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UPPER PERMIAN OCHOA SERIES OF DELAWARE BASIN, WEST TEXAS AND SOUTHEASTERN NEW MEXICO[1]

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ABSTRACT

The Ochoa series includes the uppermost Permian deposits of the southwestern United States. Most of the rocks included in the series are poorly exposed unfossiliferous evaporites. The well known subsurface section in and around the Delaware basin is described and illustrated by cross sections. A short chapter discusses theories on the origin and distribution of the characteristic evaporites.

INTRODUCTION

The Permian rocks of the Delaware basin and its bordering uplifts, in West Texas and southeastern New Mexico, have been selected as the standard Permian section for North America.[3] In this basin the system is subdivided into four series, named in ascending order Wolfcamp, Leonard, Guadalupe, and Ochoa. The type sections of the first three are well known, easily accessible, well exposed, highly fossiliferous, adequately described, conventional surface sections. The Ochoa series, on the other hand, is practically non-fossiliferous, many of the beds are not exposed, and the anomalous outcrops of the others are poorly exposed and inadequately described. For these reasons, the representative subsurface section of the Delaware basin, where the series is best developed, was taken as the type. The substitution of a subsurface for a conventional surface type section was further justified because the fully developed Delaware basin section is well known to the many geologists in the area. The present paper is designed to supplement previous publications and present a more nearly comprehensive picture of the type Ochoa.

For those unfamiliar with the area, King's recent description of the Permian stratigraphy and sedimentation is recommended as a background.[4]

DELAWARE BASIN

Delaware basin is the name applied to one of the most negative segments of the Permian basin. As shown on the map (Fig. 1), it is an irregularly pear-shaped depression occupying parts of West Texas and southeastern New Mexico. The

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[2] Geologist, Standard Oil Company of Texas. The writer is indebted to E. Russell Lloyd, Robert L. Bates, Ronald K. DeFord, John M. Hills, Ralph King, Robert E. King, Walter B. Lang, the late George A. Kroenlein, R. D. White, and a host of others who have read and criticized the manuscript or have assisted with original ideas. Data are from the files of the Standard Oil Company of Texas.

[3] John Emery Adams, M. G. Cheney, Ronald K. DeFord, Robert I. Dickey, Carl O. Dunbar, John M. Hills, Robert E. King, E. Russell Lloyd, A. K. Miller, C. E. Needham, "Standard Permian Section of North America," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23 (1939), pp. 1673–81.
C. W. Tomlinson, Raymond C. Moore, Robert H. Dott, M. G. Cheney, John Emery Adams, "Classification of Permian Rocks," *ibid.*, Vol. 24 (1940), pp. 337–58.

[4] Philip B. King, "Permian of West Texas and Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26 (1942), pp. 533–763.

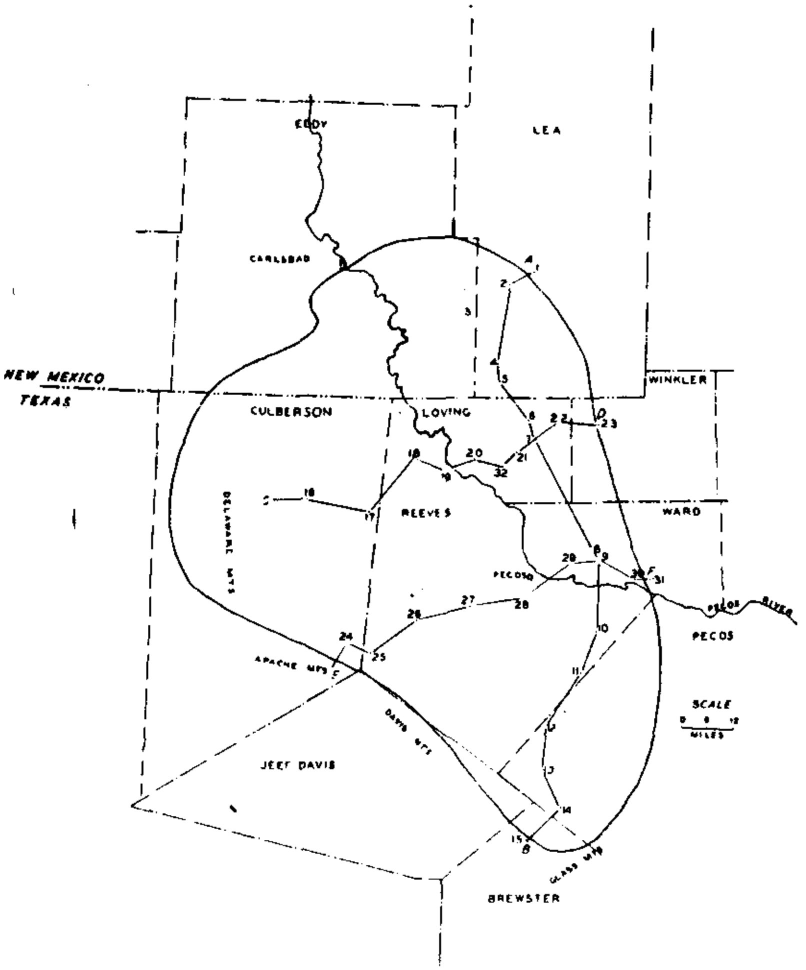

FIG. 1.—Outline map of Delaware basin with traces of cross sections.
Index of Wells Used in Cross Sections

1. Humble No. 1 Saunders
2. Masco No. 2 Cloyd
3. Marland No. 1 Gardner
4. Marland No. 1 King
5. Homestead No. 1 Clifford
6. Whiteside No. 1 Fee
7. Pinal Dome No. 1 Means
8. Slack No. 1 Hayes
9. Fitzpatrick No. 1 Dier
10. Brooks No. 1 Eddins
11. Penn No. 1 Bowles
12. Dixie No. 1 Hershenson
13. Humble No. 1 Gray
14. Humble No. 1 Kokernot
15. Dodson No. 1 Texas American Syndicate
16. Niehaus No. 1 Caldwell
17. Plymouth No. 1 Derrick
18. Grisham & Hunter No. 1 T. P. Land
19. Humble No. 1-B Kloh
20. Humble No. 1-C Kloh
21. Owens & Sloan No. 1 Johnson
22. Kingwood No. 1 Moore
23. White Eagle No. 1 Leck
24. Deep Rock No. 1 Kloh
25. Deep Rock No. 1 Tatum
26. Hill No. 1 Ely
27. Gaines & Melton No. 1 Patterson
28. Humble No. 1 Balmorhea
29. Plains No. 1 McGregor
30. Owens No. 1 Johnson
31. Kugle No. 1 Keasler
32. Dixie-Phillips No. 1 Johnson

The north-south length is approximately 165 miles and the east-west width 96 miles. Initiated early in the period, recurrent subsidence allowed the Delaware synclinal depression to receive and preserve the most nearly complete section of Permian rocks in the whole Permian Basin province. Throughout its early history, the Delaware basin was the site of pontic[5] (deep-water, marine, clastic) deposition. Typically pontic sediments consisting of black limestones, dark shales and silts, and fine sands accumulated to a thickness exceeding 7,500 feet. The bowl-like depression in which these beds are preserved was outlined by limestone reefs built along the margins of the surrounding shallow carbonate-depositing shelf seas. The system of pontic marine basins, reefs, and shelf-sea platforms reached its climax with the close of Guadalupian sedimentation.

Topographically, at the inception of the Ochoan epoch, the Delaware basin was an unfilled, geosynclinal bowl averaging approximately 1,700 feet in depth and encircled by steep-faced, cliff-like reefs between 1,200 and 2,000 feet high. Stratigraphically, it was underlain by a light sedimentary column of sands and shales in contrast to the heavy, massive limestone sections underlying the surrounding high, positive areas which stood at or just above sea-level.

STRATIGRAPHIC SUMMARY

The early Ochoa sediments are limited to the Delaware basin depression. They parallel the underlying beds in the center of the basin and butt against the Capitan reef face along the margins. When the basin was pracically filled, regional subsidence allowed the sea to climb out of the restricted depression and spread widely over the southern Permian basin. Thus the Ochoa rests unconformably on the upper surface of the Guadalupian sediments everywhere except in the Delaware basin. The absence of deep or extensive truncation or solution of the readily soluble rocks on the exposed platforms surrounding the basin before their burial by the general advance of the sea in mid-Ochoa time indicates a very slow rate of erosion and a relatively slight age differentiation.

The upper Guadalupian sediments of the Delaware basin, consisting of marine sands, dark shales, and limestones, contrast sharply with the light-colored evaporites of the overlying Ochoa. This marked lithologic change is the sharpest and most easily recognized stratigraphic break in the Permian section. Like all other reference horizons in the Ochoa, it can be more easily recognized in wells than in the normal, poorly exposed outcrops.

The change from marine to evaporite deposition was caused by the partial cutting-off of the channel or channels through which the unconcentrated sea water had previously been drawn into the basin. Chemical precipitation of evaporites followed shutting-off of free circulation. The close structural conformity between the Ochoan and Guadalupian deposits in the Delaware basin itself and on the surrounding shelf-sea areas would be most simply explained if the seaway were silted up or blocked by post-Capitan reef growths without accompanying diastrophism.

The Ochoa sediments are divided into four formations named from the base upward, Castile, Salado, Rustler, and Dewey Lake. The Rustler and Dewey Lake are distinct, easily differentiated formations. The standing of the two lower formations has been questioned and even at present the dividing horizon can not everywhere be recognized.

For many years this section of evaporites was classed as undifferentiated Castile. Cartwright,[6] recognizing that the lower part differed from the upper not only in lithologic character but also in distribution, divided the section into two formations called "Upper Castile" and "Lower Castile." The "Lower Castile," in the usage of the time, was intended to include that part of the Ochoa section limited to the Delaware basin. From the very incomplete information available, it was generally assumed that the top of the calcite-banded anhydrite in the lower part of the evaporite sequence was a definite horizon corresponding closely with the base of the anhydrite member, now called the Fletcher anhydrite, on top of the enclosing reef; thus, the "Lower Castile" was commonly considered as the zone of banded anhydrites.

Lang, realizing that if there were two formations present, their designation as "Upper Castile" and "Lower Castile" was inconsistent with good stratigraphic nomenclature, restricted the name Castile to the lower part of the pre-Rustler section and introduced the name Salado halite for the upper part.[7] His separation of the two formations was based originally on the presence or absence of potash and the Salado halite was defined to include all pre-Rustler evaporites containing more than 0.5 of 1 per cent of potash. The base of the formation, according to this definition, was determined at 2,350 feet in the Pinal Dome's Means well No. 1 in eastern Loving County, Texas. This subdivision met with some criticism. The separation of two geological formations on the basis of quantitative chemical tests was not accepted by geologists not qualified or equipped to make such tests. Furthermore, it had become apparent not only that the top of the banded anhydrite was not a constant horizon, but that the base of the potash salt also moves up and down the geologic column. It was recognized that the fluctuating base of the potash neither corresponded with the main stratigraphic break in the section nor limited the Castile formation, so defined, to the Delaware basin.

These valid objections led Lang to extend the Salado halite to include equivalents of all the beds extending across the reef rim.[8] The thin bed of anhydrite between the top of the Capitan reef and the base of the salt in the reef and back-reef areas, for which he later proposed the name Fletcher anhydrite, was

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[5] E. Russell Lloyd, "Theory of Reef Barriers," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22 (1938), p. 1709.

[6] Lon D. Cartwright, Jr., "Transverse Section of Permian Basin, West Texas and Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14 (1930), pp. 969–81.

[7] W. B. Lang, "Upper Permian Formations of Delaware Basin of Texas and New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), pp. 262–70.

[8] W. B. Lang, "Salado Formation of Permian Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23 (1939), pp. 1569–72.

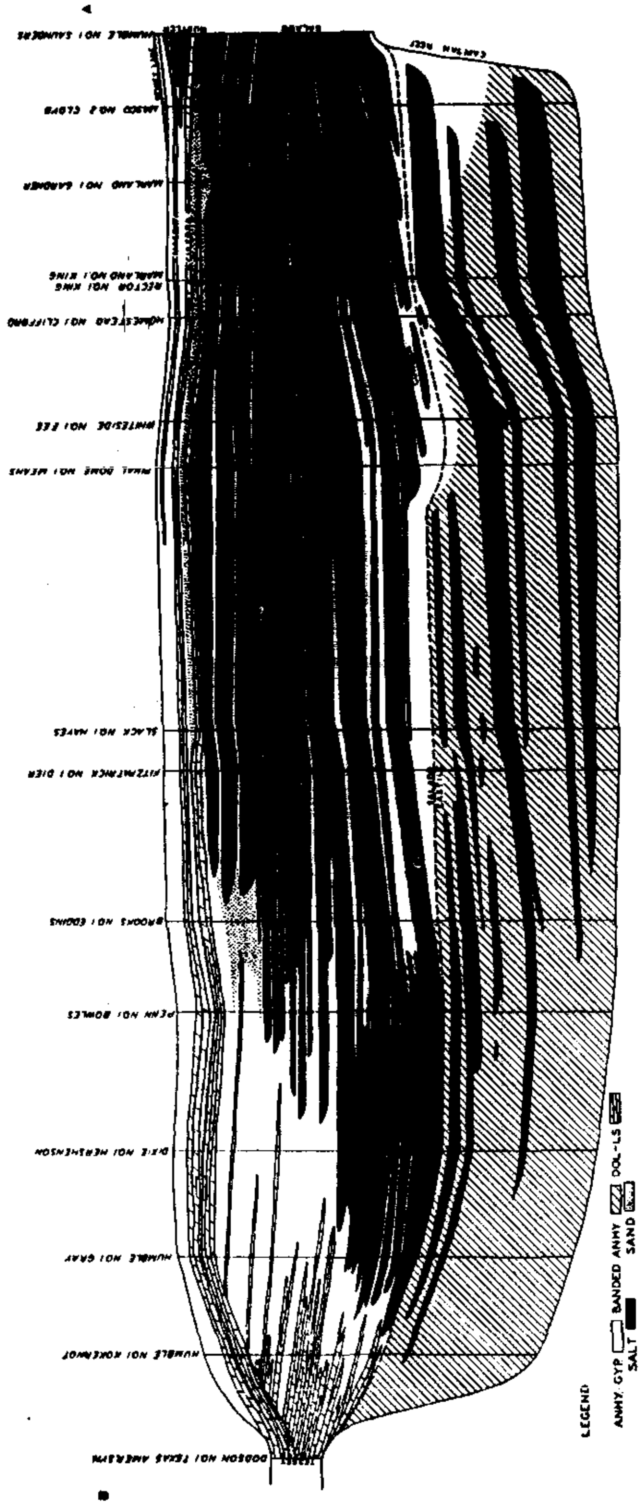

FIG. 2.—Diagrammatic south-north section (BA) of Ochoa rocks in Delaware basin. Line of section shown in Figure 1.

made the basal member of the Salado formation. By this definition, which is generally accepted, the Castile formation is limited to the Delaware basin. The unsupported definition, however, gives only a partial picture of the conditions. The writer believes, as indicated on the accompanying stratigraphic sections, that there is a natural structural and stratigraphic basis for dividing the pre-Rustler, Ochoa evaporites into two distinct formations that can be recognized in the center as well as along the margins of the Delaware basin.

Most of the redbeds of the Delaware basin previously classed as Permian[9] belong in the Triassic Pierce Canyon formation. Uppermost Permian redbeds, present in a few localities, are assigned to the Dewey Lake formation.

The outcropping Pierce Canyon redbeds of the Pecos Valley are similar lithologically to the post-Dewey Lake redbeds of the southern Permian basin and to the Quartermaster of the Panhandle. They occupy the same position with respect to the Upper Triassic Santa Rosa sandstone and, judged by the sections encountered in thousands of intervening wells, form a continuous stratigraphic unit. Regionally these redbeds overlap a wide range of Permian formations. In some localities the basal unconformity is overlooked and they are classed as Permian. They are made up largely of reworked Permian sediments with admixtures of new minerals, including coarse, rounded, but unfrosted, red quartz sand grains.

Arthur Morgan[10] of the United States Geological Survey, who studied the water resources of the area, reports that in closely spaced core tests, in central Eddy County, New Mexico, these redbeds can be shown to rest unconformably on the eroded upper surfaces of the Rustler anhydrite. R. W. Richards[11] who has recently mapped the surface geology for the United States Geological Survey, says, "I believe that the unconformity between the pre-Gatuña redbeds which Lang called Pierce Canyon and the Rustler can be found exposed in many localities east and southeast of Carlsbad."

These redbeds may be Permian in age, but judged by the lithologic dissimilarity from the underlying Permian and the evidence of local and regional unconformities, they are more probably Triassic. If they are Permian they were not deposited until the older Permian sediments had been warped and truncated. So far no conclusive proof of their Permian age has been presented.

STRATIGRAPHIC SECTIONS

The clearest way to present stratigraphic data is by use of diagrams (Figs. 2, 3, 4). Details can best be shown on simple cross sections. Since there are no

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[9] W. B. Lang, *op. cit.* (1935).
John Emery Adams, "Oil Pool of Open Reservoir Type," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20 (1936), pp. 780–96.
Ronald K. DeFord, N. H. Wills, C. D. Riggs, "Fall Field Trip, Eddy County, New Mexico," *West Texas Geol. Soc. Guidebook* (1940), pp. 2, 4, 17.
Ronald K. DeFord, "Editorial Note," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26 (1942), p. 613.

[10] Arthur Morgan, personal communication.

[11] R. W. Richards, personal communication.

measured surface sections of any of the Ochoa formations except the Rustler, the number and locations of possible cross sections, in the Delaware basin, is controlled by the distribution of suitable wells. The sections shown do not duplicate any previously published. The most dependable well logs available are those made from microscopic examinations of complete sets of carefully collected cable-tool cuttings. Most of the logs used in the sections belong in this group. Core data from critical parts of the section, in a few wells, are included. A few of the sample logs are from rotary wells. Information from drillers' logs and logs of adjacent wells was used to supplement the sample descriptions of the wells shown. Since the purpose of the writer is to present stratigraphic rather than structural in-

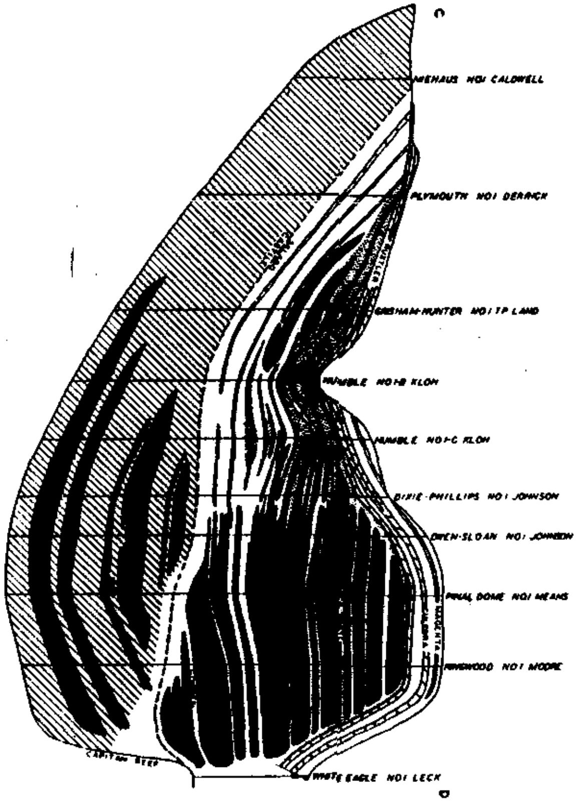

Fig. 3.—Diagrammatic west-east section (CD) of Ochoa rocks in Delaware basin. Line of section shown in Figure 1.

formation, generalized diagrammatic sections are shown. Elevations were largely disregarded and the well sections were balanced against each other in an attempt to reproduce, as nearly as possible, structural conditions near the close of Permian sedimentation. On the scale used, it was impossible to show all the minor details and gradations of stratigraphy.

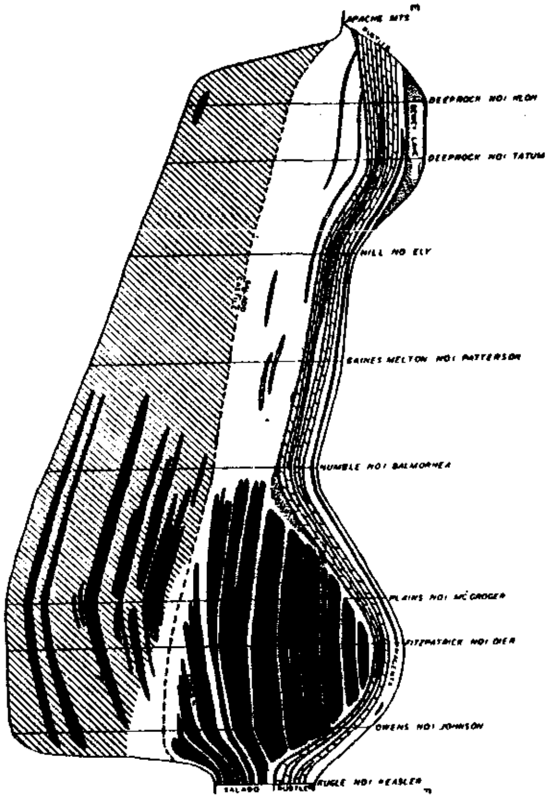

Fig. 4.—Diagrammatic west-east section (EF) of Ochoa rocks in Delaware basin. Line of section shown in Figure 1.

CASTILE FORMATION

The Castile, the basal formation of the Ochoa series, is composed of anhydrite, calcite-banded anhydrite, salt, limestone, minor amounts of other evaporites, and minute quantities of very fine clastics. No potash salts have been reported. In the Castile, as in all other Permian formations of the area, the calcium sulphate of the outcrops and of subsurface sections to a depth of about 500 feet tends to be gypsum. Beds buried to a greater depth are almost everywhere anhydrite. Throughout this paper the term anhydrite is used for both except when a distinction is to be made.

The Castile formation, which is limited to the Delaware basin, has an average thickness between 1,500 and 1,850 feet, but in west-central Ward County it reaches a maximum of more than 2,100 feet. Calcite-banded anhydrite, the main constituent of the Castile section, is made up of alternating bands or laminae of calcite and anhydrite. In most of the calcite laminae there is enough bituminous material to stain the carbonate a deep brown. The sharp color contrast between these brown sheets and the interlaminated white anhydrite stimulates curiosity. A residue of deep brown bituminous flakes remains to mark the parting when the calcite is digested in acid. Even where the calcite is missing, brown organic bands are present along the bedding planes of the anhydrite. The bituminous material, however, is nowhere mixed with the white anhydrite as it is with the calcite. Probably the bituminous flakes will yield recognizable organic remains, similar to those found in oils, when examined with sufficiently high magnification.

There are almost unlimited variations in the character of the banding. Where evenly developed, the laminae resemble chemical varves with the anhydrite layers two or three times as thick as the calcite. Udden makes the quite logical suggestion that the regular laminae represent annual cycles of sedimentation.[11] Individual carbonate partings range from scattered calcite crystals on the anhydrite bedding planes to beds of thinly laminated limestone several feet thick. The limestones are not dolomitic. The average thickness of the calcite laminae appears to be about 1/50 inch. Thin sections show that the thinnest laminae are made up of one layer of coarsely crystalline calcite, and that the thicker beds are coarsely granular limestone.

Irregularly distributed through the normal banded zones are beds of unlaminated anhydrite, ranging from ½ inch to several feet in thickness, and separated by banded zones that vary even more widely. There is a tendency for secondary calcite crystals to develop in fractures and in wavy ghostlike bands or even sprinkled about at irregular intervals, through these thicker anhydrites. The secondary calcite is almost everywhere lighter-colored than that of the normal laminae.

A thick calcite band is to be expected immediately above each thick anhydrite member. However, it seems that the anhydrite bed has to be three or four times as thick as the regular anhydrite laminae before any corresponding calcite cap develops. The sequence is not invariable. Some over-thickened anhydrites seem to have no corresponding cap, and even where the cap is exceptionally thick it may be separated from the thick anhydrite zone by one more or less normal, but commonly paper-thin, calcite lamina. The arrangement is sufficiently constant, however, to be used in orienting random cores and surface blocks. In the rare instances where the calcite cap of one thick anhydrite is followed immediately by another thick unbanded anhydrite zone, the gradation is less sharp at the top of the cap than at the base. Everywhere that thick carbonate caps have been noted, they are made up of thin calcite laminae rather than of massive or thick-bedded limestone layers. A one-foot limestone may have four or five hundred of these almost microscopic laminae. From present limited information we can not be certain that these unbanded, thick anhydrite beds and their thick calcite caps are of basin-wide distribution. Some individual calcite-cap zones have been followed for more than a mile along the outcrop only to be lost where the beds pass under a cover of soil. Since there are thick unbanded zones in the south as well as in the north end of the basin, it is assumed that the beds are continuous.

As shown on the stratigraphic sections, the top of the calcite-banded anhydrite does not mark a time-stratigraphic horizon. It extends several hundred feet up into the basal Salado in the south-central part of the basin and sinks approximately 800 feet below the top of the Castile near the northeast rim. The thickness and prominence of the calcite laminae also vary across the basin. The thickest limestone beds appear to be at or near the base of the formation in the southern and western areas, but some central basin wells show as much as 25–30 per cent calcite in cuttings and cores through hundreds of feet of section. Near the top of the banded zone the calcite partings decrease in number and thickness, but the change from prominently laminated to unbanded anhydrite is gradual and may occupy hundreds of feet. Wells in the northeast part of the basin show relatively lean banding throughout the entire laminated zone.

On the outcrops in the Delaware Mountains, the thin calcite laminae of the northern exposures appear to thicken southward, and along Paint Horse Draw, in central Culberson County, those of the basal Castile coalesce to form beds of granular gray limestone. Interspersed through these granular beds are zones of thinly laminated, bituminous calcite, similar in appearance to the calcite caps of the more northern areas. Only a little interstitial gypsum is present. Wedges of the limestone, separated by beds of more normal calcite-banded gypsum, make up the lower 300–400 feet of the formation. The so-called "petroliferous Castile" of the Loneman Mountain area is a tongue of banded calcite extending northeast from this area of Castile limestones. Apparently the bituminous material, the source of the strong petroliferous odor, was deposited with the calcite and was not derived from the underlying beds. A careful search of the limestones failed to show any microscopic fossils. Small quantities of chert are found along some of the bedding planes of the limestone, and in a few places concretionary masses several inches across had developed. Thin sections show a few dust-size quartz grains along some of the partings.

The bedded Castile limestones of the southern Delaware Mountains are relatively soft and should erode almost as fast as the enclosing gypsums. Most of them were removed before the deposition of the Rustler. The present outcrops are

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[11] J. A. Udden, "Laminated Anhydrite in Texas," *Bull. Geol. Soc. America*, Vol. 35 (1924), pp. 347–54.

about 10 miles from the original southwest edge of the Delaware basin. If the liming-up of the section was as rapid in the eroded part of the formation as it is in the present outcrops, the Castile may have been an almost solid limestone along the west margin of the basin. Unfortunately the few wells in the extreme south part of the Delaware basin do not show whether the Castile also limed up in that area. Certainly the basal beds in the intermediate San Martine area, of southeastern Culberson County, do not appear as limy as equivalent beds an equal distance from the Apache reef front farther west.

In addition to the primary variations in the calcite-banded anhydrite of the Castile formation, there are many secondary irregularities. Calcite laminae disappear in nodular masses of anhydrite. Concretionary anhydrite lenses grow between the partings and disrupt them. Bands of crinkled laminae appear to writhe about between flat beds, and in some transverse zones all evidence of bedding is lost. More important still is the faulting, fracturing, and slipping that characterize most of the cores and outcrops. Since most of the variations occur both at the surface and at depths of thousands of feet, it is assumed that most of them were produced by early diagenetic processes.

Interlaminated dolomite and anhydrite are present in several places in the evaporites of the southern Permian basin, but calcite-anhydrite banding of the type here described has not been noted anywhere in the Permian section outside of the Delaware basin.

In these descriptions, outcrop observations supplement information from cuttings, cores, and well sections, but one striking modification of the normal calcite-gypsum banding has been observed only on the outcrop. In the central and southern Delaware Mountains there are irregular areas where the gypsum is completely replaced by limestone and banded calcite. In extent these limestone masses, which resemble gash vein fillings, range in area from a few square feet to many acres. Most of them appear to lie in the lower and middle thirds of the Castile formation. Maximum thickness of the larger masses probably exceeds 100 feet. The limestone concentrations, being more resistant than the enclosing banded gypsums, stand up as hills in the eroded areas. The hills vary from low mounds, through haystack buttes to castellate peaks. Although the Castile formation was named for Castile Springs rather than for the well exposed rock towers, a more appropriate name than "castiles" can hardly be imagined for the limestone hills themselves.

In the northern castiles the dominant lithologic character is a concentration of brown calcite bands. In the better exposed outcrops it looks as though the gypsum originally interbedded with the calcite had been removed by solution and the openings thus formed partly filled by secondary carbonates, apparently aragonite, and some secondary gypsum. Unsupported masses of the rock broke off to form a breccia that is now firmly held together by secondary botryoidal growths of aragonite. The northern limit of the prominent castiles is a few miles south of the Texas-New Mexico line.

In the southern Delaware Mountains the castiles, like the limestones of the Castile formation, contain a much smaller proportion of banded calcite, its place being taken by coarsely granular gray limestone. On weathered surfaces this rock is casehardened, but under the thin hard coating it is soft, almost friable, and crumbles readily under taps of the hammer. Brecciated angular fragments of banded calcite are enclosed in the granular groundmass that replaces the botryoidal cement of the northern castiles. The banding in many of these brecciated fragments shows that the calcite was never interbedded with gypsum. In the Paint Horse Draw area the brown banded calcite in the castiles is reduced to a minimum and the granular limestone weathers with the rounded surfaces of a soft sandstone. As a result the castiles are more bulbous and less steep walled than those farther north. Lack of bedding differentiates the limestone of the castiles from the normal limestones of the surrounding areas. Chert is very uncommon and a careful search failed to reveal any fossils. These southern castiles should not be confused with somewhat similar limestone hills in the upper part of the Delaware Mountain sand. The latter contain conspicuous amounts of chert as well as laminae and lenses of sand. They are also fairly fossiliferous.

No castile masses have been recognized in the subsurface. However, many of those noted are only partly exhumed and their extent is probably much greater than is apparent in the limited outcrop. The structures are clearly of secondary origin and they would not be expected far below the surface.

The salt beds, which are the principal markers in the Castile formation, are composed of practically pure sodium chloride. Impurities include blebs and crystals of anhydrite, and laminated calcite. No potash is present. The salt lenses can be divided into three groups. The lower and middle groups each have two members. The upper group is less regular and contains many stringers too thin to be shown on the sections. With the exception of the thin salt lens near the base of the Apache reef, as shown in the Deep Rock's Kloh No. 1, all the Castile salt is limited to the northeast part of the Delaware basin. The lower salt group is best developed in the north part of the salt-bearing area, the middle group in the north and central parts, and the upper group in the central and south parts. The southern limit of the lowest Castile salt is just south of the town of Pecos but the upper beds do not reach as far north as the New Mexico line.

In the Wheat pool of Loving County, Texas, where the base of the lower salt is used as a marker to predict the top of the Delaware Mountain sand, the interval from the base of the salt to the top of the Lamar shale varies from 183 to 185 feet.[11] Northward and northeastward the interval increases to about 400 feet. Southward it decreases to about 150 feet, but in any one locality the interval is sufficiently constant to be used in local areas for structural predictions.

Chert deposits in the Castile formation appear to be limited to the banded limestones and to the calcareous parts of the castiles in the southwestern Delaware Mountains. Even here the chert is a very minor constituent of the rock. A careful hand-lens examination showed no organic structures.

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[11] John Emery Adams, *op. cit.*, p. 755 (1936).

Clastics noted in the Castile formation include fine quartz grains scattered through the calcite laminae. Their presence was unnoted until the rock was sectioned and examined petrographically. The size of these particles suggests that they represent atmospheric dust. Cores from one well showed structures resembling anhydrite pebbles in the bottom foot or so of the formation. They were not noted elsewhere and may be accretions rather than products of mechanical transportation. Udden[14] mentions the presence of shale, but deposits, if present, are limited.

Along the north and east borders of the Delaware basin the Castile is separated from the overlying Salado by an angular unconformity. Elsewhere the angularity decreases, but in the southern areas the two formations are separated by an even greater time break. In the western areas, where the Rustler beds rest on the truncated surfaces of the Castile, the angularity is apparently due to pre-Rustler uplift and erosion as well as to irregular hydration and solution of the Castile evaporites.

SALADO FORMATION

Above the Castile is another thick section of evaporites belonging to the Salado formation. The two formations are separated by an unconformity, accompanied by marked changes in distribution and lithologic character. But in spite of these great differences, there have been, and still are, difficulties in drawing the dividing line between them.

The Salado in the Delaware basin was truncated and completely overlapped by beds of the succeeding Rustler formation. Along many of the divides, tongues of Rustler still lap over onto the beveled edges of the Castile. The only Salado outcrops are thus discontinuous, poorly exposed patches of unbanded gypsum along the main drainage lines west of the Rustler Hills. In the subsurface the Salado, unlike the Castile, crosses the Capitan reef and is present in a large part of the southern Permian basin.

In the Salado formation, salt is more abundant than anhydrite. Many of the salt beds, especially the upper ones, in and around the north end of the Delaware basin, contain potash and other bittern minerals. Polyhalite is the most widespread of the potash-bearing minerals. The base of the polyhalite deposits transgresses upward across the salt section toward the southwest. None is found in the salts south and west of the Pecos River. Many of the potash-free salts of the formation are also red, due to the presence of red clastics and iron oxides. The lithology and stratigraphy of the salt and associated beds in the northeast part of the Delaware basin have been worked out and described by geologists and others studying the commercial potash deposits of the area.[15] In addition to the potash, clastics, and common red coloration, the Salado salts contain blebby anhydrite inclusions and mats of coarse, interlocking anhydrite crystals as well as the fine granular masses of anhydrite which characterize the salts of the Castile. Salado salts in the south-central part of the Delaware basin are much cleaner than those in the areas near the north rim.

Dolomite and magnesite are the common Salado carbonates, although calcite-banded anhydrite is present in the lower beds of southeastern Reeves and western Pecos counties. The dolomite and magnesite are present as stringers or as diffused grains in most of the anhydrite members at the north end of the Delaware basin. Near the Texas line the carbonates, especially in the upper part of the section, are concentrated into beds. Outside of the salt areas dolomite becomes more prominent and some of the beds can be correlated from well to well. The more general lack of correlation may be due to the wide spacing of control wells in the southern and western areas, but is more probably due to discontinuity of beds. In the south end of the Delaware basin the proportion of dolomite increases, and in the Humble's Kokernot No. 1, the southernmost well in the basin, bedded dolomites make up approximately 20 per cent of the Salado section. This concentration supports the correlation of the Salado with the Tessy formation of the Glass Mountains. Dolomite is also prominent in the western part of the basin, but no Salado dolomites have been recognized on the outcrop. Presumably, if found, they could be differentiated from Rustler dolomites by the absence of a basal conglomerate.

Sands and silts are encountered in many parts of the Salado section. The sands are coarser than most of the Permian sands but they are not characterized by the frosted quartz grains so common in the Yates and Dewey Lake formations. Both red and gray sands are present. A tongue of bedded sandstones extends south from the vicinity of Carlsbad almost to the Pecos County line. The source of supply seems to have been at the north and west. The sands are most extensive near the top of the Salado formation. The location of this sand barrier probably had some bearing on the thick accumulations of potash salts that occur in equivalent beds northeast of the main sand area. Most of the salt has been dissolved out of the Salado section in the sandstone areas, leaving a broad irregular solution trough. The position of this trough is clearly shown on the cross sections. The close association of this solution trough with the distribution of the sandstones suggests that the porous sand served as a conduit for the circulating salt waters. Isolated patches of salt were left west of the trough in northern Reeves and Culberson counties.

One sandstone member in the upper Salado of the northeastern Delaware basin and adjacent platform areas stands out conspicuously as a stratigraphic

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[14] J. A. Udden, *op. cit.*

[15] W. T. Schaller and E. P. Henderson, "Mineralogy of Drill Cores from the Potash Fields of New Mexico and Texas," *U. S. Geol. Survey Bull. 833* (1932).

G. R. Mansfield and W. B. Lang, "Texas-New Mexico Potash Deposits," *Univ. Texas Bull.* 3401 (1934), pp. 641–832.

George A. Kroenlein, "Salt, Potash, and Anhydrite in Castile Formation of Southeast New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23 (1939), pp. 1682–93.

Walter B. Lang, "Basal Beds of Salado Formation in Fletcher Core Test, near Carlsbad, New Mexico," *ibid.*, Vol. 26 (1942), pp. 63–79.

marker in wide areas. This thin sand, rarely more than 10 feet thick, lies just below Anhydrite No. 12 of the Kroenlein section. It is fine-grained sand and has the typical orange-red color of the Upper Permian sands. On the assumption that such a widespread, thin sandstone sheet must have spread over an almost level surface, the north end of the accompanying longitudinal section was aligned upon this member where it is present. A member so important in working out the sedimentary and structural history of this thick section of sediments is deserving of stratigraphic recognition. The name Vaca Triste, from Vaca Triste Draw, is proposed for this member of the Salado. The type section of the Vaca Triste sand member of the Salado is in the Continental's King well No. 1, Sec. 26, T. 25 S., R. 32 E., Lea County, New Mexico. In this well, which is shown on the north-south cross section (Fig. 2), the sand was encountered between 1,555 and 1,565 feet. The sample log for this part of the section is as follows.

Depth in Feet	
1,500–1,520	Anhydrite .8, salt .2 (Anhydrite No. 12)
1,520–1,530	Anhydrite .2, salt .8
1,530–1,555	Salt
1,555–1,565	Fine red sand (Vaca Triste member)
1,565–1,580	Anhydrite

Cuttings from this well are kept in the Standard Oil Company of Texas collection in Midland, Texas, and in many other collections in the area. The Vaca Triste sand in this well contains a showing of water.

Silts and shales are less conspicuous but more generally distributed than sands in the Salado section. Colors include brown, green, blue, gray, red, pink, violet, and black. These finer clastics are commonly lost in cuttings from oil wells but are very conspicuous in the potash core tests. One prominent member near the base of the Salado is named La Huerta silt.[16] Numerous other unnamed members, of equally wide distribution, can be recognized in the upper part of the section.

The anhydrites of the southern and western Salado areas are rather featureless deposits. The few cores examined show that the anhydrite is thin-bedded and blue-white in color. Outcrops of probable Salado age show some warping, but less evidences of thrusting and contortion of bedding than is observed in the underlying Castile. This is possibly due to the fact that there are no good outcrops and no contrasting beds easy to follow with the eye. In the main salt section of the northeastern Delaware basin, the anhydrites fall into two groups—discontinuous lenses, and widespread members which serve as markers. Most of the widespread members of the potash mine area were given numbers by Kroenlein.[17] A few changes in the correlation of these numbered beds are here adopted for the wells in southern New Mexico. No single anhydrite member can be carried over the entire salt-bearing area of the Delaware basin. The anhydrite marker members almost everywhere contain inclusions of salt, and thin stringers of silt and magnesite or dolomite. Two of them are recognized by name. The Fletcher member marks the base of the Salado in the northern Capitan reef area. The widespread Cowden anhydrite occurs 150 to 200 feet higher in the section.

Dark brown, calcite-banded anhydrite is present in southern Reeves and western Pecos counties, where the top of the banded section is about 500 feet above the base of the Salado. The banding is darker than is common in the banded Castile and the rock gives off a strong sulphur-dioxide odor when digested in acid. The calcite-banded anhydrite members of the Salado are thin and are separated by thick beds of salt. They are apparently limited to an area near the nadir of the Delaware basin.

No chert was noted in any of the Salado samples, but a few small euhedral quartz crystals with short prisms and bipyramids are scattered through the salt. Here and there grains of pyrite are found in the dolomite.

At its inception the Salado lagoon was apparently limited to a narrow crescentic trough just inside the north and east rim of the Delaware basin. The first evaporites deposited in this part of the lagoon seem to have been anhydrites. No distinctive characteristics were recognized that would separate Salado anhydrites from those of the underlying Castile. For this reason only the general position of the contact is shown in the accompanying sections. The early anhydrite deposits were followed by salt. Subsidence of the platform at the north and east quickly permitted the salt-depositing waters to cross the platform rim and cover large areas of the southern Permian basin. The earliest beds of the original trough are probably older than the Fletcher anhydrite on the crest of the Capitan reef, but they are included with the Salado because they lie above the unconformity which separates that formation from the underlying Castile.

While the Salado sea was sweeping widely north and east, it was slowly creeping southward up the center of the Delaware basin. By the time the sea floor had subsided sufficiently for approximately 600 feet of salt and anhydrite to be deposited in the northern and eastern marginal troughs, the whole Delaware basin was submerged. The resulting disconformable distribution is clearly shown on the stratigraphic sections. The south edge of the original trough may have been localized by solution of the underlying Castile salt, but the formation of the trough itself was due to crustal movements in the Castile-Salado interval. The distribution of the early Salado beds indicates that they were deposited in an arm of the sea advancing across the Permian basin from the west or southwest. All evidences of the extent of this marine arm were removed or covered by post-Permian erosion and deposition. A southwest sea connection seems probable because the Ochoa sea never extended much farther west than the present limits of the Delaware basin. In later Salado time the entrance apparently shifted to the south end of the basin.

Even though the southern Delaware basin was not submerged until a considerable thickness of salt had been deposited in the northern areas and across the platform behind the Capitan reef, the negative central part of the basin quickly

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[16] W. B. Lang, *op. cit.* (1942).

[17] George A. Kroenlein, *op. cit.*

regained dominance. As a result, the thickest Salado section, exceeding 2,200 feet, is present in east-central Loving County. Still farther south, in western Pecos County, the lower part of the Salado loses many of the conspicuous northern anhydrite members and becomes an almost solid section of salt. The anhydrite members that are present here contain banded calcite similar to that in the underlying Castile.

North and east of the Pecos River much of the Salado section above the Vaca Triste member consists largely of salt with three prominent anhydrite members. The upper salt beds extend northeastward across the reef rim of the Delaware basin and are recognized over most of the Central Basin platform. To the south and west, however, these beds are either missing or grade into anhydrite. The salt beds below the Vaca Triste also disappear toward the south and west. Limitation on the west is partly due to post-Salado erosion and solution and partly to nondeposition. The most rapid subsidence took place in the east-central Delaware basin and it is here, as already mentioned, that the thickest and most nearly complete Salado section was laid down.

Salado salt beds west of the Pecos River, in northern Reeves County, are separated from those on the east by a solution trough. The site of the solution trough was an area of thick sand deposition. As the sand rises in the section toward the southeast, so does the bottom of the solution trough. Lenses of sand interbedded with salt, in some of the wells along the margins of the slump, prove that the sand concentrations in the Salado section underlying the trough are residual and were not washed in after the sag developed. The Vaca Triste is apparently an attenuated sand stringer extending out from this sand body.

The Salado unconformably overlies the Castile evaporites of the Delaware basin and the uppermost Guadalupian sediments of the surrounding areas. There is no evidence of extensive pre-Salado erosion. This may mean that the basin was an area of very slight rainfall. It seems probable, however, that the uppermost Castile salts were dissolved to form a shallow solution valley along the original margin of these salts. This and the tilting of the Delaware basin northward probably mark a time break between the two formations. The unconformity between the Salado and the overlying Rustler formation is marked by extensive erosion and solution.

It is probable that the Salado should be correlated with the Tessey formation of the Glass Mountains. The Tessey is made up of practically pure, almost nonfossiliferous dolomites and probably represents the back-reef facies of a post-Capitan reef, into which the limed-up section of the southern Salado appears to grade.[18]

RUSTLER FORMATION

Deposition of the Rustler, the third formation of the Ochoa series, was preceded by a period of uplift and erosion in the area along the west edge of the Delaware basin. This erosion stripped off all the western Salado and may have truncated the entire Castile formation as well. The lowest Rustler outcrops observed are about 100 feet above the top of the Delaware Mountain group. As a result of uplifts beyond the limits of the Delaware basin, the oldest deposit of the Rustler formation, in its western outcrops, is a clastic member. Included are coarse, siliceous conglomerates with well rounded pebbles up to 2 or 3 inches in diameter, coarse gray sandstones, traces of red and yellow shale, coarse dolomite conglomerates, and bedded gray and buff dolomite. Many of the siliceous pebbles are etched in a peculiar manner with all the broken crystals of the original surface spalled out, leaving well rounded pebbles covered with unmarred crystal faces. The bedding in all these deposits seems to be distorted. Toward the east the conglomerates grade into sandstones.

Where the basal sandstones of the Rustler rest on the beveled surfaces of the Salado, as in the area south and east of Carlsbad, they are characterized by abrupt irregularities in thickness.[19] Apparently these variations are due to the filling of salt solution valleys in the surface of the Salado. Above the basal clastic phase, the Rustler is largely an evaporite formation and marks the final stage of evaporite deposition in the southern Permian basin.

In the subsurface where the complete Rustler section is preserved, it can be divided into two main parts, an upper 150- to 175-foot bed of anhydrite or gypsum; and a lower group of dolomite, anhydrite, sand, and shale members. Along the southwest limits of the Rustler area the anhydrites of the lower group grade into dolomites and the dolomites into limestones. Toward the north and east the the dolomite stringers, in turn, decrease in prominence, and at the northeast edge of the Delaware basin part of the upper anhydrite and the anhydrites of the lower group grade into salt. Thus in crossing the Delaware basin from southwest to northeast, we find, within the limits of one formation, an almost complete sequence of evaporite deposits.

Where the Rustler carbonates crop out in the Rustler Hills of eastern Culberson County, the section consists of dense, brecciated limestones and dolomites with rough, pitted, weathered surfaces, interbedded with sandstones and limestone conglomerates. Much of the pitting is due to the solution of gypsum inclusions. Many of the gray and green shales of the subsurface take on a purple cast after weathering on the surface. The maximum thickness here is about 375 feet and none of the upper anhydrite is exposed. Richardson collected a few fossils from these outcrops.[20] These pelecypods apparently lived under very unfavorable conditions, have not been found elsewhere, and are not diagnostic of age. Small amounts of sulphur have been produced from fault zones in the Rustler Springs area and some copper stains were noted. The most detailed published description of this area is that by Porch.[21]

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[18] P. B. King, "Geology of the Marathon Basin, Texas," *U. S. Geol. Survey Prof. Paper 189* (1937), p. 106.

[19] W. B. Lang, personal communication.

[20] G. B. Richardson, "Report of a Reconnaissance Survey in Trans-Pecos Texas North of the Texas and Pacific Railway," *Univ. Texas Min. Survey Bull. 9* (1904), p. 40.

[21] E. L. Porch, Jr., "The Rustler Springs Sulphur Deposits," *Univ. Texas Bull. 1722* (1917).

Unlike the Salado, the Rustler formation crops out over widely scattered areas both east and west of the Pecos River. Outcrop distribution is controlled by erosion, solution subsidence, and burial under Triassic and Quaternary cover. The western outcrops are limited to the basal carbonate and clastic section, with the upper anhydrites suggested by a gypsite plain east of the Rustler Hills. As the only resistant member in a thick series of softer beds, the limestones form low scarps and floor many of the gentler slopes. The slumping and disruption of the hard members due to creep of the underlying gypsum was described by Shumard,[22] who crossed the region in 1855.

East of the Pecos River, in central Eddy County, New Mexico, is a small area in which the upper as well as the lower part of the Rustler is exposed. Here, where the upper Rustler stratigraphy is similar to that of the north-central part of the Delaware basin, Lang measured the following section.[23]

1. 30 feet gypsum
2. 30 feet gypsiferous dolomite
3. 100 feet gypsum
4. 30 feet redbeds
5. 20 feet gypsum
6. 35 feet dolomite
7. 30 feet redbeds
8. 70 feet gray sandstone
9. 35 feet redbeds
10. 130 feet gypsum
11. 5 feet redbeds

The first five members in the foregoing section belong to the upper Rustler, the others to the lower part of the formation. The 30-foot gypsiferous dolomite, No. 2 in the sequence, is a persistent marker in the north half of the Delaware basin. For this stringer Lang favors the name Magenta member of the Rustler formation, after Magenta Point north of the Laguna Grande salt lake, and this name is used on the stratigraphic sections. For the 35-foot dolomite, No. 6 in the section, he favors the name Culebra member of the Rustler formation, from Culebra Bluff on the east side of the Pecos River where the member is well exposed. Because this member is a good marker in the subsurface, the name Culebra is also used in the cross sections.

The lower part of the aforementioned section is characteristic of the extreme northwest part of the Delaware basin and is limited to the area of pre-Rustler solution troughs. Perhaps the exceptional thickness of sandstone in the Rustler of this area is due to a recurrence of the processes that supplied the thick Salado sands in the same area. In the subsurface, farther south and east, another prominent dolomite bed appears near the base of the gray sandstone, No. 8 of the Lang section. This is the lower of the two main Rustler dolomite members.

Local features include a zone of euhedral quartz crystals in the anhydrite between the Magenta and Culebra dolomites, and oölites in one or the other of the two main dolomite members. The oölites are most common in that part of the Rustler overlying the Capitan reef and the back-reef areas.

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[22] Geo. G. Shumard, "Observations on the Geological Formations of the Country between the Rio Pecos and the Rio Grande, in New Mexico near the Line of the 32nd Parallel," *Trans. St. Louis Acad. Sci.*, Vol. 1, No. 2 (1858), pp. 5–7.

[23] W. B. Lang, "Geology of the Pecos River between Laguna Grande de La Sal and Pierce Canyon," *New Mexico State Engineer 12th and 13th Bien. Rept.* (1938), p. 84.

The contact of the Rustler and overlying Dewey Lake formations appears to be conformable. In the central part of the Permian basin the same can be said of the Rustler and Salado, but along the west and north margins of the Delaware basin the Rustler unconformably truncates the entire Salado section. The sharpest angular unconformity is in the western Delaware basin where the Rustler rests on the basal members of the Castile formation and is reported to rest on the Capitan limestones of the Apache Mountains. Uplift and erosion in this area may have been as much as 2,000 feet.

The Rustler marks the final incursion of the Permian sea into West Texas. In general, this sea was much fresher than those of the Salado and Castile, but being extremely shallow, gradations from one type of evaporite to another were more abrupt. If any of the Rustler is exposed in the Glass Mountains it is included in the Tessey formation of that area. The southernmost subsurface section can be differentiated from the outcropping Tessey only by the presence of small quantities of anhydrite. Even though the Rustler is separated from the underlying Permian by the most pronounced unconformity within the Permian system in West Texas and New Mexico, there is no reason for assuming that it is post-Permian in age. The basin of sedimentation is the same; the seaway supplying the water is the same; the processes of sedimentation are the same; and the character of the sediments themselves is the same, even down to the red polyhalite in the salt and the frosted quartz grains in the sands, as those of the older Permian beds.

DEWEY LAKE FORMATION

The Dewey Lake is a redbed formation in sharp contrast to the evaporites of the lower Ochoa. The gypsum that is present with the orange polished sands and red shales occurs as cement, secondary crystals, and veins. The coarse frosted quartz grains, so characteristic of the basal Dewey Lake beds in areas on the east, are missing in the Delaware basin section. The greatest thickness of Dewey Lake beds is just under 350 feet. In this area the formation is limited to the structurally low areas along the east and south edges of the Delaware basin, and no outcrops are known. Apparently pre-Triassic erosion stripped the unconsolidated redbeds from the surface of all the higher exposed areas, leaving a Rustler pavement. Then the area was completely covered by Triassic and Cretaceous sediments that still lap far beyond the limits of the truncated Dewey Lake formation.

Basal Triassic redbeds are differentiated from those of the Dewey Lake by their deeper red color, which here and there borders on purple, by their greater content of gypsum, their flood of dark minerals, their seeming lack of compactness, and their wider variations in grain size. The so-called frosted grains of the Triassic are much more polished than those of the Permian, and they commonly include a much higher percentage of reddish quartz grains. It seems probable that whereas the Permian frosted grains are frosted by solution, those of the Triassic are frosted by wind action. Some of the difficulty in separating the Permian and Triassic redbeds is due to the fact that the Triassic contains a large percentage of reworked Permian. White spots are common to most redbeds and are not diagnostic of age. Such spots are caused by reduction of the iron around an enclosed fragment of organic material or some similar reducing agent.

ORIGIN OF EVAPORITES

The origin and distribution of the various evaporites in the Ochoa series were due to physiochemical processes, many of which are not fully understood. It is the plan here to see whether adequate explanations of the several phenomena can be developed within the limits of the critical geological data.

Baker[24] has presented very convincing geological arguments to show why the extensive salines of the Permian basin must have had a primary marine source. This hypothesis is accepted without question. Observed data suggest that the evaporites were deposited in an Ochsensius-type barred basin of epi-continental extent. Water losses from such a basin would be by evaporation and by outflow of waters piled up by floods, high tides, and storms. If these losses exceeded precipitation plus inflow of streams and springs, sea water would be drawn in over the bar to make up the deficiency. Continuation of this excess loss and its replacement by sea water would lead to precipitation of evaporites. Variations in the composition and distribution of these evaporite deposits would depend on the size, shape, and depth of the basin, the distribution and extent of the fresh-water supplies, and the ease and regularity with which inflowing sea water could cross the bar.

Evaporation of sea water in a restricted container, such as a beaker, produces a regular sequence of precipitates mixed with or superposed one upon another. In larger, natural, barred basins, tens or hundreds of miles across, with a single continuous marine connection, equal evaporation per unit of area would cause an inward slope across the evaporating pan and a consequent continuous migration of the brine from the entrance to the innermost end of the basin. Increasing concentration during this journey would cause successive precipitation of the least soluble constituents in a lateral rather than a vertical sequence. The normal order of the geologically important evaporite sediments is limestone, dolomite, anhydrite, salt, and rare bitterns. Intermittent marine connections in a sizeable basin should produce deposits similar in distribution to those of the laboratory experiments. During closed periods evaporation would lower the surface of the water in the barred basin below that of the adjacent sea. Upon the breaking-down of the barrier great quantities of sea water would rush in to fill the basin up to sea-level. This water would spread over the whole area and only after it became practically stationary would evaporation produce any appreciable decrease in volume or increase in concentration.

The Castile formation seems to fulfill the requirements for intermittent marine connections while almost all the other Permian evaporites appear to have been deposited in barred basins with nearly continuous marine connections. The Castile is fairly consistent lithologically from bottom to top and from one end of the basin to the other. It seems that the minor differences can be most readily explained if we assume, in addition to the intermittent marine connections, that the beds were deposited in waters of greater than normal depth and in a relatively restricted basin.

All the geological evidence indicates that the marine waters that entered the Castile sea entered from the south or southwest through one or more narrow channels. A sand-dune ridge, perhaps made up of calcareous sands and protected by organic reefs, would be a logical type of barrier to shut off migration through such channels. Breaches could be produced by storm waves and sealed off by normal wind action. Alternate breaching and sealing of a barrier of this type might well be a seasonal occurrence. Recurrent closing and opening of the barrier would allow the waters in the basin to be lowered by evaporation or to be raised by freshening floods. Initially the waters of the Castile sea were fairly uniform in composition, and because they were derived from the open sea, salt concentrations would be those normal to the waters of the Permian oceans, which probably closely approached those of the present sea. Waters drawn across the bar would be of the same character and would carry a normal planktonic fauna. As soon as a solid barrier shut off the marine inflow, evaporation would start decreasing the volume of the relict waters and this would cause precipitation of the salts in the reverse order of their solubilities. Increased concentration would eventually cause the death of most of the organisms in the barred-basin waters.

The present average rate of surface evaporation in the area of the Delaware basin ranges between 6 and 9 feet a year. At this rate the original 1,700-foot basin would have been emptied in 200–300 years if no additional water was added. Probably long before complete desiccation occurred the barrier was broken down and a fresh supply of sea water entered. The entering water would be lighter than the concentrated water already in the basin. Because of this difference in density there would be little if any vertical mixing or diffusion between the zones of different concentration. Since only the surface suffers evaporation, this top layer of unconcentrated water would be acted on as a unit. Concentration would cause the precipitation of the least soluble constituents. Of these, calcium carbonate is the only one abundant enough to furnish a geologically appreciable deposit. If only 6 to 9 feet of water had entered the basin, the resulting layer of limestone would be paper thin. Before the thin top layer of unconcentrated water had been completely evaporated, the increase in gravity would allow the residue to sink into the underlying gravity stratum. By the time this point was reached the floating organisms would have been killed by the increasing concentration, and their remains would have showered down with the $CaCO_3$. Numerous repetitions of this partial evaporation would eventually lead to the establishment of an even more pronounced gravity stratification. In the final stages the bottom brines would have lost practically all of their original salts less soluble than sodium chloride while at intermediate depths the brines would be saturated with calcium sul-

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[24] C. L. Baker, "Depositional History of the Redbeds and Saline Residues of the Texas Permian," *Univ. Texas Bull. 2901* (1929), pp. 9–65.

phate. Once the calcium carbonate precipitate had settled through the top water, there would be no tendency for re-solution, because the bottom waters were already concentrated and the decrease in pressure from shallowing of the water would decrease its ability to hold CO_2 in solution.

The second geologically important precipitate is normally dolomite, but there is no dolomite present in the Castile evaporite section. The reason seems to be connected with the depth of the water and the concentration of CO_2. Most of the Permian evaporites outside the Delaware basin were deposited from waters only a few inches or at most a few feet in depth. Temperature and pressure and chemical composition varied but little from top to bottom and most of the carbonate was deposited from relatively concentrated waters. At the beginning of Castile deposition the Delaware basin was almost 2,000 feet deep and at the close may have held waters more than 100 feet deep. Most of the carbonate was precipitated from surface waters of relatively low concentration. Calcium carbonate deposited from waters low in sulphates goes down as calcite, and from high-sulphate waters as aragonite. Calcite is a stable mineral and once formed is not easily altered. Aragonite is unstable and in recrystallizing in the presence of a concentrated magnesium solution might be expected to form dolomite. Another hypothesis that may be advanced is that increasing pressure with depth allows sea water to hold higher concentrations of carbon dioxide in solution. It requires much less of an excess of CO_2 to hold $MgCO_3$, which is just another way of saying that magnesium carbonate is more soluble than calcium carbonate. The presence of organic matter such as that staining the calcite laminae of the Castile does not seem to be important because similar organic deposits are present in many of the Permian dolomites.

The second geologically important precipitate to be deposited in the Castile sequence was calcium sulphate. It makes very little difference now whether the $CaSO_4$ was deposited as primary gypsum or as anhydrite, or even a mixture of the two. Probably gypsum predominated and the shearing and crumpling so conspicuous in cores and outcrops was developed during dehydration as a result of burial, or by pre-solidification flowage. Once started, precipitation of $CaSO_4$ would continue until it was all out of solution or until the evaporating surface was insulated by a cover of fresh surface waters. The quantity of gypsum precipitated could greatly exceed that of the calcite because the amount in solution per unit of water was greater and the layer of water to be evaporated between the beginning and close of $CaSO_4$ deposition was much thicker. The gypsum, like the calcite, would not be redissolved when once precipitated because the bottom brines were too highly concentrated to hold additional calcium sulphate.

The third geologically important precipitate to form with continued evaporation was sodium chloride salt. Its presence in the column would indicate almost 90 per cent desiccation. The small quantity of brine remaining at this stage would be concentrated in the deepest parts of the depression, and it is here that the deposits of salt would be laid down.

Reëstablishment of inflow would find the level of the water in the basin lower than sea-level. Fresh waters would rush in to fill the void, but because of the differences in gravity there would be little mixing, and the fresher waters would spread rapidly to form a light surface blanket over the entire basin. The thickness would depend, of course, on the brine level. Except in cases of practically complete desiccation, there would be no resolution even of the most soluble precipitates because they would be insulated by a layer of heavy, concentrated brine. With the freshening of the water the processes of evaporation would begin another cycle.

The calcium carbonate precipitated from the surface waters would be mixed with considerable organic material. On consolidation this would produce the brown calcite laminae so typical of the Castile. During the colder season of the year evaporation would be very slow compared with summer losses, and the coolness of the atmosphere would tend to cool the water and increase its power to hold CO_2 in solution. It is, therefore, probable that the calcite laminae each represent the deposits of a summer or portion thereof.

Further evaporation and concentration would cause the precipitation of gypsum. Upon consolidation under pressure the gypsum would be dehydrated to anhydrite. Ordinarily by the time a fraction of an inch of gypsum had been precipitated, there would be a new incursion of the sea and the process would be repeated. This would explain the regular alternation of calcite and anhydrite laminae. An extensive, uninterrupted period of evaporation would result in the formation of a thick anhydrite. The next incursion of the sea would find the surface of the brine a greater distance than normal below sea-level, and the filling of the basin would result in a much thicker layer of new water, most of which must be evaporated before a renewal of gypsum precipitation could take place. Evaporation of the exposed surface waters in the area of the Delaware basin varies from 70 to 110 inches a year at present. It was probably of somewhat the same magnitude in the Permian. A hundred inches of water from the present sea would produce a thin layer of limestone. Two thin laminae without intervening anhydrite, such as are common in the calcite caps over the thick anhydrites, previously mentioned, would thus represent 200 inches or about 18 feet of evaporation. Two hundred thin laminae would require about 1,800 feet of water. Because this figure approaches the original depth of the basin, it is probable that the thicker calcite caps were possible only when renewed incursions delayed the renewal of gypsum precipitation far beyond its normal period. Although the calcite laminae are probably summer deposits, the anhydrites, especially the thicker ones, may have taken years to form, so that the counting of laminae is not a particularly accurate method of measuring the length of the Castile age. The method is further complicated by the introduction of several salt lenses in the section.

Apparently several times during Castile deposition evaporation proceeded so far before refreshing that salt was precipitated, but the amount of salt in the Castile is much smaller than the amount that should be present if normal Permian sea water were evaporated to the stage of salt deposition in a barred basin. There is less salt than anhydrite in the Castile and perhaps even less than there is banded calcite. It is improbable that the Permian ocean was abnormally free from NaCl during Castile time. The ocean should have had much the same concentration as during the preceding Whitehorse and following Salado stages when salt predominated. If the Castile were a thin formation the salt might have remained in solution until deposition ceased and then have escaped to the sea, but it would be impossible for the salt equivalents of 1,800 feet of anhydrite to have remained in solution in a shallowing basin. Therefore, it must be assumed that much of the concentrated brine escaped.

We do not know what or where the barrier was that separated the Castile from the open ocean. If, as has been suggested, the calcite anhydrite banding and the associated development of over-thickened anhydrite with calcite caps were produced by breaching and sealing, an effective barrier must at times have been present to prevent inflow of new sea water. If the breaching were deep enough, the concentrated bottom brines could and would have escaped. Deep breaching, of course, would have required a large amount of refilling before sealing was possible. If the barrier was an organic reef, deep cutting would have been difficult and the rebuilding would probably have required many years. This would have interfered with the regular depositional sequence and no such stratigraphic breaks have been recognized. Another and perhaps more plausible explanation might be that the heavy concentrated brines escaped through a slightly permeable barrier. With limited permeability outflow would occur when the gravity and pressure of the brine in the barred basin was higher than that of the water at the same level outside. Salt-depositing brines have gravities as high as 1.25 or higher against 1.025–1.03 for sea water. A slow outward seeping of heavy brines into the deep Marfa basin and their subsequent escape to the ocean would explain the limited amount of salt in the thick Castile evaporites.

Distribution of the salt lenses indicates that the deepest part of the basin in early Castile time was at the northern or inner end. Later it moved successively southward so that the upper salt lenses occur in the east-central basin area. In addition to being tilted, the basin shallowed so that the later salts are more numerous but thinner and less regular than the earlier ones. The chances of a shallow basin being completely desiccated without being freshened are much greater than those of a deeper one, but the amount of precipitate to be furnished by such a complete drying-up is lessened.

Under ideal conditions the calcite and gypsum laminae might be deposited with uniform thicknesses over the entire basin floor. Actually there seems to be more calcite in the south and west parts and it is completely missing from the higher Castile beds in the northeastern areas. Perhaps the inrushing fresh waters, lighter though they were, crowded the heavy brine downward, outward, and upward ahead of them so that the fresher waters never reached or were very thin at the inner end of the basin. Or it may be that evaporation removed most of the calcium carbonate during the journey of the water from the entrance to the northeast edge of the basin, or a combination of these and other factors may have been responsible. The fact that the brown organic laminae extend beyond the edges of calcite precipitation supports the hypothesis that the calcite was lost while the water was moving but not yet concentrated enough to kill all the floating organisms. At present we can not recognize great concentration of calcite in the Castile that might localize the entrance to the basin, unless it be the apparent thickening of the limestones in the Seven Heart Gap area of the southern Delaware Mountains. This would imply a break in the Capitan reef in the southern Salt Flat area.

The shallowness of the water in most of the post-Capitan seas largely determined the character and distribution of the Salado and Rustler evaporites. This shallow depth, coupled with the great expanse of evaporating area and an almost continuous connection with the sea, assured a steady and relatively rapid flow of water from the mouth to the innermost end of the basin. Because of this movement, during progressive concentration and precipitation, there was little tendency, as in the Castile, for the geologically important evaporites to alternate vertically or to show much lateral mixing. However, contacts between areas of the various types of deposits were not stable, but shifted back and forth as the supply of sea water or the area of the basin varied.

Because of its depth the Castile basin seldom if ever completely dried up. The Salado and Rustler seas, on the other hand, were mostly so shallow that sealing the barrier for a couple of years would have caused disappearance of all except the hygroscopic water. After one of these periods of exposure, inflowing waters would find soluble salts exposed in large areas of the basin. Because of the speed of inflow during the recursion, the waters reaching these areas would be unsaturated and fresh enough to dissolve considerable quantities of the exposed salts. The Upper Permian evaporites all contain minute quantities of fine clastic material such as silt and clay. These fine clastics were probably distributed by the wind. Periods of re-solution would concentrate these insoluble clastics in a thin layer of bottom mud. And since wind action had been going on constantly during the retreat of the sea, these mud beds would frequently be thick enough to form visible silt beds. Ralph King[25] suggests that such beds as the LaHuerta silt of Lang[26] and numerous other silt beds in the Salado salts mark periods of desiccation and resolution. It would not have been necessary for the whole basin to have been dried up but only for those parts in which soluble salts had been deposited. The thicker, coarser Salado sands in the northwestern part of the Delaware basin would also have been distributed by wind action. Advances of the windblown sands would take place during periods of quiescence. The sands would be reworked and buried during periods of active subsidence. As the rate of sinking slowed down, fresh extensions of the sand would occur. The same results would be secured if the sands were deposited by ephemeral desert streams.

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[25] Ralph King, personal communication.

[26] Walter B. Lang, *op. cit.* (1942).

Calcite-banded anhydrites are present in the Salado section of the south-central Delaware basin. They occur in an over-thickened section of middle Salado evaporites and are associated with an exceptionally complete salt section. These two factors together suggest that locally the bottom was sinking more rapidly than normal and that the waters were fairly deep. Heavy salt brines would concentrate in these deeps while the depth, temperature, pressure, or other factors responsible for banded anhydrite would act on the less soluble evaporites.

Theoretically the anhydrite layers in the subsurface should be about two-thirds as thick as the corresponding gypsum layers at the surface. There is, however, no way of checking the hypothesis that hydration of anhydrite in the Ochoa has produced an appreciable increase in volume. There are no continuous exposures showing both massive gypsum and massive anhydrite. Examination of deep anhydrite cores and surface gypsum samples shows laminae of comparable thickness in both facies. General relations in this and other parts of the southern Permian basin suggest that hydration is not accompanied by any great change in volume when it occurs under a heavy cover, as most of it apparently has. Gypsum creep on slopes and the arching of surface beds seem to be due to recrystallization of a much later date. Meier and Griley[27] briefly discussed the problem of hydration in Oklahoma.

ORIGIN OF CASTILES

The distribution and structure of the castiles and their relation to the Castile outcrops suggest that the limestone masses are secondary features. Sink-holes are relatively common in the gypsum area. Probably most of them are located along fractures opened during hydration of the buried anhydrite. Masses of limestone, similar to those of the adjacent castiles, are present in the mouths of some of these sinks. Calcium sulphate is more soluble than calcium carbonate and while the gypsum laminae are being dissolved from the necks of the sink-holes the calcite laminae apparently serve as attachment points for secondary calcium carbonate drawn from surface waters flowing into the sinks. Austin F. Rogers, in a personal communication to Lon D. Cartwright, Jr., remarked that thin sections of the rock from one of these castiles clearly showed the carbonate replacing the gypsum. The brecciated appearance is due to fragments falling from the walls of open passages that were later filled with secondary limestone.

SALT SOLUTION

Solution is effective wherever soluble salts are exposed to the action of unsaturated waters. It is not surprising, therefore, to find that solution has extensively modified the sedimentation, distribution, and structure of the highly soluble Ochoa rocks in the Delaware basin.

The oldest evidence of extensive salt solution in the Ochoa section was noted at the break between Castile and Salado sediments. The stratigraphic sections

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[27] J. Lawrence Meier, "Anhydrite Gypsum Problem of Blaine Formation, Oklahoma," *Bull. Assoc. Petrol. Geol.*, Vol. 18 (1934), pp. 1297–1312. Discussion by H. L. Griley, *ibid.*

show that the upper, or third, group of Castile salts forms a north-south ridge along the center of the salt basin. These salt beds terminate abruptly at the edge of a trough filled with an over-thickened section of Salado salts and anhydrite. The trough was formed when pre-Salado solution exposed and removed the thinly buried edges of the uppermost Castile salts.

Between the close of Salado and the beginning of Rustler deposition, the west edge of the Delaware basin was uplifted and truncated. This erosion left a series of parallel solution valleys, where the salt members had cropped out, separated by gypsum ridges. The irregular topography was covered and preserved by the Rustler sediments. Closely spaced core holes in the potash areas south and east of Carlsbad show these trenches. They are filled with irregular basal Rustler beds that are not present elsewhere in the basin. No great solution troughs were developed at this time, however, probably because of the thinness of the salt beds available for solution.

The next great period of solution began in the Triassic. Salado salts were removed along the east edge of the Delaware basin from the Pecos River northward into New Mexico. The solution trough developed at this time is 800 or 900 feet deep and is filled by an over-thickened section of Triassic. Early subsurface geologists, working with scattered wells and impressed by the differences in structural elevation between the Delaware Mountain sandstone and the top of the "Big lime" behind the Capitan reef, assumed that the displacement was due to a major fault downthrown on the west, and that the salt was cut out by this fault. Later field and subsurface work proved that the structural difference in the underlying Guadalupian beds was depositional and that the faulting in the Rustler was due to the removal of salt by solution. This slump faulting is diagrammatically shown on the west-east cross sections. It is probable that slight warping along the Capitan reef, at the close of the Paleozoic, fractured the overlying cover and opened channels for circulating ground waters. Preliminary warping is assumed because in the quiescent areas, near the center of the Delaware basin, salt was not dissolved even where all the Dewey Lake and the upper part of the Rustler had been stripped off. It is easy to date the trough as Triassic because any trough must be older than the over-thickened sediments that fill it and younger than the youngest sediments in which it occurs.

Pre-Cretaceous salt solution such as characterizes the Yates field[28] and Fort Stockton "high" areas has left no trace in the Delaware basin. The thick sections of Lower Cretaceous encountered in wells near the south end of the basin are beyond the original limits of the main salt section and are probably due to the filling-in of fault troughs or erosional depressions.

The main period of Delaware basin solution took place during the Tertiary. Solution appears to be limited to areas from which the Cretaceous cover had been removed. The main solution trough is roughly bordered on the east by the Pecos

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[28] John Emery Adams, "Structural Development, Yates Area, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol 24 (1940), pp. 134–42.

River, and extends from Carlsbad, New Mexico, to Toyah Lake in Texas. Significantly, this is the area with the most pronounced development of porous Salado sandstones which probably acted as conduits for circulating waters. The isolated remnants of Salado salt, west of the Pecos River in northern Reeves County, would not be present if solution had simply started at the western outcrops and moved eastward. Areas of non-solution, such as those at Barstow and Mentone, seem to form buttresses that control the present course of the Pecos River.

Maximum depth of the synclinal solution trough is not known but southwest of Mentone it exceeds 1,300 feet. Much of the solution developing such a deep trough must have taken place below the level of the spillway over which the saturated waters escaped across the Edwards Plateau toward the southeast. This would imply that the sinking trough was filled with sediments as rapidly as it formed, and that solution occurred in a sealed hydrostatic system. If a deep lake had developed in the open valley behind the spillway and solution had depended on surface drainage, an insulating layer of brine would have accumulated in the deeper basins, next to the dissolving face of the salt. Incoming fresh waters would have flowed across the surface of the heavy brine layers without flushing them out and further solution would have been checked. With circulation maintained through the porous sands in the Salado section, which cropped out high on the Front Range at the northwest, and with the valleys continually filled with shales and sands from the Cretaceous highlands on the west, solution could continue as long as there was a sufficient head of water to force the brines up over the south rim. Probably the process is still in progress.

The most recent solution valley is the one now developing in the Nash Draw southeast of Carlsbad. Here solution is taking place along the unconformity at the base of the Rustler formation. Nash Draw itself appears to be an unfilled solution valley.[29] The great increase of salt in solution in the Pecos River water from the point where it starts across the Permian evaporites to the point where it flows out onto the Cretaceous is evidence of present rapid solution.[30]

Geologists unfamiliar with Upper Permian stratigraphy have suggested that the features described as solution troughs might be due to salt flowage. We have sufficient data to disprove this hypothesis. The basin-wide uniformity of salt and anhydrite strata of the Salado and of dolomites and anhydrites in the Rustler would be highly disrupted if the ridges and valleys were due to salt flowage. Instead they extend up to the very edges of the solution valleys without any break in uniformity.

HYDRATION AND SOLUTION OF CALCIUM SULPHATE

The calcium sulphate of the Ochoa series is represented by gypsum on the outcrops and in the subsurface to a depth of about 500 feet. Below this depth the gypsum is replaced by anhydrite. It is probable that the temperature of the brine from which the Ochoa evaporites were deposited was such that part of the calcium sulphate was originally deposited as gypsum. By applying the foregoing observations, it seems probable that by the time the original deposit had been buried to a depth of about 500 feet, the pressure became great enough to dehydrate the gypsum to anhydrite. Settling due to loss of volume by this change would be uniform over the entire basin. All the beds of the Ochoa series were buried deeply enough by post-Permian deposits to insure dehydration of the entire section. The gypsums now present at or near the surface have been hydrated since the removal of this load. Hydration took place irregularly with both lateral and vertical adjustments. A certain amount of solution accompanied the hydration and, as a result, numerous domes and solution synclines were developed. Some of these structures were tested for oil during the early development of the area, but all showed normal regional dip in the unhydrated, deeper beds. The hydration structures are more numerous than those produced by salt solution, but are smaller and less pronounced.

ECONOMIC IMPORTANCE

Economically the potash deposits of the upper Salado halite are the most important features of the Ochoa series. Rock salt, petroleum, and brine chemicals have also been produced. The outcrops are marked by a very inferior type of soil even for an arid area of low productivity. Perhaps to the petroleum geologist the Ochoa rocks of the Delaware basin, or even of the whole Permian basin, are most important as an effective mask for the structure of the underlying beds.

CONCLUSION

The purpose of the writer has been to describe the rocks of the Ochoa series as they occur in and adjacent to the Delaware basin. Discussions of origin and post-depositional history are largely theoretical and incidental. They were included to show that the evaporites that we now find could have been formed by specialized, natural processes from sea water differing in no important way from that of the present ocean.

No special attempt has been made to justify setting up the practically non-fossiliferous Ochoa as a Permian series equal in rank with the three older series of Permian rocks. Here we find a great mass of evaporites, greater in thickness and equal to, or greater in volume than, the evaporite equivalents of any of the three older Permian series, and we assume the presence of a fourth series of fossiliferous rocks somewhere, even though we can not exactly locate it; we name what we have, because a name is necessary, and leave the rest to the future.

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[29] Thomas W. Robinson, "General Relations of the Geology to the Occurrence of Brine at the Base of the Rustler Formation," *New Mexico State Engineer 12th and 13th Bien. Rept.* (1934–1938), pp. 86–93.

[30] W. D. Collins and H. B. Riffenburg, "Quality of Water of Pecos River in Texas," *U. S. Geol. Survey Water-Supply Paper 596* (1927), pp. 67–88.