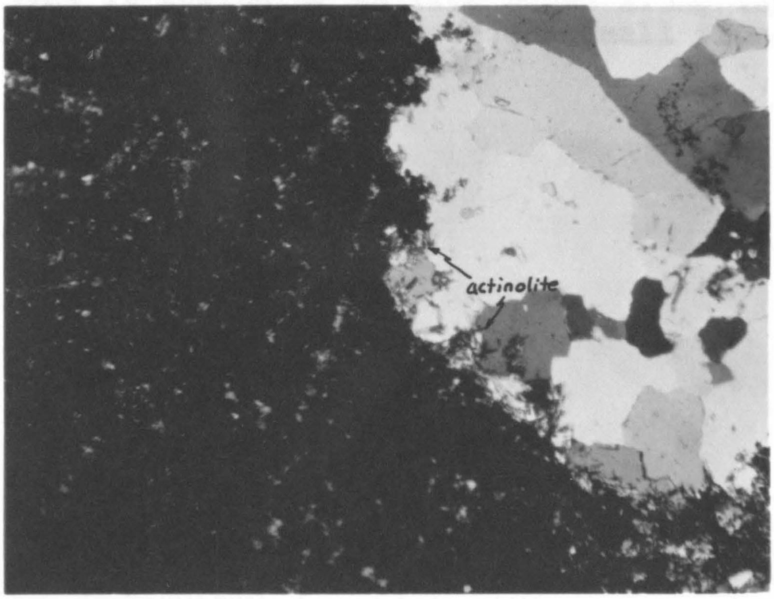


Figure 21.

McCOY MOUNTAINS (?) FORMATION

Figure 20. Zoisite-epidote-garnet quartzite; very fine-grained. Veinlet consists of calcite (gray), quartz (white), and epidote (gray, high relief). Plane polarized light. X40.

Figure 21. Conglomerate. Quartzite pebble in a fine-grained matrix of garnet and minor epidote. Some replacement is beginning to take place along the outer edge of the pebble. Note the small fibers of actinolite. x-nicols. X40.

META-IGNEOUS ROCKS

Both the Maria formation and the McCoy Mountains (?) formation were intruded by an igneous complex. In the area mapped only the igneous - Maria intrusive relations are present. However, a traverse at the east end of the south border ridge off the map area revealed the presence of variably porphyroblastic feldspathic meta-igneous rock like that in the Maria formation. The igneous material cuts into and surrounds irregular masses of volcanics and conglomerates. These intrusives are now strongly foliated fine-grained biotite-epidote-albite-quartz schists (Fig. 22). Little remains of the original igneous features. There are a few relict crystals of zoned intermediate feldspar (Fig. 24). In some samples of schist there are aggregates of extremely fine-grained epidote surrounded by granular quartz and albite (Fig. 25). They stand athwart the schistosity. These may represent completely recrystallized, somewhat calcic plagioclase feldspar. The rather high quartz content (25-30%), the considerable biotite, and the relict andesine suggest that the original igneous rock was a diorite or quartz diorite, or possibly as acidic a variety as a granodiorite.

A porphyroblastic phase (Figs. 23, 24) of the meta-igneous rock is discussed in the section on metasomatic and hydrothermal metamorphism.

The foliation dips north in general. A question arises concerning the origin of the foliation in the meta-igneous rocks.

Figure 22.

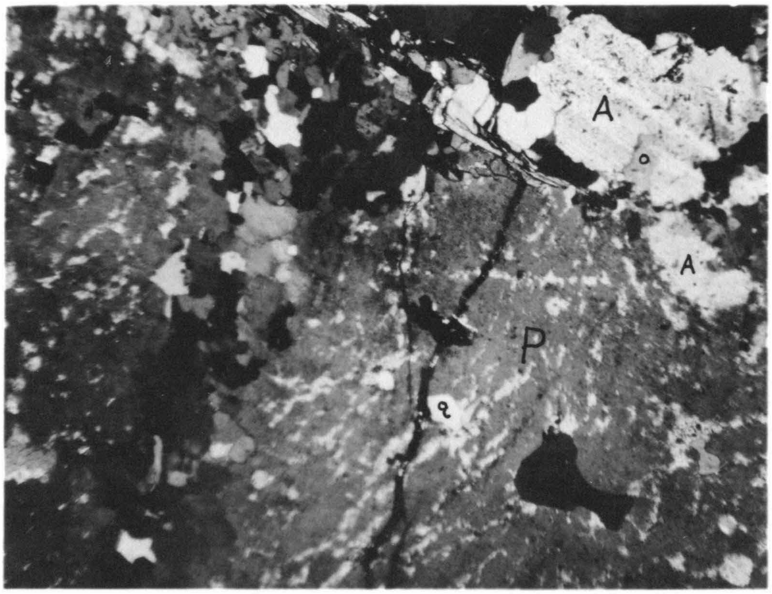


Figure 23.

Figure 22. Meta-igneous rock. Biotite-epidote-albite-quartz schist. Plane polarized light. X40.

Figure 23. Porphyroblastic meta-igneous rock. Large perthite porphyroblast with quartz (q) inclusions is being replaced by albite (A), and is cut by an irregular veinlet of clear, granular orthoclase and quartz (left center). The large albite is also cut by orthoclase (o). x-nicols. X40.

Figure 24.

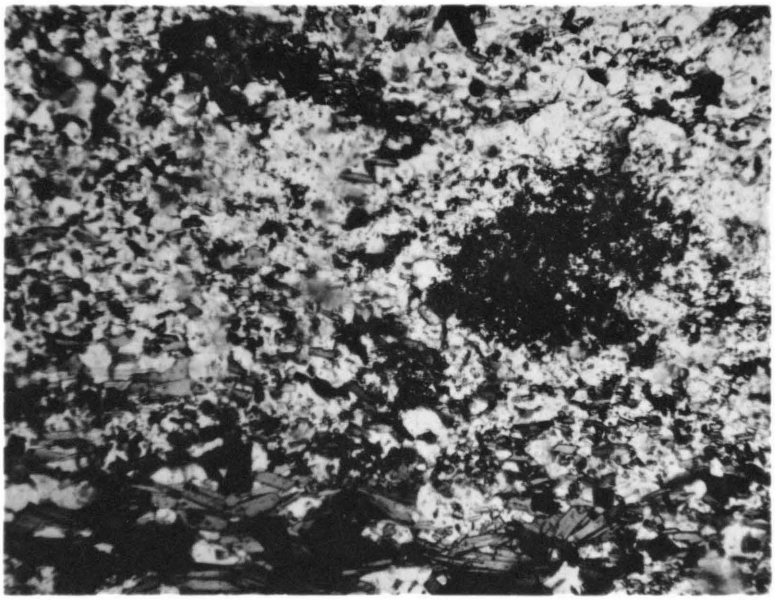


Figure 25.

Figure 24. Porphyroblastic meta-igneous rock. Relict plagioclase in perthite. Core (Na-andesine) highly altered to sericite and epidote; clear, corroded border is Na-oligoclase. x-nicols. X40.

Figure 25. Meta-igneous rock. The dark aggregate (right center) is very fine-grained epidote, surrounded by granular albite and quartz (white). This may represent a completely recrystallized, zoned plagioclase. Plane polarized light. X40.

As they are strongly schistose over their whole extent and show little trace of their igneous origin, the first assumption is that the intrusive action occurred before the onset of the regional deformation which so profoundly affected the Maria formation. However, the folds and much of the faulting in the meta-sediments end abruptly at the intrusive contacts; similarly, the meta-igneous rock is not intensely deformed throughout its whole mass as are the meta-sediments. As the early regional metamorphism was terminated by intense deformation, the intrusion must have taken place somewhat later. Also, the highly amphibolitic rocks (Fig. 29) in the contact zones have well developed decussate textures which could hardly have been maintained during such severe deformation. The fact remains, nevertheless, that the original igneous rock has been metamorphosed. The schist probably represents a low to medium grade of regional metamorphism (Harker, 1939, pp. 287-289). The amphibolitic rocks, because they represent a facies which is commonly a product of medium and high grade regional metamorphism, may have been able to resist any significant recrystallization in a lower intensity of metamorphism. This means that there was a second period of regional metamorphism. It may well represent the first ~~a~~effect produced by the deep seated igneous activity which later culminated in the emplacement of the granite comprising the Granite Mountains.

CONTACT METAMORPHISM

The intrusion of the quartz diorite produced marked contact metamorphism upon the already regionally metamorphosed and deformed Maria sediments. These effects were most pronounced in the roof zone of the intrusive where the volatile constituents were concentrated. This upper contact zone is exceedingly complex and is marked by very irregular and intimate intrusion of small dikes, sills, and tiny apophyses of igneous material. This environment was highly favorable for strong chemical activity and resulted in transfer of material between the intrusive and the country rock. The lime-silicate marbles and other marbles have been described in a previous section.

Skarns of garnet (Fig. 27), epidote, and amphibole are common in the invaded rocks. The border phase of the intrusive commonly contains an abundance of calcic minerals such as hornblende, epidote, and granular zoisite and epidote, calcic plagioclase feldspar, and, finally, euhedral sphene (Fig. 29). Undoubtedly there was some assimilation of the country rock.

Contact zones in xenoliths of marble lower in the intrusive generally are narrow, being only a few inches or a few feet wide. These zones may have tremolitic bands parallel to the contact (Fig. 28). In one case the tremolite occurs as radial aggregates up to a half inch in diameter. The calcite merely recrystallized to an granular aggregate of anhedral grains.

In several places the evidence suggests that some iron may have been introduced by the intrusion as shown by amphibole-

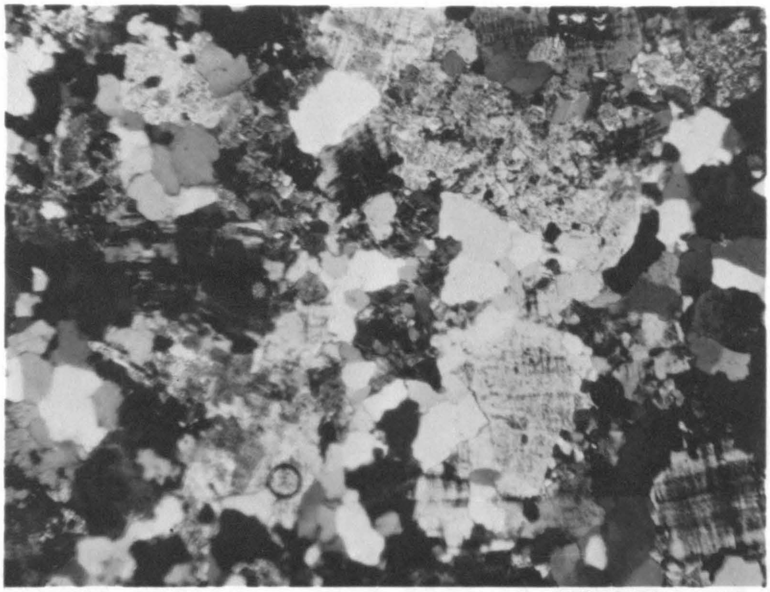


Figure 26.

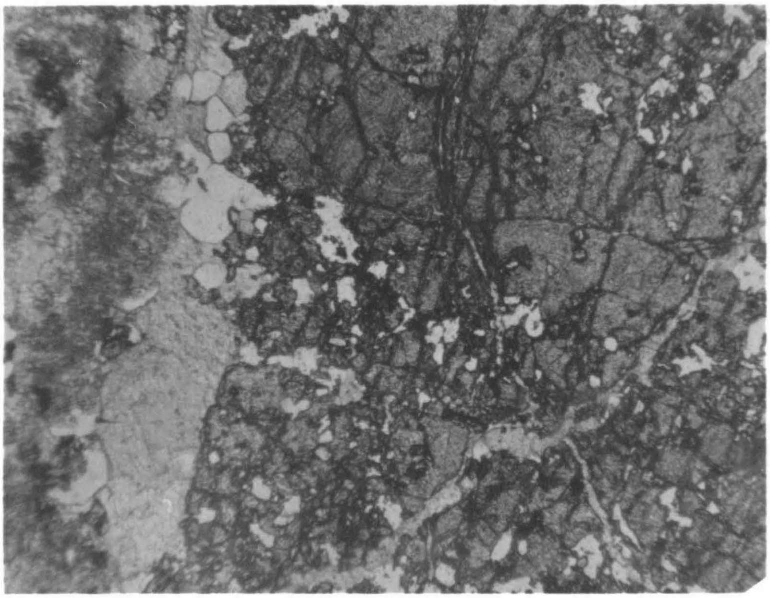


Figure 27.

Figure 26. Feldspathized quartzite. Microcline grains replacing quartz. This rock is typical of the many irregular masses occuring in the Maria formation. x-nicols. X40.

Figure 27. Skarn. Garnet (dark gray) cut by calcite veinlets (light gray). Minor granular quartz (white). Plane polarized light. X40.

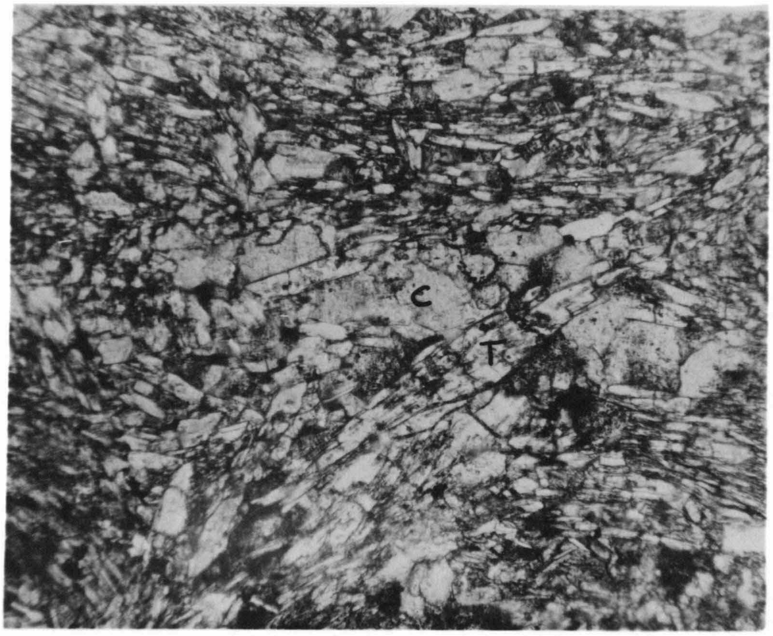


Figure 28.

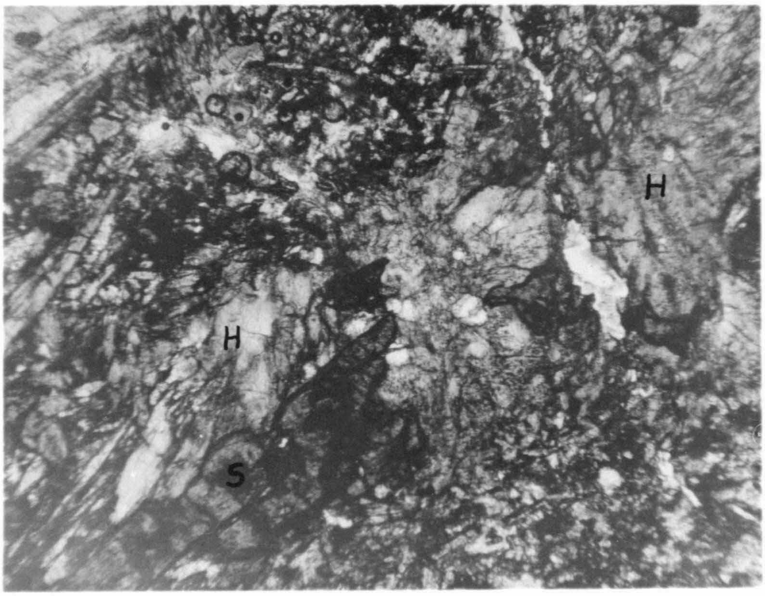


Figure 29.

Figure 28. Tremolite-marble. Specimen taken at contact with intrusive. Tremolite (T), calcite (C). Plane polarized light. X40.

Figure 29. Hornblende (H), epidote (dark, granular grains), sphene (S), and granular bytownite (white). Specimen taken in intrusive rock at contact with tremolite-marble. Plane polarized light. X40.

iron ore masses (Fig. 31) in marble xenoliths and by narrow siderite - magnetite granulites (Fig. 30) in the marble next to the intrusive.

The effect of intrusion on the gypsum is difficult to determine because few clean contacts are found on the surface. Several that could be studied were found to be fault contacts. Probably the only effect would be dehydration and this would be wiped out as soon as the material reached the zone of weathering.

The contact action of the very small, isolated intrusions scattered throughout the area appears to have been negligible. Rather, the intrusions themselves were strongly modified and now are high in such calcic minerals as hornblende, epidote, and sphene.

METASOMATIC AND HYDROTHERMAL ACTIVITY

FELDSPATHIZATION

Subsequent to the intrusion and regional metamorphism of the quartz diorite, the whole area, including the McCoy beds, was subjected to fairly intense metasomatic activity. The effects are particularly evident in the meta-igneous rock. The southern third of this rock contains porphyroblasts of alkaline feldspar. The feldspars vary in soda content from place to place so that they may be microcline, perthite, or antiperthite. The porphyroblasts are best developed along the south border of the intrusion and gradually decrease in size and abundance

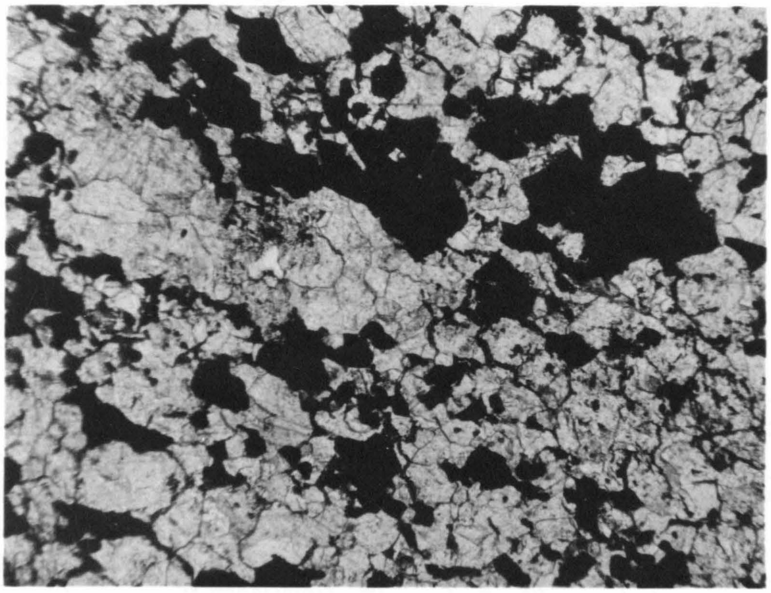


Figure 30.

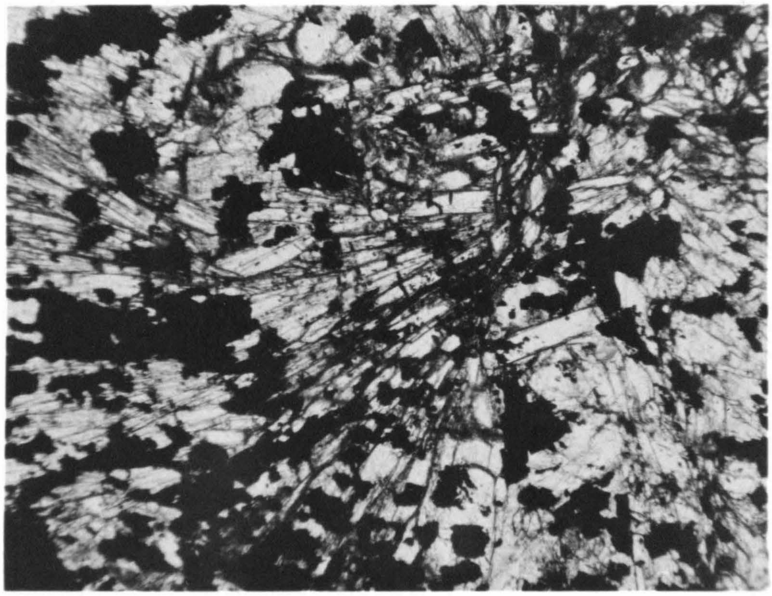


Figure 31.

Figure 30. Granular magnetite and calcite. Specimen from six inch contact zone in marble xenolith. Plane polarized light. X40.

Figure 31. Tremolite-magnetite rock. Contains minor calcite and chlorite. Material occurs as irregular masses in some of the marble xenoliths. Plane polarized light. X40.

towards the north. At one point along the south contact of the meta-igneous series the lower six inches of the rock is almost completely sericitized; above it is a foot thick, massive, granitic appearing zone. The original intrusive contact of meta-igneous rock apparently was modified by faulting and this fault zone undoubtedly was the avenue up which the feldspathizing solutions rose.

The feldspars are not always large and well developed within the porphyroblastic phase of the meta-igneous rock. One interesting locality exposes a massive, faintly foliated non-porphyroblastic rock which grades abruptly into porphyroblastic rock with schist "inclusions". The former contains abundant fine-grained albite and microcline with a few ill-formed coarser feldspars. The two rocks appear, however, to have about the same percentage of feldspars. It is possible that the formation of the large porphyroblasts has forced much of the biotite to concentrate in aggregates resembling inclusions and thus may represent a process of metamorphic differentiation. The micas in the "inclusions" still parallel the old foliation and the long dimension of the aggregates trend roughly in the same direction.

Within non-porphyroblastic phases of the meta-igneous rock, there are zones where incipient feldspathization is visible. These zones may be marked by regularly distributed, small irregular feldspars or by bands of poorly developed feldspars parallel to the foliation. These bands do not have sharp boundaries but rather grade into the schist. These bands may be only thin seams or may be several inches wide.

A paragenetic sequence for five different ages of feldspar was determined. Starting with the oldest, these feldspars are: 1) Relicts of zoned intermediate plagioclase; 2) Recrystallized, fine-grained granular albite; 3) Perthite porphyroblasts; 4) Albite, with myrmekite; and 5) fine-grained, granular orthoclase. Figure 23 shows a large perthite being cut by albite and both in turn being replaced by clear, granular orthoclase.

Crosscutting these feldspathic zones are aplitic and pegmatitic dikes and sills, generally less than a foot in width. At first glance these appear to have sharp contacts, but upon closer inspection many have hazy boundaries and have thin stringers of feldspathization extending out across and along foliation planes of the schist. The meta-igneous rock is commonly slightly more feldspathic next to these dikes. Also, relict biotite in the aplites maintain their original orientation. Nevertheless, some aplites and most of the truly pegmatitic bodies have very sharp contacts. It is a problem to decide where replacement by permeating feldspathic solutions ends and true intrusion by granitic magma begins. No doubt the borders of true magmatic intrusions will show granitization phenomena.

In the north central part of the map an area of highly feldspathized and recrystallized meta-igneous rock is present. This area seems to be limited on all sides by zones of intense shearing and granulation. The rocks show complicated recrystallization textures and as metasomatism increases, the amount of biotite decreases and potash feldspar, muscovite, iron ore increase, and even rutile appears. The same direction of foliation is found in this material as in nearby meta-igneous rock. The general shape of this area and the distribution of steep shear zones around its perimeter and inside suggest that this section may lie above a protuberance of a deep seated granitic mass. As the granite punched its way upward into the meta-igneous rocks, it created zones of intensive fracturing overhead through which vapors and fluids emanating from the magma found easy access. This deep seated granite is probably genetically related to the granite of Granite Mountain to the north.

Similarly, the meta-igneous rock along the northeast side of the area becomes increasingly more feldspathic and recrystallized as the Granite Mountains are approached. The writer visited only the very southeast end of this range. The same general relations exist in that part of the range as in the gypsum area, namely, meta-igneous rock in various stages of feldspathization and recrystallization with later crosscutting sills and dikes of aplite and pegmatite.

Small feldspathic zones (Fig. 26) are present in the metasediments but whether they are replacements, or fillings, or intrusions cannot be ascertained at this time, because in no case was it possible to view their contact relations.

The sequence of events suggested by the above observations is as follows: Emanations from a deep seated magma rose along previous fault zones, fractures, joints, and foliation planes causing varying degrees of feldspathization and recrystallization. As the magma rose more fractures developed, especially over high points, with the result that one large area and many smaller areas of intense recrystallization were created. Finally, a small amount of the granitic magma itself reached the levels now exposed and is present as small aplites and pegmatites. In this area, at least, no~~w~~ bodies of granite are present at the surface.

OTHER MINERALIZATION

Veins containing one or more minerals such as epidote, calcite, quartz, magnetite, hematite, pyrite, muscovite, and serpentine are found throughout the whole area, including the McCoy Mountains (?) formation. Green copper stains and small quantities of copper sulphides are present in a few quartz veins. Very minor gold values have been found by prospectors. Irregular stringers and pods of white quartz are found in all the rocks. Thin jasper veinlets are present in the marble in the northwest part of the area. Hydrothermal fluorite (Fig. 32), kyanite (Fig. 33), and apatite were found in a few shear zones.

The veins and shear zone type mineralization cut feldspathized rock, aplites, and pegmatites and thus represent the last stage of mineralization.

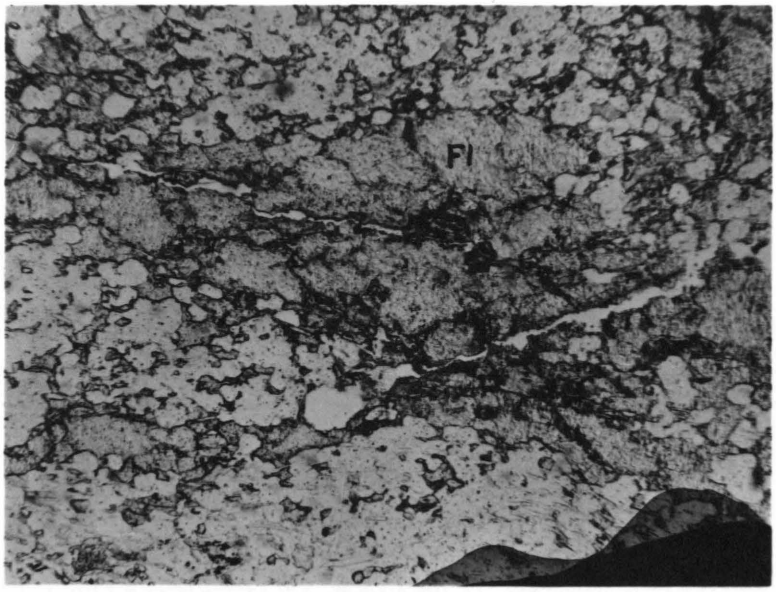


Figure 32.

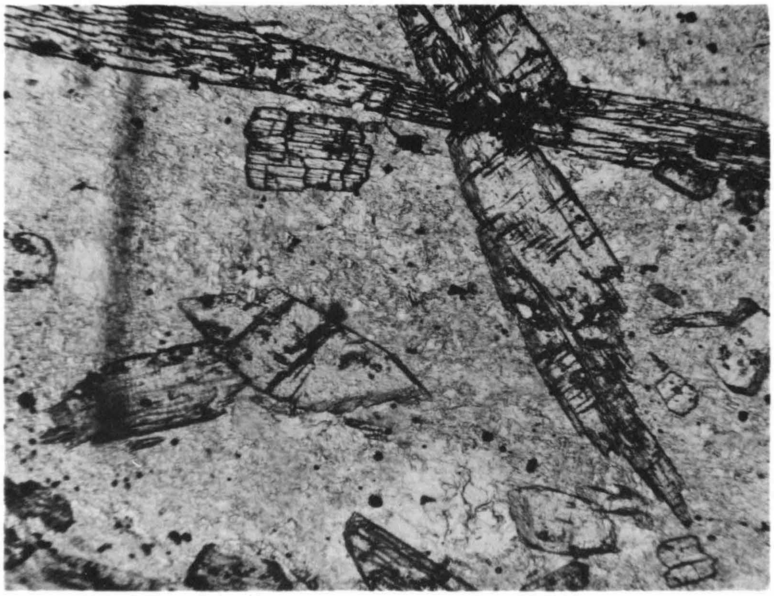


Figure 33.

Figure 32. Fluorite (Fl) introduced into an intensely sheared muscovite-quartz schist. Plane polarized light. X40.

Figure 33. Kyanite crystals in quartz-sericite schist. A few small, dark grains of magnetite. Plane polarized light. X40.

COMPARISONS AND POSSIBLE CORRELATIONS WITH OTHER AREAS

GENERAL STATEMENT

The difficulties of making an accurate age determination for the Palen Mountains gypsum deposit have already been indicated. However, a certain amount of speculation as to correlations with deposits nearby and with rocks at greater distances, even into the states of Arizona and Nevada, might be profitable. First, similar gypsum deposits in the Little Maria and Maria Mountains to the east are briefly described. Next, rocks of the deposit are compared with the rock section in the Eagle Mountains to the west. Finally, some sections in southern Nevada are considered which might be tentatively correlated with the Maria formation.

GYPSUM DEPOSITS OF THE LITTLE MARIA MOUNTAINS

Deposits of gypsum in the Little Maria Mountains (Jenkins, et al 1950, p. 227) are believed to belong to the same formation as the gypsiferous section a few miles to the west in the Palen Mountains. The beds form part of a series of slightly metamorphosed sediments, that cross the range east-west. The sediments are bordered on the north by granitic rocks and on the south by gneiss. The rocks of the gypsum belt are quartzite, crystalline limestone, and quartz-albite-mica schist, all dipping 50 to 80 degrees to the northwest. The gypsum occurs in limestone as persistent beds up to 50 feet thick and in the schist as lenticular bodies which have a more limited extent along the strike. The gypsum is a coarse grained snow white aggregate of transparent grains. In many places the gypsum contains thin layers and lenses of schist. Schist is also found in the gypsum interbedded with limestone. Anhydrite is found at depth. The alteration of anhydrite to gypsum apparently is controlled by fractures and other openings.

GYPSUM DEPOSITS OF THE MARIA MOUNTAINS

These deposits (Surr, 1911) lie about fifteen miles east of the Palen Mountains. The beds trend east-west with northerly dips varying from almost horizontal to perpendicular. Quartz monzonite gneiss borders the area both on the north and the south. The gypsum beds vary in thickness from ten to over a hundred feet and are interbedded with limestone and shale. There are two bands of gypsum bearing series each containing four beds. The limestone beds are from 100 to several hundred feet thick. The gypsum is snowy white, with grayish bands in places.

EAGLE MOUNTAIN IRON DEPOSIT

The iron ore deposits of the Eagle Mountains (Hadley,1945, p.4) occur in contact metamorphosed sediments, which have been folded, faulted, invaded by irregular sill-like bodies of quartz monzonite, and cut by dikes of fine-grained igneous rock.

TABLE 2. Rock units in the eastern part of the Eagle Mountains iron district. After Hadley (1945 p. 5)

Rock units in order of age	Lithology	Approximate thickness, feet
Slope wash and alluvium	Coarse sand and gravel, commonly cemented by caliche. Locally contains abundant boulders of iron ore.	0 to 100+
Dike rocks	Syenite porphyry, diabase, granite	
Quartz monzonite	Coarse-grained and porphyritic quartz monzonite with biotite and hornblende.	
Conglomerate	Metamorphosed limestone conglomerate.	400+
Lime-silicate rocks	Contact-metamorphic rocks composed of mica, actinolite, diopside, feldspar, and quartz.	100
Upper-ore bed	Iron ore with lenses composed dominantly of lime-magnesi~~s~~a silicates.	30 to 300
Quartzite	White to dark-gray glassy quartzite; sporadic bodies of iron ore.	200 to 300
Lower ore bed	Iron ore with lenses composed dominantly of lime-magnesi~~s~~a silicates.	40 to 140
Feldspathic quartzite	Coarse- to fine-grained feldspathic quartzite and schist.	50 to 150
Vitreous quartzite	Pure, coarsely recrystallized quartzite.	150+
	Total average thickness of metamorphic rocks	1250

Table 2 is a reproduction of the chart by Hadley (1945, p. 5) of the rock units in the eastern part of the Eagle Mountains iron district. A comparison of his section with that of the Palen Mountains shows certain broad similarities. The vitreous quartzite does not appear to be represented in the gypsum deposit. The feldspathic quartzite possibly can be correlated with the feldspathic beds in the south part of the A-A' cross section. The sporadic bodies of quartzite in the meta-igneous rock which lie stratigraphically below the lime-silicate rocks (southeast end of section B-B') cropping out along the middle of the gypsum claims in the Palen mountains may be the equivalents of the upper quartzite beds of Hadley. The lime-silicate rocks which he describes may well be contemporaneous with the lime-silicate beds in the gypsum area. The large amounts of marble, gypsum, and meta-igneous intrusives do not seem to be represented in the Eagle Mountains. The occurrence of iron ore in small quantities in the Palen Mountains under very similar conditions compared to those in the Eagle Mountains certainly suggest that these iron ore deposits may be of the same age.

SUMMARY

The gypsum deposits of the Palen Mountains, Little Maria Mountains, and the Maria Mountains belong to the same formation. In addition it seems probable that these meta-sediments are the same age as those in the Eagle Mountains although no gypsum and no large thicknesses of marble occur in the latter range.

COMMENTS ON THE AGE AND POSSIBLE CORRELATION WITH GYPSIFEROUS SECTIONS IN SOUTHERN NEVADA

Harder (1909, p. 409) gives no age for the deposit. In appearance, texture, and metamorphism, he states, the rocks resemble other sediments of the southeastern Mojave desert, which have been generally considered pre-Cambrian. He also remarks in his paper on the Eagle Mountains (1912, p. 16) that the later intrusives and flows are considered to be of Mesozoic and later age. Table 3 is a reproduction of his general section of rocks in the southeastern Mojave and Colorado deserts. (1912, p.19) His section was based on observations as he traveled from one iron ore area to another. No fossils were found so the ages are unknown and only the general relations are given. He also notes that the rocks are distributed through the ranges, some of which contain most of the formations in the series, but others consist almost entirely of one or two formations, so that it is difficult in many places to tell the relation between various rocks in the succession.

Darton (1907) describes a series of sediments in an area fifty miles north of the Palen Mountains on the Santa Fe railroad which are Cambrian in age. He also mentions a section of sediments which might possibly be of Carboniferous age. No fossils were found. These later sediments are only slightly metamorphosed quartzites and crystalline limestone. The metamorphism was apparently caused by intrusions of coarse granite. Harder (1909, p. 409) suggests that these sediments might be

TABLE 3. General section of rocks in the southeastern Mohave and Colorado deserts. After Harder (1912 p. 19)

10. Basalt

9. Unconsolidated desert deposits.

8. Basalt; slightly tilted.

7. Partly consolidated shale, sandstone, and conglomerate; horizontal.

6. Trachytic, andesitic, and rhyolitic flows; tilted and broken; probably Tertiary.

5. Red and brown sandstone, shale and conglomerate; tilted.

4. Intrusive granite, syenite, monzonite, and diorite and their porphyritic phases in sills, dikes, and irregular batholiths; probably Mesozoic.

3. Quartzites, crystalline limestone and dolomite and conglomerates; age unknown.

2. Purple and gray slates, shales, sandstones, and quartzites; age unknown.

1. Schists, crystalline limestone and dolomite, gneiss, and granite; probably pre-Cambrian.

the same age as those in the Palens although the rocks in the latter range were much more metamorphosed by heat and pressure during the intrusion of the granite to the north.

Miller (1944, p. 28) discovered crinoidal remains in the crystalline limestone associated with gypsum beds in the southeastern part of the large area of the Maria formations in the Maria Mountains. Accurate age determinations of these fragmental crinoidal remains were impossible, but it was suggested that the rocks were of Paleozoic age, possibly Silurian. Miller, nevertheless, feels that a post-Cambrian Paleozoic age of of the Maria formation seems to be reasonably well established.

The McCoy Mountains formation, according to Miller, makes up the southern part of the Palen Mountains and the Coxcomb Mountains. This formation is dated, more or less tentatively, as Paleozoic or Triassic by Miller (1944, p. 52) with the probability favoring Paleozoic age. Harder (1912) dates these same rocks as two on his general section, the gypsum series as three, the quartz diorite as four, and the granites to the north as either one or four.

Brown (1923, p. 43) in his interpretation of Harder's general section states that the first three series in the section are probably pre-Cambrian. His opinion is based mainly on the facts that these rocks are clearly the oldest in the region, having suffered the greatest metamorphism and being intruded or overlain by all the other series; that they are similar to the pre-Cambrian rocks of the Grand Canyon and other parts of Arizona; that although vast thicknesses of the sedimentary beds are exposed in places no fossils have ever been found within them. He considers it likely that the granite in Granite Mountain belongs to the oldest series. The next two series, he continues, are closely associated with the first and make up the remaining masses of the Maria, McCoy, Palen, Coxcomb, and Chuckwalla Mountains. Except for some granitic, dioritic, and porphyritic intrusives, they are probably of Mesozoic age. He identified no rocks of Paleozoic age, but admitted that further studies might indicate that some formations described as probably pre-Cambrian are probably younger.

Lee (1908, p. 15) regarded the metamorphosed sediments consisting of quartzites, argillites, and limestones in northwestern Arizona as pre-Cambrian. Bancroft (1911, p. 23) lists as pre-Cambrian granites, gneisses, schists, quartzites, limestones, dolomites and argillites, all of which are cut by intrusives of diabase, aplite and pegmatite of different ages. Mesozoic (?) granite cutting the pre-Cambrian was dated as such only because others in the Pacific area are so dated. No attempts have been made to correlate these rocks with those in the gypsum deposits fifty miles to the west.

Harder (1912, p. 27) discusses the succession of events in the Eagle Mountains. His table is reproduced here (Table 4).

TABLE 4. Succession of geologic events in Eagle Mountain region. After Harder (1912, p. 27)

9. Erosion exposing all the rock formations, accompanied by the sculpturing of mountains and followed by the development of great outwash aprons around the mountains.

8. Doming of the sediments and intrusives, accompanied by great faulting.

7. During the later part of the intrusion, or shortly after it, iron ores and metamorphic minerals were introduced by deep-seated solutions replacing the dolomite and to a slight extent the quartzite.

6. The heat and pressure accompanying the intrusion recrystallized and consolidated the sediments and perhaps locally developed metamorphic minerals.

5. Intrusion of quartz monzonite in two main sills, one in the vitreous quartzite below the dolomite lenses and the other in the quartzite conglomerate beds above the dolomite lenses. The first is discontinuous, though locally of great thickness; the second is very thick and is continuous throughout the extent of the iron-ore belt.

4. Erosion interval followed by submergence and deposition of a great thickness of quartz sandstone; then the deposition of arkosic sandstone, followed by the formation of beds and lenses of dolomite and quartz sandstone, and, lastly, of beds of sandstone and conglomerate.

3. Great dynamic metamorphism, resulting in the alteration of granite porphyry to augen gneiss and the sediments to schists and crystalline limestone.

2. Intrusion into the sediments of porphyritic granite.

1. Deposition of sandstone, siliceous shale, and dolomite.

The previous discussion emphasizes how little agreement exists among the various workers concerning both the actual and the relative ages of the rocks. The Maria formation is considered by some to be pre-Cambrian in age and by others, Paleozoic. The relative ages of the Maria formation and the McCoy Mountains (?) formation are difficult to decipher, in the Palen mountains. As the work in this area has been limited only to the gypsum deposit and the narrow region bordering the deposit on the south, a final answer cannot be given here. It has already been indicated that the green and dark green schists, argillites, shales, and conglomerates found at the southwest border of the area dip northward beneath the gypsum marble series. If there is no fault between the two formations, the McCoy Mountains (?) formation would be the older. However, if a fault separates the two formations, the alternative accepted here, then the McCoy beds could be either stratigraphically above or below the Maria formation. By postulating a reverse component of movement along such a fault as is suggested along the southeast border, it would be likely that the Maria beds were the older. Also, it was pointed out in a previous section that the McCoy beds appear to be less metamorphosed than the rocks of the Maria formation and, therefore, must be the younger of the two groups.

Moving farther away geographically, Hewett (1931, p. 87) reports beds of gypsum in the red shaly sandstone at the top of the Supai formation and between the two limestone members of the Kaibab limestone. Both these formations are Permian in age. The lowest Triassic, the Moenkopi (p. 32) consists of basal conglomerate with sandstone, limestone, and red and green shales with minor tuff beds. He describes a greenish epidotic alteration of pebbles, the alteration preceding the rounding of the pebbles during transporation. Similar pebbles are found in the conglomerates of the McCoy Mountains (?) formation along the south border of the Palen Mountains gypsum deposit.

In the Lake Mead region of Nevada, Longwell (1949, p. 929) reports that the Moenkopi formation, (Triassic) is approximately 1500 feet thick, consisting of an upper continental member of shale largely chocolate brown, in part gypsiferous, with inter-bedded sandstone, and a lower marine member consisting of interbedded limestone, shales, sandstone, and gypsum. The Kaibab limestone (Permian), is 600 to 800 feet thick and consists of an upper and a lower limestone member separated by gypsum. Beneath the Kaibab are about 2000 feet of red beds consisting of brick red and mottled sandstone with subordinate sandy shale.

The possibility should be definitely considered that the gypsum, marbles, schist, and quartzite of the Maria formation are the deformed and metamorphosed equivalents of the gypsum, limestone, shale, and sandstone of the Kaibab and the Moenkopi formations. Apparently diastrophism has occurred more often and more severely in the southeastern Mojave region, along with greater intrusive activity.

SUMMARY

The gypsum deposits of the Palen, Little Maria, and Maria Mountains all belong to the Maria formation. The meta-sediments containing the iron ore deposits of the Eagle Mountains probably are a part of the same formation.

The age of the gypsum deposits cannot be definitely given, but it seems to be more than idle speculation that the Maria formation of the southeastern Mojave desert represents highly deformed and metamorphosed equivalents of the gypsum-bearing Permo-Triassic formations of southern Nevada. With this in mind, the Maria formation is designated as Upper Paleozoic (?) age.

SUMMARY OF THE GEOLOGIC HISTORY

Table 5 is a reconstruction of the chronology of the geologic events which have been involved in the history of the Palen Mountains gypsum deposit. Dating is tenuous and even the relative positions of several of the events are debatable. However, the study of the deposit leads the author to believe that the succession of events shown below is the one most compatible with the facts so far available.

Events two and three were the beginning and end of what was undoubtedly one continuous period of deformation. The early stresses, along with the heat and pressure occasioned by deep burial, brought about recrystallization and the development of new minerals. With the passage of time, the stresses intensified until they culminated in thrusting accompanied by both brecciation and incompetent folding.

Events five, six, and seven may well represent another long period of intrusion and deformation climaxed by the emplacement of the granite to the north.

TABLE 5

Recent	11.	Faulting of Recent gravels.
	10.	Deposition of gravels.
Pleistocene and or Tertiary?	9.	Small scale normal and reverse faulting.
	8.	Erosion; deposition of Tertiary (?) or Pleistocene gravels.
		(Probably some faulting here.)
Laramide?	7.	Intense metasomatic activity including feldspathization and recrystallization followed by intrusion of aplites and pegmatites and finally by hydrothermal veins.
	6.	Faulting and perhaps very slight regional metamorphism.
Nevadan?	5.	Intrusion of quartz diorite into the Maria and McCoy beds.
Triassic?	4.	Erosion followed by deposition and burial of McCoy Mountains (?) formation.
Upper Paleozoic?	3.	Intense cataclastic deformation including folding, faulting, brecciation, and crushing.
	2.	Deep burial followed by the onset of stresses responsible for the regional metamorphism of the sediments.
	1.	Deposition of the Maria sedimentary series of limestones, gypsum, sandstone, arkose, and minor shale.

ECONOMIC GEOLOGY

The gypsum reserves in the Palen Mountains deposit amount to several hundred million tons. The calculation of a fairly accurate estimate of the reserves would be an extremely difficult job. Although the gypsum is of high quality, its value is lessened by the presence of large and small fragments of marble which are literally "floating" in the gypsum beds. These "tectonic" impurities will increase the cost of mining because their presence in any one spot cannot be predicted. For example, in several places some bulldozing has been done on beds which gave promise of being free of impurities. However, in almost all cases, irregular masses of marble were uncovered. The gypsum is cut out in many places by intrusives and faults. Wedging out between massive beds of marble is common. It is evident that, in contrast to most undeformed bedded deposits, it will be difficult to plan a long-range mining program.

In order to carry out a large-scale program of exploitation, a much more detailed mapping and sampling of the three gypsum areas must be made, supplemented by a drilling schedule to determine the depth to anhydrite and to provide more information on the sub-surface structure. While these detailed studies are being made to determine the feasibility ofa large scale development, some mining could be begun, provided close supervision of removal operations is maintained. Such supervision is necessary in order to keep close watch for masses of marble that will periodically be exposed during shoveling. In this way, impurities of marble in the shipped product will be kept to a minimum. Probably the best site for preliminary mining is in the east-central part of the southern gypsum belt where a large area of gypsum has been exposed at the surface by the stripping off of much of the overlying marble.

REFERENCES

Bancroft, Howland 1911	Ore Deposits in Northern Yuma County, Arizona: U.S. Geol. Survey Bull. 451.
Bowles, O., and Farnsworth, M. 1925	Physical Chemistry of the Calcium Sulphates, and Gypsum Reserves: Econ. Geol., vol.20, pp. 738-745.
Brown, John S. 1923	The Salton Sea Region, California: U.S. Geol. Survey Water Supply Paper 497.
Darton, N.H. 1907	Discovery of Cambrian Rocks in Southeastern California: Jour. Geology, vol. 15, pp.470-475.
Fairbairn, H.W. 1949	Structural Petrology of Deformed Rocks: pp. i-ix, 1-344, Addison-Wesley Press Inc., Cambridge, Mass.
Farnsworth, M. 1924	Effects of Temperature and Pressure on Gypsum and Anhydrite: U.S. Bur. Mines R.I.2654.
Hadley, J.B., 1945	Iron Ore Deposits in the Eastern Part of the Eagle Mountains, Riverside County, California: Calif. Div. Mines Bull. 129A.
Harder, E.C. 1909	The Gypsum Deposits of the Palen Mountains, Riverside County, California: U.S.G.S., Bull. 430, pp. 407-416.
Harder, E.C. 1912	Iron Ore Deposits of the Eagle Mountains: U.S. Geol. Survey Bull. 503.
Harker, A. 1939	Metamorphism: pp. i-ix, 1-362, Methuen and Co. Ltd., London.
Hazzard, J.C. Gardner, D.L. Mason, J.F. 1937	Mesozoic (?) Metavolcanic and Sedimentary Rocks in San Bernardino and Riverside Counties, California: Geol. Soc. America Proc. 1937, p. 279.
Hess, F.L. 1920	Gypsum Deposits of the United States: U.S. Geol. Survey Bull. 697, pp. 78-79.
Hew~~i~~ett, D.F. 1931	Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada: U.S. Geol. Survey Prof. Paper 162.
Jenkins, O.P. 1937	Source Data of the Geological Map of California: Calif. Journal of Mines and Geology, vol. 33, pp. 9-37.

Jenkins, O.P., et. al. 1950	Mineral Commodities of California: Calif. Div. Mines, Bull. 156, p. 227.
King, R.H. 1947	Sedimentation in Permian Castile Sea: Am. Assoc. Pet. Geol., Bull., vol. 31, pp. 470-477.
Lee, W.T. 1908	A Geological Reconnaissance of a Part of Western Arizona: U.S. Geol. Survey Bull. 352.
Longwell, C.R. 1950	Structure of the Northern Muddy Mountain Area, Nevada: Geol. Soc. America., Bull., Vol. 60, pp. 923-968.
Longwell, C.R. 1928	Geology of the Muddy Mountains, Nevada, with a Section Through the Virgin Range to the Grand Wash Cliffs, Arizona: U.S. Geol. Survey, Bull. 798.
Miller, W.J. 1944	Geology of Palen Springs - Blythe Strip, Riverside County, California: Calif. Journal of Mines and Geology, vol. 40, pp. 11-72.
Pettijohn, F.J. 1949	Sedimentary Rocks: pp. i-xv, 1-526, Harper Brothers, New York.
Posnjak, E. 1938	The System $CaSO_4$-H_2O: Am. Jour. of Science, vol. 235, pp. 247-272.
Posnjak, E. 1940	Deposition of Calcium Sulphate from Sea Water: Am. Jour. of Science, vol. 238, pp. 559-568.
Surr, Gordon 1911	Gypsum Deposits in the Maria Mountains of California: Min. World, vol. 34, pp. 787-790.
Thompson, D.G. 1929	The Mojave Desert Region, California: U.S. Geol. Survey Water Supply Paper 578.
Tucker, W.B., and Sampson, R.J. 1929	Riverside County: Calif. Div. Mines Rept. 25, pp. 510-514.
Turner, F.J. 1948	Mineralogical and Structural Evolution of Metamorphic Rocks: Geol. Soc. Am., Memoir 30.

OSCILLATIONS IN THE FORAMINIFERA OF THE VICKSBURG GROUP FROM A WELL IN GEORGE COUNTY, MISSISSIPPI

Thesis by

Richard A. Hoppin

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California
June, 1951

ACKNOWLEDGMENTS

The writer wishes to express his deep appreciation to Mr. M.C. Israelsky of the United States Geological Survey for the suggestion of the problem, the provision of the cores, and for his unselfish donation of time, advice, and inspiration; and to Miss Ellen Powelson for the final drafting of the index map and the oscillation chart.

ABSTRACT

An oscillation chart is presented based on the foraminiferal content of core samples of the Vicksburg Group (Middle Oligocene) from a well in southeastern Mississippi. The oscillations are due primarily to relative changes in depth at this geographic position during the deposition of the sediments. These changes are indicated by variations in the percentage distribution of the species of foraminifera.

Ten cubic centimeters of each sample were washed and then sieved through a 150 mesh screen. A count was made of the number of specimens of each species or closely related group of species in each sample. The percentage distribution of the benthonic calcareous and arenaceous forms were calculated separately because the benthonic calcareous foraminifera are the more delicate depth indicators. The relative depth significance of the benthonic calcareous foraminifera was determined by plotting their percentages against the percentage of Uvigerina spp., which are considered typically open-water elements.

The possible influence of modifications of other ecologic factors comprising the depositional environment must also be considered when interpreting faunal changes. However, as a sample covers an interval of several inches or several feet in thickness (equivalent to hundreds or thousands of years), these effects are probably insignificant. The interpretation of fossil material is further complicated by such processes as mixing, mechanical abrasion, solution, and recrystallization.

The chart reveals several transgressions and regressions in the Vicksburg Group, even though the section appeared at first glance to be made up of a monotonous, homogeneous foraminiferal fauna. A single chart could not be carried across the strong faunal break between the Red Bluff (Lower Oligocene) and the Vicksburg. By charting the two parts separately, the oscillations are more easily discerned.

The method shows promise as a correlation tool in sedimentary sections in which there were fairly rapid depth changes. An individual chart probably should not be extended over a period of time greater than an epoch because evolutionary development will tend to mask faunal changes caused by oscillations of depth.

TABLE OF CONTENTS

INTRODUCTION

For some years paleontologists and stratigraphers have been painfully aware that one of the most commonly used methods of correlation, the upper range of fossils, or "tops", has been shown to be of limited value. The distribution of marine organisms reveals that, at a given time, faunal assemblages may vary in kinds and numbers of forms both parallel to the trend of the shoreline and down the depositional dip. As environmental conditions change, a given faunal assemblage migrates from one geographical position to another in order to stay with the particular set of ecologic factors upon which the assemblage is dependent for its survival.

Similarly, at a given geographical position, as the complex of physical and biological relations that constitute the environment changes with time, different faunal assemblages will occupy that particular site. If the conditions were favorable for the preservation of fossils, a section through a sequence of sediments would show changes or oscillations of faunal groups. The character of a biocoenose is changed not only by variations of the ecologic factors but also by effects of organic evolution. Correlation by "tops" is based on evolutionary development and is usually capable of determining the time boundaries of rock units deposited through spans of time of the magnitude of geologic periods or epochs. In the younger sediments of the Gulf Coast the changes are numerous and very rapid in units representing only small portions of an

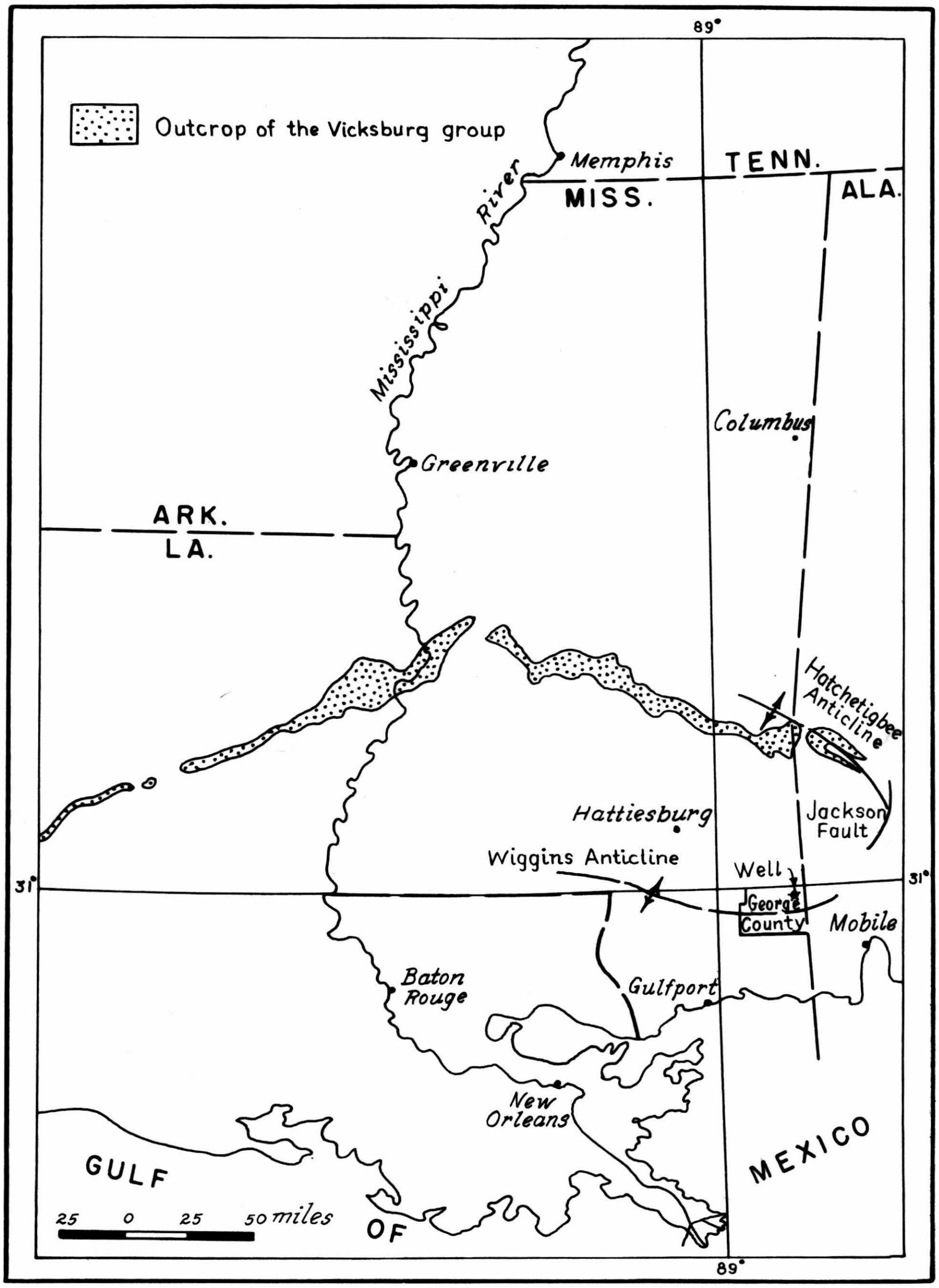


Fig. 1. Index map showing location of the well, nearby structural features, and the outcrop belt of the Vicksburg Group.

epoch and some method of time correlatiom other than "tops" must be developed. For example the checklists of Bandy (1949) and Mornhinveg and Garrett (1935) indicate that most of the "tops" occur at the top of the Vicksburg; few are present inside.

One method of correlation now being tested is the oscillation chart. M.C. Israelsky (1949) suggested that if the foraminifera could be arranged in order of their depositional depth significance, an oscillation chart might be constructed showing relative changes in depth of water at time of deposition within a well or surface column. He presented a chart based on the foraminiferal content of shaker samples ranging from 6,000 to 11,760 feet from a well in the Lirette field, Terrebonne Parish, Louisiana. The oscillations in faunal groups of the "Miocene" were strikingly revealed.

The present study was made on foraminifera in core samples of the Vicksburg Group (Middle Oligocene) from the United Gas Public Service Company Well, Luce Packing Company #1, in Sec. 25, T. 15, R. 6 W., George County, Mississippi. The location of the well and its position with relation to the outcrop of the Vicksburg and to significant nearby structural features is shown on the index map (Fig. 1). An oscillation chart has been constructed and interpreted in the light of our present knowledge of: 1) the various ecologic factors controlling the distribution of the foraminifera; and 2) Gulf Coast Oligocene history.

GEOLOGICAL SETTING

The dominant feature, determined chiefly by the study of the outcrops of Tertiary deposition in the Central Gulf Coastal Plain is deltaic sedimentation (Murray, 1947, p. 1829). The Tertiary began with the deposition of the marine, pro-deltaic Midway (Paleocene) Clays. Deltaic sedimentation reached a climax in lower Eocene (Wilcox) time after which it gradually decreased during the middle Eocene (Claiborne) until it practically ceased in upper Eocene (Jackson) time. Marine sedimentation was predominant during the Jackson and Oligocene epochs. Towards the end of the Oligocene, deltaic sedimentation increased and remained dominant during the Miocene and Pliocene.

The Oligocene sediments consist of deltaic sands, silts, and clays, and marine sands, limestones, clays, and marls. They mark the end of active marine sedimentation in the Central Gulf Coast. In a broad way, the sediments become increasingly calcareous eastward into Alabama and Florida and more silty, sandy, and thicker in western Mississippi and in Louisiana. The eastward change in facies appears to be duplicated to some extent down the depositional dip in southeastern Mississippi.

The deposition of large amounts of sediments during the early Tertiary required isostatic adjustments which resulted in large structural upwarps (Murray, 1947, p. 1829). These large upwarps and associated smaller uplifts strongly affected the amount and character of the near by sediments. The axis of one of these structures, the Wiggins anticline, passes only a few miles south of the well examined for this study. According to Murray (1947, p. 1840), the Oligocene sediments, which maintain a fairly uniform thickness over most of Southern Mississippi, appear to be locally absent in the vicinity of the Wiggins anticline. Therefore, the interpretation of sections in this area must be tempered by considering the possible effect of the upwarp on the character of the sediments found in this well.

The classification of the Oligocene by F. Stearns MacNeil (1944) is followed in this paper. His divisions, along with brief lithologic descriptions, are given below (Table 1).

Table 1. General Lithologic Section

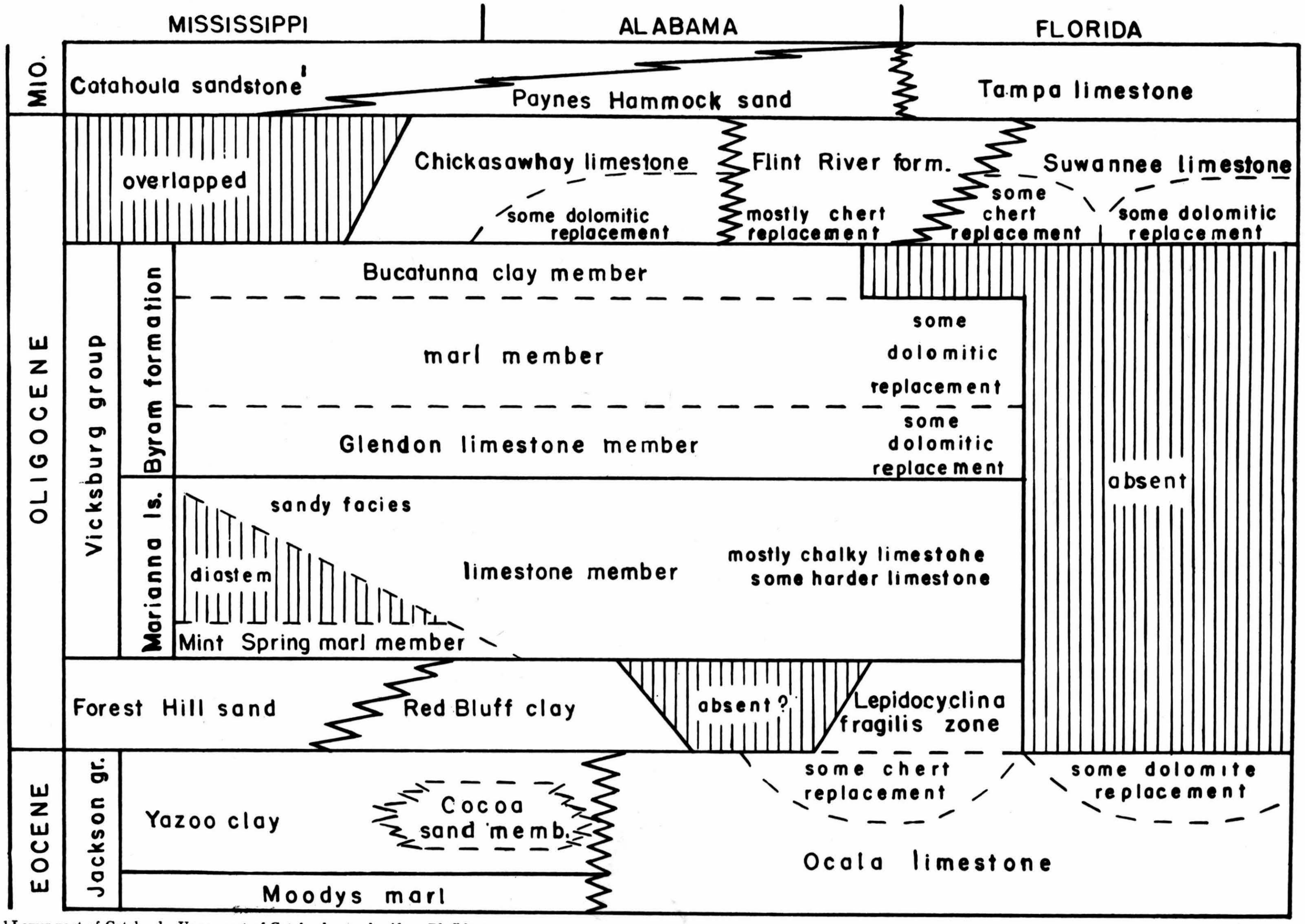
Miocene	Catahoula sandstone
Upper Oligocene	Chickasawhay limestone -- Flint River formation
	Disconformity
Middle Oligocene	Vicksburg group
	Byram formation
	Bucatunna ~~d~~clay member -- fossiliferous calcareous clay, dark lignitic clay, laminated fine sand and clay, laminated argillaceous fine sand with some beds of coarser sand, bentonite, and, in places, a streak of very fossiliferous marl at the top. Many barren zones.
	Marl member -- difficult to define lithologically because of numerous facies but is mainly a glauconitic marl.
	Glendon limestone member-- crystalline limestone.
	Marianna limestone
	Limestone member -- homogenous white

Table 1. (cont.)

		or cream colored limestone, "chimney rock."
		Mint Spring marl member -- calcareous, fossiliferous, argillaceous, glauconitic sand.
	Disconformity	
Lower Oligocene	Forest Hill Sand -- Red Bluff clay.	

In the Vicksburg, MacNeil (1944, p. 1316) includes only the beds for which the name was originally intended, namely the fossiliferous Oligocene of Warren County, Mississippi. The basal formations, the Forest Hill sand and the Red Bluff clay, and the youngest formations, the Chickasawhay limestone and the Flint River formation, although believed to be Oligocene, are excluded from the Vicksburg group inasmuch as various workers have suggested that the top or bottom or both of the Oligocene be removed from the Vicksburg. Some have regarded the lower part to be Eocene and others have dated the upper part Miocene.

The deltaic, lignitic, and laminated and crossbedded sands of the Forest Hill were being deposited in western Mississippi while the marine clays and marls of the Red Bluff were being formed in the eastern part of the state. At the same time the calcareous beds of the Marianna limestone were all ready being laid down in Florida and eastern Alabama. This is only one example of facies changes from west to east. The correlation chart (Fig. 2) indicates that other such examples must be considered in any interpretation of the Vicksburg section.



[1] Lower part of Catahoula. Upper part of Catahoula may be Alum Bluff in age.

Fig. 2. Correlation of Oligocene deposits of Mississippi, Alabama, and Florida. After MacNeil (1944, p. 1315).

The thickness of the Vicksburg at its type locality is given by Mornhinveg and Garrett (1935) as ranging from 105 feet to 125 feet. The thickness of the Vicksburg in this well is about 90 feet.

METHOD OF CHART CONSTRUCTION

The core intervals vary between fifteen and twenty-seven feet; most are twenty feet in length. One foot samples were taken at the well by the United Gas Public Service Company from the top, middle, and bottom of each interval. About half of each sample was available for study by the author. Four samples are missing but their loss fortunately does not seem to have appreciably disrupted the general trends shown. Sample 1867-82 (Bottom) in the Red Bluff, though very fossiliferous, was not picked owing to poor preservation and difficulty in loosening all the aggregates. The lithologic descriptions (Table 2) are for the most part taken directly from the original log with some additions from examination of the washed samples.

Ten cubic centimeters of each sample were washed and then sieved through a 150 mesh screen. A full count was obtained in most cases. Several samples contained such large numbers of foraminifera that it was necessary to split the washings in an Otto microsplit in order to get an amount of material that could be counted in a reasonable length of time. A count was made of the number of specimens of each species or closely related group of species in each sample. The benthonic and pelagic assemblages were separated and their relative percentages are shown at the far right of the chart. Next, the benthonic calcareous and arenaceous forms were separated and graphed separately, because the benthonic calcareous foraminifera are considered the more delicate depth indicators. Also, it is generally believed that the arenaceous types are controlled in occurrence somewhat by factors different from those which control the benthonic calcareous forms.

For purposes of charting, species or groups of species amounting to less than 1 per cent were eliminated and recalculations made for the remainder. To determine the relative depth significance of the calcareous benthonic species the recalculated percentages were plotted against the percentage of _Uvigerina spp._, which are considered to be typically deeper open-water elements. The species (or groups of species) are numbered in order of their apparent peak percentage sequence from shallower to deeper water (Table 3).

The calcareous species are somewhat arbitrarily grouped in order to more readily show the oscillations. The group boundaries are drawn in red on the chart.*

At first the whole section was plotted as one unit. However, it was found that there was such a marked difference between the assemblages of the lower mar~~k~~l and those of the upper clays that the resulting chart was highly confused. When the

---

* As the species and group numbers move to the left deepening is indicated.

two groups were charted separately the oscillations in each were clearly shown. This separation probably represents a fairly significant time break.

A separate plot of the arenaceous forms was made for purposes of comparison. However, they were not grouped.

Specimen counts of the calcareous and arenaceous benthonic species are listed along the left margin of the respective columns. Split samples were recalculated back to the original 10 cubic centimeter volume.

Samples 1 and 2 were not charted because the preservation was so poor that an accurate count was impossible.

Species identifications for the most part were made using the excellent paper of Bandy (1949) as a guide. A check list of all species is included (Table 4).

Table 2. Lithologic Description of the Core

1754 - 74 Top	Dark brown and gray, soft, friable, coarse grained, quartz sand. Slightly lignitic and glauconitic. A few grains of garnet, zircon, and tourmaline.
1754 - 74 Bottom	Brownish black, waxy, tough, noncalcareous, slightly arenaceous shale. Slightly pyritifer~~o~~ous. A few poorly preserved foraminifera.
1774 - 91 Top	Dark brown, medium hard, slightly calcareous, pyritiferous, arenaceous lignitic shale. A few grains of glauconite.
1774 - 91 Middle (1)*	Same as 1754 - 74 (Bottom) plus streaks of brown sand. Some pyrite molds. Lignitic. Bentonitic (?). Shell fragments.
1774 - 91 Bottom (2)	Same as above. A few Bryozoa fragments.
1791 - 1818 Top	Same as above. (Sample missing).
1791 - 1818 Middle (3)	Same as above. Abundant mega-fossil fragments.
1791 - 1818 Bottom	Same as above but no quartz. Considerable pyrite and shell fragments. Hard glauconitic shell lime at base of core. Bentonitic (?). Barren.
1818 - 27 Top (4)	Dark greenish gray, calcareous, pyritiferous shale. Wash sample consisted of almost 100% of foraminifera and shell fragments. Bentonitic.
1818 - 27 Bottom (5)	Same as above. Also lignitic. Bentonitic.
1827 - 47 Top	Same as above. (Sample missing).
1827 - 47 Middle (6)	Same as above. Slightly arenaceous. No pyrite or lignite. Bentonitic. Ostracodes.

Table 2. (cont.)

1827 - 47 Bottom (7)	Same as above. Bentonitic. Ostracodes.
1847 - 67 Top (8)	Same as above. Bentonitic (?). Highly pyritiferous. Ostracodes.
1847 - 67 Middle (9)	Same as above. Slightly glauconitic. Bentonitic. Ostracodes.
1847 - 67 Bottom (10)	Medium hard, light speckled gray, highly glauconitic lime. Very difficult to obtain a clean sample. Many of the foraminifera are replaced by glauconite and others are recrystallized or broken but there are still numerous beautifully preserved specimens. Ostracodes.
1867 - 82 Top (11)	Same as above.
1867 - 82 Middle (12)	Medium soft, nearly pure, white marl. Abundant Bryozoans. Fossils much better preserved than above. Ostracodes.
1867 - 82 Bottom	Same as above. (Not picked)
1882 - 1902 Top (13)	Soft, light tan, fine-grained, clay marl. Bryozoans. Foraminifera well preserved.

* Numbers in the parentheses refer to the picked samples.

Table 3. Samples Arranged in Order of Depth

VICKSBURG

% Uvigerina	Sample No.	Depth in well	Peaks	
			Calcareous	Arenaceous
0.0	8	1847-67 Top	1. Guttulina spp.	1. Textularia sp.D. 2. Textularia subhauerii 3. Textularia sp?
1.0	4	1818-27 Top	2. Cibicides americanus var. 3. Bitubulogenerina aperta 4. Bitubulogenerina vicksburgensis	4. Spiroplectammina mississippiensis
1.6	5	1818-27 Bottom	5. Cibicides americanus 6. Cibicides spp. 7. Bolivina spp. 8. Discorbis 9. Nonionella spp. 10. Quinqueloculina spp. 11. Reusella rectimargo hebetata	5. Textularia tumidula
6.6	6	1827-47 Middle	No peaks	No peaks
8.6	7	1827-47 Bottom	12. Angulogerina byramensis 13. Quinqueloculina bicostata	6. Textularia tumidula var. 7. Textularia sp.B.
15.1	3	1791-1818 Middle	14. Cibicidina mississippiensis 15. Siphonina advena 16. Eponides spp. 17. Cibicides vicksburgensis	No peaks
31.9	9	1847-67 Middle	18. Robulus spp. 19. Cibicides pseudoungerianus 20. Anomalina bilateralis 21. Cassidulina crassa 22. Uvigerina spp.	8. Textularia sp.C.

Table 3 (cont.)

RED BLUFF - EOCENE

% Uvigerina	Sample No.	Depth in well	Peaks	
			Calcareous	Arenaceous
1.6	10	1847-67 Bottom	1. Robulus spp. 2. Siphonina advena 3. Bolivina byramensis 4. Bolivina mexicana 5. Cibicides americanus 6. Cibicides spp. 7. Eponides (?) 8. Angulogerina byramensis	No peaks
3.1	11	1867-82 Top	9. Bolivina spp. 10. Cibicides pseudoungerianus var. 11. Siphonina danvillensis 12. Anomalina spp. 13. Reusella rectimargo hebetata	1. Spiroplectammina mississippiensis
8.6	12	1867-82 Middle	14. Reusella rectimargo 15. Cibicides cocoaensis	2. Spiroplectammina latior 3. Textularia sp. 4. Textularia distincta 5. Textularia aff. claibornensis
15.9	13	1882-1902 Top	16. Cibicidina missippiensis 17. Cibicides pippeni 18. Cibicides lobatus 19. Nonion micrum 20. Anomalina bilateralis 21. Discorbis spp. 22. Dentalina spp. 23. Gyroidina sp.A. 24. Cibicidina mauricensis 25. Cibicides aff. tallahatensis 26. Angulogerina danvillensis 27. Uvigerina spp.	6. Spiroplectammina alabamensis diminutiva

Table 4. Check List

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
								x	x	x	Bitubulogenerina vicksburgensis Howe
	x									x	Bulimina sp?
	x		x	x	x	x	x		x	x	Cassidulina crassa d'Orbigny
x	x	x	x		x			x		x	Cibicidina mississippiensis (Cushman)
x	x	x	x	x				x		x	Cibicides americanus (Cushman)
		x		x	x	x	x	x	x	x	Cibicides pseudoungerianus (Cushman)
x	x	x	x	x	x					x	Cibicides vicksburgensis (Cushman)
x	x	x	x		x	x		x		x	Cibicides sp?
										x	Eponides sp.A.
x	x	x		x		x	x	x	x	x	Globigerina bulloides d'Orbigny
	x	x	x	x				x		x	Eponides sp?
	x	x	x	x	x		x			x	Globigerina sp?
								x		x	Globorotalia menardii d'Orbigny
		x					x	x		x	Guttulina sp?
	x	x		x	x			x	x	x	Raphanulina gibba (d'Orbigny)
	x	x		x		x	x	x	x	x	Robulus sp?
x	x	x	x	x	x	x	x	x	x	x	Siphonina advena (Cushman)
	x	x	x			x		x	x	x	Uvigerina sp?
	x	x	x	x	x	x	x	x	x		Angulogerina byramensis (Cushman)
								x	x		Angulogerina hispidula Cushman and McGlamery
x	x	x	x	x		x		x	x		Anomalina bilateralis Cushman
									x		Bitubulogenerina aperta (Cushman)
x	x	x	x			x		x	x		Bolivina mississippiensis Cushman

Table 4. (cont.)

Sample number

13	12	11	10	9	8	7	6	5	4	3	
					x	x	x	x	x		Cibicides americanus var
								x	x		Entosolenia laevigata (Reuss)
			x		x	x	x	x	x		Guttulina byramensis (Cushman)
							x	x	x		Lagena sp?
		x					x	x	x		Nonionella hantkeni (Cushman and Applin)
				x			x		x		Nonionella tatumi Howe
			x			x		x	x		Quinqueloculina sp?
x	x	x	x	x	x	x	x	x	x		Spiroplectammina mississippiensis (Cushman)
				x	x	x	x	x	x		Textularia tumidula Cushman
x	x	x	x	x		x	x	x	x		Robulus convergens (Borneman)
								x	x		Robulus sp C
									x		Robulus sp D
								x			Angulogerina rugoplicata Cushman
								x			Articulina advena (Cushman)
								x			Articulina byramensis ? Cushman
								x			Asterigerina sp A
		x						x			Bolivina jacksonensis Cushman and Applin
		x	x					x			Bolivina mexicana Cushman
x		x					x	x			Bolivina c.f. plicatella Cushman
							x				Bolivinella subpectinata Cushman
x			x				x				Bulimina ovata d'Orbigny
							x				Cassidulinoides sp
x	x	x	x				x				Cibicides lobatus (D'Orbigny)

Table 4. (cont.)

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
								x			Cibicides aff. westi Howe
								x			Cibicides sp G.
x	x				x			x			Dentalina soluta Reuss
								x			Dentalina sp B
		x						x			Discorbis arcuato-costata Cushman
x		x						x			Discorbis auracana (D'Orbigny, Cushman)
								x			Discorbis byramensis Cushman
								x			Discorbis c.f. orbicularis (Terguem)
		x						x			Discorbis subpatelliformis Cushman and McGlamery
x	x		x					x			Discorbis sp?
					x	x	x	x			Guttulina aequalis d'Orbigny
		x	x					x			Gümbelina cubensis Palmer
								x			Gumbelitria sp?
								x			Gyroidina byramensis Cushman and Todd
								x			Gyroidina sp?
								x			Hauerina fragillissima H.B. Brady
								x			Heronallenia vicksburgensis Cushman
								x			Lagena hexagona (Williamson)
x								x			Nonion planatus Cushman and Thomas
	x		x					x			Nonion sp?
								x			Nonionella crassipunctata Cushman
								x			Nonionella pauciloba Cushman

Table 4. (cont.)

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
x			x					x			Planulina sp?
								x			Polymorphina advena Cushman
					x	x	x	x			Quinqueloculina bicostata d'Orbigny
								x			Quinqueloculina tessellata? Cushman
		x						x			Reusella rectimargo (Cushman) hebetata Cushman
		x	x	x	x	x	x	x			Robulus cultratus Montfort
								x			Rotalia parva Cushman
		x						x			Siphoninella byramensis Cushman
x								x			Spirillina vicksburgensis Cushman
								x			Spiroloculina antellarum d'Orbigny
								x			Spiroloculina grateloupi d'Orbigny
	x	x	x	x	x	x	x	x			Textularia sp?
								x			Triloculina sculpturata Cushman
								x			Virgulina vicksburgensis Cushman
	x		x				x				Bolivina sp?
							x				Gyroidina byramensis Cushman and Todd
x	x		x	x			x				Robulus carolinianus Cushman
				x			x				Robulus sp B
				x	x	x	x				Textularia subhauerii Cushman
						x	x				Textularia tumidula var
				x		x	x				Textularia sp B
					x	x	x				Textularia sp D
						x					Massilina?

Table 4. (cont.)

Sample number

13	12	11	10	9	8	7	6	5	4	3	
	x					x					Raphanulina inaequalis (Reuss)
x	x	x				x					Robulus vicksburgensis (Cushman)
x	x	x	x		x	x					Uvigerina vicksburgensis Cushman and Ellisor
x		x			x						Nodosaria ?
				x							Lenticulina sp A
				x							Quinqueloculina cookei Cushman
				x							Quinqueloculina sp A
				x							Quinqueloculina sp B
				x							Robulus submamilligera (Cushman)
				x							Textularia sp C
				x							Uvigerina sp A
				x							Uvigerina sp B
		x	x								Bolivina byramensis Cushman
		x	x								Anomalina sp?
		x	x								Bolivina spA
			x								Cibicides c.f. choctawensis Cushman and McGlamery
	x	x	x								Cibicides aff. mimulus Bandy
x	x	x	x								Cibicides pippeni Cushman and Garrett
x	x	x	x								Cibicides pseudoungerianus (Cushman) aff. lisbonensis Bandy
x	x	x	x								Cibicides aff. pseudoweullerstorfi Cole
		x	x								Cibicides sp.F
x	x	x	x								Cibicidina aff. mauricensis (Howe and Roberts)
			x								Clavulina sp ?

Table 4. (cont.)

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
		x	x								Lenticulina rotulata (Lamarck)
	x	x	x								Lepidocylina sp ?
	x	x	x								Liebusella byramensis turgida (Cushman)
			x								Marginulina sp ?
x		x	x								Nodosaria obliqua (Linnaeus) H.B. Brady
			x								Nonion alabamensis Cushman and Todd
			x								Pullenia quinqueloba (Reuss) angusta Cushman and Todd
			x								Pyrgo inornata (d'Orbigny)
	x		x								Reusella rectimargo (Cushman)
	x	x	x								Robulus limbosus (Reuss)
			x								Robulus sp A
	x		x								Saracenaria stavensis Bandy
x	x	x	x								Siphonina danvillensis Howe and Wallace
		x									Alabamina scitula Bandy
		x									Anomalina cocoaensis Cushman
		x									Anomalina jacksonensis (Cushman and Applin) limbosa Cushman and Ellisor
		x									Asterigerina sp ?
		x									Bolivina alzanensis Cushman
		x									"Bolivina caelata" Cushman
		x									Bolivina mexicana Cushman aliformis Cushman
		x									Bolivina c.f. mornhinvegi Cushman

Table 4. (cont.)

Sample number

13	12	11	10	9	8	7	6	5	4	3	
		x									Bolivina pisciformis Galloway and Morrey
	x	x									Bolivina taylori Howe
		x									Bolivina sp B
		x									Bolivina sp C
		x									Camerina ?
x		x									Cassidulina alabamensis Bandy
	x	x									Cibicides cocoaensis (Cushman)
x	x	x									Cibicides aff. lawi Howe
	x	x									Cibicides sp C
	x	x									Cibicides sp I
	x	x									Cibicidina aff. blanpedi (Toulmin)
		x									Cibicidina danvillensis (Howe and Wallace)
		x									Dentalina vertebralis (Batsch)
	x	x									Discorbis hemisphaerica Cushman
		x									Gaudryina stavensis Bandy
x	x	x									Globigerina inscrebscens Bandy
x		x									Globigerina rotundata d'Orbigny jacksonensis Bandy
x	x	x									Globigerina trilocularis d'Orbigny
		x									Loxostoma delicatulum (Cushman)
		x									Planorbulinella larvata (Parker and Jones)
		x									Operculina c.f. ocalana Cushman
	x	x									Robulus alto-limbatus (Gümbel)
		x									Robulus cocoaensis (Cushman)

Table 4. (cont.)

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
x	x	x									Robulus euglypheus Bandy
x	x	x									Robulus pseudovortex Cole
	x	x									Uvigerina curta Cushman and Jarvis
	x	x									Vaginulina legumen (Linne) elegans d'Orbigny
x	x										Angulogerina danvillensis Howe and Wallace
x	x										Angulogerina c.f. vicksburgensis Cushman
	x										Anomalina costiana Weinzerl and Applin
	x										Astacolus sublitus (Nuttall)
	x										Baggina thalmanni ? Pijpers
	x										Bitubulogenerina howei Cushman
	x										Bolivina hunerei Howe
	x										Bolivina moodysensis Cushman and Todd
x	x										Bolivina salebrosa Bandy
	x										Bulimnella sp ?
x	x										Cassidulinoides howei Cushman
x	x										Cibicides floridanus (Cushman) diminutivus Bandy
	x										Cibicides pippeni Cushman and Garrett stavensis Bandy
	x										Cibicides aff. tallahatensis Bandy
	x										Cibicides sp D
	x										Cibicides sp E
	x										Dentalina indifferens Reuss
	x										Dentalina sp

Table 4. (cont.)

Sample number

13	12	11	10	9	8	7	6	5	4	3	
	x										Entosolenia orbignyana (Seguenza) elliptica (Cushman)
	x										Eponides choctawensis Cushman and McGlamery
	x										Eponides mexicanus (Cushman)
	x										Eponides ouachitaensis Cushman and Todd
x	x										Globigerina dutertrei d'Orbigny
x	x										Globigerina ouachitaensis senilis Bandy
x	x										Guttulina hantkeni Cushman and Ozawa
x	x										Gyroidina sp A
x	x										Nonion micrus Cole
	x										Spiroplectammina latior Bandy
	x										Textularia aff. claibornensis Weinzerl and Applin
x	x										Textularia distincta (Cushman)
	x										Valvulineria jacksonensis Cushman
x											Bifarina vicksburgensis (Cushman)
x											Bolivina jacksonensis Cushman and Applin
x											Cassidulina armosa Bandy
x											Dentalina cucarensis Cole
x											Dentalina jacksonensis (Cushman and Applin)
x											Discorbis assulata Cushman
x											Discorbis farishi Cushman and Ellisor

Table 4. (cont.)

Sample number											
13	12	11	10	9	8	7	6	5	4	3	
x											Eponides jacksonensis (Cushman and Applin)
x											Eponides aff. lisbonensis Bandy
x											Globigerina dissimilis Cushman and Bermudez
x											Globigerina eocaenica Terguem
x											Globigerinoides pseudodubia Bandy
x											Globorotalia crassata densa (Cushman)
x											Gümbelina sp ?
x											Guttulina communis (d'Orbigny)
x											Lagena costata (Williamson) Reuss
x											Massilina decorata Cushman
x											Nodosaria cookei Cushman
x											Nonion nicobarensis Cushman
x											Nonionella spissa Cushman
x											Polymorphina liosoma Bandy
x											Saracenaria moresiana
x											Spiroplectammina alabamensis (Cushman) diminutiva Bandy
x											Uvigerina gardnerae Cushman
x											Uvigerina yazooensis Cushman

DEPTH CHANGES THE MAJOR CAUSE OF OSCILLATIONS

Evidence from recent studies

It has been assumed that the oscillations recorded in the section from this well are caused by changes in depths of the sea bottom. It would be well to consider, in view of the many ecologic factors and the complex interrelationships between them, if this assumption is valid.

In recent years a number of profiles have been prepared off the shores of Southern California (Natland, 1933), the east coast of North America (Phleger, 1939, 1942; Parker, 1948), Florida and the West Indies (Norton, 1930), and the Red Sea (Said, 1950). In all of these profiles the foraminiferal assemblages are found to show progressive changes seaward and the zones or faunal groups are given bathymetric limits. The temperature limits are also given for the zones in most of the profiles. It is interesting to note that each profile differs from the others both in the number of zones and in the bathymetric limits of similar zones. These differences are partly due to temperature controls with the result that marine faunas of any bathymetric level are roughly zoned according to latitude, modified to some extent by the disposition of warm and cold currents (Krumbein and Sloss, 1951, p. 238).

Some workers argue that temperature is the all important ecologic factor; but the fact remains that the temperature itself is still dependent upon depth. In the Red Sea the top and bottom temperatures differ by only two degrees, yet a good depth zonation exists.

In high latitudes the zoning is complicated by seasonal overturning. Pelagic assemblages seem to reflect climatic changes more than do benthonic populations. Any annual variation in temperature is generally limited to the upper 100 meters of the oceans (Sverdrup, et al, 1946, pp. 131-133). Probably only the very large, long term climatic changes affect the bottom life.

Even though the recent profiles do show a real depth zonation, one must not, however, neglect consideration of the many ecologic factors that are known which might cause modifications within the faunal assemblages or in the depths at which the breaks occur from profile to profile. Table 5 is a list of ecologic factors compiled from a number of sources. Undoubtedly more can be, and in the future will be added. Many of the controls are either dependent upon depth or they vary in the same direction as depth; others are only of minor influence; some are not ~~a~~effective below certain depths; still others are only ~~a~~effective locally or temporarily. It is evident that at shallow depths their influence is much more pronounced than in deeper waters where they are of little or no direct importance.

<u>Table 5. Ecologic Controls Affecting the Foraminifera.</u>

1. Temperature - Dependent to a large extent on depth.
   - a. Actual maximum and minimum temperatures, especially the latter.
   - b. Annual variation
2. Salinity - closely related to temperature. Most important near shore.

)Secondary in importance according to Schmidt, (1935,p.11).

Table 5. (cont.)

3. Light - Only of indirect influence on benthonic forms below the euphotic zone. Affected by amount of suspended organic and inorganic matter.

4. Food supply -- Mainly important in regulating total numbers.

5. Rate of sedimentation -- Will affect total count.

6. Pressure -- Probably minor.

7. Nature of bottom -- May cause some differences but probably will not change the main trends
    a. Topography - Benches might cause local reversals of profile.
    b. Kind of sediment.

8. Distance from shore -- More important at shallow depths.

9. Degree of agitation (turbidity) - ~~a~~effects probably local and temporary.

10. Nature of general movement of water
    Mixing by waves, winds, and currents. Probably an overrated factor, especially if only dominant forms are used for calculations (Myers, 1944, p. 23).

11. Chemical composition

    a. Relative quantity of salts in solution
    b. Amount of available oxygen
    c. pH
    d. Oxidation - reduction potentials of the bottom material
    e. Amount of nitrogen and phosphate

12. Barriers (Sills)

13. Convective overturning

14. Upwelling

15. Runoff from land

Added to the complexity of environmental control are the variables among the animals themselves (Table 6).

Table 6. Variables Among the Animals Themselves

1. Migratory habits
2. Reproductive habits
3. Rate of reproduction
4. Nutritional requirements
5. Slightly different types of the same species may be adapted to different depths (Differences in size and thickness of test).
6. Size and shape of test -- Myers (1943, p. 29) says that most foraminifera with large planospiral, fusiform, or discoidal tests are limited to firm sandy or sandy-mud bottoms within the sublittoral zone not below the depths at which photosynthetic organisms thrive and are most numerous in areas adjacent to coral reefs.
7. Different degrees of tolerance to various ecologic conditions.

Although much has been accomplished in recent years in gaining an insight into the general habitat of the different genera and species of the Foraminifera, the information is still too inadequate to establish the definite principles of faunal distribution. Myers (1941, 1942, 1943, 1944, 1948), who has added considerably to our knowledge of the ecology of the foraminifera, significantly notes (1948, p. 30) that some of the work being done on recent foraminifera may be hurt because the investigators have failed to determine which species actually inhabited the several life zones, that is, they dealt only with empty tests.

Summary

Recent profiles indicate that depth zones can be established. However, correlations from one profile to another in the absolute sense are to be made with care because modifications of the other ecologic controls will cause changes in faunal assemblages and in the absolute depth limits of the zones. This will be especially true when attempts are made to correlate over a wide geographical range. For example, as a result of temperature controls, the bathymetric level of a particular biocoenose may vary somewhat from place to place. Similarly, the faunas of a given bathymetric level will change in character with latitude. Another complication that must be considered is the ability of many arctic and temperate species to extend their range toward the equator by moving down the bathymetric gradient along isotherms in order to maintain a constant temperature environment.

In cognizance, therefore, of the impractibility of utilizing absolute depth limits for correlation purposes, the bathymetric groups employed in the oscillation chart are derived on the basis of their relative depth significance.

THE INTERPRETATION OF FOSSIL MATERIAL

Information concerning the ecology of the recent foraminifera is incomplete and inadequate. In the interpretation of fossil assemblages in a geologic section the factor of time is superimposed upon the highly complicated three dimensional patterns of environment. If the premise is accepted that the major zoning found in recent profiles is a function of relative depth, then it is logical to expect that oscillations of marine fauna recorded in a well should be caused by changes in the depth of the water at that site. The possible influence of the other factors should still be considered. However, as a sample covers an interval of several inches up to several feet in thickness (equivalent to hundreds or thousands of years), it seems plausible that most of the effects due to small fluctuations of ecologic factors would be practically indistinguishable and only the broader depth changes would be preserved.

In the construction of a chart based on the relative depth significance of foraminiferal species in a fossil column, it is presumed that the response to environmental conditions of species identical with, or closely similar to recent species has remained the same. As the age of the rocks increases, the ease with which environmental conditions can be deciphered decreases owing to the presence of fewer and fewer present day species. Just how far similarity of test morphology to similarity of environment can be equated remains problematical. Nevertheless, Tertiary faunas, at least, are closely related enough to present faunas that speculations should not be too far amiss. As the knowledge of recent ecology steadily increases, so shall interpretations of the environments of fossil assemblages be more confidently extended farther into the geologic past.

Another problem involved in the interpretation of fossil assemblages is the element of mixing. According to Said (1950, p. 15) the foraminifera found in any one sample may represent any one or more of the following sources:

1. Those that actually lived on the bottom at that particular point.
2. Tests of adult forms that were discarded in the process of reproduction.
3. Excretions of predators of foraminifera.
4. Transported there by currents.

In the case of fossil samples add:

5. Contamination from sources of sediment.

The error due to original mixing factors is probably small except possibly in near shore and shallow water zones where sorting due to current action may be locally important. By utilizing only the dominant species in a sample for the calculations, much of this error is eliminated. Evaluation of the importance of contamination from older sediments at the source is difficult. Authorities disagree as to the ability of the foraminiferal tests to stand the rigors of erosion and redeposition. Some think few will survive, but others believe a fair number will safely pass through the ordeal due to their flotability and small size. The latter advocates are probably impressed with the capacity of the foraminifera to endure strenuous treatment during the preparation of washed samples. As one becomes more familiar with the faunal succession in the rocks of a particular region, he can more readily detect those older species which contaminate the sample.

Further errors may occur in samples which were subject to strong mechanical abrasion and to diagenetic changes such as solution and recrystallization. Pyrite and glauconite molds are common. In such samples (as in 10, 11, and 12 in this study) it is impossible to identify all the specimens. In some cases less than half the original fossil content may be recognizable. Lowman (1947, p. 18) states that diagenetic processes can differentially destroy fossils, thereby modifying percentage abundance distributions.

TOTAL NUMBERS VERSUS PERCENTAGE DISTRIBUTION

There are differences of opinion concerning which is the more valid indicator of a particular assemblage, total number of specimens or the relative percentages of the species. Each biocoenose is in a state of balance with respect both to its environment and to its many faunal elements. Samples of the same faunal group may vary greatly in number of specimens, but will still have the same relative percentages of species in order to maintain that balance. Abundance is strongly dependent upon food supply and upon rate of production and therefore will usually vary with the seasons and with geographical location. In fossil samples the numbers may bear little resemblance to the original abundance due to the masking effect of differential rates of sedimentation.

There appears to be no objection, therefore, to the use of percentages. In addition, the percentage method is to be valued for the ease with which a definite analysis can be made of the relative importance of the different species in the samples.

INTERPRETATION OF THE CHART

The chart shows that in addition to the faunal breaks there is a very pronounced deepening between samples 10 and 9. The deepest point in the section sampled is sample 9. It probably can be correlated with the transgression of the Marianna limestone. (MacNeil, 1944, p. 1328). The Red Bluff in this well correlates very well faunally and lithologically with the same formation at Little Stave Creek, Alabama (MacNeil, 1944, p. 1322; Bandy, 1949). This break seems, therefore, to be an excellent time line and might serve as a good base line for comparing the oscillations with those in other wells. Samples 10, 11, 12, and 13 show a very regular deepening through the Red Bluff and into the Jackson.

Within the Vicksburg group, the deepening in sample 9 is followed by shallowing in sample 8, moderate deepening in sample 7, gradual shallowing through samples 6, 5, and 4, another fairly strong deepening in sample 3, and finally, probable shallowing through samples 2 and 1.

It is difficult to divide the Vicksburg here into its smaller units by comparison with outcrop descriptions because of the down dip changes. One might tentatively place the lower limit of the Bucatunna clay at about 1827 feet using lignite as a marker. It is possible that the deepening in sample 7 might be correlated in time with the Glendon limestone. No attempt here is made to divide the Vicksburg except to suggest the possibilities mentioned just above.

The sand lying above the Vicksburg at approximately 1760 feet is the Catahoula sandstone of Lower Miocene age.

A comparison of the Red Bluff with the Vicksburg discloses that the latter, excluding sample 9, was deposited at relatively shallower depths than was the Red Bluff. Robulus spp. and Siphonina advena, for example, are in group I of the Red Bluff, but are in groups IV and III of the Vicksburg. Species common to the two sections do not maintain the same relative positions in each section, but, except for Siphonina advena, they are all small in percentage or irregular in distribution.

The section reveals that no species characteristic of brackish water type and only a small percentage from near shore zones are represented. Comparison of the section with recent profiles suggests that the shallowest depth of the Vicksburg at this location was about 90 to 100 meters. As faunal zones are less distinct and have broader ranges in deeper waters it it to be expected that oscillations at these points would be more difficult to perceive. That oscillations can be detected in a section which upon spot checking or even checklisting appears to present a monotonous, stable fauna is perhaps the most encouraging result of this study.

The oscillations in the arenaceous column correspond qualitatively with those indicated by the calcareous column. The percentage distribution of the pelagic forms is roughly related to the oscillations in the calcareous column. Higher percentages of Globigerina are present in the deeper water samples than in those representing shallower water.

GENERAL COMMENTS ON THE USE OF THE CHART

The great advantage of the chart lies in its relativity. A well located up dip may contain faunas representative of much shallower water. Attempts to correlate the two wells using "tops" and lithology might be difficult because the sections would be very different. However, each would record the same transgressions and regressions. If the two columns are matched using the same time line as a base, the correlations can be easily made.

The method would be of great use for locating time horizons in an oil field. If one well is completely plotted, an experienced worker could conceivably use the one chart and make his correlations without having to make other than a qualitative study of the other wells. After the main deep points and shallow points in the detailed section have been determined and the faunal assemblages have been thoroughly studied, it is possible that corresponding points in the other wells may be located merely by inspection. As correlations are made over greater distances, more wells will have to be plotted in detail. Care must be used in areas in which local differential upwarping and downwarping occurred contemporaneously with deposition. Later faulting will also cause difficulties of interpretation.

One disadvantage of the method lies in the time required to pick, count, identify, and plot up a section. Even if a good check list is available, considerable time must be spent trying to identify every specimen, many of which may be poorly preserved. Naturally, the more familiar the micropaleontologist is with an area, the faster the work will proceed. One solution to this problem might be to count fewer species, say only those making up 10 percent or more of a sample. It may even be possible to use only three of four dominant, depth-sensitive species and still be able to chart the oscillations.

CONCLUSIONS

The study of oscillations in a section through the Vicksburg group produced two significant results:

1. Though the section appeared at first glance to be made up of a rather monotonous, homogeneous foraminiferal fauna, a plot of the percentage distributions of species and species groups nevertheless recorded very distinct oscillations.

2. A single chart could not be carried across a strong faunal break such as occours between the Red Bluff and the Vicksburg. By making separate charts above and below this time line a clear picture of the oscillations was resolved.

The author feels that the oscillation chart method will prove to be a very worthy correlation tool in sedimentary sections in which there were fairly rapid depth changes. Unfortunately, only a few charts have been constructed and no comparison of sections has been made. Further experimentation is definitely desirable and warranted.

Wells within a local area such as an oil field should be expected to correlate perfectly down to the smallest changes, except where complicated by faulting. Regionally, there will be minor differences due to differential movements contemporaneous with deposition, but the larger transgressions and regressions might still be correlated. Finally, with due allowance for local movements and regional disturbances, it may some day be possible to correlate strong eustatic changes from one hemisphere to the other by the use of oscillation charts.

BIBLIOGRAPHY - GENERAL

Cushman, J.A.

1940, Foraminifera, Their Classification and Economic Use. Harvard Univ. Press, Cambridge, Mass.

1941, A Study of the Foraminifera Contained in Cores from the Bartlet Deep. Amer. Jour. Sci., vol. 239, pp. 128-147.

Cushman, J.A. and Henbest, L.G.

1940, Geology and Biology of North Atlantic Deep-sea Cores Between Newfoundland and Ireland: pt. 2, Foraminifera. U.S. Geol. Survey, Prof. Paper 196-A, pp. 35-50.

Ellisor, Alva C.

1940, Subsurface Miocene of Southern Louisiana. Amer. Association Petr. Geol., Bull., Vol. 24, pp. 435-475.

Galloway, J.J.

1933, A Manual of Foraminifera. Principia Press, Bloomington, Indiana.

Glaesner, M.F.

1947, Principles of Micropaleontology. John Wiley & Sons, New York, N.Y.

Israelsky, Merle C.

1949, Oscillation Chart. Amer. Assoc. Petr. Geol., Bull., Vol. 33, pp. 92-98.

Krumbein, W.C., and Sloss, L.L.

1951, Stratigraphy and Sedimentation. pp. i-ix, 1-497. W.H. Freeman and Co., San Francisco, Calif.

Lowman, S.W.

1947, Recent Clastic Sediments Project. Amer. Assoc. Petr. Geol. Research Com., 1946-47, Project 5.

Myers, E.H.

1941, Ecological Studies of the Foraminifera: Report Subcommittee on the Ecology of Marine Organisms. Nat.

Res. Council, No. 1, pp. 43-46.

1942, Ecologic Relationships of some Recent and Fossil Foraminifera: Report Comm. Marine Ecol. and Paleoecol., Nat. Res. Council, No. 2, pp. 31-36.

1943, Ecologic Relationships of the Larger Foraminifera: ibid, No. 3, pp. 26-30.

1944, Biology of the Foraminifera in Relation to Stratigraphy and Petroleum Geology: ibid, No. 4, pp. 22-25.

1948, Bibliography on the Ecology of the Foraminifera: ibid, No. 7, pp. 28-37.

Natland, M.L.

1933, The Temperature and Depth Distribution of some Recent and Fossil Foraminifera in the Southern California Region. Scripps Institute Oceanogr., Bull., Tech. Ser., vol. 3, No. 10, pp. 225-230.

Norton, R.D.

1930, Ecologic Relations of some Foraminifera. Scripps Institute Oceanogr., Bull., Tech. Ser., vol. 2, No. 9, pp. 331-388.

Parker, Frances L.

1948, Foraminifera of the Continental Shelf from the Gulf of Maine to Maryland. Mus. Comp. Zool., Bull., vol. 100, No. 2, pp. 211-253.

Phleger, F.B., Jr.

1939, Foraminifera of Submarine Cores from the Continental Slope, Part 1. Geol. Soc. Amer., Bull., vol. 50, pp. 1395-1422.

1942, Ibid: Part 2. Geol. Soc. Amer., Bull., vol. 53, pp. 1073-1098.

Phleger, F.B. and Walton, W.R.

1950, Ecology of Marsh Bay Foraminifera, Barnstable, Mass. Amer. Jour. Sci., vol. 248, pp. 274-294.

Phleger, F.B. and Hamilton, W.A.

1946, Foraminifera of two Submarine Cores from the North Atlantic Basin. Geol. Soc. Amer., Bull., vol. 57, pp. 951-966.

Said, Rushdi

1950, The Distribution of Foraminifera in the Northern Red Sea. Contr. Cushman Lab. Foram. Res., vol. 1, pts. 1, 2, pp. 9-29.

Schmidt, Hermann

1935, Die bionomische Einteilung der fossilen Meeresboden, Fortschritte der Geologie und Paleontologie, Band XII, Heft 38, Berlin. (Translation by M.C. Israelsky).

Sverdrup, H.U. et al

1946, The Oceans. Prentice Hall, New York, N.Y.

Trask, Parker D.

1948, Environmental Conditions of Deposition in the Gulf of Mexico. Rep. Comm. Treatise Marine Ecol. and Paleoecol., No. 8, pp. 101-103.

Vaughan, T.W.

1940, Ecology of Modern Marine Organisms with Reference to Paleogeography. Geol. Soc. Amer., Bull., vol.51, pp. 433-468.

Zobell, Claude E.

1946, Marine Microbiology. pp. i-xv, 1-240. Chronica Botanica Company, Waltham, Mass.

- PALEONTOLOGY

Bandy, O.L.

1949, "Eocene and Oligocene Foraminifera from Little Stave Creek, Clarke County, Alabama". Bull. Amer. Paleont., vol. 32, No. 131, pp. 1-210, pls. 1-27.

Cushman, J.A.

1922, The Byram Calcareous Marl of Mississippi and its Foraminifera. U.S. Geol. Surv., Prof. Paper 129-E, pp. 87-122, pls. 14-28.

1922, The Foraminifera of the Mint Spring Calcareous Marl Member of the Marianna Limestone. U.S. Geol. Surv., Prof. Paper 129-F, pp. 123-152, pls. 29-35.

1923, The Foraminifera of the Vicksburg Group. U.S. Geol. Surv. Prof. Paper 133, pp. 11-71, pls. 1-8.

1933, New Foraminifera from the upper Jackson Eocene of the Southeastern Coastal Plain Region of the United States. Contrib. Cushman Lab. Foram. Res., vol.9, pt. 1, pp. 1-21, pls. 1,2.

1929, Notes on the Foraminifera of the Byram marl. Contrib. Cushman Lab. Foram. Res., vol. 5, pt. 2, pp. 40-48, pl. 8.

1935, New Species of Foraminifera from the Lower Oligocene of Mississippi. Contrib. Cushman Lab. Foram. Res., vol. 11, pt. 2, pp. 25-39, pls. 4,5.

1937a, A Monograph of the Foraminiferal sub-family Virgulininae. Cushman Lab. Foram. Res., Special Publ.9, pp. i-xv, 1-228, pls. 1-24.

1937b, The Described American Eocene Species of Uvigerina. Contrib. Cushman Lab. Foram. Res., vol. 13, pt. 3, pp. 74-87, pls. 11,12.

1946, A Rich Foraminiferal Fauna from the Cocoa Sand of Alabama. Cushman Lab. Foram. Res., Special Publ.16, pp. 1-40, 8 pls.

Cushman, J.A. and Edwards, Patricia

1938, Notes on the Oligocene Species of Uvigerina and Angulogerina. Contrib. Cushman Lab. Foram. Res., vol. 14, pt. 4, pp. 74-89, pls. 13-15.

Cushman, J.A. and Garrett, J.B.

1938, "Three New Rotaliform Foraminifera from the Lower Oligocene and Upper Eocene of Alabama". Contrib. Cushman Lab. Foram. Res., vol. 14, pt. 3, pp.62-66, pl. 11.

Cushman, J.A. and McGlamery, Winnie

1938, Oligocene Foraminifera from Choctaw Bluff, Alabama. U.S. Geol. Sur. Prof. Paper 189-D, pp. 101-19, pls. 24-28.

1939, New Species of Foraminifera from the Lower Oligocene of Alabama. Contrib. Cushman Lab. Foram. Res., vol. 15, pt. 3, pp. 45-49, pl. 9.

1942, Oligocene Foraminifera near Millry, Alabama. U.S. Geol. Sur., Prof. Paper 197-B, pp. 65-84, plts. 4-7.

Cushman, J.A. and Todd, Ruth

1945, Foraminifera of the Type Locality of the Moody's Marl Member of the Jackson Formation of Mississippi. Contrib. Cushman Lab. Foram. Res., vol. 21, pt. 4, pp. 79-105, pls. 13-16.

1946, A Foraminiferal Fauna from the Byram Marl at its Type Locality. Contrib. Cushman Lab. Foram Res., vol. 22, pt. 3, pp. 76-102, pls. 13-16.

Howe, H.V.

1930, Distinctive New Species of Foramifera from the Oligocene of Mississippi. Jour. Paleont., vol. 4, No.3, pp. 263-267.

1939, Louisiana Cook Mountain Eocene Foraminifera. Louisiana Dept. Cons., Geol. Bull. 14, pp. I-XI, 1-122, pls 1-14.

Mornhinveg, A.R. and Garrett, J.B.

1935, Study of Vicksburg Group at Vicksburg, Mississippi. Amer. Assoc. Petr. Geol.,Bull., vol.19, pp.1645-1667.

Nuttall, W.L.F.

1932, Lower Oligocene Foraminifera from Mexico. Jour. Paleont., vol. 6, No. 1, pp. 3-35.

-STRATIGRAPHY

Cooke, C.W.

1918, Correlation of the Deposits of Jackson and Vicksburg Ages in Mississippi and Alabama. Wash. Acad. Sci., Jour., vol. 8, pp. 186-198.

1922, The Byram Calcareous Marl of Mississippi. U.S. Geol. Survey, Prof. Paper 129-E, pp. 79-86.

1935, Notes on the Vicksburg Group. Amer. Assoc. Petr. Geol., Bull., vol. 19, p. 1170.

1933, The Correlation of the Vicksburg Group. U.S. Geol. Survey, Prof. Paper 133, pp. 1-9.

MacNeil, F. Stearns

1944, Oligocene Stratigraphy of Southeastern United States. Amer. Assoc. Petr. Geol.,Bull., vol.28, pp.1313-1354.

Murray, G.E.

1947, Cenozoic Deposits of Central Gulf Coastal Plain. Amer. Assoc. Petr. Geol., Bull., vol. 31, pp. 1825-1850.

Stephenson, L.W.

1928, Major Marine Transgressions and Regressions and Structural Features of the Gulf Coastal Plain. Amer. Jour. Sci., ser. 5, vol. 16, pp. 281-298.