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THE JURASSIC TODILTO BASIN

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THE ENVIRONMENT OF THE JURASSIC TODILTO BASIN, NORTHWESTERN NEW MEXICO

By

Douglas W. Kirkland

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Geology

The University of New Mexico

1958

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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CONTENTS

235366

Page

ILLUSTRATIONS

Figures Page

Page

Page

ABSTRACT

The Todilto evaporites of Upper Jurassic age were precipitated in a basin which covered more than 34,000 square miles of northwestern New Mexico and parts of Colorado and Arizona. The Todilto formation consists of a lower Limestone and an upper Gypsum member, and has a maximum thickness of a little more than 100 feet. Both members are varved.

The varves of the Limestone member consist of three distinct laminae: limestone, sapropel, and silt. Calcium carbonate was precipitated in the summer because of evaporation and decreased carbon dioxide concentration. The maximum rate of deposition of organic material occurred during the fall and winter as plankton died off. During the winter and spring a clastic layer was deposited. The clastic grains decrease in frequency in varves having thick limestone laminae and increase in varves having thin limestone laminae, which suggests a relationship between influx of clastic grains and temperature or rainfall, or both. A different type of varve predominates in the Gypsum member. It consists of laminae of bituminous limestone and gypsum. Seasonal variation in the carbon dioxide concentration of the basin water is believed to have been the main factor governing the precipitation of limestone and gypsum.

ABSTRACT

The Todilto formation of Upper Jurassic [illegible] is [illegible] in a basin which covers [illegible] northwestern New Mexico and parts of Colorado and Arizona. The Todilto formation consists of a lower limestone and an upper gypsum member, and has a maximum thickness of [illegible] feet. [illegible] are varved.

The varves of the limestone member consist of three different laminae: limestone, [illegible], and [illegible]. Calcium carbonate was precipitated in the [illegible] and [illegible] carbon dioxide concentration. [illegible] material occurred during [illegible] during the winter and spring [illegible]. The [illegible] grains decrease in frequency [illegible] and increase in [illegible] relationship between [illegible] and temperature or rainfall, or both. A different type of varve predominates in the gypsum member. It consists of [illegible], [illegible] limestone and gypsum. [illegible] variation in the carbon dioxide concentration [illegible] is believed to have been the main factor [illegible] the precipitation of limestone and gypsum.

Changes in varve thickness were caused by changes in climate. Thick varves indicate dry or warm years and thin varves represent moist or cool years. Measurement of 1,592 varves revealed a cyclic pattern of changes in varve thickness, interpreted as warm or dry intervals alternating with moist or cool intervals every 60 and 180 years.

The varve studies made it possible to reconstruct certain elements of the Upper Jurassic climate of northwestern New Mexico. The average summer temperature was about 85° F and the average winter temperature about 57° F. Precipitation was seasonal with most of the rainfall occurring in the winter and spring. The low plains surrounding the basin were arid, while the highlands around the drainage basin were well watered. The evaporation rate was greater than 80 inches per year.

The varved nature of the limestone and gypsum has made an estimate of the rate of sedimentation of the Todilto formation possible:

Interval	Absolute time	Thickness
Gypsum member	5,300 years	90 feet
Limestone member	14,300	6.5
Totals	19,600	96.5

The Todilto evaporites are believed to have originated in a saline lake rather than in a marine embayment because: (1) the short period of deposition suggests climatic rather than structural control for the influx of water into the basin; (2) death assemblages of two genera of fossil fish occur at several localities around the edge of the basin and a review of the fossil and lithologic associations of these genera at other fossil localities suggests that they were non-marine; (3) the Ca^{++}, CO_3^{--}, and SO_4^{--} ions, necessary for the formation of the limestone and gypsum, could have been supplied from the weathering of Permian and Triassic rocks in the Todilto drainage basin; and (4) the paleogeography of the Gypsum member, which was deposited in an area of about 12,000 square miles in the center of the basin, suggests a slowly drying lake.

The Todilto [illegible] saline lake rather than [illegible] (1) the short period of deposition [illegible] control for the influx of water into the basin, (2) [illegible] of two genera of fossil fish [illegible] formation around the edges of the basin and [illegible] of these genera in other [illegible] marine (3) [illegible] for the formation of the limestone and gypsum [illegible] derived from the weathering of Permian and Triassic rocks in the Todilto basin; and (4) the paleogeography [illegible] deposited in an area of about 17,000 square [illegible] of the basin, suggests a steadily growing lake.

INTRODUCTION

General Description

The Todilto limestone and gypsum of late Jurassic age is an evaporite sequence of problematical origin underlying about 34,500 square miles in northwestern New Mexico, northeastern Arizona, and southwestern Colorado (Fig. 28). The Todilto basin roughly coincides with the Upper Cretaceous San Juan Basin. The term "blanket" describes the Todilto formation because its maximum thickness is only about 100 feet. Harrison (1949, p. 88) obtained a thickness of 252 feet in the Hagan Coal Basin, Sandoval County, New Mexico, but this figure is probably excessive.

The Todilto formation is divided into two members. The lower member, a dark gray to brown, thin-bedded to laminated, bituminous limestone, has an average thickness of about 7 feet. In the northern part of the Lucero Uplift, near Laguna, Valencia County, New Mexico, the Limestone member has a maximum thickness of 45 feet. When broken, the limestone emits a distinct hydrogen sulfide odor.

The upper member of the Todilto formation consists of a crystalline gypsum unit of variable thickness. The gypsum is confined to the center of the basin where it ranges in thickness from a pinch-out to over 100 feet. The gypsum is mostly massive; however, near the

TODILTO FORMATION

General features

The Todilto limestone and gypsum [illegible] evaporite sequence of [illegible] and [illegible] square miles in northwestern New Mexico, northeastern Arizona, and southwestern Colorado ([illegible]). The [illegible] coincides with the Upper Jurassic [illegible]. [illegible] "blanket" deposit [illegible] thickness is only about 100 feet. [illegible] (1947, p. 22) [illegible] thickness of 252 feet in the Navajo Coal Basin, Sandoval County, New Mexico, but this figure [illegible].

The Todilto Formation [illegible] members. The lower member, a dark gray to brown, [illegible] limestone, has an average thickness of about 5 feet. In the [illegible] part of the Laguna [illegible], [illegible], Valencia County, New Mexico, the limestone member [illegible] broken, the limestone emits a [illegible] odor.

The upper member of the Todilto Formation consists of crystalline gypsum and is of variable thickness. The gypsum is confined to the center of the basin where it ranges in thickness [illegible] to over 100 feet. The [illegible], however, and the top of the member, thin beds of red and green shale, siltstone, fine-grained sandstone, and limestone are sometimes found.

Statement of the Problem

The Todilto formation has been considered marine because of the substantial thickness of the Gypsum member, the presence of fossil fish interpreted as marine, and the similar stratigraphic position of the marine Curtis formation to the northwest. Other evidence suggests that the Todilto formation is nonmarine and was deposited in a large, shallow, saline lake in an arid basin. The object of this study was to determine the origin and environment of deposition of the Todilto formation by a detailed petrographic study.

Pre-Todilto Boundary

In exposures along the front of the Nacimiento Mountains the contact between the Limestone member and the underlying Entrada sandstone is sharp. Intertonguing between the Entrada and Todilto formations has been mentioned by Silver (1948, p. 77), Read et al. (1949), and Rapaport, Hadfield, and Olson (1952, p. 22). Baker, Dane, and Reeside (1947, p. 1668) reported that the Todilto limestone in places unquestionably grades downward into the Entrada sandstone. The Pony Express limestone of the Wanakah formation, which correlates with the Todilto limestone, has a sharp contact with the underlying Entrada sandstone top of the member, which has a [illegible] and green [illegible], [illegible] grained sandstone, and [illegible] are [illegible].

[illegible] of the [illegible]

The [illegible] formation [illegible] substantial thickness of [illegible] interpreted as marine, [illegible] marine Curtis formation [illegible] the [illegible] formation is [illegible] saline lake in an [illegible] the origin and environment of [illegible] detailed petrographic study.

[illegible]

In exposures along [illegible] the [illegible] tact between the limestone [illegible] is shown. Interfingering [illegible] and [illegible] formation has been mentioned by [illegible] (1948, p. [illegible]), [illegible] (19[illegible], p. [illegible]), [illegible] (19[illegible], p. 1969) reported that the [illegible] graded downward into the [illegible] stone of the [illegible] formation [illegible] with the [illegible] limestone, but a sharp [illegible] sandstone near Durango, Colorado (Imlay, 1952, p. 960). Smith (1954, p. 14) noted that at some localities in Valencia County beds of Todilto limestone truncate cross laminations of the Entrada sandstone with sharp angular unconformity. In northwestern New Mexico, Harshbarger, Repenning, and Irwin (1957, p. 38) found the contact between the upper sandy member of the Entrada sandstone and the Todilto limestone to be sharp.

belongs in biblio.

Post-Todilto Boundary

Lookingbill (1953, p. 35) observed that the contact between the Todilto limestone and the overlying Morrison formation in the Gallina uplift, Rio Arriba County, New Mexico, has a very irregular surface which can probably be attributed to early Morrison erosion. Along the west flank of Tierra Amarilla anticline, Sandoval County, New Mexico, the Todilto Gypsum member was observed by the writer to grade transitionally into the overlying Morrison formation (Fig. 24).

Stratigraphic Position

The rank and stratigraphic assignment of the Todilto formation have undergone considerable shifting. Baker, Dane, and Reeside (1947, p. 1668) consider the Todilto limestone and gypsum to be members of the Wanakah formation. The Todilto evaporites are considered a formation by Northrop (1950, p. 36), Harshbarger, Repenning, and near Durango, Colorado (Dane, 19[illegible], p. [illegible]). Smith ([illegible], p. [illegible]) noted that at some localities [illegible] stone [illegible] angular unconformity. [illegible] Repenning, and Irwin (19[illegible], p. [illegible]) [illegible] the [illegible] member of the [illegible] formation and the [illegible] to be sharp.

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Jackson (1951, p. 97), Wright and Becker (1951, p. 610), Rapaport, Hadfield, and Olson (1953, p. 23-27), and others.

The Todilto formation has been correlated with the Wanakah formation of southern Colorado (Goldman and Spencer, 1941, p. 1761). Both formations occupy the same stratigraphic position as the Curtis formation of Colorado, Utah, and Arizona, and the evaporite sequence overlying the Lykins formation in the Denver Basin of eastern Colorado (McKee, et al., 1957, p. 2).

The stratigraphic position of the Todilto formation is shown in Figures 1, 2, and 3. The Entrada sandstone which underlies the Todilto formation is eolian in part. The Entrada sandstone is probably entirely nonmarine; although, Harshbarger, Repenning, and Irwin (1957, p. 44) consider it to be partially marine. In the Nacimiento-Sandia Mountains region, the Morrison formation overlies the Todilto formation. The Morrison formation is a nonmarine sequence of rapidly changing facies of red and green shale, sandstone, and some limestone.

Baker, Dane, and Reeside (1936, p. 55) sum up the Morrison environmental conditions as follows:

> "The thesis that the Morrison deposits represent river and lake sediments laid down upon a little dissected and poorly drained surface perhaps under semiarid climatic conditions has been supported in the main by virtually everyone who has dealt with the Morrison."

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Figure 1. View north of Mesa Alta, Sec. 22, T. 23 N., R. 2 E.

Figure 2. View northwest; 1.5 miles south of Warm Springs, Sec. 12, T. 16 N., R. 1 W.

Figure 3. Generalized stratigraphic column of Mesozoic rocks on the eastern side of the San Juan Basin.

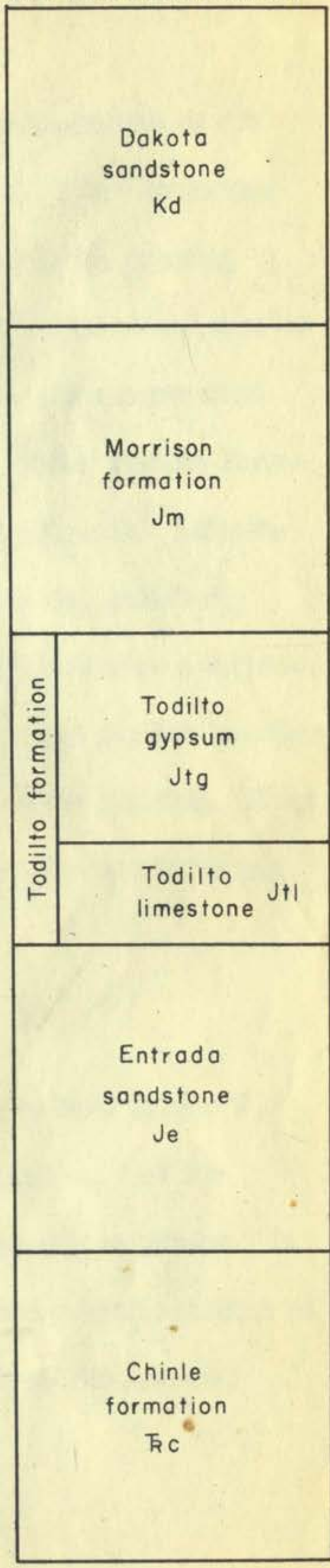
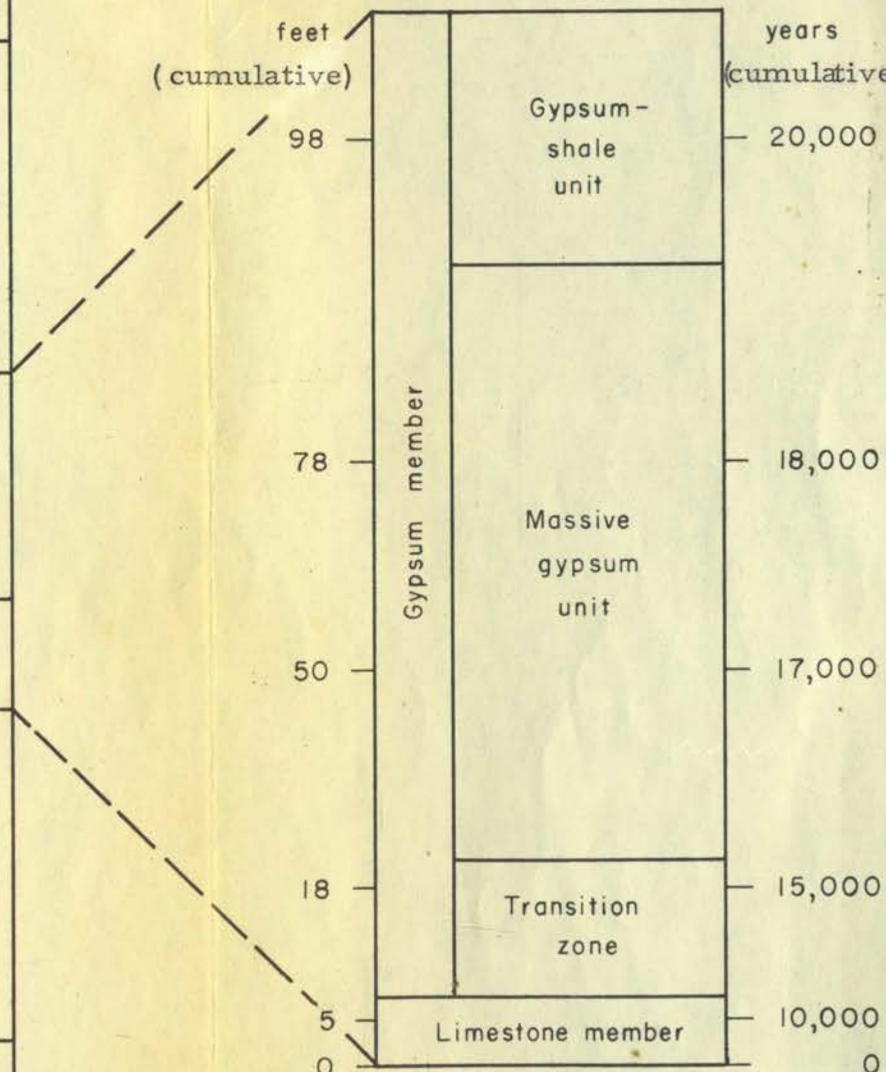


Figure 4. Generalized stratigraphic column of Todilto formation.



Method of Investigation

The field study was largely restricted to the southern end of the Nacimiento Mountains, Sandoval County, New Mexico. The Limestone member in this area is an easily identifiable persistent rim capping the Entrada sandstone. The Gypsum member is well exposed and can be traced for miles along the Nacimiento fault. Sections were measured and samples collected at two localities. Core chips of the Todilto limestone and gypsum were obtained from four localities (Fig. 5). Laboratory methods consisted largely of a study of thin sections, polished sections, and etched limestone slabs. Stain tests, quantitative analyses, and insoluble residue studies were also employed. All of the thin sections and etched limestone slabs were cut at right angles to the bedding. Except for Figures 7 and 8, photomicrographs have been oriented with the top of the section toward the top of the page.

Acknowledgments

The writer wishes to express his appreciation to Mr. Roger Y. Anderson for guidance in this study, for helpful criticism, and for suggestions bearing on the origin of the Todilto evaporite sequence. In addition Mr. Anderson assisted in the preparation of several sections of the report, particularly the discussions dealing with fossil fish and climate.

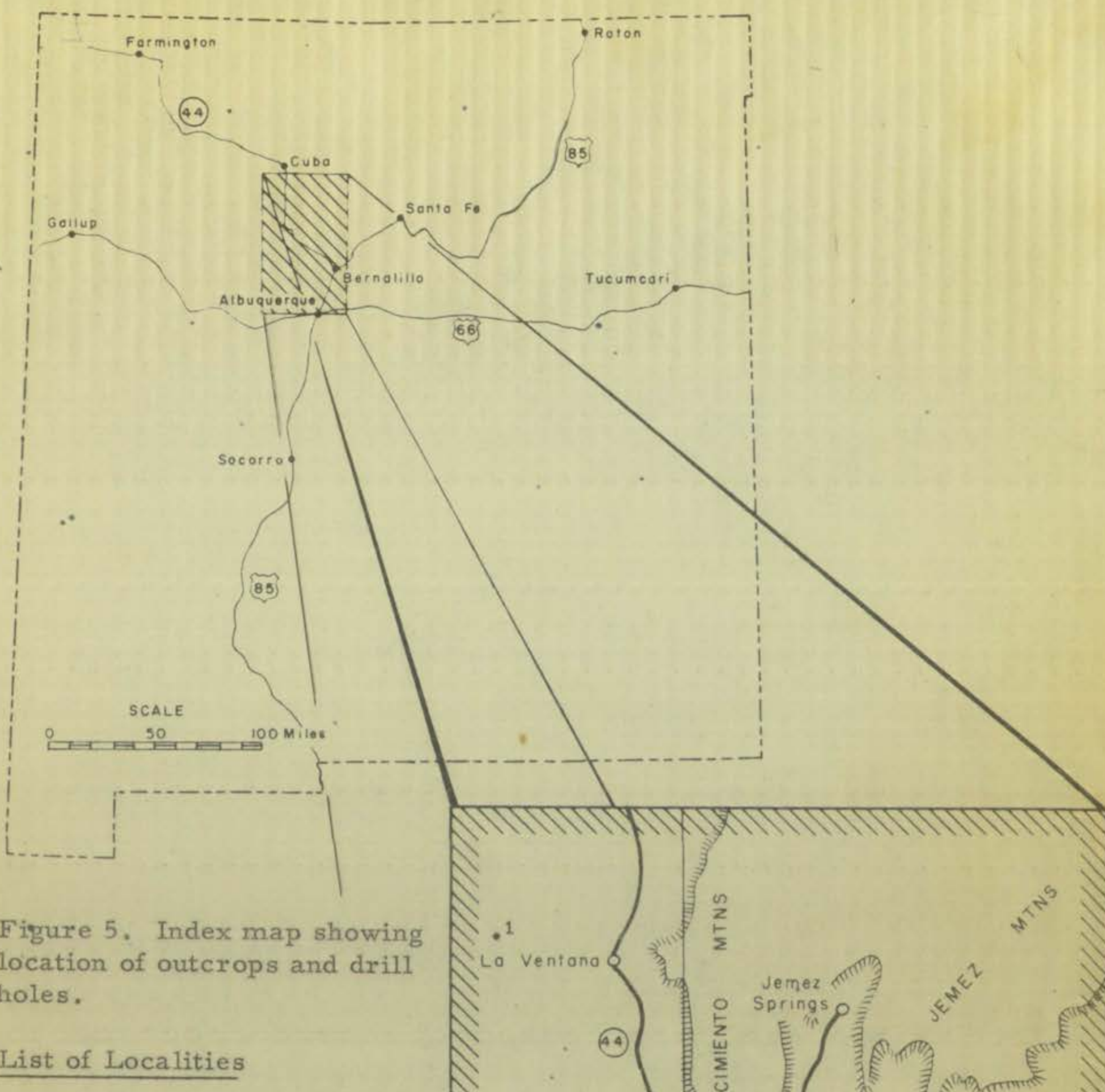


Figure 5. Index map showing location of outcrops and drill holes.

List of Localities

1. El Paso Natural Gas - No. 1 Elliot State

2. Cliff face west of highway

3. El Paso Natural Gas pipe line cut on west limb of Tierra Amarilla anticline

4. White Mesa

Dr. J. Paul Fitzsimmons was consulted on various problems dealing with identification and interpretation of thin sections, and the writer feels particularly indebted for his patient help. Mr. Henry S. Birdseye critically reviewed portions of the paper and kindly supplied core samples for study.

Finally the writer wishes to express his thanks to his fellow students for their sound observations and friendly assistance in proof-reading. Special thanks are due Miss Peggy Carter who helped with the drafting.

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PETROLOGY

The Todilto formation is divisible into a lower Limestone and an upper Gypsum member. The upper member can be further divided into three units: (1) a transitional zone, (2) a massive gypsum unit, and (3) a gypsum-shale unit (Fig. 4).

Todilto Limestone Member

General statement

The limestone forms a sharp contact with the underlying Entrada sandstone in the area studied. The Limestone member grades into the overlying Gypsum member, the upper contact being defined as the first prominent gypsum layer. At locality 2 (Fig. 5), the limestone has a thickness of 5.5 feet. At this locality the Entrada sandstone consists of a yellowish brown, fine- to very fine-grained, calcareous-cemented, quartzose sandstone. Drill holes into the Entrada sandstone on White Mesa (Fig. 17) penetrated a dark gray, fine-grained, calcareous cemented, quartzose sandstone. The dark gray color is probably caused by minor amounts of siderite, which, upon exposure to the atmosphere, becomes brown or buff (Pettijohn, 1957, p. 347). Lenses of fine-grained sandstone up to 1.5 inches thick were observed several inches above the basal limestone laminae at Tonque Arroyo, Sandoval County, New Mexico.

STRATIGRAPHY

The Todilto formation is divided into a lower limestone and an upper Gypsum member. The upper member can be [illegible] into three units: (1) a transitional zone, (2) a massive gypsum unit, and (3) a gypsum-shale unit (Fig. 9).

Todilto Limestone Member

General statement

The limestone forms a sharp contact with the underlying Entrada sandstone in the area studied. The limestone together with the overlying Gypsum member, was [illegible] prominent gypsum layer [illegible] locality 2 (Fig. 4), the limestone [illegible] thickness of 5.5 feet. At this locality, the Entrada [illegible] of a yellowish brown, fine- to medium-grained, [illegible] quartzose sandstone. [illegible] Mesa (Fig. 11) [illegible] grained, [illegible] quartzose sandstone. The rock [illegible] concretions of [illegible], which [illegible] brown or buff (Pettijohn, [illegible]). [illegible] up to 1.5 inches [illegible] basal limestone [illegible]

The nature of the laminations

Thin sections of Todilto limestone typically show repetitions of three distinct laminae: light brown microcrystalline limestone, thin, straw-colored organic material, and a thin lamina of clastic material (Fig. 6). These three laminae constitute a cycle which is repeated an average of 2,200 times per foot of section. Each unit of three laminae is interpreted as representing an annual cycle of sedimentation or a varve. The annual nature of glacial varves is recognized, but difficult to prove (Deevey, 1953, p. 290; Zeuner, 1952, p. 35). Similarly, absolute proof of the annual nature of non-glacial varves is difficult to provide. The varved nature of the laminae in the Todilto limestone is suggested, however, by their analogy with the unconsolidated varves forming in recent non-glacial lakes in Europe (Nipkow, 1920) and Canada (Whittaker, 1922). The three laminae composing the varves of the Todilto limestone member are discussed below in their order of deposition.

Limestone laminae

The limestone laminae are made up of a microcrystalline calcite mosaic. In samples collected 1.5 miles south of Warm Springs (Fig. 5), 1,592 limestone laminae had an average thickness of 0.13 mm. Limestone laminae are absent in some varves and in others are up to 6.3 mm thick.

The nature of the laminae

This section of Tedder [illegible] consists of [illegible] of three distinct laminae [illegible], thin, straw-colored organic [illegible] and a [illegible] material (Fig. 6). These three laminae [illegible] repeated an average of [illegible] three laminae is interpreted as representing [illegible] mentation on a [illegible]. The annual nature of [illegible] but difficult to prove (Bradley, 1929, [illegible] 1932, p. 30). Similarly, absolute proof of the annual nature of [illegible] is difficult to provide. [illegible] limestone is suggested, however, [illegible] dated varves forming in [illegible] Europe ([illegible] 1929) and Canada ([illegible]). [illegible] varves of the [illegible] order of deposition.

Limestone laminae

The limestone laminae [illegible] of a [illegible] mosaic. In samples [illegible] 1,592 limestone [illegible] stone laminae [illegible] thick.

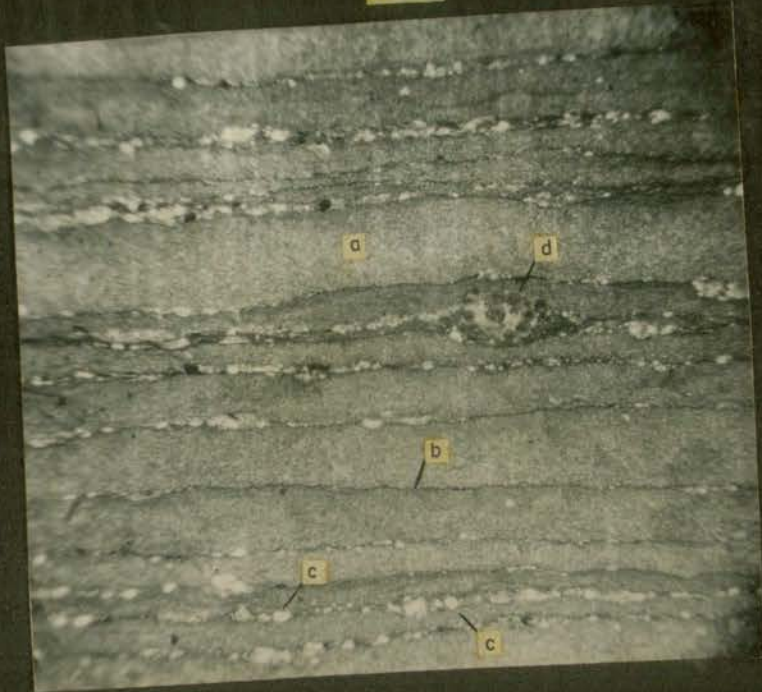

Figure 6. Photomicrograph of a thin section of Todilto limestone (plain light); a, microcrystalline limestone; b, organic layer; c, clastic grains; d, oolite pod. Sample obtained from locality 2 (Fig. 5), 55 inches above the Todilto-Entrada contact.

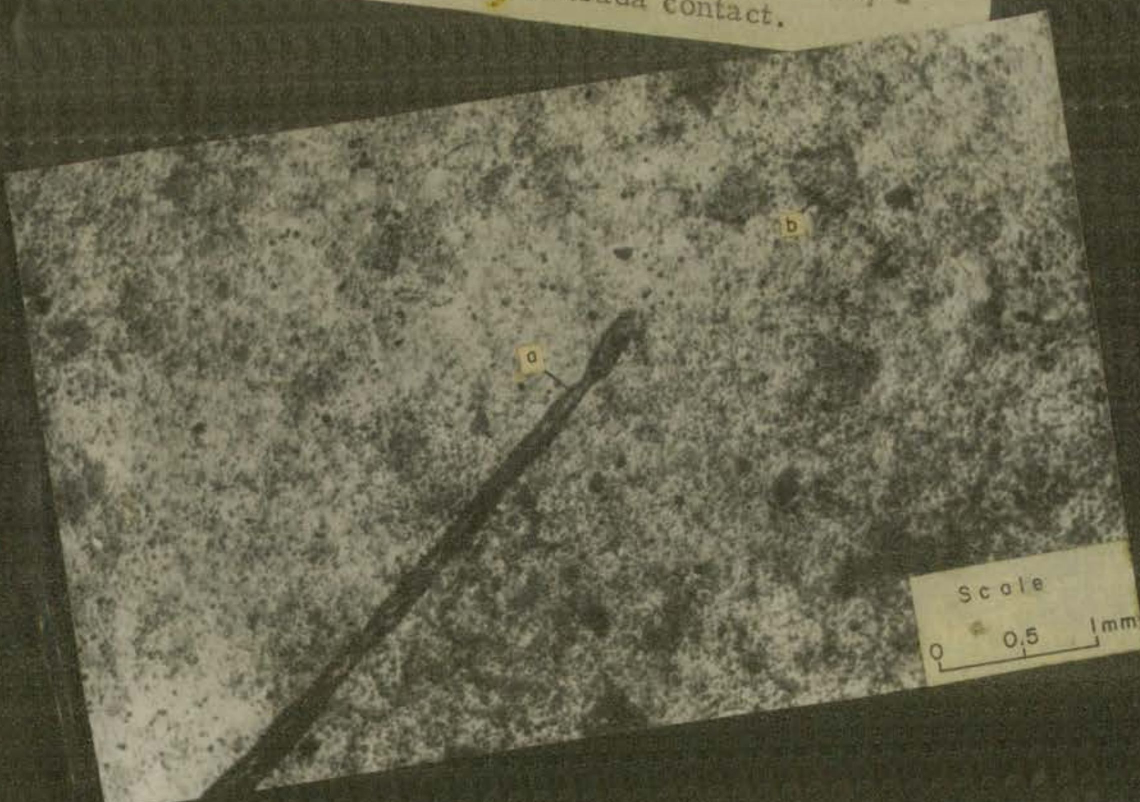

Figure 7. Photomicrograph of single organic layer taken parallel to the bedding plane (plain light); a, fragment of vascular plant; b, clastic grain. Sample obtained from locality 2 (Fig. 5), about 53 inches above Todilto-Entrada contact.

Four environmental factors are believed to have had a major influence in controlling the seasonal deposition of limestone laminae. The most important factor was probably temperature. During the summer an increase in water temperature reduced the amount of carbon dioxide in solution; consequently, the amount of calcium bicarbonate in solution was reduced (the chemical nature of the CO_2-$Ca(HCO_3)_2$-$CaCO_3$ system is discussed on page 37). An increase in evaporation, which accompanied an increase in temperature, was also a factor controlling the concentration of calcium carbonate. A third environmental factor controlling the deposition of limestone was the seasonal inflow of water into the evaporite basin from the surrounding drainage basin. Periods of above average inflow diluted the concentration of NaCl and Na_2SO_4 in the surface water. Inasmuch as carbon dioxide is more soluble in dilute solutions of these salts, more calcium bicarbonate could have been held in solution after periods of above average inflow even if the inflowing water was saturated with calcium carbonate. A fourth environmental factor controlling the deposition of limestone, which was of great importance, was the process of photosynthesis carried on by phytoplankton. The plankton, probably algae, took carbon dioxide out of the system, which reduced the acidity of the water and thereby reduced the solubility of the water for calcium carbonate. Still another factor which played an unknown role in calcium carbonate formation was the probable existence of bacteria within the saline water. Some calcium

carbonate may have been precipitated by physical means from colloidal solutions or from the settling out of fine calcium carbonate particles brought into the basin by rivers (Rankama and Sahama, 1949, p. 465).

The thickness of the annual limestone laminae is believed to have been controlled by climatic factors such as rainfall and temperature. Annual cycles in which limestone laminae are thin or absent, for example, are interpreted as indicating cooler and wetter years. Variables controlling the thickness of limestone laminae independent of climate are believed to have been relatively insignificant.

Organic laminae

Sharp contacts exist between limestone laminae and organic laminae. The organic layers show little variation in thickness. They are extremely thin with an average thickness of approximately 0.008 mm. They are optically isotropic and are composed of sapropel, which at the time of deposition was an ooze composed of plankton and water. The organic laminae give rise to the fetid odor from a freshly broken surface of the limestone. Compression by overlying sediments has probably reduced the initial thickness considerably.

Approximately 30 organic laminae from different horizons in the limestone member were microscopically examined. Individual sapropel layers were set free by dissolving adjacent limestone laminae with dilute carbonate may have been precipitated by [illegible] from [illegible] solutions or from the [illegible] carbonate [illegible] brought into the basin by rivers (Bradley and [illegible], [illegible]).

The [illegible] of [illegible] laminations [illegible] have been [illegible] such as [illegible]. Annual cycles in which [illegible] are [illegible]. For example, are interpreted as [illegible] and [illegible]. [illegible] controlling the [illegible] of [illegible] are believed to have been [illegible].

Organic Laminae

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[illegible] layers. [illegible] layers were derived [illegible].

hydrochloric acid. The sapropel laminae, in spite of their thinness, prove to be extremely tough. Every lamina showed fragments which were identified as tracheids and fibers from vascular plants (Fig. 7). These plant particles were probably brought into the Todilto basin by streams.

Conditions which favored preservation of sapropelic sediments were the presence of toxic decomposition products in the bottom water which inhibited the growth of benthonic organisms, deposition below the zone of agitation, and a probable lack of overturn.

The well-preserved microstratigraphy of the Todilto limestone seems to preclude strong or moderate currents in depth. In the surface water, however, the existence of currents can be inferred from the presence of evenly distributed clastic particles on top of the organic layers. The bottom waters were charged with hydrogen sulfide and held relatively great amounts of calcium carbonate in solution. This probably served to enhance the chemical stratification. Both thermal and chemical stratification were likely. It seems probable that in much of the Todilto evaporite basin there was little or no exchange of bottom and surface water.

The decomposition of organic material formed hydrogen sulfide which provided a poor environment for the growth of benthonic organisms hydrochloric acid. The hardened [illegible], in spite of their thickness, proved to be extremely tough. Every layer [illegible] fragments which were identified as tracheids [illegible] (Pl. 7). These plant particles were probably brought [illegible] streams.

Conditions which [illegible] the sediment were [illegible] which inhibited the growth of [illegible] below the zone of [illegible].

The well-preserved [illegible] seems to [illegible]. In the surface water, however, the [illegible] presence of [illegible] organic layers. [illegible] relatively [illegible]. This probably served to [illegible] physical and chemical [illegible] evaporite [illegible] surface water.

The [illegible] which [illegible]

and probably accounts for their absence among the fossils of the Todilto limestone. The toxic water, on the other hand, was probably the cause of excellent preservation of fossil fish found in the Limestone member in Guadalupe and Valencia Counties, New Mexico, and near the Piedra River in southwestern Colorado.

The formation of calcium carbonate crystals and the production of planktonic organisms probably reached their peak at about the same time that the basin water reached its maximum annual temperature. Summer planktonic booms in Recent marine and fresh waters have been reported by a number of workers (Davis, 1955, p. 68). The carbonate particles settled comparatively rapidly to the bottom, but the living organic material, because of its low specific gravity and large surface area, remained in suspension until later in the season. In late summer or autumn, as the plankton were killed by decreasing temperature, their maximum fall as sedimentary particles reached a peak. The distinct stratification can be attributed to the lag between the peak of growth of organisms in the summer and their peak of fall as sedimentary particles in the autumn and winter.

Clastic laminae

Lying on top of and within the sapropel laminae is a thin, intermittent, often indistinct layer of clastic particles. The particles range and probably accounts for their excellent preservation in the Todilto limestone. The saline water, as [illegible], was probably the cause of excellent preservation of fossil fish found in the limestone member in Guadalupe and Valencia Counties, New Mexico, and near the Piedra River in south-western Colorado.

The formation of distinct laminae in chalk and the probability that planktonic organisms probably reached their peak at about the same time that the black water [illegible] conditions [illegible]. Summer planktonic blooms in modern lakes and brackish waters have been reported by a number of workers (Davis, 1948, p. [illegible]). The carbonate particles settled comparatively rapidly to the bottom, but the light organic material, because of its low specific gravity and large surface area, remained in suspension until later in the season. In late summer or autumn, as the plankton were killed by decreasing temperatures, their maximum fall [illegible] after a peak. Thus distinct stratification can be attributed to a lag between the peak of growth of organisms in the summer and their peak of fall of [illegible] organic particles in the autumn and winter.

<u>Clastic laminae</u>

Lying on top of and within the laminated limestone are thin, intermittent, often indistinct layers of clastic grains. The particles range in size from 0.02 mm to 0.06 mm. In many instances the grains appear to have been pushed down into the underlying organic layer (Fig. 9). The clastic particles are predominantly quartz. A few plagioclase particles were observed. The clastic grains are abundantly to sparsely scattered over the top of the organic layers, but the layer is seldom more than a single grain thick and generally consists of an incomplete blanket of grains covering the organic layer (Fig. 8).

Their position between limestone and organic laminae, indicates that most of the clastic particles were brought into the evaporite basin during the winter and spring.

Fresh water brought by streams into the evaporite basin would have floated on the surface of the saline basin water. Suspended sediments would have been distributed throughout the surface water and ultimately settled over the entire bottom of the evaporite basin. In general, as the number of clastic grains blanketing the sapropel layer increases, the thickness of the overlying limestone decreases. There are several possible explanations for this relationship. If the clastic grains were brought into the basin by wind, years of relatively high average wind intensity would be accompanied by abnormally low average summer temperature. A relatively high frequency of clastic grains in size from 0.02 mm to 0.06 mm. In many thin sections the grains appear to have been pushed over into the underlying organic layer (Fig. 7). The clastic particles are predominantly quartz. A few plagioclase particles were observed. The clastic grains are abundantly to sparsely scattered [illegible] the organic layers. Where the layer is seldom more [illegible] grains thick and generally consists of an incomplete [illegible] of grains covering the organic layer (Fig. 8).

Their position between [illegible] and organic laminae, indicates that most of the clastic particles were deposited [illegible] during the winter and spring.

Fresh water brought [illegible] would have floated on the surface. [illegible] sediments would have been distributed [illegible] water and ultimately settled over the entire [illegible]. In general, as the number of clastic [illegible] increases, the thickness of the [illegible]. There are several possible explanations [illegible] grains were brought in [illegible] average wind [illegible] summer temperature. A relatively high [illegible] clastic grains

Figure 8. Photomicrograph of a single organic layer showing the distribution of clastic grains on the bedding plane (crossed nicols). Sample obtained from locality 2 (Fig. 5), about 53 inches above the Todilto-Entrada contact.

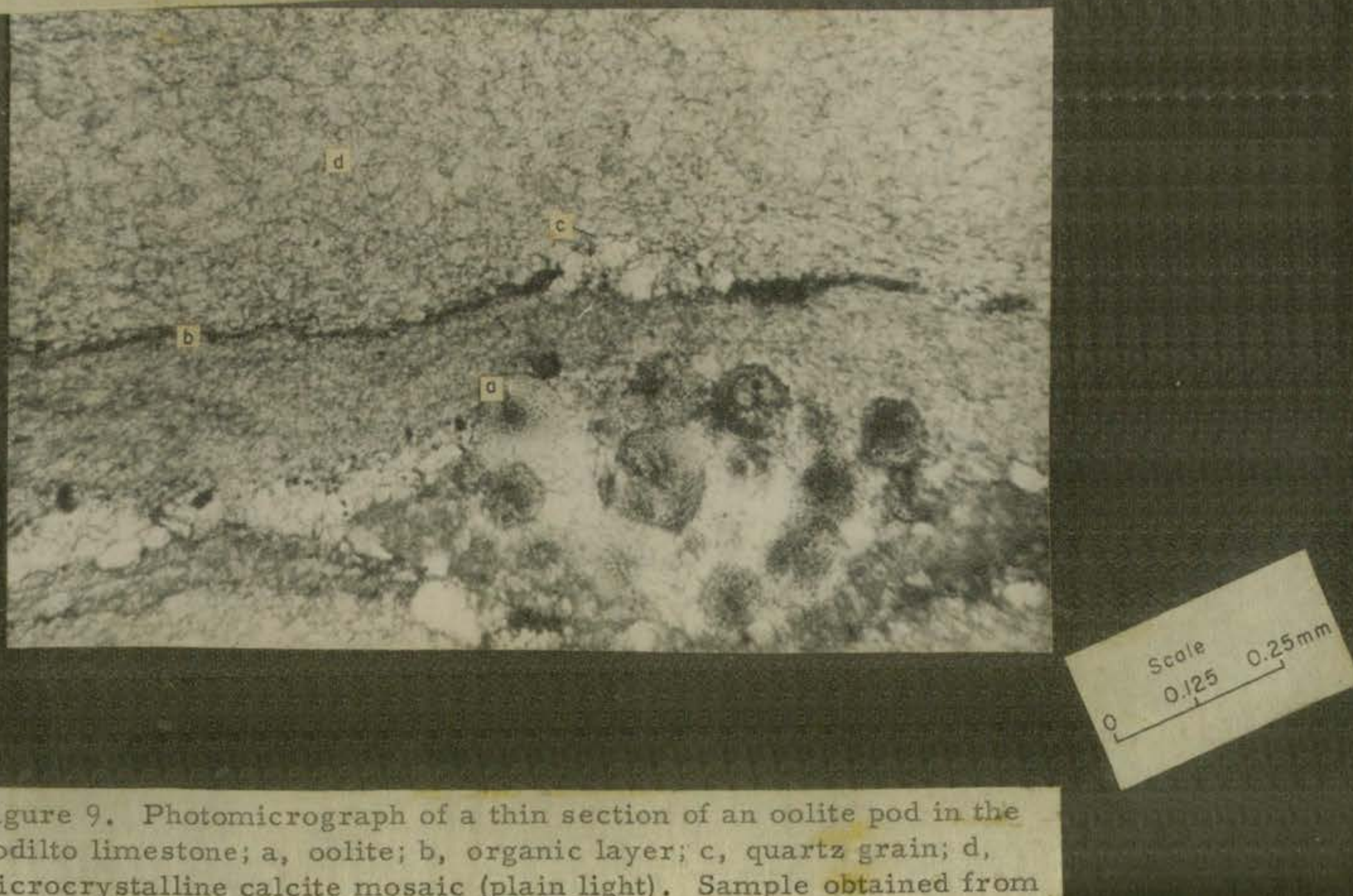


Figure 9. Photomicrograph of a thin section of an oolite pod in the Todilto limestone; a, oolite; b, organic layer; c, quartz grain; d, microcrystalline calcite mosaic (plain light). Sample obtained from locality 2 (Fig. 2), 55 inches above the Todilto-Entrada contact.

covering a sapropel layer indicates a relatively high average annual wind velocity; a thin limestone lamina would suggest a low average summer temperature. If the clastic grains were brought into the basin by running water the frequency of clastic grains would be roughly indicative of the volume of spring and winter inflow into the basin. Low rainfall and inflow would result in a low frequency of clastic grains and would effectively decrease the ability of the basin water to hold calcium carbonate in solution, thereby resulting in the deposition of a relatively thick limestone the following summer. It seems probable that both fluvial and eolian transportation brought clastic grains into the evaporite basin.

Calcite oolites are occasionally associated with clastic particles (Fig. 9). The oolites range in size from 0.07 mm to 0.35 mm. They usually occur as pods in the lows of undulating organic layers. The oolites have radial structure. Under crossed nicols this structure is expressed by a black cross and in some cases by concentric interference rings, a pseudo-interference figure of the uniaxial type. The stratigraphic position of the oolites between organic and limestone laminae (Fig. 6) indicates that their formation probably occurred in the winter and spring. The oolites suggest slight currents which caused rotation during their formation.

Mineral associations

Figure 10 is a photomicrograph of a thin section of Todilto limestone from a depth of 95 feet at White Mesa, Sandoval County, New Mexico (core hole 2, Fig. 17). Lenticular crystals probably barite or celestite, lie roughly parallel to the bedding in a peculiar en echelon arrangement. Under plain light the crystals are yellow. Rapaport, Hadfield, and Olson (1952, p. 24) report traces of amber-colored barite in the Todilto Limestone member of the Zuni Uplift. Northrop (1958) has seen large crystals of amber-colored barite near the Haystack mine, McKinely County, New Mexico.

Quantitative analyses of samples of limestone taken 55 inches above the top of the Entrada sandstone at locality 2 (Fig. 5) yielded the following information: 91 percent (by weight) $CaCO_3$, 7.4 percent clastic particles, and 1.4 percent organic material. Rapaport, Hadfield, and Olson (1952, p. 24) report that the limestone of the Zuni Uplift is composed of about 96 percent calcium carbonate.

Allen and Balk (1954, p. 77) report the following partial analysis by H. B. Wiik of one of the massive Todilto limestone beds north of Gallup, McKinley County, New Mexico:

Mineral associations

Figure 17 is a photomicrograph of a thin section of [illegible] stone from a depth of [illegible] feet at [illegible] (core hole 2, Fig. 12). [illegible] crystals of [illegible] lie roughly parallel to the bedding [illegible]. Under plain light the crystals are yellow. [illegible] (1952, p. 24) report [illegible] of amber-colored [illegible] limestone [illegible] at the [illegible]. [illegible] (19[illegible]) [illegible] crystals of amber-colored [illegible] County, New Mexico.

Quantitative analyses of [illegible] above the top of the [illegible] following information [illegible] clastic particles, and 1.4 percent [illegible]. [illegible] and Olson (19[illegible], p. 24) report that the limestone [illegible] composed of about 94 percent calcium carbonate.

Allen and Balk (1954, p. [illegible]) [illegible] by E. E. [illegible] Gallup, McKinley County, New Mexico.

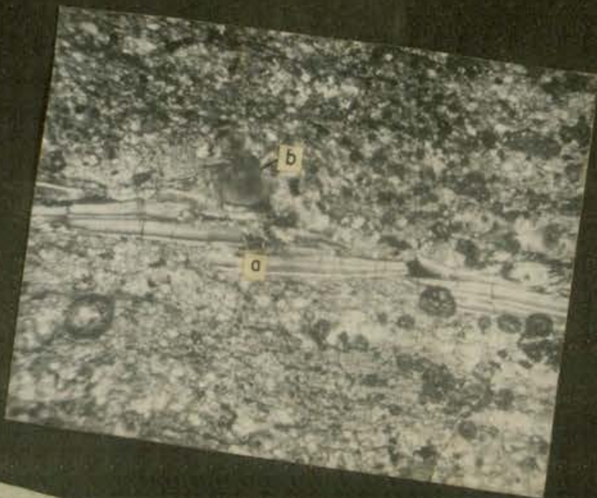


Figure 10. Photomicrograph of thin section of Todilto limestone (partially crossed nicols); a, en echelon arrangement of mineral, possibly barite or celestite; b, calcium carbonate oolite. Sample obtained from a depth of 95 feet in core hole 2 (Fig. 17).

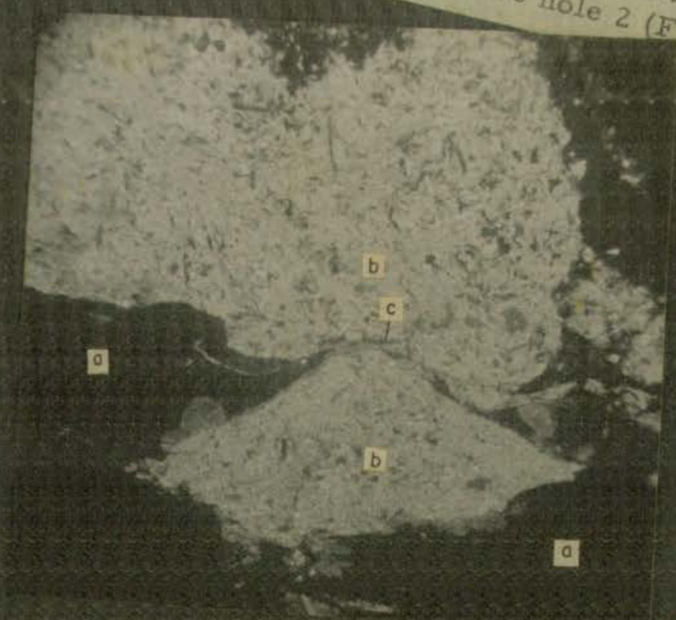


Figure 11. Photomicrograph of a thin section of the transition zone (crossed nicols); a, limestone; b, anhydrite; c, organic layer. At "c" the limestone lamina may have been replaced by anhydrite leaving the organic lamina intact. Location: El Paso Natural Gas - No. 1 Elliot State (about 3,900 feet).

	Percent
SiO_2	6.55
Al_2O_3	0.32
Fe_2O_3 (total iron)	0.28
CaO	51.90
MgO	0.68

The quantity of MgO is relatively low. Five samples taken at one-foot intervals from the bottom to the top of the limestone section at locality 2 (Fig. 5) were treated with the silver nitrate-potassium chromate test for the detection of dolomite (Krumbein and Pettijohn, 1938, p. 496). No trace of dolomite was detected.

Five inches above the base of the Todilto limestone at locality 2 (Fig. 5) a 3/4-inch bed of limonite and hematite was observed. Krumbein and Garrels (1952, p. 19) state that hematite forms in a reducing environment at a pH above 8.2.

Regional considerations

The maximum extent of the Todilto limestone is represented in Figure 28. The limestone member shows a marked increase in thickness near the ancient short line southwest of Albuquerque in the Lucero Uplift (Silver, 1948, p. 77) and in southwestern Colorado (Read *et al.*, 1949).

	percent
SiO_2	[illegible]
Al_2O_3	[illegible]
Fe_2O_3 (total iron)	[illegible]
CaO	[illegible]
MgO	[illegible]

The quality of [illegible] is relatively [illegible] samples taken at one-foot intervals from the bottom to the top of the limestone section at locality 2 (Fig. [illegible]) were treated with dilute hydrochloric acid [illegible] (Frederickson and [illegible], p. [illegible]). [illegible]

Three [illegible] the [illegible] locality [illegible] ([illegible]) [illegible] and [illegible]. [illegible] and [illegible] ([illegible], p. [illegible]) [illegible] of [illegible] above [illegible].

Regional considerations

The maximum extent of the [illegible] limestone [illegible] is represented in Figure [illegible]. The limestone [illegible] increases in thickness near the [illegible] in the [illegible] ([illegible], 1958, p. [illegible]) [illegible].

This has several possible explanations. Water near the edge of the basin may have been warmer than water in deeper parts. If comparatively cool waters, with calcium bicarbonate in solution, were moved by currents into a warmer environment, carbon dioxide would have been expelled and calcium carbonate precipitated. A second possible cause of the thick marginal deposits of limestone is the emptying of relatively cool fluvial water, saturated with calcium carbonate, into the evaporite basin. The comparatively warm basin water would have driven off carbon dioxide and caused the deposition of calcium carbonate.

Todilto Gypsum Member

General statement

At locality 3 (Fig. 5) on the west flank of Tierra Amarilla anticline, a thickness of 140 feet was obtained for the Gypsum member. Faulting of the steeply dipping beds has probably introduced considerable error. Northrop (1957) estimates the Gypsum member in the White Mesa area to be 77 to 100 feet thick. Further north along the west front of the Nacimiento Mountains the thickness of the Gypsum member is variable and at some localities the member is completely absent, probably because of early Morrison erosion. Gabelman (1955, p. 392) has drawn the western pinch-out of the Gypsum member about 30 miles west of San Ysidro, Sandoval County, New Mexico. Gypsum deposition was confined to the central part of the Todilto basin (Fig. 28). The Todilto Gypsum

This has occurred [illegible] possibilities. [illegible] near the edges of the basin may have been [illegible] water in [illegible] parts. [illegible] relatively cool waters, with calcium [illegible] in solution, [illegible] by currents [illegible], carbon dioxide would have been [illegible]. A second possible [illegible] the thick [illegible] deposits of limestone is the [illegible] of relatively cool fluvial water, saturated with calcium carbonate, [illegible] basin. The [illegible] would have driven off carbon dioxide and caused the deposition of calcium carbonate.

Todilto Gypsum Member

General statement

At locality 3 (Fig. 2) on the west flank of [illegible] anticline, a thickness of 180 feet was obtained for the Gypsum Member. Faulting of the steeply dipping beds has probably introduced considerable error. Northrop (1957) estimates the Gypsum Member in the White Mesa area to be 75 to 100 feet thick. Farther north along the west front of the Nacimiento Mountains the thickness of the Gypsum Member is variable and at some localities the gypsum is completely absent, probably because of early Morrison erosion. Harshbarger (1957, p. [illegible]) has drawn the western pinch-out of the Gypsum member about [illegible] miles [illegible] of Valdez, Sandoval County, New Mexico. Gypsum deposition was confined to the central part of the Todilto basin (Fig. 20). The [illegible] member consists of three units: (1) the transitional zone between the Limestone member and the massive gypsum, (2) the massive gypsum unit, and (3) the gypsum-shale unit.

Transition zone

The base of this zone was established as the first prominent gypsum lamina within the limestone-organic-clastic sequence. The upper limit is established where the gypsum takes on a massive appearance. On White Mesa (locality 4, Fig. 5) the thickness of the transition zone ranges from 25 to 40 feet (Birdseye, 1958). At Mesa Alta north of Jemez Plateau (Sec. 22, T. 23 N., R. 2 E.) the transition zone is abnormally thick and constitutes the major part of the Gypsum member. The environmental changes which caused the shift in lithology from predominantly limestone to predominantly gypsum in the White Mesa area took place over 2,200 years. This was established by counting the varves per unit thickness on polished slabs (Fig. 15) and by field counts.

Most of the thin sections from the transition zone show lenticular gypsum bodies (Figs. 12 and 13). The origin of these nodules is not certain. Evaporites, because of their ability to go into solution, are particularly susceptible to diagenetic change. The nodules may have been diagenetically formed by replacement and crystal growth pressure, or they may have formed as concretions during deposition. If the gypsum

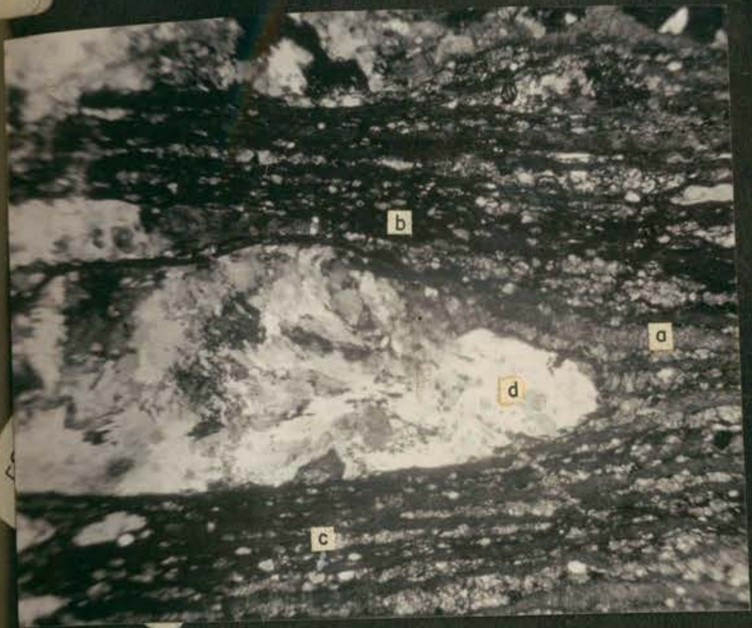
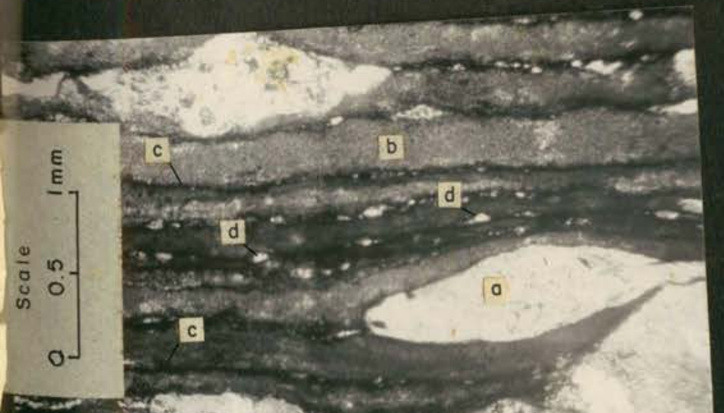


Figure 12. Photomicrograph of thin section of the transition zone (crossed nicols); a, limestone lamina; b, organic laminae, c, clastic grain; d, gypsum. Sample obtained from core hole 2 (Fig. 17) at a depth of 103 feet.



igure 13. Photomicrograph of thin section of transition zone rossed nicols); a, gypsum nodule; b, limestone lamina; c minae; d, clastic grain.

was originally deposited as a thin layer of calcium sulfate, diagenetic changes, possibly associated with the conversion of anhydrite into gypsum, might have caused the lateral movement of the thin gypsum layers into nodular bodies. Another possibility is that gypsum concretions formed in the few months between the deposition of the overlying and underlying limestone and organic laminae (Elston, 1958). New laminae which were deposited over the concretions would have formed a gentle arch (Figs. 12 and 13). The gypsum composing the fibrous gypsum laminae (Figs. 14 and 15) may have migrated from the massive gypsum through vertical fractures, but field observations do not confirm this.

Figure 16 shows an unusual gypsum texture found in single sample. Under crossed nicols the gypsum appears to be composed of an aggregate of anhedral crystals which have an ill-defined, fibrous appearance and show an undulating lineation. Figure 15 is a polished section which has been etched with dilute hydrochloric acid. The lateral migration of gypsum into nodular bodies is well displayed. Several fibrous gypsum laminae, which show no tendency to form nodular bodies, can be seen parallel to the organic laminae.

Massive gypsum unit

Most of the Todilto Gypsum member, in the exposures near the southern Nacimiento Mountains, consists of gypsum which appears to be massive, but on close inspection shows contorted laminae of bituminous

Figure 14. Photomicrograph [illegible] on of transition zone (crossed nicols); a, organic [illegible] nal quartz grains; b, fibrous gypsum; c, microc[illegible] tone; d, gypsum nodule lined with calcite crystals a[illegible] .1 mm. Sample obtained from locality 2 (Fig. 5).

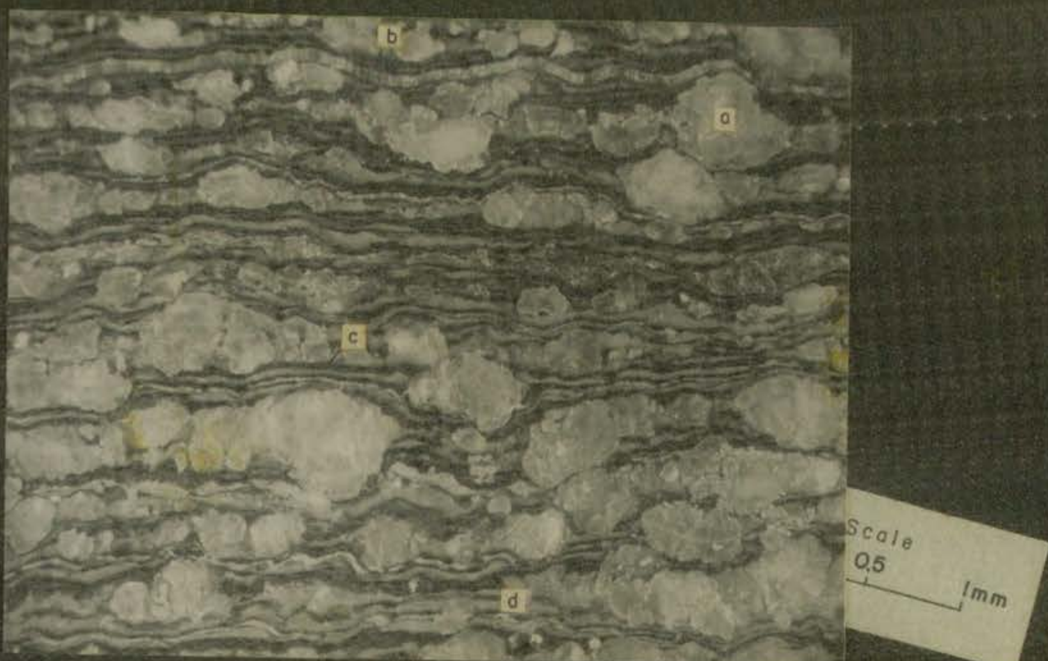


Figure 15. Photomicrograph of etched slab of transition zone; a, gypsum nodule; b, fibrous gypsum layer; c, organic lamina (thin dark layer); d, limestone lamina. Sample obtained from locality 2 (Fig. 5), about 63 inches above the Todilto-Entrada contact.

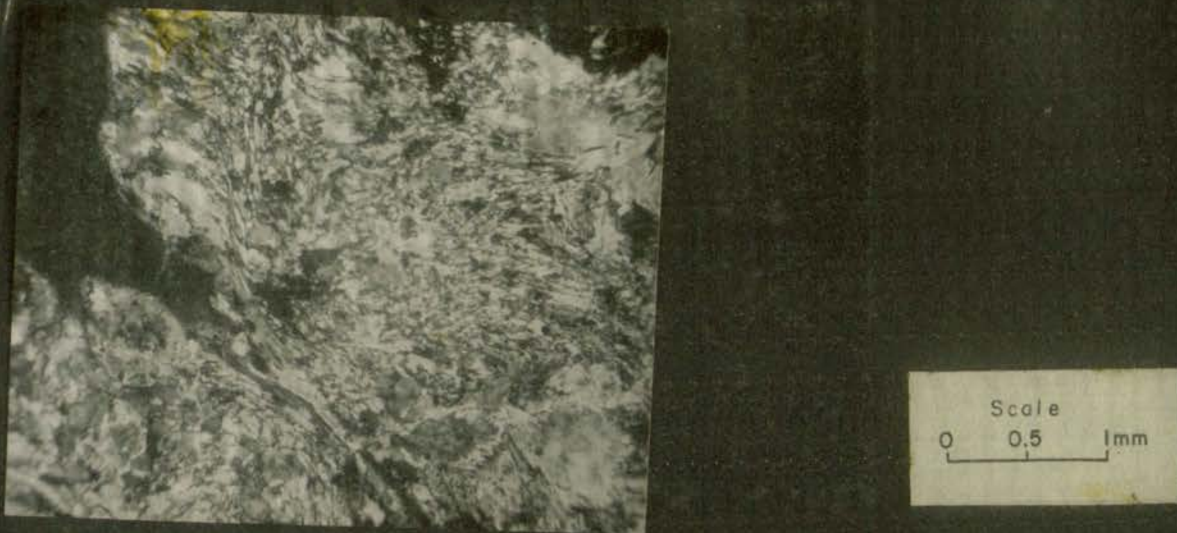


Figure 16. Photomicrograph of thin section of transition zone (crossed nicols). The gypsum crystals show an undulating lineated texture. Sample obtained from core hole 9 at a depth of 80 feet.

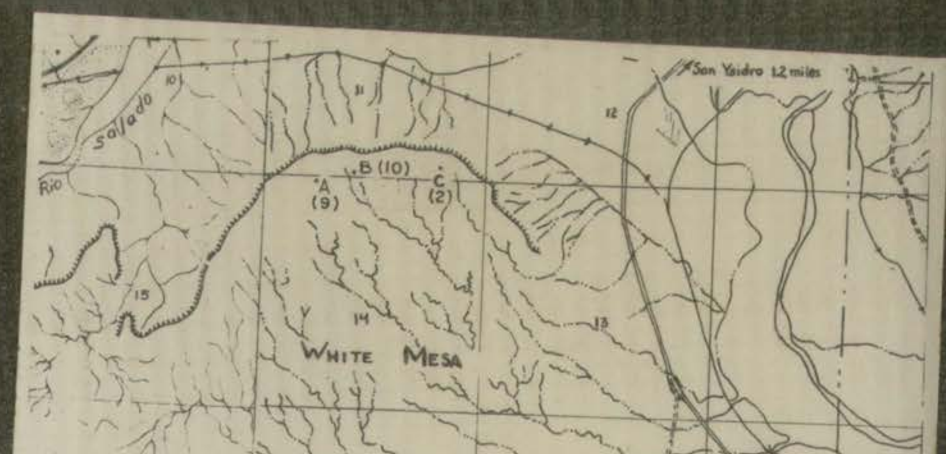


Figure 17. Location of American Gypsum Corporation's test holes; T. 15 N., R. 1 E.; A, core hole 9; B, bore hole 10; C, core hole 2.

limestone. Thin sections were made from core chips at 5- to 10-foot intervals from holes 2 and 9 on White Mesa (Fig. 17). The core holes were drilled by the American Gypsum Corporation prior to commercial exploitation.

The massive gypsum consists primarily of two rock types. The first is made up of anhedral gypsum crystals which range in size from 0.008 to 0.06 mm, and laminae of dark brown, bituminous limestone about 0.25 mm thick. The second rock type is a finely crystalline gypsum containing larger diagenetically formed crystals and bituminous limestone laminae. The coarse grains have a maximum size of 1.35 mm and consist of prismatic euhedral to subhedral crystals. The larger crystals comprise 10 to 30 percent of the rock. The smaller crystals are anhedral and have a grain size of approximately 0.012 mm.

Anhydrite was found in a core chip taken from a depth of approximately 3,900 feet in the El Paso Natural Gas - No. 1 Elliot State well. Anhydrite was also found in drill cuttings from a depth of 40 to 45 feet at hole 10 (Fig. 17). The anhydrite is made up of a mosaic of rectangular grains (Fig. 19).

Nature and origin of the laminations

Laminae of dark brown bituminous limestone are present through the entire sequence of massive gypsum. The laminae are often highly

Figure 18. Photomicrograph of thin section of massive gypsum unit showing euhedral, diagenetically formed crystals. Sample obtained from core hole 9 (Fig. 17) at a depth of 60 feet.

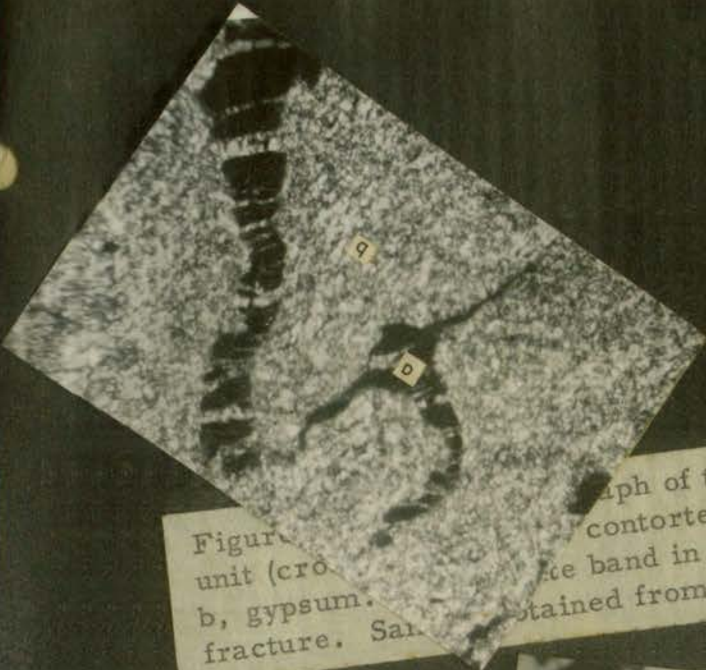
Figure 19. Photomicrograph of thin section of anhydrite (crossed nicols). Sample obtained from core hole 10 (Fig. 17) at a depth of 40-45 feet.

irregular, but were apparently deposited as thin horizontal layers which were later deformed (Figs. 20 and 21). This is supported by the sub-parallel nature of the laminae and by their roughly horizontal trend. In thin section the limestone laminae are nearly opaque and show little recognizable structure (Figs. 20 and 21). Thin organic laminae represent the bedding planes where the calcite is missing because of replacement, plastic flow, or nondeposition.

Organic material appears as distinct layers or intimately mixed with calcium carbonate. It is never mixed with the gypsum or anhydrite. The thickness of the limestone and gypsum layers was difficult to measure because of their irregularity. The bituminous limestone laminae average about 0.025 mm and the gypsum layers about 5.8 mm.

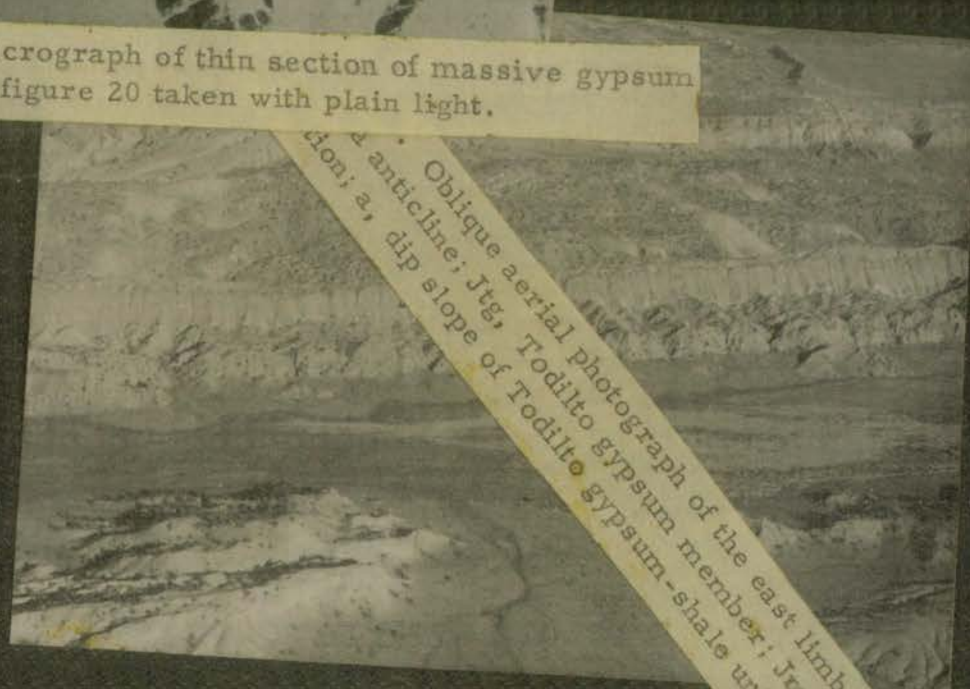
Limestone laminae within gypsum and anhydrite are common in evaporite sequences. The main constituents of the Permian Castile formation of southern New Mexico is calcite-banded anhydrite (Adams, 1944, p. 1604). Ver Plank (1952, p. 36) has described gypsum with paper-thin layers of brown opaque dolomite or calcite from a locality 5 miles east of Ventucopa, Ventura County, California. A sequence of marl-gypsum laminae from the Upper Miocene Sulphur series of Sicily has been described by Ognibeu (1955, p. 276). Wilder (1920, p. 39) states:

> "...the gypsum of Virginia is curiously banded with black streaks of hydrocarbon, which entirely disappear when the gypsum is heated to moderately high temperatures."



Figur... ...ph of thin section of massive gypsum unit (cro... ...contorted lamina of bituminous limestone; b, gypsum. ...te band in the lower left corner fills a fracture. Sa... ...tained from locality 2 (Fig. 5).

Figure 21. Photomicrograph of thin section of massive gypsum unit. Same view as figure 20 taken with plain light.



... Oblique aerial photograph of the east limb of Tierra ...d anticline; Jtg, Todilto gypsum member; Jm, Morrison ...tion; a, dip slope of Todilto gypsum-shale unit.

From Oklahoma, Snider (1913, p. 4) has described beds of gypsum which are irregularly mottled or banded with darker material. Lang (1950, p. 1479) believes that a correct interpretation of cyclic bituminous material, calcite, and gypsum might lead to a disclosure of the environmental conditions during the deposition of these chemical deposits. Scruton (1953, p. 2509) states that the laminations of anhydrite and bituminous calcite in the Castile formation could have been caused by changes in salinity due to variations in temperature, evaporation, sea-level, or wind. Dellwig (1955, p. 105) suggests the following reason for the lime-gypsum alternations in the evaporite sequence of southwestern Michigan:

> "...it has been demonstrated that either increased salinity or increased temperature will cause a decrease in carbonate solubility....it is known that increased salinity or increased temperature also cause a decrease in solubility of calcium sulfate. For the same degree of change, however, the effect is not as great for calcium sulfate as it is for calcium carbonate. If, therefore, the concentration of the brine were at such a point that both the carbonate and the sulfate were being precipitated, carbonate precipitation might be favored during the warm seasons and sulfate precipitation during the colder seasons."

Stieglitz (1909, p. 235) discussed the system $CaCO_3$-CO_2-$CaSO_4$, and from his data it seems probable that changes in salinity caused cyclic deposition of bituminous limestone and gypsum.

[illegible] precipitation of gypsum

which [illegible]

([illegible] p. 109) believed [illegible]

[illegible]

environmental conditions during [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

> ... [illegible] ... temperature [illegible] ... [illegible]

[illegible] ([illegible], p. 33) [illegible]

and [illegible]

[illegible] cyclothems [illegible]

In order to illustrate the principles involved, an ideal case will be considered in which only two salts, $CaCO_3$ and $CaSO_4$, are saturated in a solution in contact with the atmosphere and at atmospheric pressure. The Handbook of Chemistry and Physics (1947) states:

> "In a solution containing two salts which yield a common ion the ratio of solubilities of the two salts is the ratio of the solubility products".

For example, at 20° C:

$$\frac{\text{solubility product of } CaSO_4}{\text{solubility product of } CaCO_3} = \frac{3.5 \times 10^{-6}}{2.0 \times 10^{-8}} = \frac{175}{1}$$

In a solution in which the ratio between $CaSO_4$ and $CaCO_3$ was different from 175:1 one of the pure salts would be separated until the ratio was reached. Pure calcium sulfate would precipitate if the carbonate ions in solution were kept below 1/175 of the sulfate ions. If, on the other hand, the carbonate ions in solution were increased to a concentration above 1/175 of the sulfate concentration, calcium carbonate would precipitate.

Carbon dioxide concentration has no direct effect on the solution of calcium sulfate (Shternina, 1949). However, the concentration of carbon dioxide determines the amount of calcium carbonate which can be changed to the more soluble bicarbonate, and the absorption or elimination of carbon dioxide may cause solution or precipitation of calcium carbonate.

In order to illustrate the principles involved, an ideal case will be considered in which only two salts, $CaCO_3$ and $CaSO_4$, are saturated in a solution in contact with the atmosphere and at atmospheric pressure. The *Handbook of Chemistry and Physics* (1967) states:

> "In a solution containing two salts which yield a common ion the ratio of solubilities of the two salts is the ratio of the solubility products".

For example, at 20° C:

$$\frac{\text{solubility product of } CaSO_4 \quad 1.6 \times 10^{-5}}{\text{solubility product of } CaCO_3 \quad 1.0 \times 10^{-8}} \quad \frac{175}{1}$$

In a solution in which the ratio between $CaSO_4$ and $CaCO_3$ was different from 175:1 one of the pure salts would be separated until the ratio was reached. Pure calcium sulfate would precipitate if the carbonate ions in solution were kept below 1/175 of the sulfate ions. If, on the other hand, the carbonate ions in solution were increased to a concentration above 1/175 of the sulfate concentration, calcium carbonate would precipitate.

Carbon dioxide concentration has no direct effect on the solution of calcium sulfate (Sherman, 1965). However, the concentration of carbon dioxide determines the amount of calcium carbonate which can be changed to the more soluble bicarbonate, and the absorption or elimination of carbon dioxide may cause solution or precipitation of calcium carbonate.

The effect of carbon dioxide on the solubility of calcium carbonate can be explained as follows:

(1) $CO_2 + H_2O \rightleftharpoons H_2CO_3$

(2) $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$

(3) $H^+ \quad CO_3^{--} \rightleftharpoons HCO_3^-$

(4) $Ca^{++} + CO_3^{--} \rightleftharpoons CaCO_3$

(5) $Ca^{++} + 2HCO_3^- \rightleftharpoons Ca(HCO_3)_2$

In equation 1, carbon dioxide in the atmosphere reacts with water to form carbonic acid. This reaction is highly sensitive to such environmental factors as temperature, salinity, and atmospheric pressure. "The hydrogen ions generated in the dissociation of carbonic acid (equation 2) are largely united with the carbonic ions to produce bicarbonate ions (equation 3), HCO_3^-, which are only sparingly dissociated. This process disturbs the calcium carbonate equilibrium, and additional calcium carbonate is dissolved (equation 4) until the solubility product of calcium carbonate reaches its previous value..." (Rankama and Sahama, 1950, p. 465).

In the Todilto basin the chemical equilibrium between calcium, carbonate, and sulfate ions was much more complex because of additional ions in solution and continuous variation of the physical environment. It is believed, however, that during the deposition of the Todilto Gypsum member, changes in the amount of carbon dioxide in the basin water caused the precipitation of calcium sulfate and calcium carbonate to oscillate about the solubility ratio of calcium carbonate and calcium sulfate.

The effect of carbon dioxide on the solubility of calcium carbonate can be explained as follows:

(1) $CO_2 + H_2O \rightleftharpoons H_2CO_3$

(2) $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$

(3) $H^+ + CO_3^{=} \rightleftharpoons HCO_3^-$

(4) $Ca^{++} + CO_3^{=} \rightleftharpoons CaCO_3$

(5) $CaCO_3 + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$

In equation 1, carbon dioxide in the atmosphere reacts with water to form carbonic acid. This reaction is kinetically very slow and depends on environmental factors as temperature, salinity, and atmospheric pressure. The hydrogen ions generated in the dissociation of carbonic acid (equation 2) are largely united with the carbonate ions to produce bicarbonate ions (equation 3), HCO_3^-, which are only sparingly dissociated. This process disturbs the calcium carbonate equilibrium, and additional calcium carbonate is dissolved (equation 4) until the solubility product of calcium carbonate reaches its previous value...." (Krumbein and Sloss, 1963, p. 469).

In the Todilto basin the chemical equilibrium between calcium, carbonate, and sulfate ions was much more complex because of the other ions in solution and continual variation of the physical environment. It is believed, however, that during the deposition of the Todilto Gypsum Member, changes in the amount of carbon dioxide in the brine water caused the precipitation of calcium carbonate and calcium sulfate to fluctuate about the solubility ratio of calcium carbonate and calcium sulfate.

During the deposition of the Todilto gypsum the climate was distinctly seasonal. In the summer, increased temperature, salinity, and photosynthesis drove carbon dioxide from the water and caused deposition of calcium carbonate. During the winter and spring, cooler temperatures, inactivity of plankton, and reduced salinity allowed more carbon dioxide to be held in solution, caused $CaCO_3$ to go into the more soluble $Ca(HCO_3)_2$, and caused deposition of calcium sulfate.

A planktonic boom probably occurred during the summer or late spring when temperatures became warm. The planktonic rain coincided with the deposition of calcium carbonate, which upon lithification formed a bituminous limestone. Organic material was also added to the sediments during the whole period of gypsum deposition. This is evidenced by a hydrogen sulfide odor from freshly broken surfaces of gypsum. This lithology differs noticeably from the distinct calcium carbonate-sapropel layering of the limestone member, but each Limestone gypsum sequence is also believed to represent a varve. Using an average thickness of 5.8 mm per varve, an interpolated estimate of 3,100 years was obtained as the time necessary for the deposition of the massive gypsum unit.

During the deposition of the Todilto gypsum the climate was distinctly seasonal. In the summer, increased temperature, salinity, and photosynthetic uptake of carbon dioxide from the water mass caused deposition of calcium carbonate. During the winter and spring, cooler temperatures, the activity of plankton, and reduced salinity allowed more carbon dioxide to be held in solution, causing $CaCO_3$ to go into the more soluble $Ca(HCO_3)_2$ and caused deposition of calcium sulfate.

A plankton bloom probably occurred during the summer or late spring when temperatures became warm. The planktonic rain coincided with the deposition of calcium carbonate, which upon lithification formed a bituminous limestone. Organic material was also added to the sediments during the whole period of gypsum deposition. This is evidenced by a hydrogen sulfide odor from freshly broken surfaces of gypsum. This lithology differs noticeably from the distinct calcium carbonate-gypsum layering of the limestone member, but such laminated gypsum sequence is also believed to represent a varve. Using an average thickness of 1.8 mm per varve, an interpolated estimate of 3,100 years was obtained as the time necessary for the deposition of the massive gypsum unit.

Insoluble residues

Insoluble residues from gypsum samples were obtained by dissolving them in a solution of 1 part sodium thiosulphate to 4 parts water (Goldman, 1952, p. 70). The quantity of clastic material obtained from the samples was low. Darton (1928, p. 168) reports that gypsum collected near Senorito, Sandoval County, New Mexico contained 97 percent pure gypsum, 3 percent of probable calcium carbonate, and only 0.18 percent insoluble residue. The low clastic content of the gypsum member can be explained by its comparatively rapid rate of accumulation or by a decrease in the competency of streams or wind.

Gypsum-shale unit

A 14-foot layer of clastic rock overlies the massive gypsum at locality 3 (Fig. 5). Above this is 31 feet of interbedded coarsely crystalline gypsum and calcareous shale (Figs. 22 and 23). The contact between the Todilto and Morrison formations is covered.

Figure 24, a detailed stratigraphic column of the gypsum-shale unit, demonstrates the cyclic nature of the sedimentation. Each gypsum-shale group forms a cycle (Figs. 22 and 23). The average thickness of the gypsum layers is about 4 inches, and they range in thickness from 9 to 0.75 inches. The gypsum layers are composed of coarse, interlocking

Insoluble residues

Insoluble residue from gypsum samples [illegible]

them in a solution [illegible] (…

1952, p. 70). The quantity of clastic material [illegible] samples

was low. [illegible] (1920, p. 129) [illegible] gypsum [illegible]

Socorro, Sandoval County, New [illegible] percent [illegible]

3 percent of [illegible] calcium carbonate, and only [illegible] per cent [illegible]

residue. The low clastic content of the gypsum member [illegible]

by its comparatively rapid rate of [illegible]

competency [illegible].

Gypsum-shale unit

A 14-foot layer of clastic rock [illegible] gypsum at

locality 2 (Fig. 2). [illegible]

gypsum and calcareous shale (Fig. [illegible]). The [illegible]

Todilto and [illegible] is [illegible].

Figure 24, a detailed stratigraphic section of the gypsum-shale unit,

demonstrates the cyclic nature of [illegible] gypsum-shale

group forms a cycle (Figs. [illegible] and [illegible]). [illegible]

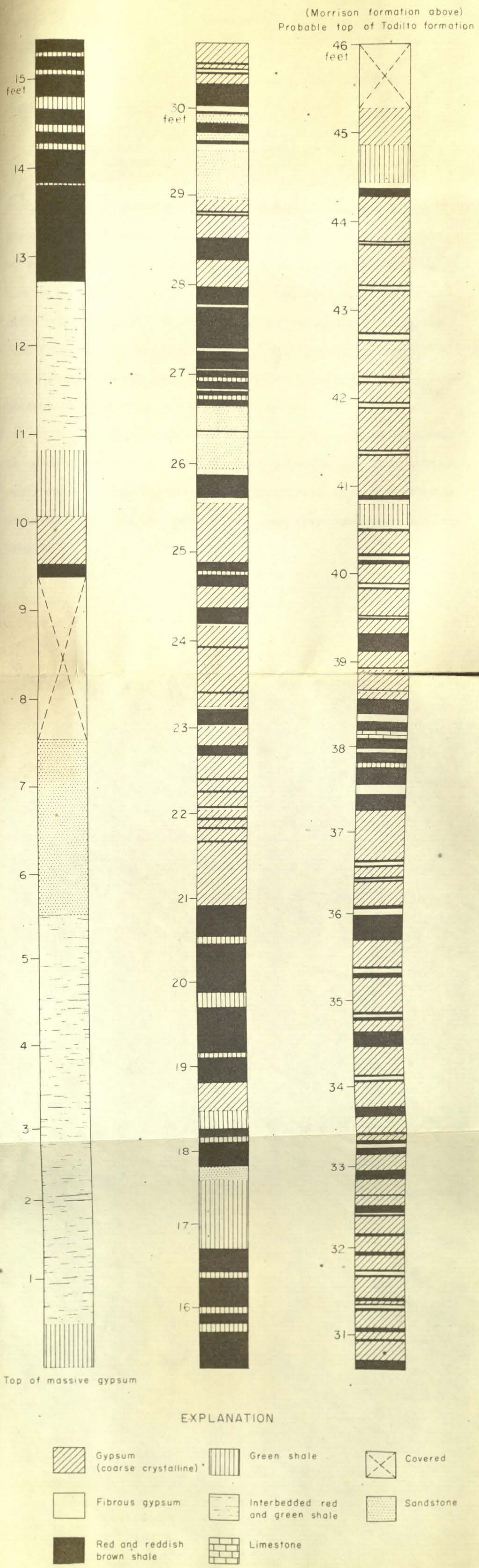
gypsum layers is about [illegible] inches, and they range in thickness [illegible]

0.74 inches. [illegible] gypsum layers [illegible]

re 22. Outcrop of gypsum-shale unit on the west flank of
ra Amarilla anticline, locality 3 (Fig. 5).

Outcrop of gypsum-shale unit on the west flank of
arilla anticline, locality 3 (Fig. 5); a, coarse
e gypsum; b, reddish brown shale; c, fibrous gypsum.

Figure 24. Graphic representation of the stratigraphy of the gypsum-shale unit of the Todilto gypsum member, Tierra Amarilla anticline, Sec. 18, T 15 N., R. 1 W.



euhedral and subhedral crystals (Fig. 26). The shale intervals between the gypsum beds range in thickness from a fraction of an inch to 13 inches. Calcite or organic laminae were not observed within the gypsum layers.

In a general discussion of the red bed-quartzose sandstone-evaporite association Krumbein (1951, p. 78) states:

> "The red unfossiliferous shale suggests a brackish or fresh water environment, and the interspersed beds of anhydrite and thin densely crystalline dolomite imply recurrent short-lived marine invasions..."

The interpretation that each gypsum layer implies a marine transgression is questionable, especially when applied to the Todilto sediments. The periodicity and thin bedding of the shale and gypsum suggest that the factor controlling the nature of the sediments was climate, not shifts in sea level. It is likely that mud was brought into the evaporite basin from the surrounding drainage basin during periods of high water. This lowered the concentration of the sulfate ion and caused a temporary decrease in the rate of calcium sulfate deposition.

Five beds of grayish brown, fine- to very fine-grained, subrounded to rounded, well-sorted, calcareous and gypsiferous cemented sandstone occur within the gypsum-shale unit. The thickness of the thickest bed is 36 inches; that of the thinnest is 1 inch. Most of the sandstone grains are frosted.

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Five beds of gypsiferous [illegible], [illegible] to rounded, well-sorted, [illegible] occur within the gypsum-bearing unit. The thickness of the [illegible] is 36 inches; that of the thinnest is [illegible] frosted.

Figure 26. Photomicrograph of a thin section of gypsum from the gypsum-shale unit which exhibits a coarse crystalline texture (crossed nicols). Sample obtained from locality 3 (Fig. 5).

Figure 27. Photomicrograph of thin section of fibrous gypsum from gypsum-shale unit (crossed nicols). Sample obtained from locality 3 (Fig. 5).

The red, reddish brown, and green shale are similar in appearance to shale within the overlying Morrison formation. The top of the Todilto formation is considered to be the uppermost gypsum bed. The lithology and conformable contact relations in the White Mesa area suggest that the gypsum-shale interval represents a transition from predominantly chemical to predominantly clastic deposition.

Veins of fibrous gypsum occur in all the shale beds. The needle-like crystals of gypsum have grown perpendicular to the bedding (Figs. 23 and 27). Schmidt (as quoted by Buckley, 1951, p. 471) has explained the methods of growth of cross-fiber veins as follows:

> "Solutions saturated with calcium sulfate were supplied by capillary openings normal to a plane of weakness. Solutions move to the plane by capillary attraction, and a crystal, once started, continues to grow at the junction of the vein wall and the gypsum crystal. The crystals are thin and fragile, but are able to support tremendous weight because of close grouping."

Regional considerations

The extent of the Gypsum member is shown in Figure 28. It was deposited in an area of about 12,000 square miles, generally confined to the center of the basin. The Limestone member has a much greater area (34,600 square miles). The restriction of the Gypsum member suggests that the size of the basin had decreased by the time calcium sulfate reached the saturation point.

DEPOSITIONAL HISTORY

The base of the Limestone member is composed largely of organic and clastic laminae. Limestone laminae are thin or absent. This type of deposition lasted for several hundred years.

Hematite-rich layers and iron concretions are present near the base of the Limestone member in the Warm Springs area. They may represent the initial stage of evaporite deposition, and suggest that the water in which deposition occurred was alkaline.

In the White Mesa area the Entrada sandstone and overlying Todilto limestone are in sharp contact. Lenses of sandstone interspersed between laminae in the lower part of the limestone member occur at Tonque Arroyo (Sec. 1, T. 13 N., R. 5 E.), in the Zuni Uplift, along the Piedra River in southwestern Colorado, and elsewhere. Harshbarger, Repenning, and Irwin (1957, p. 46) have interpreted these sandstone lenses as continuous deposition from typical Entrada sedimentation to typical Todilto sedimentation.

After several hundred years the environmental factors reached an equilibrium which persisted without significant change for several thousand years. Near Warm Springs, Sandoval County, New Mexico, 5.5 feet of Todilto limestone was deposited in about 12,500 years.

Near the top of the Todilto Limestone member, gypsum was introduced as an occasional fourth lamina into the typical annual cycle. Still higher in the section the four-fold depositional cycle (calcium carbonate-sapropel-clastics-calcium sulfate) became predominant and continued for approximately 2,200 years at locality 2 (Fig. 5). As the environmental controls gradually shifted, calcium sulfate became the principal precipitate and the influx of clastic grains subsided. Near San Ysidro, Sandoval County, New Mexico, this period of sedimentation lasted about 3,100 years, during which more than 70 feet of calcium sulfate and minor amounts of calcium carbonate and organic particles were deposited.

Late in the deposition of the gypsum member the environment was altered by an influx of clastic material. This change suggests a return to more humid climatic conditions. Oscillations of gypsum and shale became the prevalent sedimentary cycles. Then, with transition into the Morrison formation, clastic material became dominant. The time required for the deposition of the 40-foot gypsum-shale interval in the White Mesa area cannot be determined by varve analysis. Deposition probably occurred at a comparatively rapid rate inasmuch as the sediments were deposited in the last phase of a shrinking basin saturated with calcium sulfate.

The time required for the deposition of the entire Todilto formation is estimated to be slightly more than 20,000 years.

Near the top of the Todilto limestone member, gypsum was introduced as an occasional fourth member into the typical annual cycle. Still higher in the section the four-fold depositional cycle (calcium carbonate-sapropel-clastics-calcium sulfate) became predominant and continued for approximately [illegible] years at locality 17 (Fig. 9). As the environmental controls gradually shifted, calcium sulfate became the principal precipitate and the influx of clastic grains subsided. Near San Ysidro, Sandoval County, New Mexico, this period of sedimentation lasted about [illegible] years, during which more than 70 feet of calcium sulfate and minor amounts of calcium carbonate and organic particles were deposited.

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The time required for the deposition of the entire Todilto formation is estimated to be slightly more than [illegible] years.

SOURCE OF THE SALTS

General Statement

Two sources have been postulated for the Todilto evaporite deposits. The basin may have been a gulf or bay, as illustrated by Harshbarger, Repenning, and Irwin (1957, p. 47), in which limestone and gypsum were concentrated by evaporation of sea water entering through a restricted opening. Some of the salts could have been contributed by streams, but a marine connection would still have been the source for most of the evaporites. On the other hand, the salts may have been of fluvial origin, deposited in a closed lake.

Marine Origin

A marine origin is favored by three lines of evidence. First, the Todilto formation can be correlated with the marine Curtis formation of southern Utah. A strait may have connected the Todilto basin with the Curtis sea. Second, the large quantity of gypsum can most easily be explained by marine origin. Finally, the strongest argument for a marine origin is the presence of fossil fish of "marine affinity" in the Todilto limestone (Baker, Dane, and Reeside, 1947, p. 1668; Imlay, 1952, p. 960).

SOURCE OF THE SALTS

General Statement

Two sources have been postulated for the Todilto evaporite deposits. The basin may have been a gulf or bay, as suggested by Harshbarger, Repenning, and Irwin (1957, p. 44), in which anhydrite and gypsum were concentrated by evaporation of sea water replenished through a restricted opening. Some of the salts could have been contributed by streams, but a marine connection would still have been the source for most of the evaporites. On the other hand, the salts may have been of fluvial origin, deposited in a closed basin.

Marine Origin

A marine origin is favored by three lines of evidence. First, the Todilto formation can be correlated with the marine Curtis formation of southern Utah. A strait may have connected the Todilto basin with the Curtis sea. Second, the large quantity of gypsum and anhydrite is readily explained by marine origin. Finally, the strongest argument for marine origin is the presence of fossil fish of [illegible] type in the Todilto limestone (Baker, Dane, and Reeside, [illegible], p. [illegible]; [illegible], p. 760).

Imlay (1952, p. 961) believed that the Curtis sea may have been connected with the Todilto basin in southern and southeastern Utah, because in this area the outcrops of the Todilto limestone are roughly parallel to the southern limits of the Curtis formation for about 200 miles (Fig. 28). McKee et al. (1957, p. 3) proposed that several marine connections may have existed, but evidence is lacking. For example, erosion of Mesozoic and Paleozoic rocks from the Sangre de Cristo Uplift would have removed all evidence of a channel just south of the Ancestral Rockies. Harshbarger, Repenning, and Irwin (1957, p. 46) noted that the Entrada sandstone is abnormally thin between Mexican Water, Arizona, and Cortez, Colorado, and suggested that the thinning was due to submarine erosion in a channel connecting the Curtis sea with the Todilto basin. The evidence is inconclusive because subaerial erosion could also account for thinning of the Entrada.

Beds of halite are not known in the Todilto formation. If the Todilto limestone and gypsum originated as precipitates from sea water, currents must have prevented the deposition of sodium chloride. A circulation system somewhat similar to that suggested by King (1947, p. 473) would have been in operation. Surface currents of normal sea water may have flowed through the restricted channel into the basin, while currents at depth returned highly saline water to the sea.

Imlay (1952, p. 852) believed that the Curtis sea may have been connected with the [illegible] Utah, because [illegible] roughly parallel to the [illegible] about 200 miles (Fig. 22). [illegible] et al. ([illegible], p. [illegible]) [illegible] that several marine connections may have [illegible]. For example, erosion of [illegible] Sangre de Cristo Uplift would have [illegible] just south of the Ancestral Rockies, [illegible]. Irwin (1957, p. 46) noted that the [illegible] this between Mexican Water, Arizona, [illegible] Colorado, and suggested that the [illegible] connecting the Curtis sea with the [illegible] inconclusive because [illegible] of the Entrada.

Beds of [illegible] are [illegible] Twelve-mile [illegible] water, currents [illegible] A circulation [illegible] (1957, p. 472) would have [illegible] water may have flowed [illegible] while currents at depth [illegible].

We can infer that such a channel was deep and fairly narrow, because the flow would have been predominantly from the sea into the basin if the channel were shallow and wide. Evidence of a deep narrow channel is wanting. The thinning of the Entrada reported by Harshbarger, Repenning, and Irwin (1957, p. 46) might indicate the existence of a broad submerged ridge, but hardly a deep, narrow channel.

If a two-way circulation system existed, it might have created currents of sufficient magnitude to prevent the formation of the characteristic laminations and the currents also might have prevented the stagnation of the bottom water.

Nonmarine Origin

Fossil fish have been found in five localities in the Todilto limestone. Imlay (1952, p. 960) and Harshbarger, Repenning, and Irwin (1957, p.46) consider these fossil fish to have marine affinities. Two genera of fish have been described from the Todilto limestone. Specimens of Pholidophorus americanus Eastman, were described by Koerner (1930, p. 463) and mentioned by Dunkle (1942, p. 62). Marine affinities for this fish were implied by a comparison with the only earlier description of the species by Eastman (1899, p. 398). The descriptions were based on specimens found by Darton in Jurassic sediments of the Black Hills. The South Dakota sediments are marine. Darton's fish, however, were not directly associated

We can infer that such a channel [illegible] developed fairly early, because the flow would have been predominantly from the [illegible] basin if the channel were shallower than [illegible] channel is [illegible]. The [illegible] Rasmussen, and Irwin (1962, p. [illegible]) [illegible] submerged sills, but [illegible].

If a two-way circulation [illegible] currents of sufficient [illegible] laminations and the currents [illegible] of the bottom water.

Environmental [illegible]

Fossil fish have been found in [illegible] the Pacific [illegible]. Imlay (1952, p. 960) and [illegible] (1927, p. 46) consider these fossil fish to be [illegible] have been described from [illegible]. Specimens of [illegible] americanus [illegible] were [illegible] by [illegible] (1901, p. [illegible]) and mentioned by Dunkle (1942, p. [illegible]). [illegible] implied by a [illegible] by Hartman (1899, p. [illegible]). [illegible] found by Darton in [illegible] sediments are marine. [illegible] with a marine fauna, but were the only fossils found in a sandstone below a marine sequence and about three feet above an eroded surface of red beds (Darton, 1899, p. 388).

The species Leptolepis schowei Dunkle was described from the Todilto limestone (Dunkle, 1942, p. 62). Dunkle states that the same species was also found in red beds of the Upper part of the Lykins formation of Colorado in association with a fossil conifer strobilus. A new species of Leptolepis described by David (1941, p. 318) came from a thinly laminated siliceous shale of Lower Cretaceous age east of Eureka, Nevada. Here again, Leptolepis is associated with fossil plants.

Harshbarger, Repenning, and Irwin (1957, p. 46) believed the fish could not have lived in the toxic water of the basin, but were killed after being carried in by currents from the Curtis sea. This does not explain why all occurrences of fish were found on the edge of the basin farthest from the "Todilto strait". The fish usually occur as isolated death assemblages of many specimens near the ancient shore of the Todilto basin (Fig. 28). It is entirely possible that the fish were adapted to living in streams and were killed after entering the evaporite basin. Another possibility is that the fish lived in areas of essentially fresh water adjacent to the mouths of inflowing streams. If this were true, with a marine fauna, but were the only fossils found in a limestone below a marine sequence and about three feet above a gypsum sur- face of red beds (Darton, 1928, p. 88).

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Harshbarger, Repenning, and Irwin (1957, p. 43) believe the fish could not have lived in the brackish water of the basin, but were killed after being carried in by currents from the Curtis sea. This does not explain why all occurrences of fish were found at the edge of the basin farthest from the "Todilto strait". The fish usually occur as isolated death assemblages of many specimens near the ancient shore of the Todilto basin (Fig. 25). It is entirely possible that the fish were adapted to living in streams and were killed when entering the evaporite basin. Another possibility is that the fish lived in areas of essentially fresh water adjacent to the mouths of inflowing streams. If this were true,

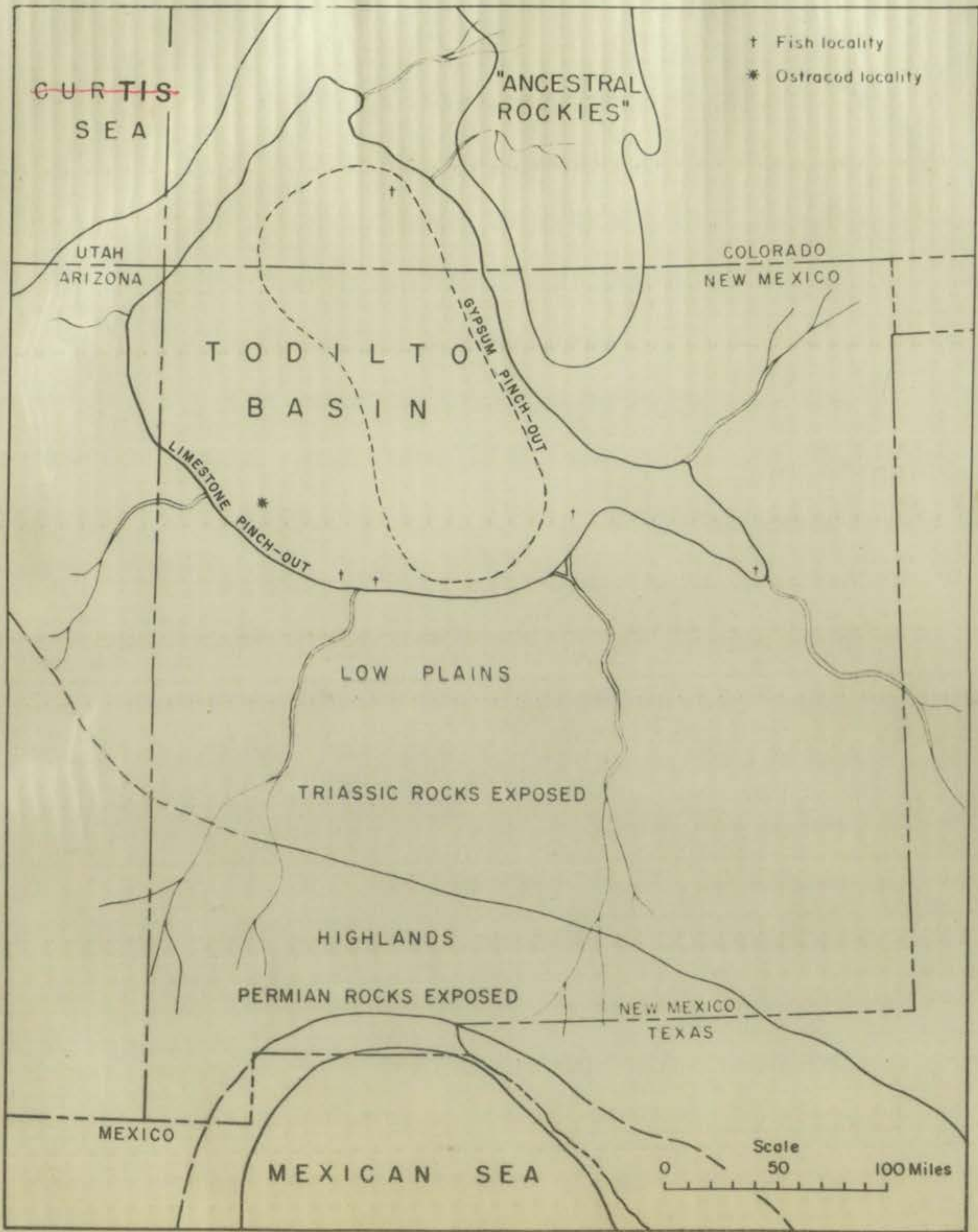

Figure 28. Paleogeographic map of the Todilto basin. The area of deposition of calcium carbonate was about 34,600 square miles. The water of the basin receded to a central area of about 12,000 square miles before calcium sulfate began to precipitate. Weathering of Permian and Triassic strata in the moist highlands may have provided a source for the salts deposited in the Todilto basin.

periods of mass mortality might have occurred during drouths. The association of Pholidophorus and Leptolepis at other localities with coarse clastics, red beds, a conifer strobilus and other plant fossils, and the distribution of the fossil fish in the Todilto basin, suggest that the fish were living in a nonmarine environment.

If it is assumed that the Todilto limestone and gypsum were supplied by sea water which flowed through a strait connecting the Curtis sea with the Todilto evaporite basin, and that the distinct cycles of sedimentation represent varves, then a great volume of sea water passed through the strait into the basin each year. A calculated inflow of at least 165,000,000 acre-feet per year was obtained by assuming a calcium carbonate concentration of 123 parts per million, an area of 34,600 square miles for the evaporite basin, and an average annual deposition rate of 0.127 mm for the Todilto Limestone member. The toxic waters over sapropel accumulations provide an ideal environment for the preservation of planktonic and nektonic animals. If we assume a marine origin, we have a substantial inflow of marine water, an excellent environment for the preservation of fossils, but a formation characterized by an almost complete absence of fossils. It is difficult to imagine a situation that would explain the lack of fossils if there had been a marine connection.

periods of [illegible] might [illegible] . The

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by an almost complete [illegible]

situation [illegible]

connection.

A fresh-water ostracod species, Metacypris todiltensis Swain, has been found in the Todilto limestone near Thoreau, Valencia County, New Mexico. Swain (1946, p. 553) states that it is most closely related to M. whitei Jones from the nonmarine Morrison formation of Colorado. Jones (1956, p. 285) states that Metacypris is quite common in lacustrine sediments.

The geologically short time required for deposition of the Todilto formation suggests climatic rather than structural control for the influx of water into the basin. Deposition began at about the same time throughout most of the basin as shown by similar thicknesses of limestone laminae and even thicknesses of the limestone member over an extensive area. Only about 20,000 years were required for the deposition of the entire Todilto formation. If the evaporite basin originated as a marine embayment, the sill of the embayment would have had to be lowered rapidly enough to allow a transgression over the 34,600 square miles of the basin in a very short time. It seems more reasonable to believe that climate controlled the growth of a lake. During deposition of the San Rafael group, the climate was hot and dry, as shown by the extensive deposits of dune sand, but by early Todilto time more humid conditions had returned. The Todilto limestone may represent a transition to more humid conditions which started the growth of a shallow lake in a closed basin. In late

Todilto time the climate became progressively more arid, as suggested by a decrease in the supply of clastic particles and by the deposition of calcium sulfate. Eventually the aridity gave way to more humid conditions that prevailed during deposition of the Morrison formation. This sensitive climatic control suggests that the source of moisture and salts was from seasonal precipitation around a closed basin rather than from a tectonically controlled influx of marine water.

Precession of the equinoxes and the eccentricity of the earth's orbit result in a climatic cycle of approximately 21,000 years (Bradley, 1929, p. 105; Gilbert, 1895, p. 124). Todilto time, which lasted about 20,000 years may represent one such cycle. The limestone and gypsum units would represent different phases of the cycle.

The microstratigraphy of the Todilto limestone shows some similarities to the Green River varved marlstones of Colorado, Utah, and Wyoming. The Green River sediments were deposited during middle Eocene time in a series of lakes which covered more than 25,000 square miles. The annual alternation of organic and limestone laminae is common to both the Todilto and Green River formations. Bradley (1929, p. 105) estimates that the time necessary to accumulate 1 foot of Green River varved marlstone was 2,000 years. The time necessary for the deposition of 1 foot of Todilto limestone was on the order of 2,200 years.

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Precession of the equinoxes and the eccentricity of the earth's orbit result in a climatic cycle of approximately 21,000 years (Bradley, 1929, p. 105; Gilbert, 1895, p. 124). Todilto time, which lasted about 20,000 years may represent one such cycle. The limestone and gypsum units would represent different phases of the cycle.

The microstratigraphy of the Todilto limestone shows some similarities to the Green River varved marlstones of Colorado, Utah, and Wyoming. The Green River sediments were deposited during middle Eocene time in a series of lakes which covered more than 25,000 square miles. The annual alternation of organic and limestone laminae is common to both the Todilto and Green River formations. Bradley (1929, p. 105) estimates that the time necessary to accumulate 1 foot of Green River varved marlstone was 2,000 years. The time necessary for the deposition of 1 foot of Todilto limestone was on the order of 2,200 years.

The streams which flowed into the Todilto basin probably derived most of their salts from Permian and Triassic strata exposed south and southeast of the basin (Fig. 28). The Quality of Water Branch of the United States Geological Survey provided partial chemical analyses of stream water flowing over Permian and Triassic strata in Guadalupe, Chaves, De Baca, San Miguel, and Eddy Counties, New Mexico. The Ca^{++}, HCO_3^-, and SO_4^{--} ion concentrations of these streams are probably similar to the ion concentrations of Upper Jurassic streams which flowed into the Todilto evaporite basin. The following is a comparison of the average of the chemical analyses supplied by the Quality of Water Branch and the analysis of average sea water:

Stream water, southern New Mexico				Average sea water (Twenhofel, 1950, p. 508)	
ion conc.		molecular conc.			
Ca^{++}	363 ppm	$CaCO_3$	158 ppm	$CaCO_3$	123 ppm
HCO_3^-	192 ppm	$CaSO_4$	1,296 ppm	$CaSO_4$	1,260 ppm
SO_4^{--}	1,296 ppm				

The concentration of $CaCO_3$ and $CaSO_4$ are about the same for stream water and sea water, which suggests that fluvial or marine origins for the Todilto chemical sediments are both possible.

The streams which flowed into the Todilto basin probably derived most of their salts from Permian and Triassic strata exposed south and southeast of the basin (Fig. [illegible]). The Quality of Water Branch of the United States Geological Survey provided partial chemical analyses of stream water flowing over Permian and Triassic strata in Guadalupe, Chaves, De Baca, [illegible], and Eddy Counties, New Mexico. The Ca^{++}, HCO_3^-, and SO_4^{--} concentrations of these streams are probably similar to the concentrations of Upper Jurassic streams which flowed into the Todilto evaporite basin. The following is a comparison of the average of the chemical analyses supplied by the Quality of Water Branch and an analysis of average sea water:

Stream water, southern New Mexico		Average sea water ([illegible], 1956, p. [illegible])
ion conc.	molecular conc.	
Ca^{++} 365 ppm	$CaSO_4$ ([illegible])	$CaSO_4$ [illegible] ppm
HCO_3^- 192 ppm	$CaCO_3$ [illegible]	$CaCO_3$ [illegible] ppm
SO_4^{--} 1,296 ppm		

The concentration of $CaCO_3$ and $CaSO_4$ [illegible] in stream water and sea water, which [illegible] for the Todilto chemical sediments [illegible].

Allochthonous plant fragments were observed in organic laminae from the Todilto limestone (Fig. 7). They are usually tracheids and fibers from vascular plants, probably conifers (Anderson, 1958). The tracheids were probably brought into the Todilto basin by streams flowing from coniferous forests in the highlands of Arizona and southern New Mexico (Fig. 28), and their abundance suggests fluvial inflow.

The area of gypsum deposition was smaller than the area of calcite deposition and was generally confined to the center of the basin (Fig. 28). The overlap of the two members represents the area of withdrawal between the time when the basin water became saturated with calcium carbonate and the time when the basin water became saturated with calcium sulfate, a period of approximately 13,000 years.

A connection which supplied a constant exchange of water from the Curtis sea and the shrinking evaporite basin seems improbable. If this were the case, a drop in sea level or an uplift of the basin would be necessary to cause the withdrawal of water into a central area. In addition, the connecting channel would have to be deep, narrow, and long. As previously stated, evidence of such a channel is wanting.

Conclusion

The writer believes that paleontological evidence and information supplied by the sediments indicate that the Todilto sediments are nonmarine in origin.

Allochthonous plant fragments were also present in organic residues from the Pecos [illegible] (Fig. 7). [illegible] and fibers from vascular plants, probably conifers (Anderson, 1960). The tracheids were probably brought into the [illegible] from coniferous forests in the highlands of Arizona and northern New Mexico (Fig. 28), and their abundance [illegible].

The area of gypsum deposition decreased [illegible] calcite deposition and was generally confined to the center of the basin (Fig. 28). The overlap of the two [illegible] drawal between the time when the [illegible] with calcium carbonate and the time when the [illegible] with calcium sulfate, a period of approximately [illegible] years.

A connection which supplied a constant recharge of water from the Curtis sea and the [illegible]. If this were the case, a drop in sea level [illegible] necessary to cause the [illegible]. [illegible] the connecting channel would have to be [illegible]. As previously stated, evidence of such [illegible] is lacking.

Conclusion

The writer believes that [illegible] supplied by the sediments [illegible] in origin.

CLIMATIC CYCLES AND CLIMATE

Climatic Cycles

General statement

An analysis of the varved sediments for cycles longer than the annual cycle was made using the following technique. Slabs of limestone were cut perpendicular to the bedding; the exposed face was polished and then etched with dilute hydrochloric acid. The etching removed about 1 mm of limestone and left the organic layers standing in relief. The organic layers were then stained. The surface was covered with Canada balsam and a cover slip and photomicrographed. Figure 29 is representative of the photomicrographs obtained by this process and Figure 30 is a compilation of most of the sections used in the study. Measuring was done by using photomicrographs in conjunction with observation of the etched sections under the microscope. It was impossible to determine in every case whether an organic layer represented one or two layers. Because of this difficulty in counting, the number of varves per unit thickness may be 5 to 10 percent too low.

Long cycles

The thickness of 1,592 limestone laminae were plotted against time (Fig. 31). Cycles of 180 years and 60 years were observed. The

Figure 29. Photomicrograph of etched section of Todilto limestone; a, limestone; b, organic lamina. Sample obtained from location 2 (Fig. 5).

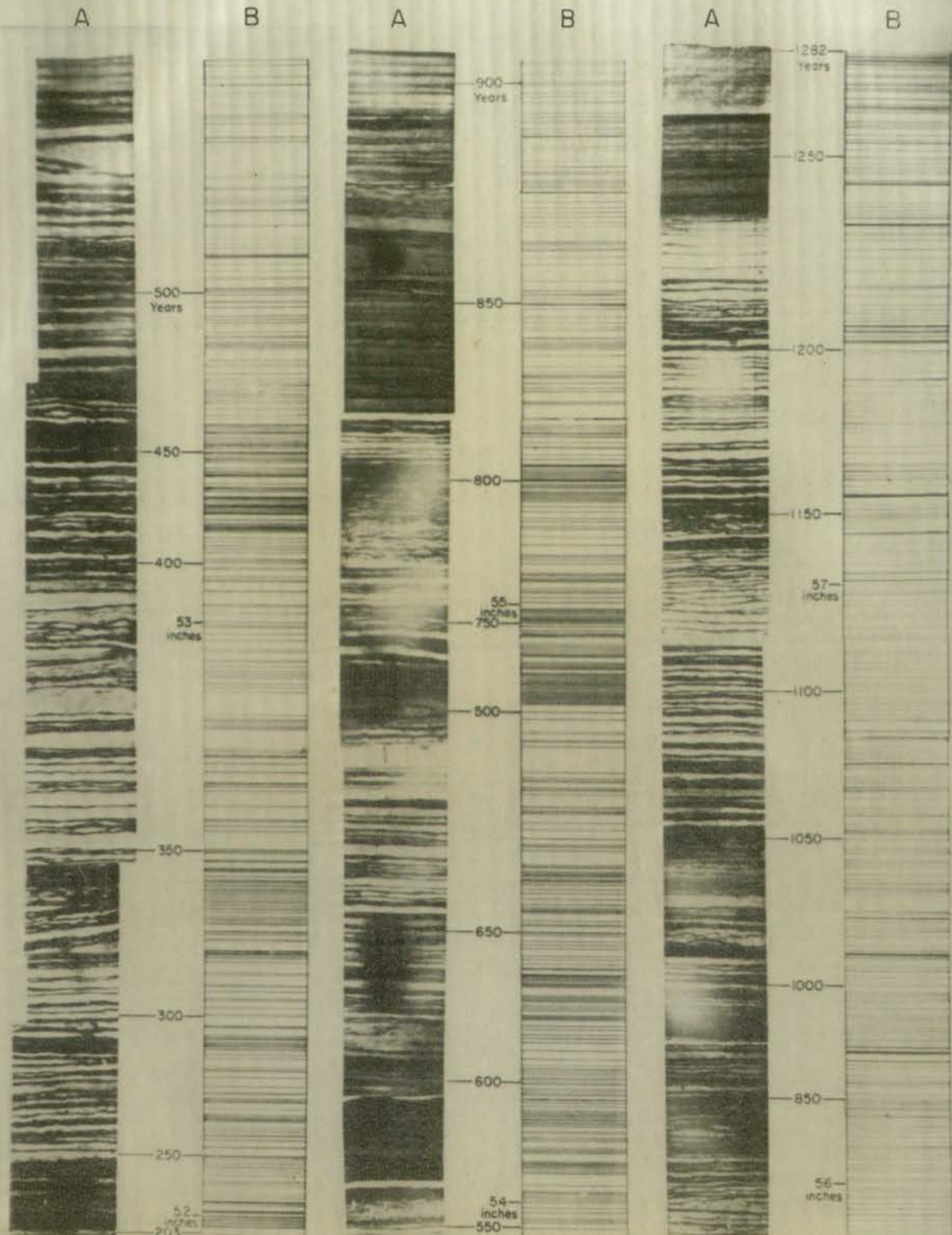

Figure 30. Photomicrographs of a portion of the Todilto limestone from an interval 52 to 58 inches above the Todilto-Entrada contact at locality 2 (Fig. 5). The columns marked "A" are photomicrographs (x 3.8) of etched limestone slabs in which the organic laminae have been dyed purple. The adjoining columns, marked "B", are reconstructions made by using photomicrographs in conjunction with observations of etched sections through the microscope. A varve 51 inches above the Todilto-Entrada contact was arbitrarily chosen as the zero point for the chronology.

Figure 31. Curve showing variation in varve thickness with time. Cycles of 180 and 60 years are discernible. The 0 year in the chronology was established as a varve 51 inches above the base of the Todilto limestone at locality 2 (Fig. 5). The curve was constructed using the smoothing formula: thickness $= \frac{A+2B+C}{4}$.

180-year cycle does not correlate with any well-established cycle. The 60-year cycle is partially obscured by the 180-year cycle for a period of 1,300 years, but is well represented on the graph between 1,300 and 1,592 years. Korn (1938) observed distinct cycles of 56.6 years in Upper Devonian and Lower Carboniferous shale of Thuringia, Germany. Bradley (1929, p. 107) observed cycles of about 50 years in the Middle Eocene Green River formation of Colorado, Utah, and Wyoming. Recent cycles of approximately 56 years have been detected by meteorologists (Zeuner, 1952, p. 44). Antevs (1929, p. 83) states that glacial varves in small recessional moraines in the Berkshire Hills, Massachusetts seem to record a periodicity of 55 to 77 years.

Short cycles

Some periodicity is shown in the repetition of thick limestone laminae every 4 to 12 years. These changes may be related to a sunspot cycle.

Climate

The rate of evaporation from the ancient Todilto lake can be estimated. The persistence and uniformity of the rhythmically deposited laminae indicate that inflow and evaporation were essentially in balance. Since the water within the basin was either saturated or close to the saturation point of calcium carbonate, the weight of calcium carbonate

180-year cycle does not correlate with any well-established cycle. The 60-year cycle is partially dominated by the 180-year cycle for a period of 1,380 years, but it would seem to be on the grand between 1,380 and 1,593 years. Korn (p. 8) observed that cycles of 56.6 years in Upper Devonian and Lower Carboniferous shale of Thuringia, Germany. Bradley (1929, p. 107) observed cycles of about 50 years in the Middle Eocene Green River formation of Colorado, Utah, and Wyoming. Brückner cycles of approximately 35 years have been detected by meteorologists ([illegible], 19[illegible], p. 49). Antevs (1925, p. 32) states that glacial varves in small [illegible] moraines in the Berkshire Hills, which [illegible] seem to show a periodicity of 55 to 77 years.

Short cycles

Some periodicity is shown in the repetition of thick limestone laminae every 6 to 12 years. These changes may be related to the sun-spot cycle.

Climate

The rate of evaporation from the ancient Indian lake can be estimated. The persistence and uniformity of the chemically deposited limestone indicate that inflow and evaporation were approximately in balance. Since the water entering the basin had to be saturated or close to the saturation point of calcium carbonate, [illegible] brought into the basin during one year approximately equaled the weight deposited during that year. By knowing the area of the Todilto basin, the concentration of calcium carbonate in the streams entering the Todilto basin (page 56), and other factors, the rate of evaporation can be calculated as follows:

W1 = Weight of calcium carbonate contained in inflowing water in one year

V = Volume of inflow in one year

Ww = Weight of one cubic foot of water

y = Percent of calcium carbonate contained in the inflowing water

$$W1 = V \times Ww \times y$$

W2 = Weight of calcium carbonate deposited in one year

A = Area of deposition of calcium carbonate

z = Average thickness of limestone laminae

s.g. = Specific gravity of limestone

$$W2 = A \times z \times s.g.$$

since we have assumed that W1 equals W2

$$V \times Ww \times y = A \times z \times s.g.$$

$$V/A = z \times s.g./Ww \times y$$

The volume of water (V) entering the basin in one year would assume a depth (d) which was inversely proportional to the area (A).

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A = Area of deposition of calcium carbonate

z = Average thickness of limestone laminae

$s.g.$ = Specific gravity of limestone

$$W2 = A \times z \times s.g.$$

since we have assumed that W1 equals W2

$$V \times Ww \times y = A \times z \times s.g.$$

$$V/A = z \times s.g./Ww \times y$$

The volume of water (V) entering the basin in one year would assume a depth (Z) which was inversely proportional to the area (A).

$d = V/A$; therefore, $d = z \times s.g./Ww \times y$

We have assumed that evaporation and inflow were in balance; therefore, evaporation (e), measured in inches per year, is equal to the depth (d) which the water entering the basin during one year would have assumed.

$$d = e$$

therefore, $e = z \times s.g./Ww \times y$

If we assume a fluvial concentration of 158 ppm $CaCO_3$ (page 56) and apply the above formula, an evaporation rate of 86 inches per year is indicated.

$$e = \frac{0.127 \times 2.72}{25.4 \times .000158} = 86 \text{ inches}$$

The average annual temperature surrounding the Todilto basin cannot be precisely determined from evaporation because humidity, wind velocity, atmospheric pressure, and insolation are unknown. However, arid regions of today with evaporation of between 80 and 90 inches per year from reservoir surfaces, and with seasonal variations similar to those inferred for the Todilto evaporite basin, have average summer temperatures of about 85° F and average winter temperatures of about 57° F. These temperatures are probably representative of the seasonal temperatures surrounding the Todilto evaporite basin during Upper Jurassic time. The climate was probably arid-subtropical, like the climate in the interior of southern California today. The basin itself was arid around its margin, and the lake was fed by rivers with their headwaters in well-watered uplands. The precipitation was seasonal, with

$d = V/A$; therefore, $d = m \times s.g. / W \times y$

We have assumed that evaporation and inflow were in balance; therefore, evaporation (e), measured in inches per year, is equal to the depth (d) which the water entering the basin during one year would have assumed.

$$d = e$$

therefore, $e = m \times s.g. / W \times y$

If we assume a fluvial concentration of 158 ppm $CaCO_3$ (page 56) and apply the above formula, an evaporation rate of 86 inches per year is indicated.

$$e = \frac{0.327 \times 3.785}{25.4 \times .000158} = 86 \text{ inches}$$

The average annual temperature surrounding the Todilto basin cannot be precisely determined from evaporation because humidity, wind velocity, atmospheric pressure, and insolation are unknown. However, arid regions of today with evaporation of between 30 and 90 inches per year from reservoir surfaces, and with seasonal variations similar to those inferred for the Todilto evaporite basin, have average summer temperatures of about 85° F and average winter temperatures of about 57° F. These temperatures are probably representative of the seasonal temperatures surrounding the Todilto evaporite basin during Upper Jurassic time. The climate was probably arid-subtropical, like the climate in the interior of southern California today. The basin itself was arid around its margin, and the lake was fed by rivers with their headwaters in well-watered uplands. The precipitation was seasonal, with most of the rainfall in the winter and spring. Intervals of warm dry climate alternated with slightly longer intervals of cooler temperature about every 180 years. At other times the warm and cool intervals occurred about every 60 years.

The rain shadow which covered the Todilto basin may have been related to the Nevadian orogeny. The western mountain chain blocked low-level moisture from the Pacific Ocean, but enough moisture probably passed into the interior at higher elevations to water the slopes of the uplands. In addition some winter and spring moisture may have been derived from a cyclonic cell established over the Curtis sea. Summer aridity suggests that little tropical moisture was derived from the south, a situation which could have been the result of an unfavorable circulation pattern or due to the presence of an Upper Jurassic highland to the south (Fig. 28).

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