Waste Isolation Pilot Plant

Compliance Certification Application

Reference 14

Anderson, R.Y., Dean, W.E., Kirkland, Jr., D.W., and Snider, H. I. 1972.
Permian Castile Varved Evaporite Sequence, West Texas and New Mexico.
Geological Society of America Bulletin, Vol. 83, pp. 59-86.

Submitted in accordance with 40 CFR §194.13, Submission of Reference Materials.

DATE: 02/28/96
DELIVERY DUE: 03/18/96

R E P R I N T

WESTINGHOUSE ELECTRIC CORPORATION
WASTE ISOLATION DIVISION
P.O. BOX 2078
CARLSBAD, NM 88221

PURCHASE ORDER PO 72921

VENDOR: I56086
Information Express
Attn: Julie Sweetkind
3250 Ash St.
Palo Alto, CA 94306

PAYMENT TERMS: 1% 10 NET 30 DAYS
FOB: Destination Prepaid & Not Allowed
SHIP VIA: UPS GROUND

This Order is issued under Westinghouse Prime Contract DE-AC04-86AL31950 with the U.S. Dept. of Energy. DPAS DO-E2 rating applies.

SHIP TO: Westinghouse Electric Corp.
Waste Isolation Division
For the U.S. Dept. of Energy
WIPP Site
30 Miles Southeast of Carlsbad
Carlsbad, NM 88220

BILL TO: Westinghouse Electric Corp.
Waste Isolation Division
Accounts Payable Dept.
P.O. Box 2078
Carlsbad, NM 88221

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NOTE: RECEIVING HOURS - 7:30 A.M. TO 3:30 P.M. MONDAY THRU FRIDAY

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P.O. Coding : EXT2
QA Code : N40
West Commodity : GDR
Acct Commodity : 42

Line Nmbr	Item ID / Description	Quantity Ordered	U/M	Unit Price	U/M	Total Price
1	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. ANDERSON, R.Y., DEAN, W.E., KIRKLAND, JR., D.W., AND SNIDER, H.I. 1972 PERMIAN CASTILE VARVED EVAPORITE SEQUENCE, WEST TEXAS AND NEW MEXICO. GEOLOGICAL SOCIETY OF AMERICA BULLETIN, VOL. 83, PP. 59-86	10.00000	EA	38.000	EA	380.00
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3	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BACHMAN, G.O., 1976 CENOZOIC DEPOSITS OF SOUTHWESTERN NEW MEXICO AND AN OUTLINE OF THE HISTORY OF EVAPORITE DISSOLUTION, JOURNAL OF RESEARCH, U.S. GEOLOGICAL SURVEY. VOL. 4, NO.2, PP. 135-149. NO LONGER AVAILABLE PER USGS	10.00000	EA	10.000	EA	100.00
4	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BROOKINS, D.G. AND S.J. LAMBERT. 1987 RADIOMETRIC DATING OF OCHOAN (PERMIAN) EVAPORITES, WIPP SITE, DELAWARE BASIN, NEW MEXICO, USA, IN: MATERIALS RESEARCH SOCIETY. ED. 771-780	10.00000	EA	22.000	EA	220.00
5	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BROOKINS, D.G., J.K. REGISTER, AND H. KRUEGER. 1980 POTASSIUM-ARGON DATING OF POLYHALITE IN SOUTHEAST NEW MEXICO, GEOCHIMICA ET COSMOCHIMICA ACTA 44, 635-637. PERGAMON PRESS, JOURNALS DIV. MAXWELL HOUSE, FAIRVIEW PARK, ELMSFORD, NY 10523 (914) 592-7700	10.00000	EA	18.000	EA	180.00
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Permian Castile Varved Evaporite Sequence, West Texas and New Mexico

ABSTRACT

Laminations in the Upper Permian evaporite sequence in the Delaware Basin appear in the preevaporite phase of the uppermost Bell Canyon Formation as alternations of siltstone and organic layers. The laminations then change character and composition upward to organically laminated claystone, organically laminated calcite, the calcite-laminated anhydrite typical of the Castile Formation, and finally to the anhydrite-laminated halite of the Castile and Salado.

Laminae are correlative for distances up to 113 km (70.2 mi) and probably throughout most of the basin. Each lamina is synchronous, and each couplet of two laminated components is interpreted as representing an annual layer of sedimentation—a varve.

The thickness of each couplet in the 260,000-varve sequence (a total thickness of 447.2 m, 1467 ft) has been measured individually and recorded and provides the basis for subdividing and correlating major stratigraphic units within the basin. The uppermost 9.2 m (30.3 ft) of the Bell Canyon Formation contains about 50,850 varve couplets; the Basal Limestone Member of the Castile about 600; the lowermost anhydrite member of the Castile (Anhydrite I) contains 38,397; Halite I, 1,063; Anhydrite II, 14,414; Halite II, 1,758; Anhydrite III, 46,592; Halite III, 17,879; and Anhydrite IV, 54,187. The part of the Salado collected (126.6 m) contains 35,422 varve couplets. The Bell Canyon–Castile sequence in the cores studied is apparently continuous, with no recognizable unconformities.

The dominant petrologic oscillation in the Castile and Salado, other than the laminations, is a change from thinner undisturbed anhydrite laminae to thicker anhydrite laminae that generally show a secondary or penecontemporaneous nodular character, with about 1,000 to 3,000 units between major oscillations or nodular beds. These nodular zones are correlative throughout the area of study and underly halite when it is present. The halite layers alternate with anhydrite laminae, are generally recrystallized, and have an average thickness of about 3 cm. The halite beds were once west of their present occurrence in the basin but were dissolved, leaving beds of anhydrite breccia. The onset and cessation of halite deposition in the basin was nearly synchronous.

The Anhydrite I and II Members thicken gradually across the basin from west to east, whereas the Halite I, II, and III Members are thickest in the eastern and northeastern part of the basin and thicken from southeast to northwest. This distribution and the synchroneity indicate a departure from the classical model of evaporite zonation.

INTRODUCTION

The Castile Formation (Upper Permian) in the Delaware Basin of Texas and New Mexico is often cited as perhaps the best example of a large deep-water evaporite deposit for which there are no modern analogs. In addition, the Castile is well known for its remarkably distinct laminations of calcite and anhydrite, which are assumed by many to reflect annual sedimentation.

The regular interlamination of salts of different solubilities (calcite and anhydrite; anhydrite and halite) implies that depositional controls must have fluctuated in response to some periodic process or event. Udden (1924) sug-

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Geological Society of America Bulletin, v. 83, p. 59–86, 18 figs., January 1972

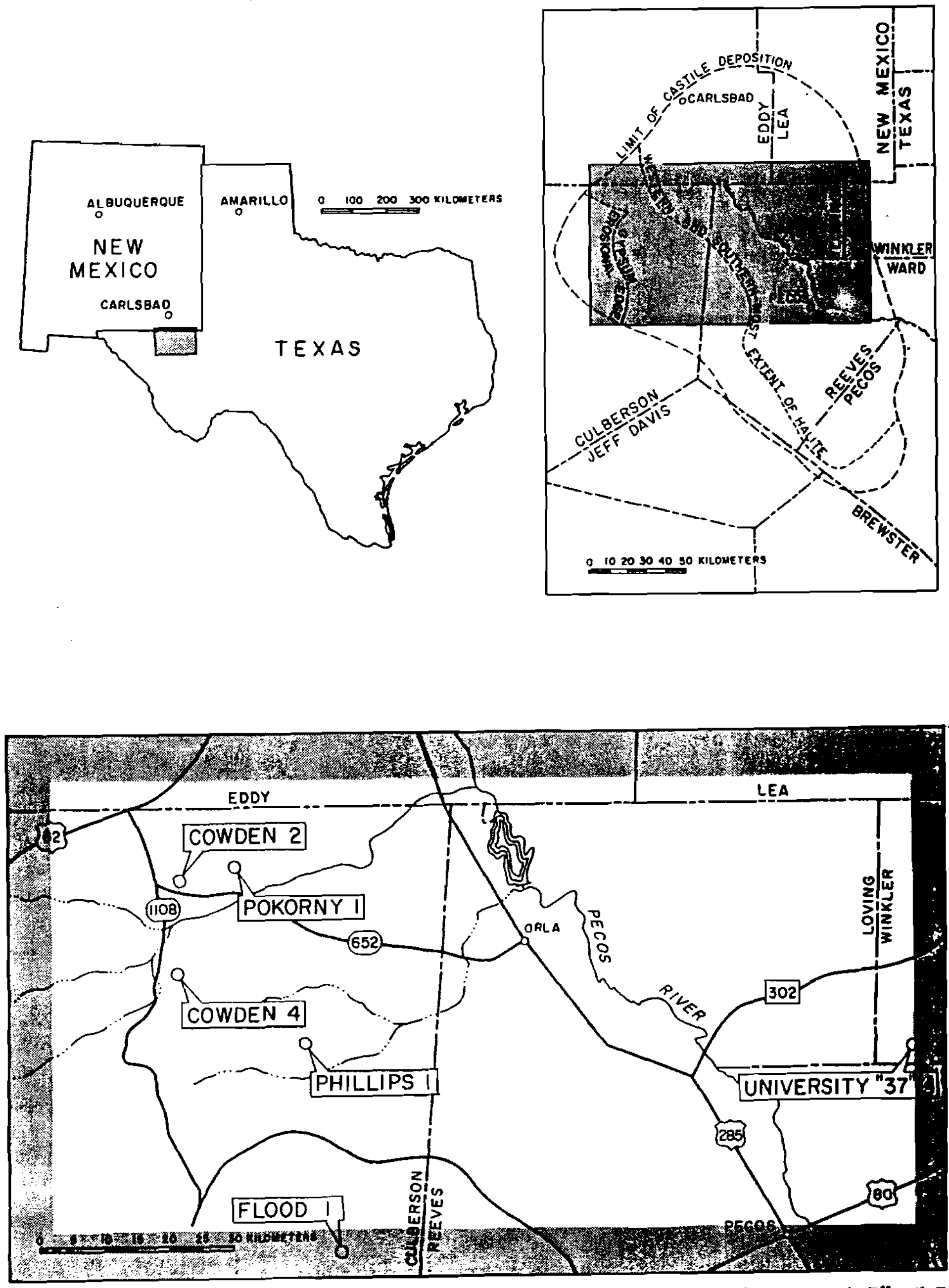

Figure 1. Index maps showing location of the cores studied and their general relationship to features of the Delaware Basin. Well locations as follows: UNM-Cowden no. 2, Sec. 34, Twp. 1, Blk. 62, T. and P. R. R. Co. UNM-Cowden no. 4, Sec. 33, Twp. 2, Blk. 62, T. and P. R. R. Co. UNM-Pokorney no. 1, Blk. 61, T. and P. R. R. Co. UNM-Phillips no. 1, Sec. 3, Blk. 118, PSL. David Flood no. 1 Grisham and McAlpine, Sec. 42, Blk. 54, PSL. Union Oil Co.–University "37" no. 4, Sec. 37, Blk. 20, Univ. Lands Survey.

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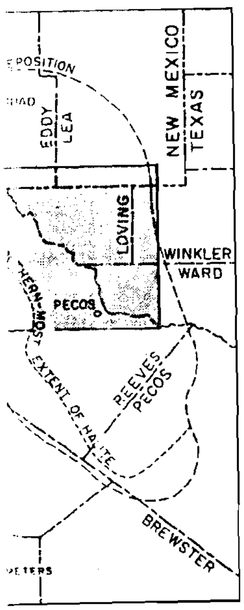
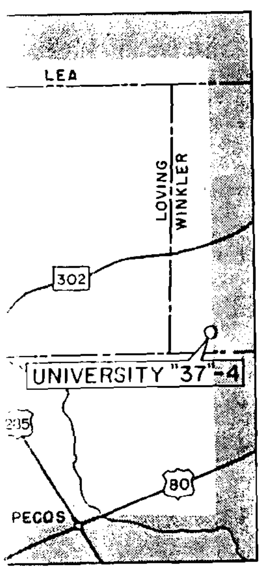




Pokorney no. 1, Blk. 61, T. 'hillips no. 1, Sec. 3, Blk. 110, Grisham and McAlpine, Sec. Oil Co.-University "37" no. Lands Survey.

gested that each calcite-anhydrite couplet represented an annual increment of sediment—a varve. Most investigators who have discussed the Castile agree with Udden's annual interpretation but have been unable to agree on a periodic mechanism. Adams (1944) suggested that new sea water was introduced by seasonal breaching and sealing of a barrier. Briggs (1957) suggested that freshening due to annual maximum spring tides could produce the Castile laminations. Neither of these explanations seems adequate to account for the great lateral continuity and synchroneity of depositional conditions over an area the extent of the Delaware Basin, as demonstrated by correlation of laminae.

Organically rich layers are associated with calcite laminae in the Castile. Richter-Bernburg (1964) explained a similar association in calcite-anhydrite couplets in the Permian Zechstein Formation of Germany by assuming that organic matter represented mass killing of planktonic organisms. It seems likely, however, that laminae concentrations of organic matter are the result of a periodic (annual?) increase in plankton productivity (blooms). The investigations of Carpelan (1957) and Phleger (1969) have shown that evaporite basins can have levels of primary productivity greater than adjacent "normal marine" environments. If such organisms were phytoplankton, then there is a mechanism for calcite deposition in the seasonal blooming process and the attendant removal of CO_2 from the water.

Organically rich layers are also associated with the anhydrite of anhydrite-halite couplets where seasonal evaporation can be invoked as the mechanism for layered halite deposition. In fact, organic or organically rich layers are common to all the laminae types in the Bell Canyon-Castile sequence, and form a basis for the assumption that throughout the sequence the lamination process is in tune with, if not influenced by, seasonal and probably annual plankton productivity.

While it has never been conclusively demonstrated that laminae couplets such as those of the Castile are varves, no other hypothesis for couplet timing in laminated evaporites has been given serious consideration, and this investigation is framed upon the assumption that each couplet (organic-siltstone, organic-calcite, calcite-anhydrite, anhydrite-halite) represents an annual cycle of sedimentation.

Earlier investigations by several of the authors (Anderson and Kirkland, 1966; Kirkland and Anderson, 1970) revealed that the laminations could be correlated with great precision over the entire basin (distances up to 113 km or 70.2 mi). The laminations continue in an uninterrupted sequence from the preevaporite phase below the Castile upward into the Salado Formation in a series of some 260,000 laminae couplets, and provide a reference scale for determining the precise volume and distribution relation of the various components in the system. The continuous time series of laminations also provides a basis for examining the behavior of such a basin over much of its life history.

This report deals with the broader aspects of the evaporite system and considers chiefly the petrology and stratigraphic relations of the major units in the basin. These units have been correlated within the basin on the basis of individual laminae and indexed to a master time series. The laminations themselves are an additional focal point in the study. Also, some interpretations are made concerning basin paleogeography, solution, and other problems.

The study is based partly upon sonic, electric, and sample logs, and field observations, but mainly on a number of cores collected from Culberson County, Texas, in the west-central part of the basin and one core from Winkler County, Texas, in the east-central part (*see* Fig. 1 for locations). One of these cores (University of New Mexico-Phillips no. 1) includes part of the Salado Formation, all of the Castile, and part of the underlying Bell Canyon Formation.

Each section of this 5 cm (2 in.) core was marked as it was removed from the core barrel in order to maintain proper sequence and superposition. The core was slabbed, polished, and marked off at 5.08-cm (2-in.) intervals. Photographs of the core were enlarged three times, and printed on strips of photographic paper. Each couplet (for example, calcite-anhydrite) was interpreted, marked, and measured on the photographs, and the core measurements were recorded on computer cards. The result is a time series of approximately 260,000 varve couplets beginning in the Bell Canyon Formation, about 10.67 m (35 ft) below the base of the Castile and continuing to a basal limestone breccia, probably of the Rustler Formation, that rests on top of the laminations in the lower part of the Salado Formation, a thickness of about 447.2 m (1467 ft).

REGIONAL SETTING

So much previous work has been done on the regional aspects of evaporites in the Delaware Basin that no attempt will be made here to present a complete picture of the setting of the basin.

Regional aspects of the Delaware Basin and its evaporite sequences (Table 1) are discussed in the reports of J. E. Adams (1944, 1965, 1967), Adams and Frenzel (1950), Hills (1942), P. B. King (1937, 1942, 1948), R. H. King (1947), Lang (1935, 1937), Lloyd (1929), Newell and others (1953), and other investigators.

The basin has generally been visualized as surrounded by a carbonate platform (reef) with a marine opening to the south or southwest. Prior to evaporite deposition, fine clastic sediments were deposited within the basin under what may have been deep water, "starved basin" conditions (Adams and others, 1951). Sandstone and siltstone beds grade upward into laminated claystone which is interrupted by limestone (Lamar Member of the Bell Canyon Formation) apparently derived from the margin of the basin (Tyrrell, 1969). Carbonate deposition at the basin margins and laminated clay and silt deposition within the basin apparently continued at the same time that clastic-evaporite deposition occurred in the "back-reef" areas (Artesia Group).

Finally, a sequence consisting mainly of beds of laminated calcite and anhydrite intercalated with beds of anhydrite-laminated halite was deposited within the basin as the Castile and Salado Formations. Eventually, the basin became filled and Salado evaporite deposition spread northward and eastward over an area of greater extent than the structural outline of the basin. During Salado time, potassium salts were deposited within southeastern New Mexico and a small part of Texas.

PETROLOGY

The laminations of the preevaporite and evaporite phases of Bell Canyon–Castile Formations provide a unique means for describing and interpreting petrologic variations. Laminations of one sort or another occur in a continuous uninterrupted sequence from the organically laminated siltstone of the Bell Canyon, through the basal limestone and the calcite-anhydrite couplets of the Castile, and into the Castile halites. The arrangement and character of the laminations change in successive lithologies and it is this change by the addition or subtraction of individual laminae types that results in the gross changes that are defined as stratigraphic units. This same type of lamina by lamina change, producing gross lithologic variations, also occurs in the Jurassic Todilto Formation of New Mexico (Anderson and Kirkland, 1960) and probably is characteristic of many laminated evaporite sequences.

A system of identifying the position of a particular lamination or feature within the preevaporite and evaporite time series has been adopted that is based upon the position of a lamina above the base of a particular stratigraphic unit or member of the sequence. For example, the designation Anhydrite I, T_0 + 1,187–1,190, 166.6 cm, indicates that the particular feature occurs 166.6 cm, or 1,187 to 1,190 laminae couplet units, above the base (T_0) of the Anhydrite I Member.

Preevaporite Phase

Just below the laminated zone, the Bell Canyon Formation in the University of New Mexico–Cowden no. 4 (Fig. 1) is composed of well-sorted, angular quartz grains and minor feldspar grains with a sparse clay matrix and carbonate cement (Fig. 2A). The first laminations appear as fragments of dark brown organic material that are aligned in layers about 1 mm apart (Fig. 2B). This condition prevails as the quartz grains diminish in size and frequency upward in the sequence, and as the amount of clay increases the organic laminae become better defined and more persistent. Eventu-

TABLE 1. STRATIGRAPHIC TABLE OF PERMIAN ROCKS OF THE DELAWARE BASIN, WEST TEXAS AND SOUTHEAST NEW MEXICO

Series	Formations	Members
Ochoa	Dewey Lake Redbeds	
	Rustler	
	Salado	
	Castile	Anhydrite IV
		Halite III
		Anhydrite III
		Halite II
		Anhydrite II
		Halite I
		Anhydrite I
Guadalupe	Bell Canyon	Basal Limestone
	Cherry Canyon	
	Brushy Canyon	
Leonard	Bone Spring Limestone	
Wolfcamp	undifferentiated	

ally, silt grains diminish to a point where the unit is a laminated claystone (Fig. 2C). Siltstone and claystone beds then alternate with a time frequency of several thousand laminae couplets.

Two fossil components are found in the laminated siltstone and claystone units: extremely minute fusulinids and shell(?) fragments replaced by silica (Fig. 3C) and yellowish brown algal(?) remains (Fig. 3B). The algal(?) remains are about 60 μ in diameter. Their wall thickness is about 10 μ and the central part of the compressed bodies are often filled with silica. No aperture was observed. The yellowish brown grains are aligned parallel to the dark brown laminae. They appear in the siltstone sequence shortly after lamination begins, but occur sparingly throughout most of the sequence. A few cm below the base of the Castile, these organic remains are very abundant and form thin layers with a brown color in reflected light.

The small fusulinids occur throughout the claystone and siltstone units of the upper Bell Canyon Formation, but are more abundant in the claystone. Apparently two forms are represented; one is spherical, and the other which is less common, is fusiform. Structure is poorly preserved owing to partial or complete silicification, but the ovoid form resembles the neoschwagerinid species *Yabeina texana* reported from the Lamar by Skinner and Wilde (1955), but is less than one-tenth the size and appears to have a few more volutions. The elongated form may be a boultonid, but is even more poorly preserved than the *Yabeina*-like form.

Evaporite Transition

The base of the Castile is marked by the first appearance of calcite layers between dark brown organic laminae similar to those in the siltstone and claystone units of the Bell Canyon (Fig. 2D). The contact between the Basal Limestone Member of the Castile and the laminated claystone of the Bell Canyon Formation is very abrupt and occurs over a few couplets. *Yabeina*-like forms continue for a few centimeters into the Basal Limestone Member of the Castile, but are confined to the organically rich laminae between the calcite layers. The yellowish brown algal(?) remains are not found in the Castile Formation.

Some basal calcite laminae contain a mosaic of equidimensional calcite crystals with many of the crystals having sutured boundaries. As time progresses, the discrete brown organic laminae that are characteristic of the pre-evaporite phase (Fig. 2D) become unrecognizable and are replaced by diffuse brown organic material intimately mixed with the calcite laminae (Fig. 2E).

The onset of sulfate deposition at the base of the Anhydrite I Member is marked by two different types of anhydrite. One type occurs as layers of relatively large anhydrite grains which have a yellowish brown coloration in transmitted light, probably resulting from organic stain. These anhydrite crystals, which are dark brown in reflected light, are associated with small (25μ) calcite rhombs and are several times larger than unstained anhydrite grains in the accompanying thicker anhydrite laminae (Fig. 2E, F; Fig. 4A). The yellowish brown anhydrite crystals are frequently oriented with their long dimension parallel to bedding, and are generally either in contact with or mixed with layers of calcite rhombs. These laminae form some of the sharpest and most distinct laminae visible in outcrop and in core.

This mode of deposition continues for several thousand couplets at the base of the Anhydrite I Member before giving way to alternating laminae of anhydrite and organically stained calcite (Fig. 2G, H), which is typical of the Castile.

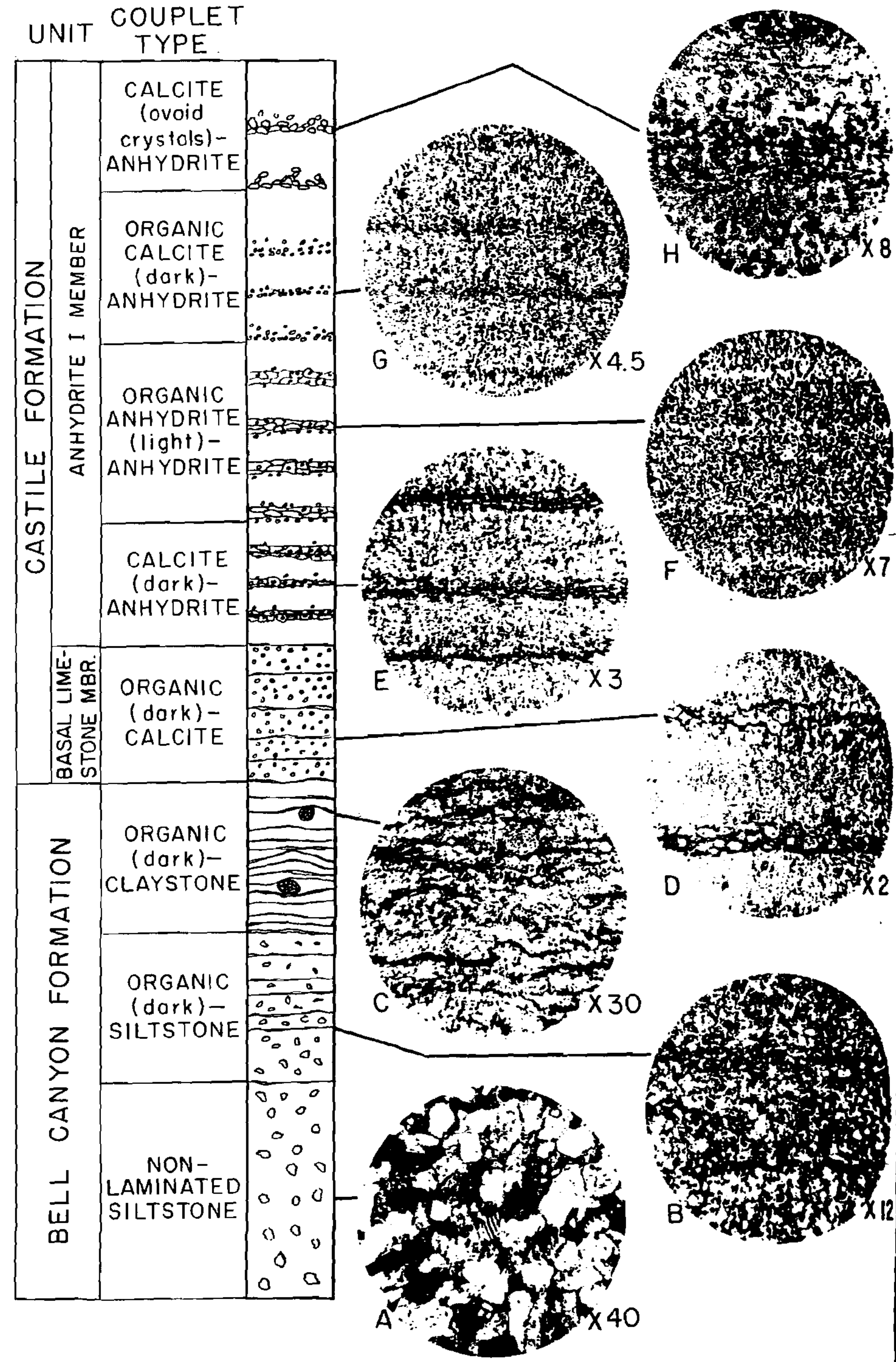
Calcite-Anhydrite Laminae

The general petrologic description of Udden (1924), Adams (1944), and expanded description by Anderson and Kirkland (1966) applies to most of the calcite-anhydrite laminations of the Castile Formation, and some additions to and refinements of these descriptions are presented below.

Calcite. Calcite layers in the Basal Limestone and lower part of the Anhydrite I Member (Fig. 2D, E, F, G) are composed of crystals about 25 μ in diameter and are remarkably constant in size (Fig. 3D).

Examination of thin sections ground to a thickness of 4 to 5 μ shows the crystals to be rhombs of calcite (Fig. 3E, F). Some crystals are euhedral; more commonly, the margins are crenulated and the corners rounded, giving the crystals a rounded appearance at low magnification. Calcite "rosettes" were sometimes observed with six or more calcite rhombs around a nucleus of calcite or unidentified material.

The size of the small equidimensional calcite rhombs does not change upward in the laminae



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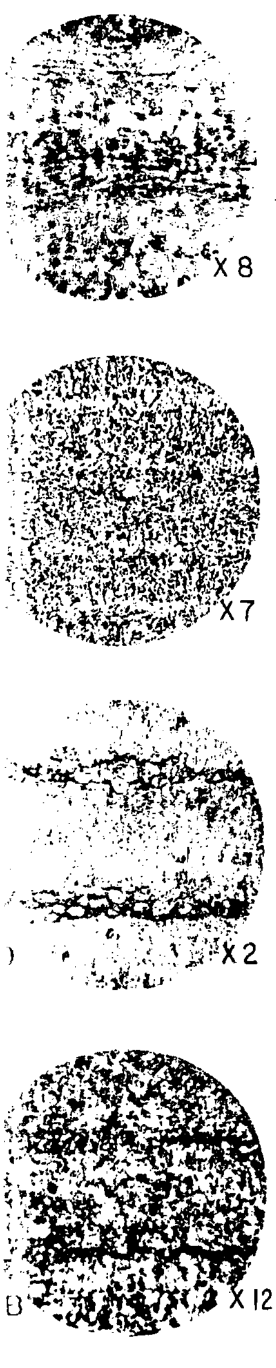


but the frequency often diminishes, giving the laminae an upper boundary that is less sharp than the lower boundary. The calcite crystals commonly appear to be suspended in the anhydrite groundmass and removed from adjacent grains by several diameters distance (Fig. 3E, F). There is some mixing of rounded and euhedral calcite rhombs in the same lamina, but the degree of rounding or angularity within a particular lamina is usually the same over the distances between the Cowden no. 2 and Phillips no. 1 cores (30 km).

Throughout much of the Castile, calcite laminae are composed of larger ovoid or fusiform crystals usually about 75 μ in diameter and intimately mixed with and stained by brown organic matter (Fig. 2H; Fig. 3A). These are the calcite crystals described by Udden (1924). Typically, a calcite lamina has a sharp basal contact and a less distinct upper contact that represents the mixing of calcite crystals with the lower part of the overlying anhydrite lamina.

Measurement of maximum lengths of 800 of these calcite crystals indicate that no important differences in calcite crystal size occur between cores separated by 15 to 30 km, nor is there a significant vertical gradation of grain size within particular carbonate layers. The measured laminae are from a part of the section which is relatively low in calcite (about 12 percent), but apparently no major differences in calcite crystal size occur even in high-carbonate parts of the section except near the base of the Castile where the crystals are smaller and have a different form.

Figure 2. **Transitional lithology at the top of the Bell Canyon Formation and at the base of the Castile Formation (nomenclature is explained in text). (A) Non-laminated siltstone, Siltstone I unit, Bell Canyon Formation. (B) Laminae of siltstone and organic matter, Siltstone III unit, T_0 + 10,470, 233.5 cm, Bell Canyon Formation. (C) Laminae of claystone and organic matter, Claystone II unit, T_0 + 10,581, 115.6 cm, Bell Canyon Formation. (D) Laminae of calcite and organic matter, Basal Limestone Member, T_0 + 75, 2.0 cm, Castile Formation. (E) Laminae of calcite, anhydrite, and organic-rich anhydrite, Anhydrite I Member, T_0 + 1,187-1,190, 166.6 cm, Castile Formation. (F) Laminae of organic-rich anhydrite and anhydrite, Anhydrite I Member, T_0 + 1,191-1,195, 166.6 cm, Castile-Formation. (G) Laminae of calcite and anhydrite, Anhydrite I Member, T_0 + 13,987-13,990, 1,201.0 cm, Castile Formation. (H) Laminae of calcite (ovoid crystals) and anhydrite, Anhydrite I Member, T_0 + 10,791-10,793, 859.9 cm, Castile Formation; the calcite laminae consist of rounded rhombs of calcite. This couplet form is typical of most of the Castile.**

The habit of the calcite crystals ranges from ovoid rhombs (Fig. 3A), to larger and closely packed but still distinct crystals, to laminae of calcite crystals that have become highly intergrown and sutured. The calcite crystals do not usually show a preferred orientation except in very thin carbonate laminae (one or two crystals thick) where crystals are commonly imbricated subparallel to stratification. Organic matter that stains calcite often becomes concentrated, forming a more or less distinct organic lamina in the upper, lower, or middle part of a particular calcite lamina.

Anhydrite. Most anhydrite in the Castile Formation consists of an interlocking aggregate of subhedral to euhedral crystals in a dense, interlocking, fine-grained matrix (Fig. 4B). The crystals have a distinct rectangular outline. These rectangular crystals are larger than the crystals in the "matrix" and commonly form a closely packed aggregate, the so-called "pile-of-bricks" texture, and thought by many investigators to be the normal habit of primary anhydrite (Carozzi, 1960, p. 422). The smaller crystals of the matrix have the same habit as the larger crystals. The long and short dimensions of 200 larger crystals were measured and were found to have a mean short dimension of 23 μ, a mean long dimension of 30 μ, and a mean long-short ratio of 1.36. There appears to be no important difference in crystal size between the Phillips and the two Cowden sections and there is no important vertical gradation in crystal size as described by Ogniben (1955 and 1957) in gypsum and anhydrite laminae from the Sulfur Series of Italy.

Although a vertical gradation in size of anhydrite crystals does not occur within sulfate laminae, anhydrite crystals associated with the organic-anhydrite at the base of the Castile are frequently larger than anhydrite crystals in the purer sulfate laminae as noted in the discussion of the transition zone.

In addition to matrix crystals and rectangular crystals, a third type occurs as laths with a width of about 0.1 mm and a length up to several millimeters long. The laths have indistinct, irregular boundaries and often contain inclusions of rectangular anhydrite "blocks." Laths can be found in all orientations, but the long dimensions of most are approximately

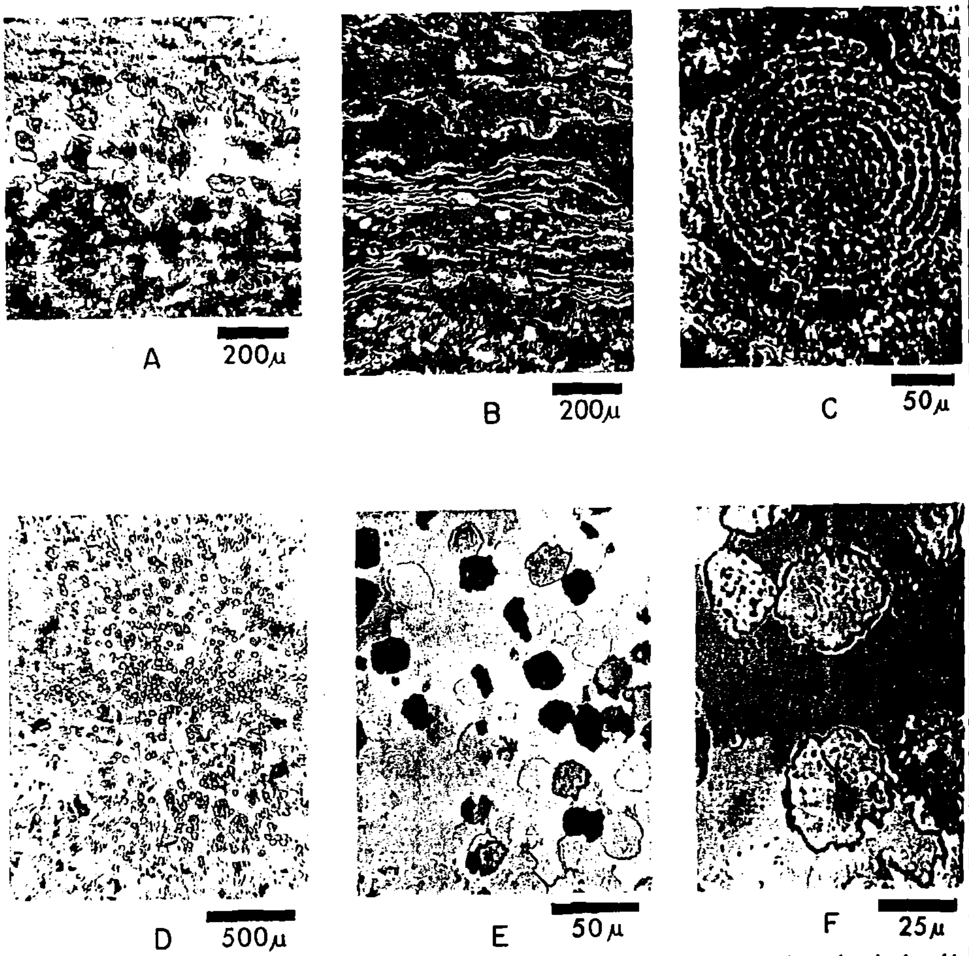


Figure 3. Fossils in the uppermost Bell Canyon Formation and crystal textures in the Castile Formation. (A) Rounded-rhombohedrons of calcite; note that the frequency of calcite crystals diminishes upward into the overlying anhydrite lamina, Anhydrite I Member, T_0 + 10,792, 859.9 cm. (B) Algal(?) remains, Claystone III unit, T_0 + 5,600, 74.3 cm. (C) Minute fusulinid, compare *Yabeina* sp., Claystone III unit, T_0 + 3,840, 50.3 cm. (D) Small ($\sim 25\mu$) calcite rhombs in calcite laminae near base of Anhydrite I (*see* Fig. 2G); note organization of calcite crystals into lamina in center of photo. (E,F) Enlarged views of calcite rhombs in partially polarized light; note that some crystals retain rhombic form and are "floating" in anhydrite groundmass.

normal to stratification. They commonly, but not invariably, occur within or adjacent to thin carbonate laminae, which are distorted or pierced by the laths.

At the top of the evaporite sequence in the Salado Formation, the calcite-anhydrite couplets typical of most of the Castile give way to thicker anhydrite laminae separated by calcite layers which have blebs of organic matter coating the calcite grains (Fig. 4C).

Halite Layers

Halite layers from a few millimeters to more than 10 cm thick are abruptly added to the calcite-anhydrite couplet pattern at the onset of halite deposition. The anhydrite laminae continue at about the same thickness with the introduction of halite, but the calcite layers become less obvious and less well defined and are only intermittently present as distinct laminae.

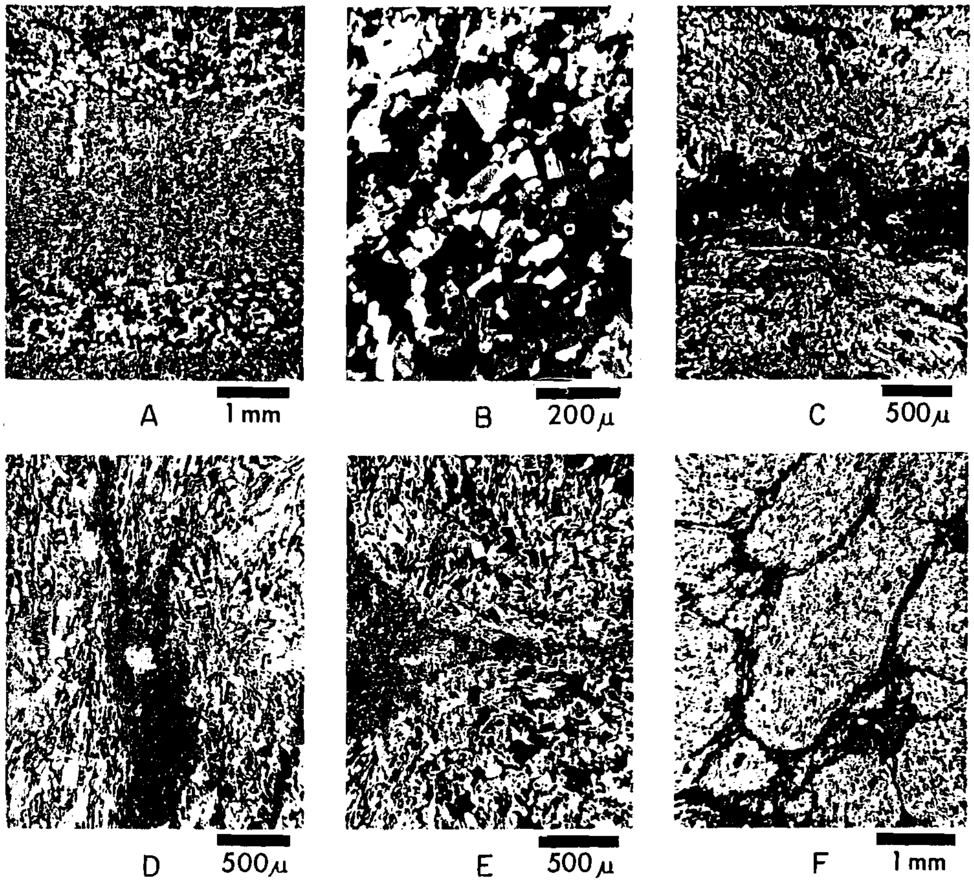


Figure 4. Calcite and anhydrite crystal textures, Castile and Salado Formations. (A) Anhydrite and organic-rich anhydrite laminae (*see* Fig. 2F); note contrasting size of anhydrite crystals, with larger crystals in organic-rich zones (polarized light); Anhydrite I Member T_0 + 21,630-21,631, 2,195.6 cm. (B) Typical blocky anhydrite (polarized light); Anhydrite I Member, T_0 + 13,976, 1,200.0 cm. (C) Laminae of organic stained calcite and anhydrite, Salado Formation; 12,737.8 cm above base of Salado Formation, T_0 + 35,014-35,015. Note that organic matter forms a coating on the calcite grains. (D) Calcite rhombs (dark) between nodules of anhydrite; note alignment of anhydrite crystals adjacent to calcite band, Anhydrite I Member, T_0 + 216–218, 35.6 cm. (E) Similar to (D), but in polarized light, Anhydrite I Member, T_0 + 216-218, 35.6 cm. (F) Reticulate pattern formed by reorganization of anhydrite laminae into nodules, Anhydrite I Member, T_0 + 216-218, 35.6 cm.

Some of the halite layers from the upper part of the Castile retain the original crystal structures, including internal laminae that are concentrations of organic material or anhydrite, and bubbles and vacuoles. Most halite layers, however, have become recrystallized (Fig. 5D).

Other Components

Small crystals of pyrite are sparsely present in the Castile, generally at the base of calcite laminae. They can be observed in insoluble residues and sometimes on polished surfaces and in thin sections, but are observed best on x-radiographs of slabs approximately 3 mm thick cut normally to stratification (*see* discussion in Anderson and Kirkland, 1966).

Very small quartz and zircon grains with maximum intercepts of approximately 50 μ have been observed in insoluble residues of Castile material. Their quantity has not been determined accurately, but it is probably less than 0.1 percent. The quartz grains are rounded and do not show crystal outlines. The zircon grains are prismatic and often show pyramidal terminations.

Small (50 to 500 μ) black magnetic particles have been extracted from the Castile. The particles are generally irregular in shape, and are similar to magnetic particles described from salt samples (Mutch, 1964 and 1966). The laminae associations of these clastic and magnetic fractions have not been determined.

LITHOLOGIC VARIATION

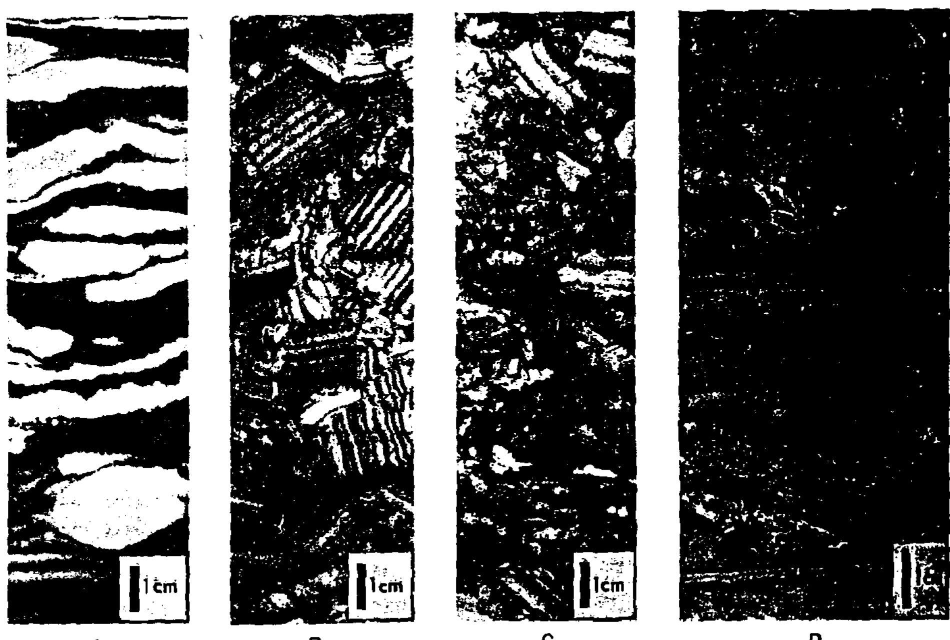
Laminae Variation

Within the anhydrite members, the typical pattern of lamination is the alternation of calcite and anhydrite laminae previously described. Changes in thickness or proportions of laminae generally occur in a regular or systematic manner and produce oscillations in thickness such as those illustrated in Figure 6. Parts of the sequence, however, may contain abnormally thin or thick layers of carbonate or anhydrite that alternate in an irregular pattern (*see* Anderson and Kirkland, 1966, Fig. 2).

The systematic changes in the proportions of calcite, anhydrite, or organic matter may result in zones or beds that appear to be almost entirely carbonate or almost entirely sulfate in outcrop or core but that nevertheless contain some small proportion of the other materials.

Nodular Anhydrite Beds

Stratigraphic intervals of nodular anhydrite (Fig. 5A) are associated with parts of the sequence where sulfate laminae are thick. Many but not all of the prominent peaks in the graph of the time series (Fig. 6), which represent a high rate of sulfate deposition, are associated with the development of nodules. The nodular zones are also characterized by a loss of definition of carbonate laminae, and by a change in the appearance of the organic fraction from brown to dark gray or black in reflected light; changes which may also take place without the development of a nodular zone. The number of



A B C D

Figure 5. Lithology of nodular, breccia, and halite beds. (A) Nodular anhydrite in Anhydrite I, Castile Formation. (B) "Collapse" type breccia in Anhydrite IV. Note angular fragments in tight packing with little matrix. This breccia occurs above a blanket solution breccia near the top of Anhydrite IV at about T_0 + 37,000. (C) Blanket solution breccia correlative with Halite I, Castile Formation. (*D*) *Halite-anhydrite* couplets, Halite II, T_0 + 130-134.

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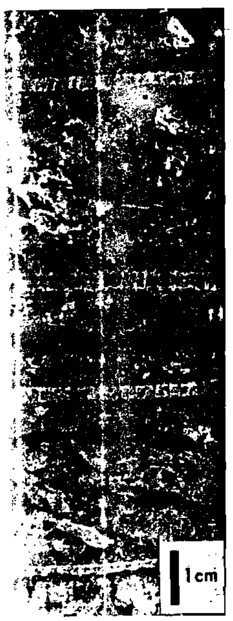

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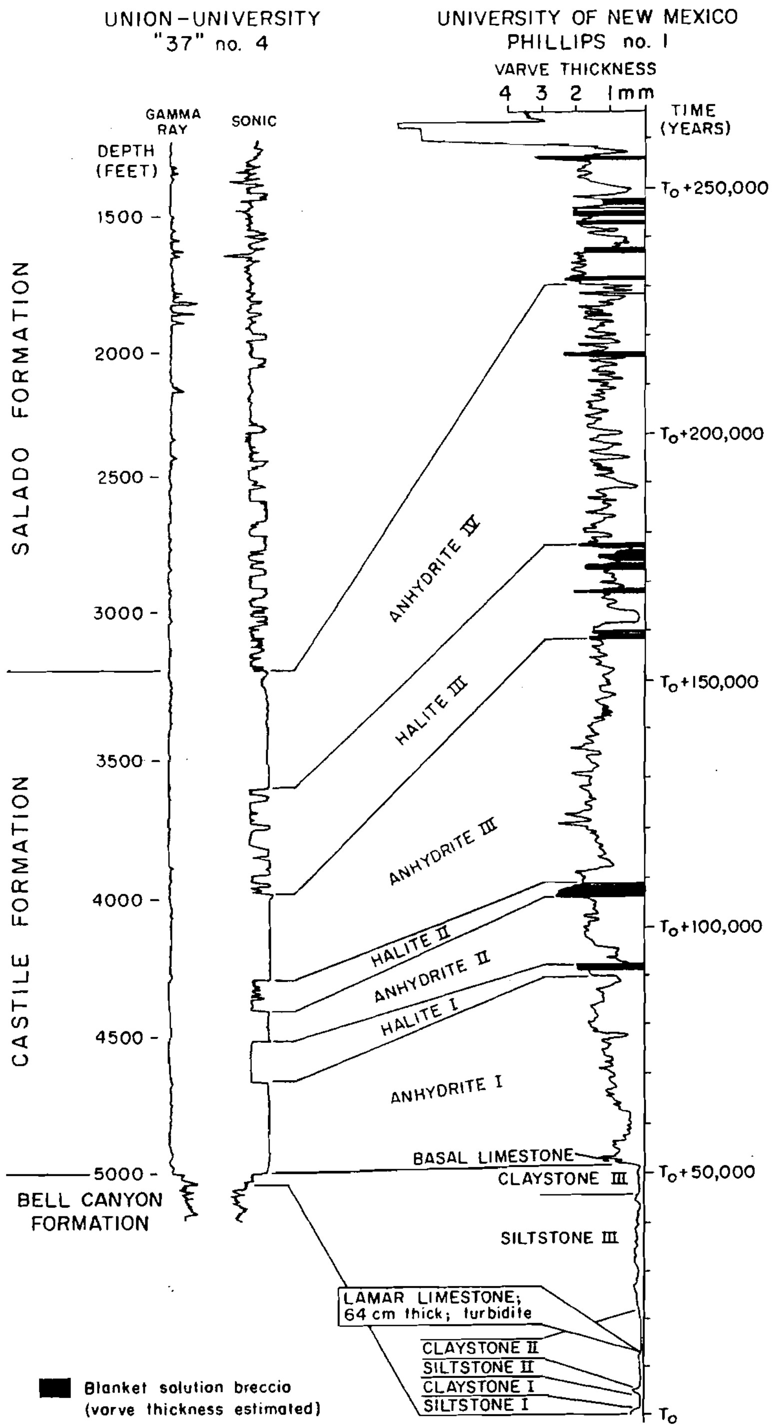

Figure 6. Correlation between sonic log of Union Oil Co.–University "37" no. 4 and smoothed (500-unit moving average) calcite-anhydrite couplet-thickness time series of the UNM-Phillips no. 1. Couplet thickness estimated for halite units.

couplets involved in a nodular zone vary from less than 50 to several hundred.

The nodular pattern is the result of sulfate mobility and recrystallization within previously existing sulfate laminae. The recrystallization and development of nodules exhibits many stages, but the nodular anhydrite rarely completely loses its laminated appearance. Development of nodules into a "chicken wire" stage seldom occurs. The anhydrite crystals in the nodules lose their blocky character and recrystalize into "felty" anhydrite (Fig. 4D, E). In the lower part of the formation, where the calcite crystals are often small equidimensional rhombs, the calcite crystals in the laminae between nodules are sometimes drawn out into thin strands only one crystal layer thick (Fig. 4E, F).

The nodular growth clearly took place after the deposition of undisturbed laminae and may have been related, perhaps indirectly, to increased salinity of water. This is supported by the association of nodules with increased sulfate deposition and by the fact that halite layers are always immediately underlain by nodular zones, although there are many nodular zones without overlying halite layers. Furthermore, those nodular zones underlying halite show the greatest nodular development.

The nodular beds are perfectly correlative in all the cores examined and for distances up to 113 km (70.2 mi) between cores located on opposite sides of the basin (*see* Fig. 7B). The onset of nodule formation is remarkably constant throughout the basin, further suggesting that some general control involving the entire basin, such as salinity, was a factor in their development. The nodular beds are present throughout the Castile-Salado sequence, and although they are common in the upper part of the sequence, where interstratified beds of halite are more common, the first nodular bed occurs about 1,000 couplets after the beginning of anhydrite deposition at the base of the Castile Formation.

Halite and Breccia Beds

Castile halite in the Union Oil Company–University "37" no. 4 core consists of alternating layers of recrystallized halite several centimeters thick and layers of anhydrite up to several millimeters thick (Fig. 5D).

Halite beds in the eastern part of the basin once extended beyond their present western limit into the western part of the basin (Figs. 1 and 8). The dissolved salt intervals are now beds of anhydrite breccia (Fig. 5C) of a thickness approximately equivalent to the sum of the thicknesses of anhydrite laminae present in the correlative halite units. Hence the 140-ft (42.7 m) section of salt plus anhydrite in the lower halite member of the Castile was reduced to a blanket breccia about 3.4 m (11 ft) thick after solution of salt.

Stratigraphic correlation of laminae shows that the onset of halite deposition occurs at almost the same stratigraphic position in the laminated sequence in the eastern and western parts of the basin. The development of nodular anhydrite beneath halite has altered original thickness relations and made correlation difficult to demonstrate statistically. However, distinctive groupings of distorted laminae, brown calcite-anhydrite couplets and gray calcite-anhydrite couplets with equivalent numbers of laminae in the Union–University "37" and University of New Mexico–Phillips cores, and a distinctive white lamina, have been used to establish stratigraphic correlation for the laminae immediately beneath Halite I (Fig. 7A). Halite precipitation in the eastern sequence preceded precipitation in the western part of the basin, (as inferred from the stratigraphic position of equivalent fragmented layers of solution breccia) by only 15 years, or a halite thickness of 85 cm (2.7 ft).

Nodular anhydrite development beneath Halite III did not completely distort the original thickness relations of calcite-anhydrite couplets and stratigraphic correlation can be established on the basis of synchronous thickness changes in the two series (Fig. 7B). The nodular zone at the base of Halite III begins at the same laminae couplet in both sequences but halite laminae occur in the Union–University "37" core 27 couplet units prior to the occurrence of solution breccia in the University of New Mexico–Phillips no. 1 core, or a halite thickness of 76 cm (2.5 ft).

Beds of laminated anhydrite as thin as one foot thick within halite beds more than 50 ft (15.2 m) thick are also present as unbrecciated layers within correlative breccia units, involve approximately the same number of laminae, and maintain their identity and remain undisturbed within overlying and underlying breccia beds despite the removal of salt. The presence of thin anhydrite beds within halite members can also be inferred from sonic logs and these beds can be correlated with breccia zones in the University of New Mexico-Phillips no. 1 core (Fig. 3).

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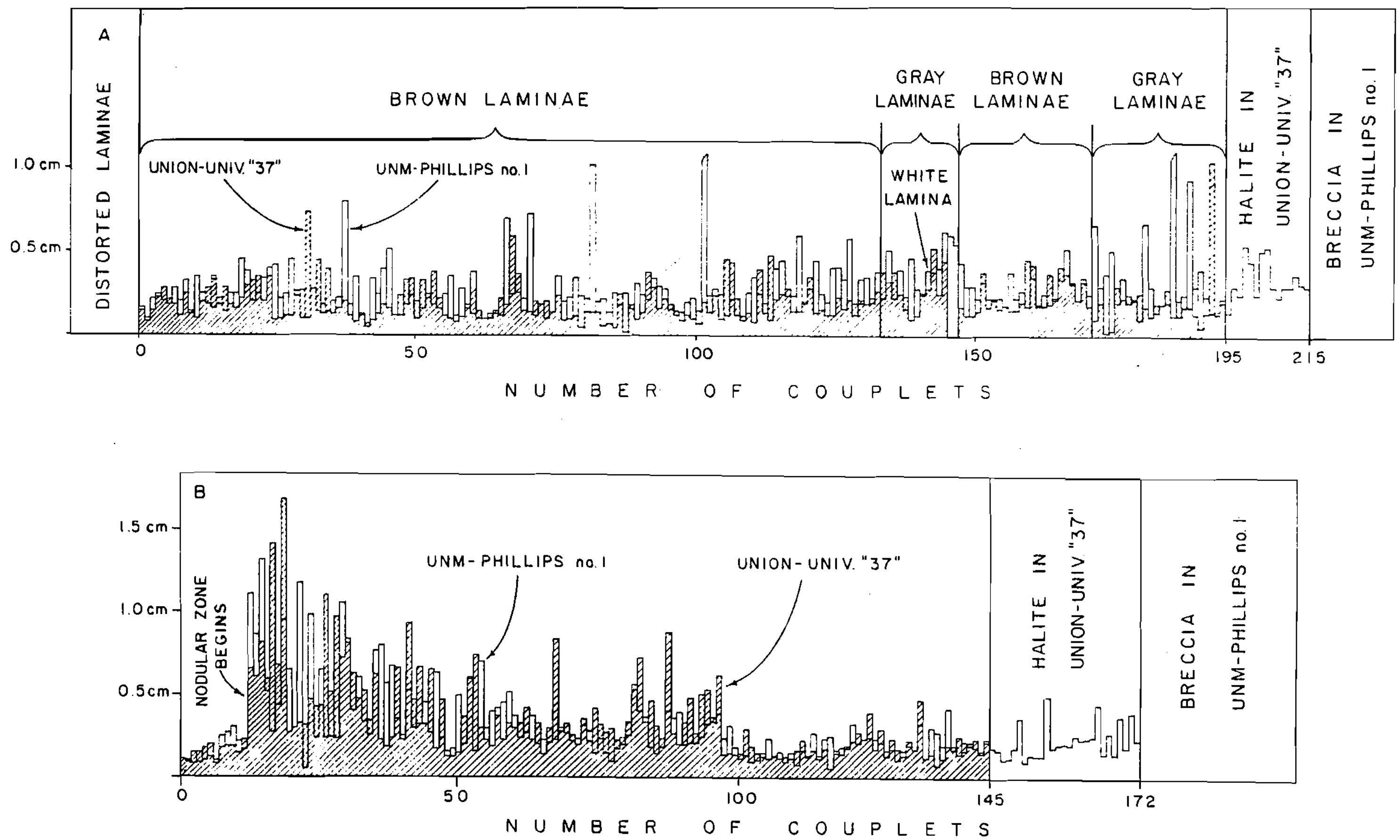

Figure 7. Correlation diagrams showing timing of halite deposition at the base of Halite I (A) and at the base of Halite III (B) in the Union-University "37" no. 4 (hachured) and UNM-Phillips no. 1 varve sequences. Note that halite laminae occur in the Union University "37" sequence 15 yrs prior to their equivalent position as solution breccia in the UNM-Phillips no. 1 sequence for Halite I and 27 yrs prior to breccia in Halite III. Note also that nodular development begins at the same time in both cores (*see* Fig. 6 for depth and time series locations).

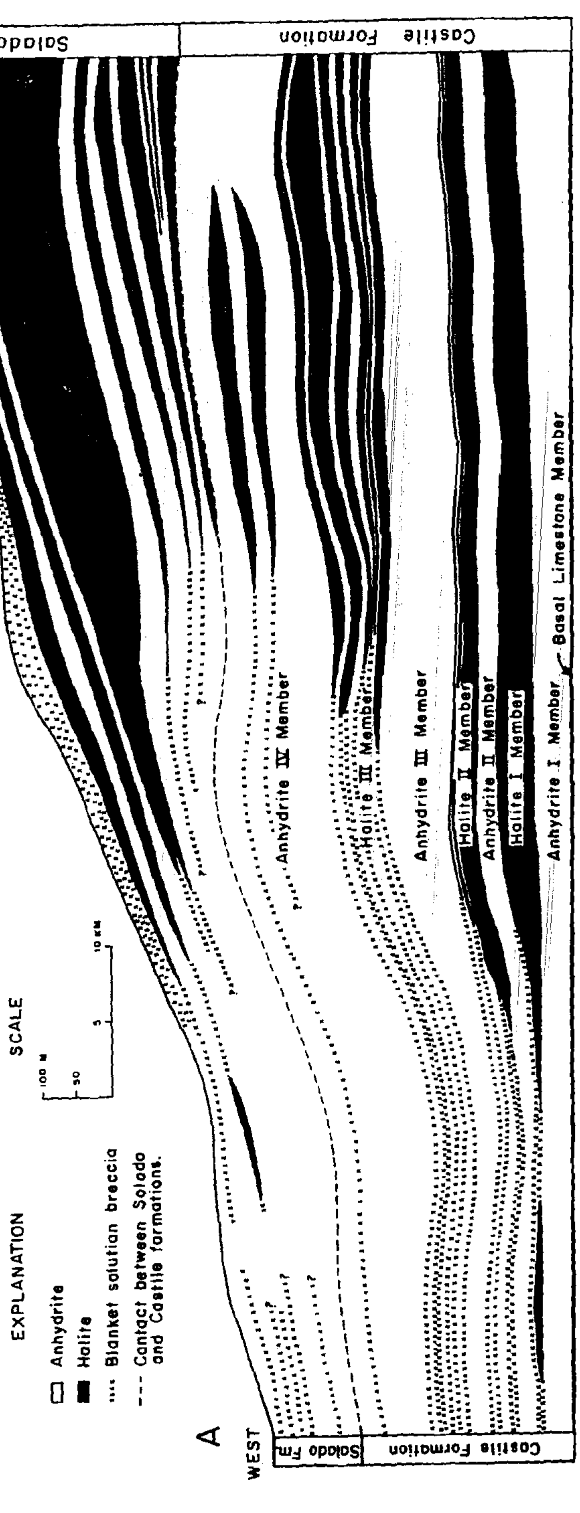

Figure 8. Diagramatic east-west cross section of Castile and Salado Formations from the UNM-Phillips no. 1, Culberson County, Texas (A) to the Union-University "37" no. 4, Winkler County, Texas (A') (see Fig. 1 for locations), showing relation of halite and blanket solution breccia units, and the distribution of halite beds within the Castile Formation.

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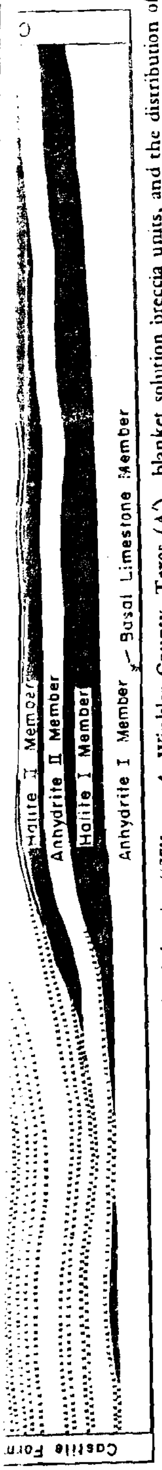

Figure 8. Diagrammatic east-west cross section of Castile and Salado Formations from the UNM–Phillips no. 1, Culberson County, Texas (A) to the Union-University "37" no. 4, Winkler County, Texas (A') (*see* Fig. 1 for locations), showing relation of halite and blanket solution breccia units, and the distribution of halite beds within the Castile Formation.

The breccia generally consists of rectangular-shaped, subangular fragments of single laminae or groups of laminae embedded in a matrix of anhydrite (Fig. 5C). The fragments, generally less than one cm in length, occur in various orientations, but most occur with stratification, if visible, and long dimension near the horizontal. Many of the fragments appear to have been only slightly displaced.

In some of the blanket breccia beds it is difficult to correlate the upper contact because of solution collapse that resulted in a collapse-type breccia (Fig. 5B) consisting of larger, more angular fragments than the blanket solution breccia, and with little matrix. Good examples of collapse-type breccia have been observed at the top of the Halite II Member and in the upper part of the Anhydrite IV Member above blanket solution breccia.

SUBDIVISION AND DISTRIBUTION OF THE CASTILE AND UPPERMOST BELL CANYON FORMATIONS

The Castile Formation has been subdivided here into eight members which permit examination of the present areal distribution patterns of halite and anhydrite. Siltstone and claystone units in the uppermost Bell Canyon Formation probably extend over most of the Delaware Basin and have been subdivided into six working units. The type section for the subdivision is a partial core from the Union-University "37" no. 4 supplemented by a sonic log, from which correlation can be made throughout most of the basin. An additional supplement to the type section is the University of New Mexico–Phillips no. 1 core, which includes the entire Castile Formation and can be considered a "master" or "type" time series for the basin. The relation between these two sequences and position of members is shown in Figure 6. The number and average thickness of varves in each unit are given in Table 2.

Upper Bell Canyon Formation

The upper part of the Bell Canyon Formation can be subdivided into a number of units, Siltstone I through Claystone III (Fig. 6), which are correlative over a large part of the Delaware Basin.

The siltstone and claystone units of the uppermost Bell Canyon varved sequence are easily recognizable in the cores from the western part of the basin, but they are not as well defined in the core from the eastern part. There is excellent correlation of laminae in

TABLE 2. SUBDIVISIONS OF THE UPPER BELL CANYON–CASTILE SEQUENCE, DELAWARE BASIN, TEXAS AND NEW MEXICO

	UNM–Phillips #1		
Formation	Number of varve couplets	Thickness	Average thickness of calcite-anhydrite varve couplets
Salado Formation (partial section, undifferentiated)	35,422	12,660 cm	0.36 cm
Members			
Castile Formation			
Anhydrite IV	54,187	9,842 cm	0.18 cm
Halite III (including anhydrite beds)	*17,879	2,748 cm	0.16 cm
Anhydrite III	46,592	9,554 cm	0.21 cm
Halite II (including anhydrite beds)	† 1,758	801 cm	0.45 cm
Anhydrite II	14,414	2,738 cm	0.19 cm
Halite I	† 1,063	330 cm	0.31 cm
Anhydrite I	38,397	5,092 cm	0.13 cm
Basal Limestone	600	28 cm	0.04 cm
Estimated totals (Castile Formation)	174,890	31,133 cm	
Units			Average thickness of clastic-organic varge couplets
Bell Canyon Formation			
Claystone III	5,800	78 cm	0.01 cm
Siltstone III	24,814	551 cm	0.02 cm
Claystone II	15,650	166 cm	0.01 cm
Siltstone II	1,086	44 cm	0.04 cm
Claystone I	††ca. 2,000	24 cm	ca. 0.01 cm
Siltstone I	††ca. 1,500	61 cm	ca. 0.04 cm
Estimated totals (Bell Canyon Formation)	50,850	924 cm	
Combined totals	261,162	44,717 cm	

* Number of layers in halite fraction determined by extrapolation.
† Number of layers determined in Union–University "37" #4 core; thickness of calcite-anhydrite fractions only.
†† Number of layers in UNM–Cowden #4 core.

these units between the Phillips no. 1 and Cowden no. 4 cores, a distance of 24 km (Fig. 9), although the Cowden no. 4 section is about one-third thicker and contains more calcium carbonate than the Phillips no. 1 section.

Laminae in the siltstone-claystone units in the Union-University "37" no. 4 core are about the same thickness but with less siltstone and more carbonate than in the Phillips no. 1 and Cowden no. 4 cores. Only a two-ft (0.61 m) sequence of laminae could be correlated with certainty. Lamina proportions in the Union-University "37" no. 4 core differ considerably from those in the other two cores, yet it is remarkable that laminae which have a large clastic component would retain their identity over a distance of 113 km (70.2 mi).

The Lamar Limestone Member of the Bell Canyon Formation interrupts the Claystone II unit of the varve sequence in the Phillips no. 1 core between T_0 + 7,306 and 7,581; 33.0–147.0 cm. The graded turbidite limestone beds occur between the same laminae in both the Phillips no. 1 and Cowden no. 4 cores but are more numerous and thicker in the Phillips section. A few similar limestone beds several centimeters thick are also found below Siltstone III in the Union-University "37" no. 4 core on the other side of the basin, but it could not be determined if they were precisely at the same stratigraphic position. A short laminated section of 275 clastic-organic couplets is interbedded with the Lamar Limestone.

Castile Formation

Basal Limestone Member. Many evaporite sequences begin with a basal carbonate, and the Castile is not an exception. The Basal Limestone Member of the Castile, however, is very thin and occupies only about 1/400 of Castile time and about 1/1500 of Castile stratigraphic thickness. This member, which contains no anhydrite, extends throughout much of the Delaware Basin and was recognized as a distinct unit by King (1942). In the Phillips no. 1 core, the member has a thickness of about 28 cm and in the University "37" no. 4 about 50 cm. The unit consists of about 600 calcite-organic couplets. It is considered a member because of its distinct character and persistence. An isopach map was not constructed because the unit cannot definitely be delimited on wire-line logs.

Anhydrite I Member. The thickness distribution of the lowermost anhydrite unit, which contains about 38,000 couplets, is shown by an isopach map constructed chiefly from sonic logs (Fig. 10). The thickness is a fairly constant 170 ft (51.8 m) in the western part of the basin and increases in the eastern part to about 350 ft (106.7 m). Anhydrite I becomes more calcareous in the southwestern Delaware Basin (Adams, 1944) and thickens radially to the north and east from this area.

The continuity of laminations within the Anhydrite I Member and other anhydrite members of the Castile is illustrated by the correlations in Figure 11. The correlations are for cores from widely separated parts of the basin and show the relatively small degree of change in the amount of sulfate precipitated on a lamina by lamina basis, even for opposite sides of the basin as is the case for Figure 11C. Figure 11A and B show photomicrographs of thin sections of correlative intervals with a north-south separation of about 65 mi (105 km; *see* Fig. 1).

This continuity of lateral distribution differs for the organic, carbonate, and sulfate fractions that comprise the laminations. The three components can be separated from each other by sampling and analyzing the material on a unit-time basis (*see* Anderson, 1967; Kirkland and Anderson, 1969). Correlation coefficients for the percent of each component in 10-couplet and 50-couplet samples from different parts of Anhydrite I and for the actual amount

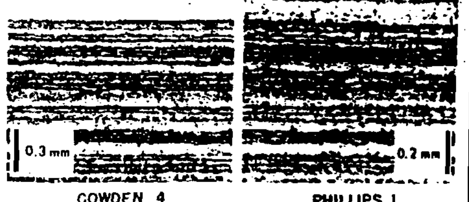

Figure 9. Laminated siltstone from correlative sections of the upper part of Bell Canyon Formation. Quartz silt laminae alternate with laminae of organic matter (dark); Siltstone III unit, T_0 + 10,200-10,250, 229.5-230.5 cm.

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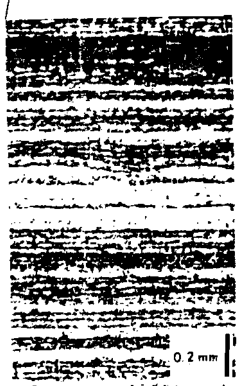

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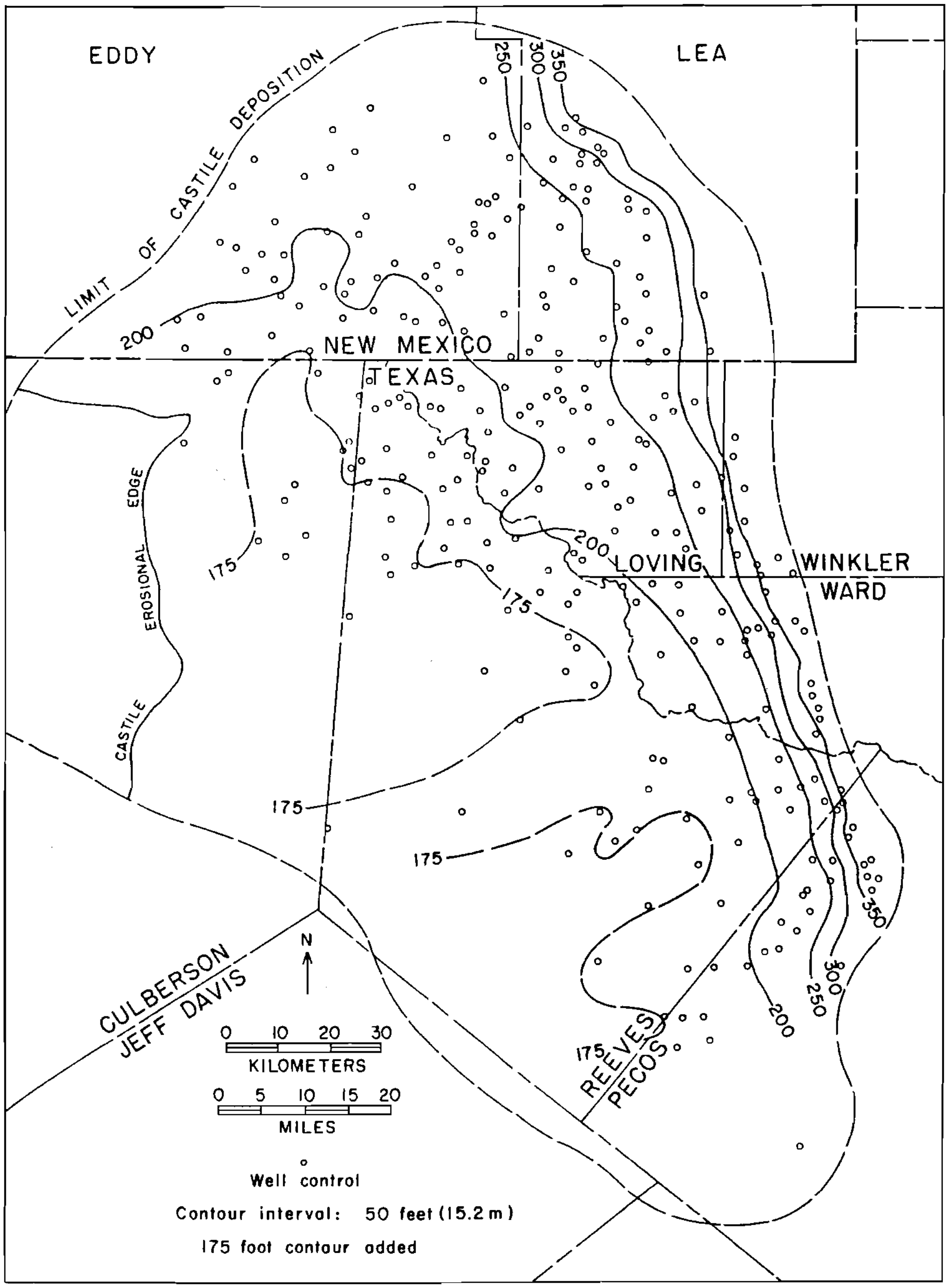

Figure 10. Thickness distribution of Anhydrite I Member, Castile Formation.

(thickness) of each component in the same samples show that lateral continuity is greatest for the sulfate (Tables 3 and 4). Carbonate distribution is more variable than sulfate but correlation coefficients are still high and significant, whereas the organic fraction (as determined by weight loss) has a more variable distribution.

A comparison of the correlation coefficients for the different cores (Table 3) also reveals that there is greater continuity between the Phillips no. 1 core and the two Cowden cores, which are 24 km (14.9 mi) and 32 km (19.8 mi) to the northwest, than between the two Cowden cores which are separated from each other by 14 km (8.7 mi) in a north-south direction. This difference in continuity with direction in the basin is best illustrated in the moving correlation coefficient for couplet thickness between the three cores (Fig. 12). The greater continuity in a northwest-southeast direction agrees with the thickness trend in that part of the basin as illustrated by the 175 ft (53.3 m) isopach in Figure 10.

Statistical correlation studies have not yet been done for the Union Oil Company–University "37" no. 4 cores from the eastern part of the basin, which includes only the uppermost and lowermost part of Anhydrite I. Stratigraphic correlations of laminae, however, reveal that couplets in certain parts of the varve sequence maintain almost exactly the same thickness proportions and general appearance (for example, contact relations, color) over the 113 km (70.2 mi) distance. Other parts of the sequence have couplets with

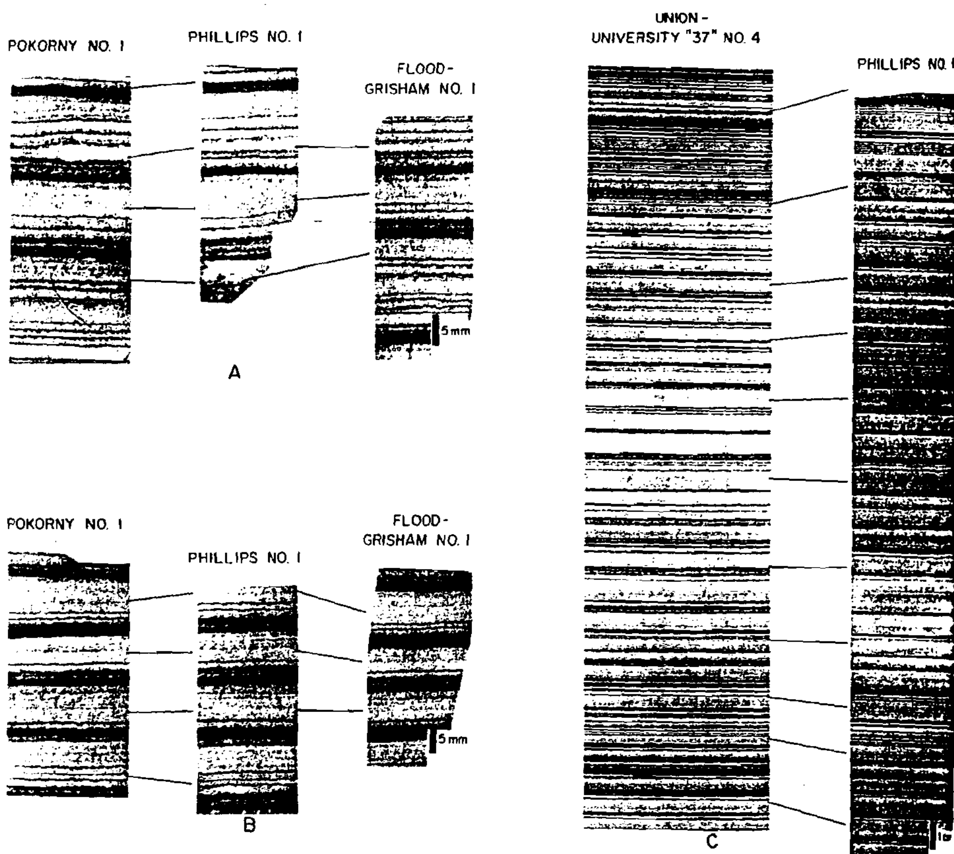

Figure 11. Correlative Castile Sections (A,B) Correlative intervals (thin sections, plain light); couplets of organic-rich calcite (dark) and anhydrite. The Pokorny no. 1 is 29.0 km (18.0 mi) north-northwest of the Phillips no. 1, and the Phillips no. 1 is 32 km (19.8 mi) north-northwest of the Flood-Grisham no. 1. (C) Correlative couplets of organic-rich calcite (dark) and anhydrite (core slabs); the Union-University "37" no. 4 is 91.0 km (56.4 mi) east of the Phillips no. 1.

thickness proportions sufficiently different to make lamina by lamina correlation extremely difficult, although the longer trends and more variable couplets can be readily matched (Figs. 7B and 11C).

Halite I Member. The lowermost halite member of the Castile is the thickest and most extensive of the Castile halite units. In the University "37" no. 4 core, the Halite I Member contains 1063 ± 20 anhydrite-halite couplets with an average thickness of 3.1 cm. The anhydrite-halite couplets are thickest at the base of Halite I and decrease gradually upward within the unit.

TABLE 3. CORRELATION COEFFICIENTS FOR 10-COUPLET SAMPLES FROM ANHYDRITE I, T_0 + 33,921-34,871 FROM COWDEN 2, COWDEN 4, AND PHILLIPS CORES OF THE CASTILE FORMATION

Variable	Cowden 2 vs. Cowden 4	Cowden 2 vs. Phillips	Cowden 4 vs. Phillips
Couplet thickness	<u>0.58</u>	<u>0.70</u>	<u>0.77</u>
Percent $CaCO_3$	<u>0.54</u>	<u>0.52</u>	<u>0.63</u>
Percent organic	-0.04	0.14	0.04
Percent $CaSO_4$	<u>0.56</u>	<u>0.55</u>	<u>0.61</u>
Absolute carbonate	<u>0.29</u>	<u>0.39</u>	<u>0.31</u>
Absolute organic	0.10	-0.05	0.15
Absolute sulfate	<u>0.55</u>	<u>0.73</u>	<u>0.77</u>

N = 95; 99% confidence limits = ±0.27

Values which are significant at the 99% level are underlined. Thickness values are summations of 10 individual laminae; percent carbonate, organic, and sulfate were determined by loss on ignition; absolute carbonate, organic, and sulfate were calculated by multiplying the percent value by couplet thickness.

TABLE 4. CORRELATION COEFFICIENTS FOR 50-COUPLET SAMPLES FROM ANHYDRITE I, T_0 + 24,770-26,620 FROM COWDEN 2, COWDEN 4, AND PHILLIPS CORES OF THE CASTILE FORMATION

Variables	Cowden 2 vs. Cowden 4	Cowden 2 vs. Phillips	Cowden 4 vs. Phillips
Couplet thickness	<u>0.99</u>	<u>0.99</u>	<u>0.99</u>
Percent $CaCO_3$	<u>0.99</u>	<u>0.99</u>	<u>0.99</u>
Percent organic	-0.01	<u>0.81</u>	-0.09
Percent $CaSO_4$	<u>0.99</u>	<u>0.99</u>	<u>0.99</u>
Absolute $CaCO_3$	<u>0.93</u>	<u>0.94</u>	<u>0.95</u>
Absolute organic	<u>0.54</u>	<u>0.86</u>	<u>0.55</u>
Absolute $CaSO_4$	<u>0.99</u>	<u>0.99</u>	<u>0.99</u>

N = 28; 99% confidence limits = ±0.50

Values which are significant at the 99% level are underlined. Thickness values are summations of 50 individual couplets; percent carbonate, organic, and sulfate were determined by loss on ignition; absolute carbonate, organic, and sulfate were calculated by multiplying the percent value by couplet thickness.

Halite I thickens gradually from south to north in the eastern part of the basin and has a maximum thickness of more than 400 ft (122 m) in Lea County, New Mexico (Fig. 13). Most of this northward thickening is probably due to an increase in thickness of individual laminae judging from the near synchroneity of halite deposition in the eastern and western parts of the basin (Fig. 7A). Even if halite began precipitating 200 yrs earlier in the north than in the University of New Mexico–Phillips no. 1 core, this would mean an annual deposition rate of as much as 10 cm (3.9 in.) of halite in the northern part of the basin. The original thickness of Halite I in the western part of the basin cannot be determined. The thickness of the solution breccia zone equivalent to the Halite I is about 330 cm in the Phillips no. 1, Cowden no. 2, and Cowden no. 4 cores and all that can be determined about the past thickness of halite in this area is that enough halite was interstratified with anhydrite laminae to cause brecciation upon solution.

Anhydrite II Member. The Anhydrite II Member in the University of New Mexico–Phillips no. 1 core contains about 14,000 calcite-anhydrite couplets. The thickness of Anhydrite II (Fig. 14), like the thickness of Anhydrite I (Fig. 10), increases from west to east, with lines of equal thickness nearly paralleling the eastern and northern margins of the basin (Figs. 10 and 14). However, the rate of eastward thickening of Anhydrite II is much less than the rate of thickening of Anhydrite I.

Halite II Member. The Halite II Member is about 200 ft (61.0 m) thick in the northern part of the basin and about 115 ft (35.0 m) thick in the Union Oil Company–University "37" no. 4 core. The halite is interrupted by five beds of carbonate-laminated anhydrite, ranging from a few centimeters to over 1 m thick that can be observed readily on sonic logs. The entire Halite II Member including the couplets in the anhydrite beds encompasses 1758 ± 10 couplets of which about 1139 ± 10 are anhydrite-halite and the others calcite-anhydrite. The average thickness of the halite-anhydrite couplets is 2.3 cm with the thickness decreasing gradually upward within each halite unit between the five laminated anhydrite beds.

The same five beds of laminated anhydrite occur between breccia beds in the Phillips no. 1 core, but the relation is vague in the upper few feet of breccia because of faulting and collapse.

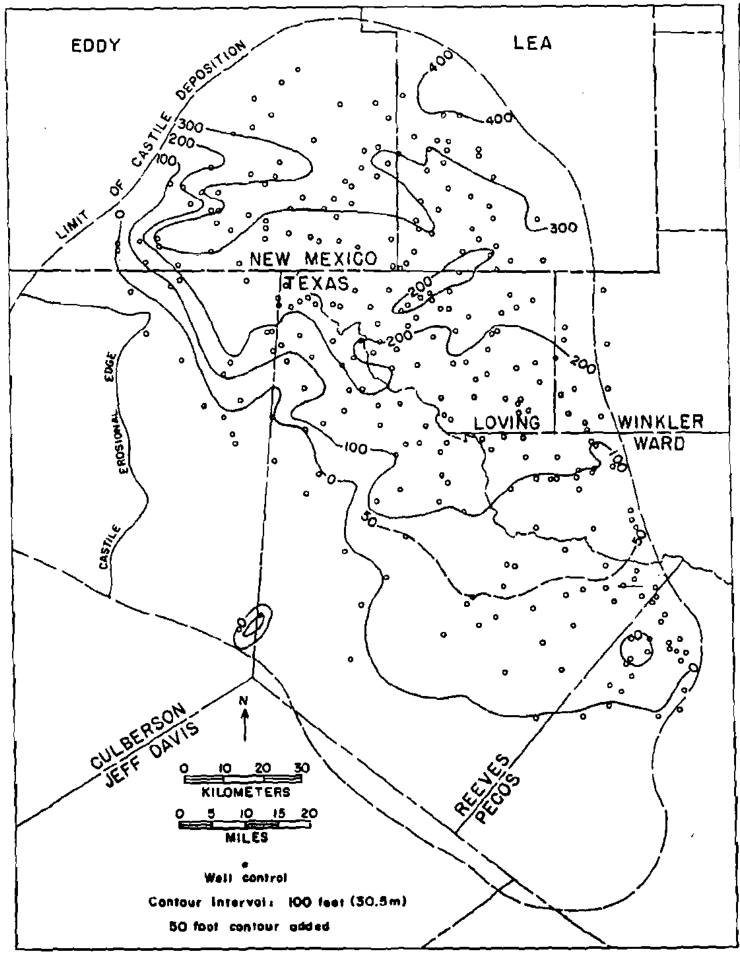

Figure 13. Thickness distribution of Halite I Member, Castile Formation.

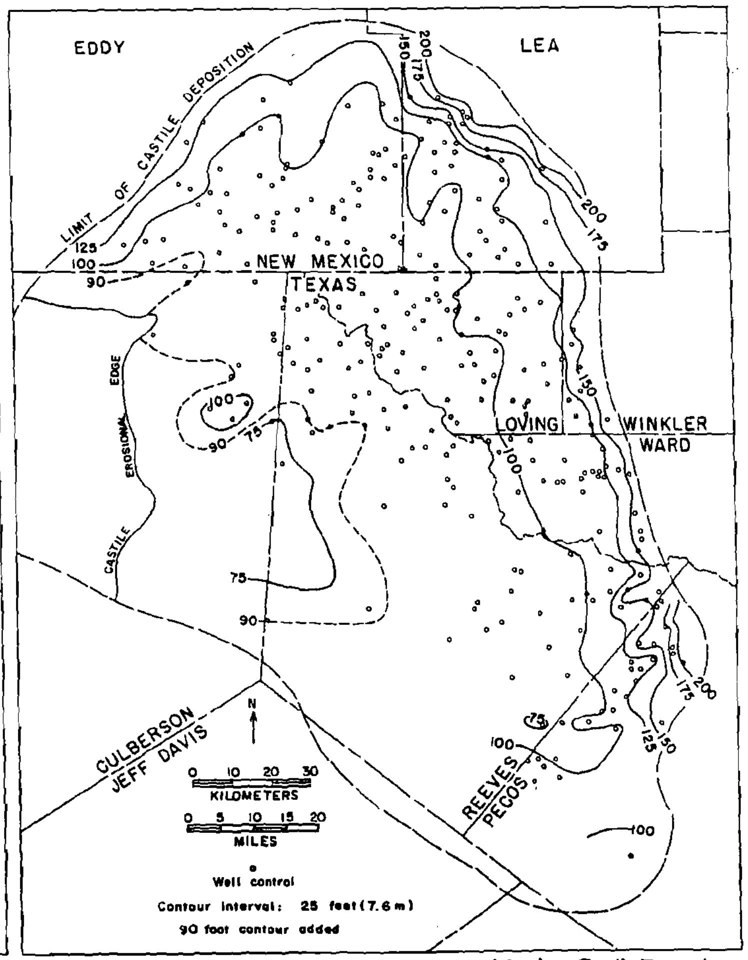

Figure 14. Thickness distribution of Anhydrite II Member, Castile Formation.

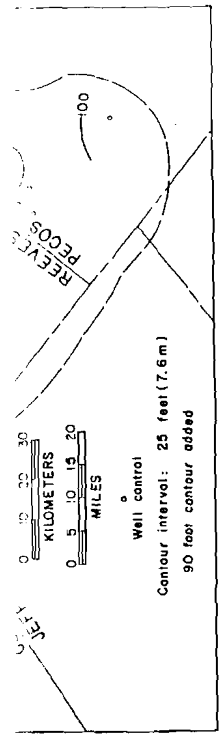

Figure 14. Thickness distribution of Anhydrite II Member, Castile Formation.

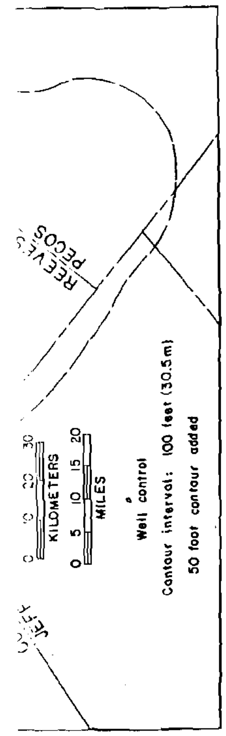

Figure 13. Thickness distribution of Halite I Member, Castile Formation.

The distribution pattern of Halite II is similar to that of the Halite I Member, but Halite II extends farther south and not as far west (Fig. 15). The western limit, however, does not correspond to the original depositional limit because the corresponding solution breccia units are well developed in the western part of the basin and Halite II may have originally extended as far as, or perhaps farther than, Halite I.

Anhydrite III Member. The Anhydrite III Member in the Phillips no. 1 core is a sequence of calcite-laminated anhydrite above the Halite II Member, contains about 46,600 couplets, and is generally 280 (85.3 m) to 300 ft (91.4 m) thick. It thickens from west to east but at a lesser rate than either Anhydrite I or Anhydrite II. The lowest halite bed of the overlying Halite III Member is absent in the western part of the basin and an anhydrite bed within the Halite III Member lies directly upon the anhydrite of Anhydrite III, therefore, isopach map was not constructed.

Halite III Member. This member is a mixed halite-anhydrite unit with more time involved in anhydrite than halite deposition, but with halite occupying a greater thickness. The distribution of halite within this unit is shown in Figure 16. The University "37" no. 4 core collected only the lower three halite units in Halite III. These three beds contain 297 ± 10 halite-anhydrite couplets with an average thickness of 4.6 cm per couplet. The sonic log of the Union Oil Co.-University "37" no. 4 well (Fig. 6) indicates that the Halite III Member contains approximately 72 m of halite and 40 m of interbedded anhydrite. Projecting the rate of 4.6 cm per couplet obtained for the cored halite units to all salt in the Halite III gives a total time of halite deposition of approximately 1,600 years. The total time of deposition of the Halite III Member is estimated to be about 18,000 years.

Anhydrite IV Member. Anhydrite IV contains about 54,000 calcite-anhydrite couplets. The number of couplets assigned to Anhydrite IV depends upon which breccia beds within the Phillips core are selected as representing the onset of dominant halite deposition in the Salado Formation. The thick breccia beds at about T_0 + 240,000 in the time series (Fig. 6) correlate with halite beds within the Salado. The breccia bed in the varve sequence selected as the top of Anhydrite IV (Salado boundary) occurs at T_0 + 53,979; 9,842 cm above the top of Halite III. In the Phillips no. 1 core, this

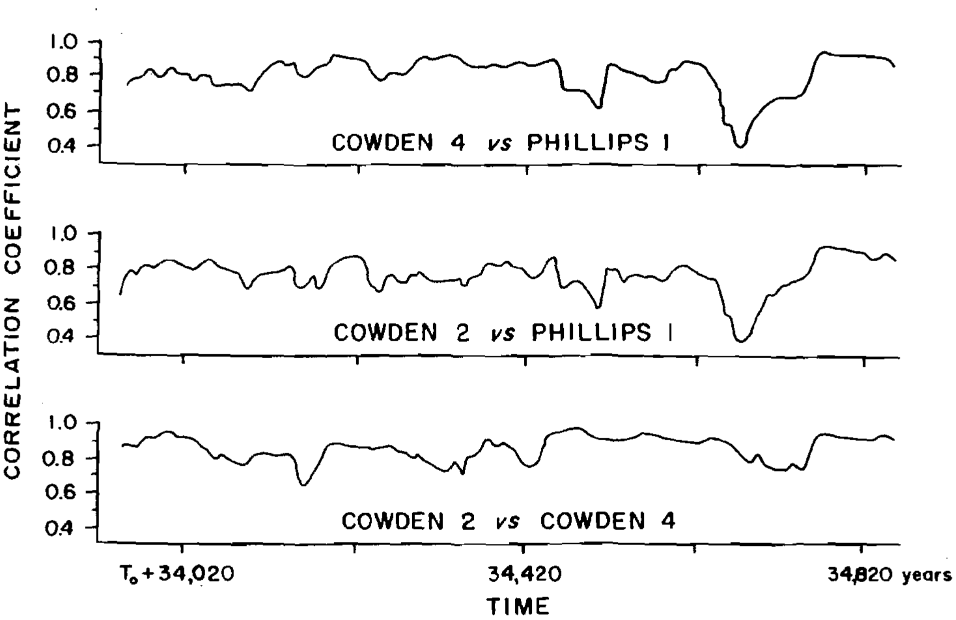

Figure 12. Moving correlation coefficients for couplet thickness between Cowden 4, Cowden 2, and Phillips 1 cores, T_0 + 33,921-34,871 zone of Anhydrite I member, Castile Formation (N = 51 yrs).

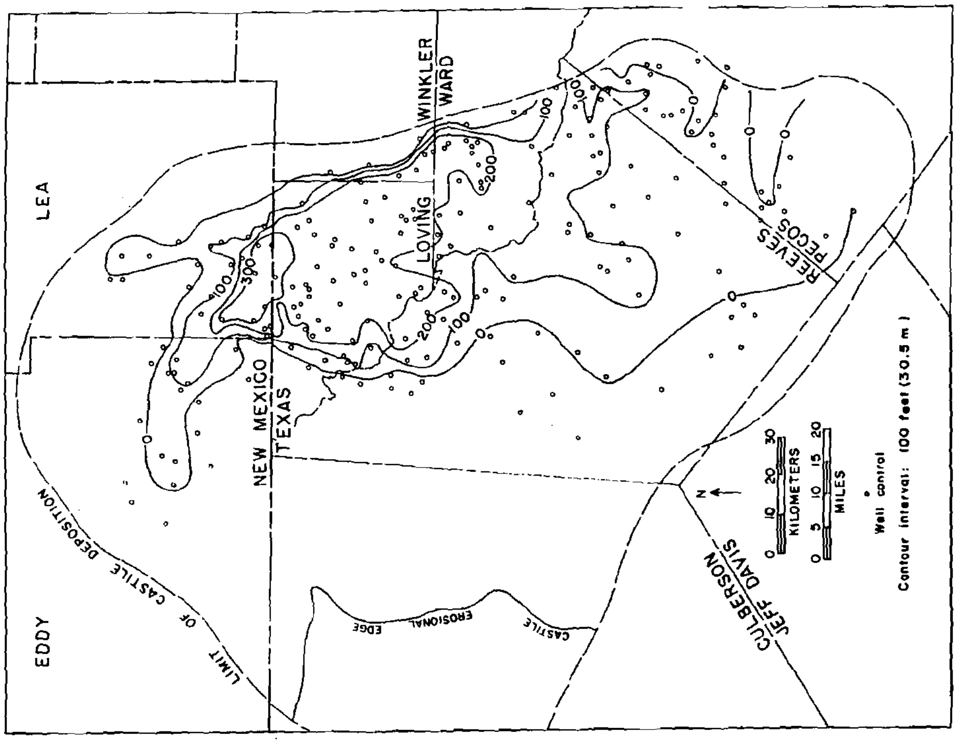

Figure 16. Thickness distribution of halite units within Halite III Member.

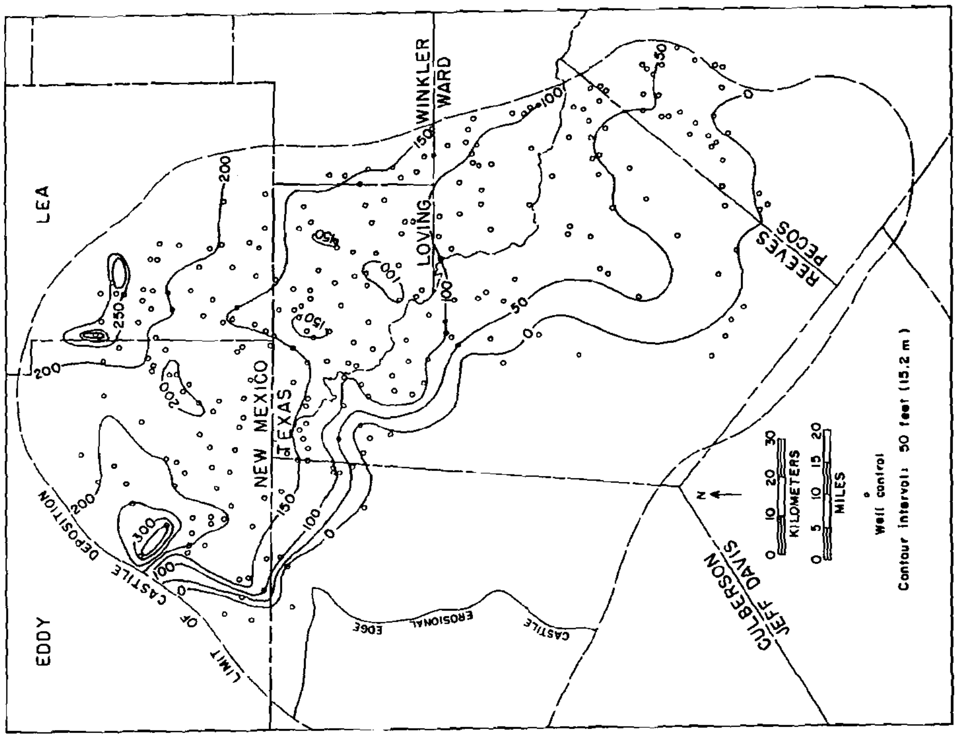

Figure 15. Thickness distribution of Halite II Member, Castile Formation.

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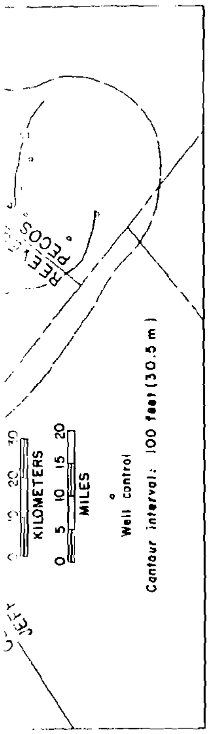

Figure 16. Thickness distribution of halite units within Halite III Member.

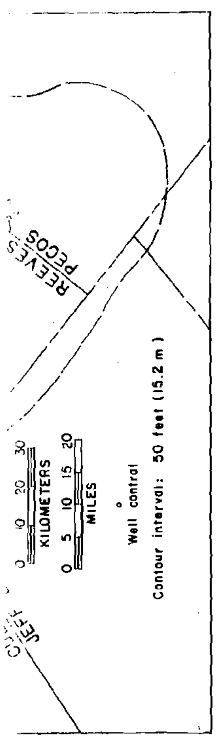

Figure 15. Thickness distribution of Halite II Member, Castile Formation.

breccia bed occurs in a sequence of couplets in which the calcite laminae are thinner than for typical Castile anhydrite and in which sulfate lamina thickness increases by about 50 percent (*see* Fig. 6, near T_0 + 230,000). Thereafter, the calcite-anhydrite couplet thickness remains high in the Salado except for a few brief intervals, which occur at about 240,000, and 250,000 couplets above the base of the time series.

A thick breccia bed occurs in the Phillips core, well down into Anhydrite IV, at T_0 + 37,214. This bed marks the presence of a dissolved halite. Based on the thickness of other breccia beds which can be correlated to halite beds of known thickness and depositional rate, the dissolved halite bed probably contained at least 400 couplets and was probably 40 to 50 ft (12.2 to 15.2 m) thick. A halite bed of this thickness should be recorded on sonic logs, but appears only as a slight "kick" on some logs in the northeastern part of the basin. However, in the southeastern part of the basin, this interval contains more than 300 ft (91.4 m) of halite (Fig. 17) and is interrupted by several anhydrite beds. The correlative breccia in the Phillips no. 1 core contains no nonbrecciated beds suggesting that some halite beds in Anhydrite IV, unlike halite beds in all lower units, may have had no equivalents in the western part of the basin.

Salado Formation

Halite is the dominant lithology in the basal Salado Formation in the eastern part of the basin, whereas anhydrite with blanket breccia beds is the dominant lithology in the western part where the Phillips no. 1 core contains the lower one-third of the Salado Formation. The Salado distribution pattern (Fig. 18) contrasts markedly with that of the halite and anhydrite members in the underlying Castile. The Castile members are confined to the Delaware Basin proper. The Salado, however, overlaps the Delaware Basin and is present on adjoining areas to the north and east. The thickest deposition in the Salado is north of the locus of the thickest Anhydrite IV Member and overlies the thickest part of the Halite II Member, but covers a broader area.

EFFECTS OF SOLUTION

The interpretation that breccia beds in the University of New Mexico–Phillips no. 1 core represented halite beds in the eastern part of the basin had been made on the basis of sonic log correlations prior to the availability of the Union-University "37" halite core. The Winkler County core, however, revealed that thin anhydrite beds of only a few decimeters thick within more massive halite units maintained their position and character after halite solution. This fact, and the observation that single anhydrite laminae, once separated by several centimeters of halite, were sometimes little disturbed upon solution, showed that the withdrawal of halite was a very gentle process.

With the exception of one halite bed in Anhydrite IV, every halite bed observed in the Winkler County core from the eastern part of the basin has an equivalent breccia bed in the University of New Mexico–Phillips no. 1 core. Inasmuch as this core locality is only about 32 km (20 mi) from the western edge of the basin, there is every reason to suppose that halite deposition once extended to, or nearly to, the western margin. The present western solution margin of halite units within the Castile shifts progressively eastward, with Halite II more areally restricted than Halite I. The halite in the Salado, however, extends farther westward than the present western solution limit of Castile halite (Fig. 8). This suggests that an episode of solution might have taken place prior to Salado deposition. The isopach map of the halite beds within Anhydrite IV (Fig. 17) shows a very irregular distribution of halite in the east-central and northeastern part of the basin that is not present in any of the lower Castile halites and could also represent solution prior to Salado deposition.

It seems more likely, however, that all of the solution took place after Salado time and that the irregular distribution pattern in Anhydrite IV developed later. A comparison of the Anhydrite IV isopach for halite and the published map of Tertiary basin fill of Maley and Huffington (1953) shows a very close agreement between the locus of Cenozoic basin fill in the Delaware Basin and the areas of thin or missing halite in Anhydrite IV. Similarly, there is also a correlation between the Cenozoic basins and thin areas in the Salado.

SYNCHRONEITY AND VARIATION OF STRATIGRAPHIC UNITS

A comparison of the isopachs of the Anhydrite I and II and the Halite I and II Members reveals that halite gradually thickens toward the north-northeast with a trend that differs

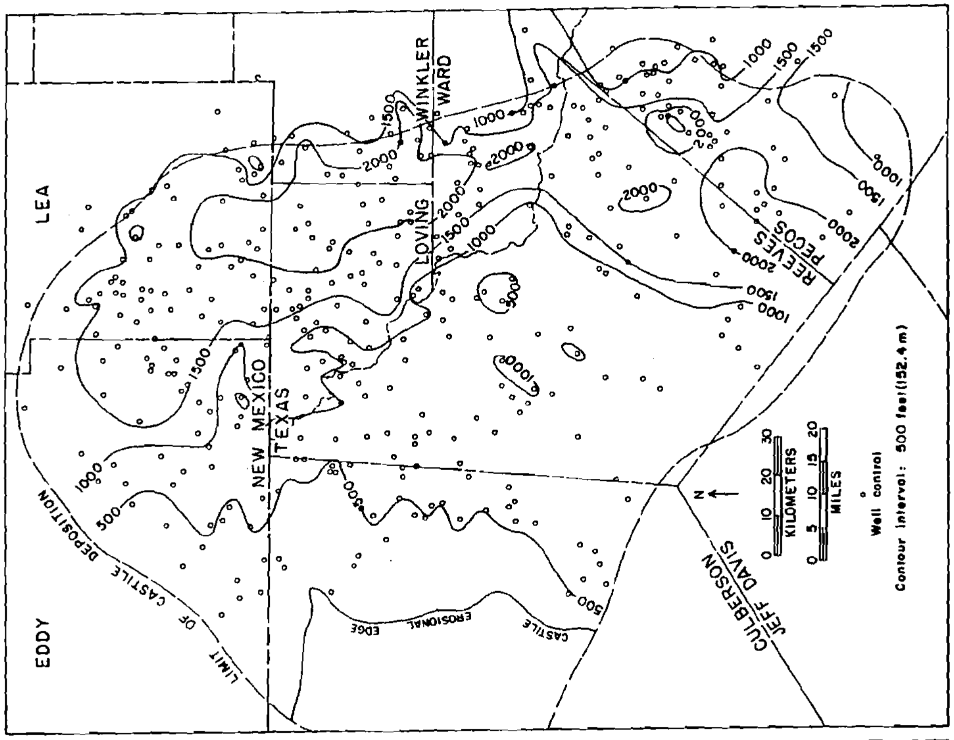

Figure 18. Thickness distribution of Salado Formation.

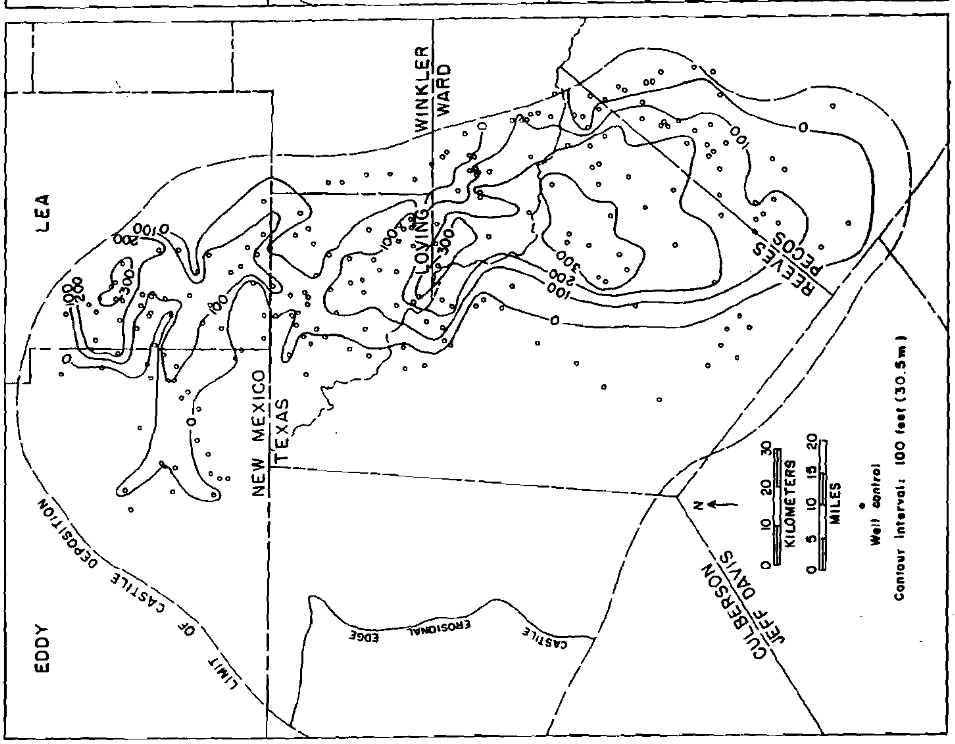

Figure 17. Thickness distribution of halite units within Anhydrite IV

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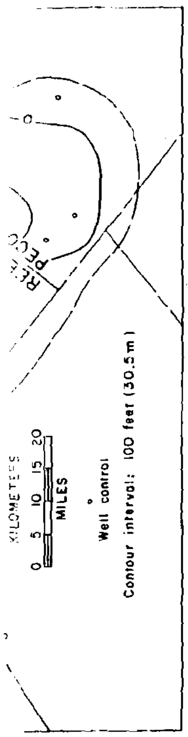

Figure 17. Thickness distribution of halite units within Anhydrite IV Member, Castile Formation.

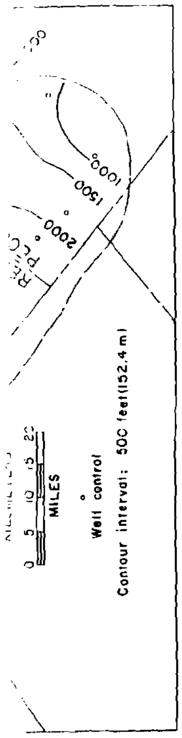

Figure 18. Thickness distribution of Salado Formation.

by about 90° from the anhydrite trend. Comparison of laminae at the base of Halite I and Halite III in the Union–University "37" core in Winkler County and the same laminae in the Cowden cores in the west-central part of the basin, a distance of 113 km (70.2 mi), shows a 15- and 27-yr difference in the onset of halite deposition (Fig. 7).

Halite and anhydrite beds within Halite II appear to show the same degree of synchroneity. It is more difficult to observe the end of halite deposition in major units owing to collapse of nonbrecciated laminated anhydrite immediately above solution breccia, but judging from correlations of individual anhydrite beds within Halite II, approximately the same number of laminae are involved, suggesting that the end of halite deposition in different parts of the basin was also nearly synchronous.

The synchroneity of halite deposition and the markedly different trends for halite and anhydrite, suggest that the classical model of evaporite salt zonation, as described, for example, by Scruton (1953) must be modified for the Delaware Basin. Some lateral zonation exists, but factors that triggered halite deposition seem to have affected almost the entire basin simultaneously.

The isopach maps of the Anhydrite I and II Members indicate a thickening from west to east in the form of a fan-shaped wedge. The fanlike shape is best illustrated by the 175 ft contour in Anhydrite I and the 90 ft contour in Anhydrite II (Figs. 10 and 14). According to basin reflux models of King (1947) and Scruton (1953) the thickness of a particular evaporite facies should thicken radially from the marine connection. If this is the case for the Delaware Basin, then the distribution patterns of anhydrite in the Castile suggest that marine water entered the basin from the west over or through the reef, rather than from the south as suggested by Kroenlein (1939), King (1942) and Adams (1944). The halite distribution patterns would favor the interpretation of a southern source but inasmuch as anhydrite represents about 97 percent of Castile time it may be more reasonable to look for an alternate explanation for the differing halite distribution.

BASIN DEPTH

No sedimentary features observed or reported from the Castile Formation can be construed as evidence for shallow water deposition. The so-called ripple marks (Lang, 1937; Porch, 1917) are not *sedimentary* structures, but are minor tectonic features that originated after consolidation (Kirkland and Anderson, 1970). The nodular beds in the Castile, while superficially resembling the nodular beds associated with tidal flat sedimentation, are closely associated with normal varving and in fact are varved themselves and show no primary breaks in the continuity of sedimentation.

Estimates of the depth of water have ranged from 150 to 700 m (King, 1934; Adams and Frenzel, 1950; Adams, 1944; Kroenlein, 1939) and are based chiefly on the present-day relief between the top of the Capitan Formation (the "reef") and the base of the Castile. Newell and others (1953, p. 189) and Adams and Frenzel (1950) discuss this method.

Ideally, the depth of water within an evaporite basin should have little effect on the precipitation process (Schmalz, 1969) and the accumulated sequence should reflect changes in environmental conditions of the water body. In the Castile sequence, however, there is a progressive change in the proportion of materials over an interval of several hundred thousand years.

Within the three halite members, for example, intercalated beds of halite and anhydrite become more and more common higher in the formation. Halite I is a single bed of halite. Halite II is interrupted by five thin anhydrite beds and Halite III by six major anhydrite beds. In addition, the time series plot of couplet thickness (Fig. 6) shows a progressive increase in the amplitude of a dominant oscillation in sulfate thickness that has a frequency between 1,000 and 3,000 years (*compare*, for example, the tendency toward oscillation in Anhydrite I and IV).

These progressive changes within the basin could be attributed to prolonged trends in climate or sea level or they could simply be the result of a progressive shallowing of the basin and the increasing impact of climatic change or freshening upon a smaller water volume within the basin.

CONCLUSIONS

The lamination (varving) process began prior to evaporite deposition and continued uninterrupted throughout the deposition of a basal limestone member, four anhydrite members, and three halite members of the Castile Formation. Individual laminations persist laterally for 113 km (70.2 mi) and probably extend throughout the basin.

The calcite-anhydrite laminations that are typical of the Castile changed character during times of high sulfate deposition. The same thick anhydrite layers developed into beds of nodular anhydrite after formation; nodular laminae and zones are also correlative within the basin. The episodes of high sulfate deposition or nodule development are separated by 1,000 to more than 3,000 laminae couplets.

Halite deposition in each member was of short duration (1,000 to 2,000 yrs) and the timing of deposition was in response to the same changes that produced thick sulfate laminae. Halite beds originally extended throughout the basin and are represented now by blanket beds of solution breccia in the western part of the basin.

Anhydrite members of the Castile thicken eastward and halite members thicken northward, with a trend difference of about 90°; the onset and end of halite and anhydrite deposition is nearly synchronous over 113 km (70.2 mi) and probably over the entire basin, suggesting that the classical model of evaporite zonation must be modified for the Castile sequence. Also, influx of water into the basin was apparently from over or through the western reef or platform.

A progressive upward increase in episodes of halite deposition and an increase in the fluctuation of sulfate deposition with time suggest a prolonged and sustained change in environment or progressive shallowing of the basin.

ACKNOWLEDGMENTS

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