GEOLOGY OF A PART OF WESTERN TEXAS AND SOUTHEASTERN NEW MEXICO, WITH SPECIAL REFERENCE TO SALT AND POTASH

By H. W. Hoots

PREFACE

By J. A. Udden[1]

It is with great pleasure that I accept the invitation of the Director of the Geological Survey, Dr. George Otis Smith, to write a brief foreword to this report on the progress of a search for potash in which both the United States Geological Survey and the Texas Bureau of Economic Geology have cooperated for a number of years. It is a search which now appears not to have been in vain.

The thought that potash must have been precipitated in the seas in which the salt beds of the Permian accumulated in America has, I presume, been in the minds of all geologists interested in the study of the Permian "Red Beds." The great extent and great thickness of these salt beds early seemed to me a sufficient reason for looking for potash in connection with any explorations of these beds in Texas. On learning, through Mr. W. E. Wrather, in 1911, of the deep boring made by the S. M. Swenson estate at Spur, in Dickens County, I made arrangements, through the generous aid of Mr. C. A. Jones, in charge of the local Swenson interests, to procure specimens of the materials penetrated. It was likewise possible, later on, to obtain a series of 14 water samples from this boring, taken at depths ranging from 800 to 3,000 feet below the surface. These samples were obtained at a time when the water had been standing undisturbed in the hole for two months, while no drilling had been done. At that time the hole was open below the depth of 1,350 feet. On analysis of the soluble solids from these samples, it appeared that two samples taken at 2,200 feet below the surface had a decidedly greater amount of potash than any of the other samples, either above or below. This suggested the presence of potash in some layer at or near that depth. To verify this suggestion if possible, tests were made for potash in 28 samples of cuttings taken at depths between

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732 and 3,294 feet. Not a trace of potash could be found in more than two samples of these cuttings. The cuttings at 2,047 feet showed traces of potash, and those at 2,110 feet showed a pronounced trace. This result strengthened the belief that potash existed in the walls of the hole somewhere near the depth of 2,200 feet in greater amount than at other depths, and that there might be at or near this depth one or more potash-bearing strata.

Not long after the publication of a bulletin[2] in which these facts were presented samples of a red saltlike mineral were received from some other borings in the same region, and some of these samples were found to contain 14 per cent of potassium, calculated as chloride. In the winter of 1911 and 1912 I learned that deep borings had recently been made in the vicinity of Amarillo, where heavy salt beds had been penetrated. These localities were visited, and large samples of salt were collected from the dump and closely examined in the laboratory of the bureau. In a couple of hundred pounds of salt a number of small red particles were found, making perhaps as much as 2 or 3 grams in weight. Analysis of these red grains showed the presence of 6.14 to 9.23 per cent of potash calculated as potassium oxide (K_2O). The depths from which these samples had come could not be accurately ascertained. The red potash-bearing mineral was observed in samples from three different wells. Though the red mineral could not be identified, it evidently represented some potash-bearing salt, segregated from the common salt in the ground. This conclusion seemed to make it almost certain that a potash-bearing mineral existed in association with the heavy salt beds penetrated by these borings, most likely as a separate layer. The results appeared to me so important that a special bulletin entitled "Potash in the Texas Permian"[2a] was prepared, giving data on the borings and on the subsurface geology of the region and calling attention to the existence in the Panhandle and in the Llano Estacado of a basin of great extent in which the Permian salt beds had been deposited. This may be said to have ended the first stage in the search for potash in Texas.

Recognizing the importance of a possible discovery of potash, the United States Geological Survey in the winter of 1915–16 began a test boring to explore the possible potash-bearing beds at Cliffside. This boring, which was discontinued in 1917, brought to light some pieces of red salt in quantities large enough for analysis and for obtaining a better knowledge of its nature. These pieces, however, proved to be red halite and red anhydrite and not a potash-bearing mineral. This boring was made with a standard rig and did not

[2] Udden, J. A., The deep boring at Spur: Texas Univ. Bull. 363, pp. 82–87, 1914.
[2a] Udden, J. A., Texas Univ. Bull. 17, 1915.

go through the salt beds. It proved a disappointment, for only traces of potash were found in the analysis of its salts.

In 1918 several persons had become interested in making deep tests for oil in the Panhandle and in the Llano Estacado. At the suggestion of David White a cooperative arrangement was then made between the Bureau of Economic Geology of Texas and the United States Geological Survey for further pursuit of this search for potash. O. C. Wheeler was jointly engaged by the two organizations to visit the several oil prospects in the Panhandle and in Oklahoma for the purpose of procuring samples of salt and other cuttings brought to light in the prospecting. Mr. Wheeler collected a large amount of information and many samples, but no samples containing potash. He left the work in the summer of 1920, and D. D. Christner was engaged to continue the search. About this time several deep tests for oil were begun in the Llano Estacado, farther south. In February, 1921, Mr. Christner found potash in the Bryant well, in Midland County. Then followed the discovery of rich potash salts in the A. Pitts Oil Co.'s River well, in Ward County; the Burns well, in Dawson County; the Means well, in Loving County; the Long (G. A. Jones) well, in Borden County; and the McDowell well, southwest of Big Spring. Drill cuttings from these wells yielded pieces of red salt that proved to be polyhalite, one of the well-recognized potash-bearing minerals of Germany. These discoveries made it certain that potash exists in this region in distinct beds representing conditions of extreme desiccation in the Permian. They left no doubt in the minds of those interested that at some point in this region commercially important quantities of potash had been deposited somewhere in association with the extensive salt deposits, which were then known to extend over a region several hundred miles in length and at least 200 miles in width. It was with great regret that the Bureau of Economic Geology found itself compelled at this point to withdraw from the work on account of lack of funds. Mr. Christner discontinued work for the bureau in September, 1921, but he was retained by the United States Geological Survey until November 26, 1921. Since that time the work has been in the hands of the author of the present paper, H. W. Hoots, and his successor, W. B. Lang.

I shall always be glad to remember that when the bureau could no longer continue its cooperation in the search for potash the work was taken over by the United States Geological Survey and carried through to what promises to be a successful termination. I wish to congratulate Mr. Hoots on having prepared so able and exhaustive a report on the investigation. Congratulations are also due to the United States Geological Survey for having procured information recently on the existence of layers of potash in this region that has warranted the announcement that "the United States has here potash reserves of probable commercial value within practical reach from the surface."

The next stage in this search will, no doubt, be exploration by core drilling, or even the sinking of shafts, to determine the size of the deposits that have already been located.

INTRODUCTION

BASIS OF REPORT

The United States Geological Survey, in cooperation with the Texas Bureau of Economic Geology and Technology, has for several years maintained a field observer in some part of western Texas to collect and test samples for potash. Samples of cuttings and brines from wells encountering rock salt in central Kansas, western Oklahoma, southeastern New Mexico, and western and northwestern Texas have been tested by the field observer and later analyzed in the chemical laboratory of the Geological Survey at Washington. The result is that the area lying at the south end of the Llano Estacado of western Texas and including a part of southeastern New Mexico has proved to be the most promising territory in this part of the country for possible deposits of potash in commercial quantities.

While engaged in collecting and testing samples of cuttings and brines from wells being drilled in this area between October, 1921, and September, 1922, the writer studied the geology revealed by surface exposures and by records of wells drilled principally for oil. It is hoped that the results obtained may prove useful to operators who may in the future wish to explore for potash and to geologists who may wish to do more detailed work within the area.

The geologic map (Pl. X) was made by strictly reconnaissance methods and does not portray in detail the geology of any part of the area. It is, however, more accurate than the more general maps previously published.

LOCATION AND EXTENT OF AREA

The area under discussion is in western Texas and southeastern New Mexico and includes the southern portion of the Llano Estacado, the northern edge of the Edwards Plateau, the upper Colorado River valley, and the central Pecos River valley. It lies in latitude 30° 30′ to 32° 58′ north and longitude 100° 37′ to 104° 15′ west. The area covers approximately 25,000 square miles and is roughly rectangular in outline. It includes Scurry, Borden, Dawson, Gaines, Andrews, Martin, Howard, Mitchell, Sterling, Glasscock, Midland, Ector, Winkler, Loving, Ward, Crane, Upton, and Reagan counties and the northeast half of Pecos and Reeves counties in Texas and the south half of Lea County and the southeast quarter of Eddy County in New Mexico.

In the preparation of the structure-contour map (Pl. XVII), the map showing distribution and thickness of salt beds (Pl. III), and two of the subsurface cross sections the records of a number of wells drilled north of this area have also been used.

ACKNOWLEDGMENTS

The cooperation and assistance given by employees and officials of operating companies have made this work possible. Those to be especially mentioned are the Pinal Dome Corporation, of Santa Maria, Calif.; the Arthur Pitts Oil Co., Ramsey Oil Co., and Ira J. Bell Co., of Pecos, Tex.; the General Oil Co., of Houston Tex.; the Texon Oil & Land Co., of New York; the Farmers Oil Co., of Lancaster, Pa.; and the La Mesa Oil Co., of La Mesa, Tex. Individuals to whom credit for similar cooperation is due are Mr. E. J. Anderson, of Snyder, Tex., and Dr. A. C. Traweek, of Matador, Tex. It is desired also to express appreciation of the cooperation of companies and individuals drilling wells in the northern Panhandle of Texas from which samples were collected by field men other than the writer.

Mention is gratefully made of the hospitality and unstinted assistance given by citizens of Odessa and Midland and inhabitants of the surrounding country.

For information and data concerning the general geology of the region the writer is especially indebted to his predecessor, Mr. Drue D. Christner, of Austin, Tex., who also collected most of the potash samples; to Mr. Floyd C. Dodson, of the Texas Consulting Co., of Fort Worth; and to Dr. J. W. Beede and Dr. J. A. Udden, of the Texas Bureau of Economic Geology and Technology. Dr. Charles N. Gould, of Oklahoma City, Okla., and Mr. Wallace E. Pratt, of Houston, Tex., have contributed information concerning the geologic structure of the Amarillo country.

The writer wishes to acknowledge the many valuable criticisms and suggestions he has received from members of the United States Geological Survey, and from members of the Department of Geology at the University of Kansas. The unsparing counsel of Dr. R. S. Knappen, of this department, has been invaluable in the preparation of this paper.

Acknowledgment is also made of previously published data herein reproduced. Mr. G. R. Mansfield, of the United States Geological Survey, has kindly permitted the use of his diagram showing the percentages of potash, the depths at which notable amounts were found, and the character of material penetrated by several wells in

western Texas. This diagram appears as Plate IV. Mr. George Steiger, also of the Geological Survey, has generously permitted the reproduction of his paper "Some field tests and an assay of Texas potash salts" in this report. (See pp. 51–54.)

RESULTS OF INVESTIGATION

The rocks exposed at the surface in this region range in age from upper Permian to Recent. A study of the records of 80 wells drilled in the region has revealed the character and general stratigraphic relations of still older strata belonging to the lower Permian and upper Pennsylvanian. Deposits of rock salt, anhydrite, and red beds, the aggregate thicknesss of which ranges from 2,000 to 5,000 feet, make up the greater part of the Double Mountain formation and, in some areas, the Clear Fork formation. These are the upper formations of the Permian of north-central Texas.

The beds of rock salt in this region, whose known aggregate thickness ranges from a few feet in the longitude of eastern Mitchell and Scurry counties, Tex., to 1,391 feet near the southeast corner of New Mexico, contain probably more than 50,000 billion tons of salt. These beds have been described by Darton,[3] who gives a lower estimate. The figure here given assumes an average salt thickness of 400 feet over a large area in eastern New Mexico and adjoining parts of western Texas in which there is nearly a complete lack of subsurface data. However, the estimate seems justified in view of the existence of thick salt beds to the north, east, south, and southwest of this area and their probable continuity with appreciable thickening beneath the area. Salt is not being mined in these States at present, and although there is here practically an unlimited supply, it is improbable, for the reasons stated on page 43, that either Texas or New Mexico will become an important salt-producing State in the near future.

Interbedded with the thick salt strata are thinner layers containing considerable amounts of potash in the form of the mineral polyhalite. Although the potash of these beds is of high quality and is comparable to much of the potash imported from Germany and France, it has not yet been definitely proved that the quantity present in any part of this region is sufficient for commercial exploitation. However, only a small amount of subsurface investigation has been carried on. This investigation, although largely haphazard, unorganized, and carried on principally by examination of samples from wells drilled for oil by operators who had little more than a casual interest in the possibilities of potash, has given surprising results. There are seven wells[4]

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[3] Darton, N. H., Permian salt deposits of the south-central United States: U. S. Geol. Survey Bull. 715, pp. 205–223, 1921.

[4] Other potash-bearing wells have been drilled since this report was written. See U. S. Geol. Survey Mineral Resources, 1923, pt. 2, pp. 178–185, 1925.

near the south end of the Llano Estacado in which high percentages of potash have been found, and it is noteworthy that these are the only wells in an area of 20,000 square miles which have been drilled deep enough to encounter appreciable amounts of salt and from which samples have been collected and analyzed. This area lies in longitude 101° 10′ to 104° and latitude 31° to 33° and includes all but the east and west edges of the region under discussion. There is also a large area to the north, embracing the northern part of the Llano Estacado and the Panhandle, which has potash possibilities. In view of these developments and the vastness of the region, the southern portion of which is especially promising, the outlook is most encouraging. It is of special interest that all samples containing notable amounts of potash have come from beds at depths of less than 2,350 feet. So far as depth is concerned all such beds are minable.

Field investigations should continue without delay and should be carried on by competent organizations. Such organizations should follow systematic plans of operation which, when completed, will have thoroughly tested the region. Because of the probable irregular distribution of the potash deposits, success will probably be attained only after the drilling of a number of test wells. It is imperative that core drills be used for all tests.

If potash in commercial quantities is found, it is likely that the area containing the greatest thickness of salt will prove to be the most productive. Additional suggestions to operators are given on pages 50–51.

No samples of cuttings have been found to contain any of the more soluble potash salts, such as sylvite,[4a] which were deposited under similar conditions and at about the same time in the Stassfurt region of Germany. These salts are, however, to be confidently expected in samples from future wells that thoroughly test the salt and potash bearing strata.

In addition to a discussion of the lithologic characteristics and probable stratigraphic relations and time equivalents of the salt and potash bearing strata, this paper contains sections and descriptions of overlying surface rocks that are exposed in the region, though only the Permian, Triassic, and Comanche rocks have received much consideration.

The general subsurface structure of the region has been determined and illustrated by the use of the records of deep wells drilled principally for oil. These wells are listed on pages 116–118. Logs of some of them are shown graphically in Plates XI–XVI. This study supports the current belief that the High Plains of western Texas and eastern New Mexico are underlain by a large geosyncline trending in a general north-south direction. That the outline of this

[4a] See footnote, p. 45, for mention of samples tested which contain sylvite.

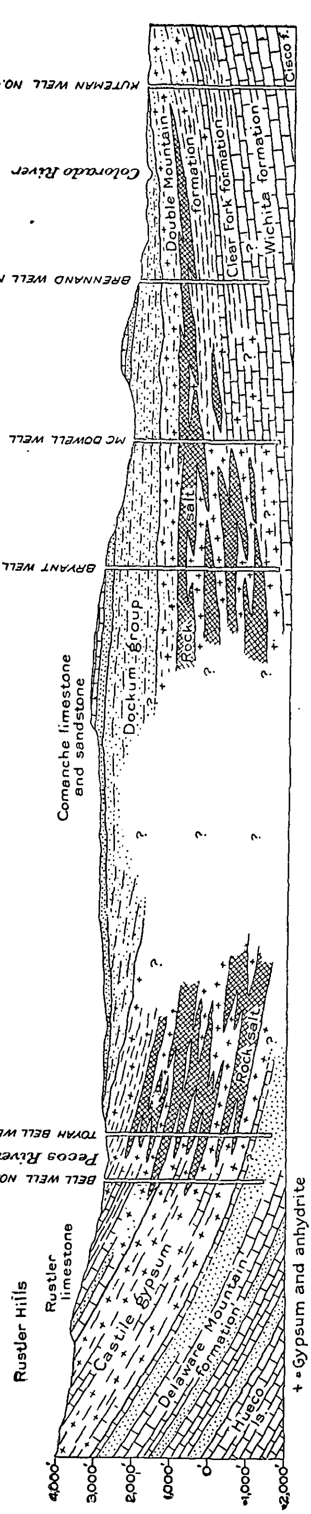


FIGURE 3.—Cross section through the salt-anhydrite series from the trans-Pecos region eastward to Nolan County, Tex., showing possible stratigraphic relations of the salt beds. The Castile gypsum is believed by Darton to overlap westward upon the Capitan limestone. Correlations of Permian formations to the west with those to the east, in northcentral Texas, have not been established.

major structural basin is not without irregularity is suggested by the contouring of several smaller anticlinal and synclinal folds. Doubtless other minor structural features exist, but owing to the lack of adequate subsurface data their location and magnitude can not be determined.

An attempt has also been made to present briefly the physical conditions that directly preceded, attended, and followed the epoch of salt and potash deposition.

THE SALT BEDS

AGE

The salt beds of Texas, so far as known, are all of middle and upper Permian age. (See fig. 3.) The oldest are believed to be contained in the Clear Fork formation, the middle formation of the Permian of north-central Texas, and are present in notable quantities only in former basins which, during Clear Fork time, occupied areas of restricted circulation, in general far out from shore. These areas lie in the latitude and longitude of Midland, Ector, Winkler, and Loving counties and probably extend some distance to the north and south. By far the greater part of the salt beds are younger than Clear Fork and belong to the Double Mountain formation, also Permian. Indeed, it is not impossible that all of the major salt series belongs to the Double Mountain and to the contemporaneous Blaine formation, which is known only in Oklahoma and the eastern Panhandle of Texas but probably occurs also beneath the Mesozoic and Cenozoic cover farther south and west, near the center of the western Texas geosyncline. In Double Mountain time conditions favoring salt deposition apparently were extended shoreward, with the result that the salt beds of this age are more widespread, occurring throughout the region bounded approximately by Pecos River on the west, the latitude of northern Terrell County on the south, and the east side of Mitchell and Scurry counties on the east and extending into the Panhandle and western Oklahoma on the north. (See Pl. III.)

Darton[5] has classified the salt of eastern New Mexico as belonging to the Manzano group. This group is regarded by Beede as at least in part equivalent to the Wichita formation (early Permian) and possibly in part older than the Wichita.

The salt beds of the Panhandle and western Oklahoma may be somewhat older than those farther south, for the commercially important salt beds still farther north in Kansas are found in the Wellington formation,[6] which Beede[7] has tentatively correlated as approximately equivalent to a part of the Wichita of north-central Texas. This would make the salt beds of Kansas considerably older than those of western Texas. The stratigraphic relations of the salt beds of Kansas, Oklahoma, and Texas are not definitely known. The difference in the age of these beds may be due to final evaporation in two separate basins at different times, or, if marine conditions were continuous from Kansas to Texas, to the deposition of salt first near the northeast or landward extremity of the shallow sea and progressively later southwestward. The salt beds near the southeast corner of New Mexico would then be youngest of all and would represent the last salt deposited from Permian desiccation.

EXTENT

Salt deposits underlie an area of approximately 70,000 square miles in Texas and New Mexico. This area has an average length of 360 miles from north to south and an average width of 275 miles from east to west. The map (Pl. III) portrays fairly definitely the extent of these deposits to the east, south, and west and shows by appropriate numbers the location of the wells to which reference is made in the text.

[5] Darton, N. H., Permian salt deposits of the south-central United States: U. S. Geol. Survey Bull. 715, p. 206, 1921.

[6] Moore, R. C., unpublished report on the salt beds of Kansas, also previous publications.

[7] Beede, J. W., Notes on the geology and oil possibilities of the northern Diablo Plateau in Texas: Texas Univ. Bull. 1852, p. 31, 1920.

THICKNESS

The greatest known aggregate thickness of salt in this area of salt deposition is 1,391 feet, found in the Means well (No. 37, Pl. XVI), in northeastern Loving County. This is not an extraordinary thickness for this area, as two other wells not far distant—the Toyah-Bell well (No. 38, Pl. XI), in southern Loving County, and the River well (No. 67, Pl. XVI), in southern Ward County—encountered 1,025 and 1,130 feet of salt, respectively. On Plate III are recorded the exact thicknesses of salt penetrated by wells throughout the region. The thickness of salt in the broad, unexplored belt along the north-south boundary between Texas and New Mexico is unknown, but probably in much of this belt, especially in the southern part, it exceeds 1,000 feet. The salt beds thin out gradually toward the east and abruptly toward the west. Recorded thicknesses in Scurry, Mitchell, and Sterling counties are generally less than 100 feet. It is probable that salt does not occur more than a few miles east of Scurry and Mitchell counties.

Although the thickness of salt strata decreases very abruptly toward the west along Pecos River, it is apparent from the examination of cuttings from wells at critical points that there is little change in the thickness of the series of strata deposited solely by chemical precipitation. The logs of wells to the west that record little or no salt show a corresponding increase in the amount of anhydrite. It is believed that the rapid change is due, then, not to a fault that trends roughly parallel to Pecos River, as has been suggested, but to a difference in the degree of salinity of the waters east and west of the present location of Pecos River at the time the salt and anhydrite were deposited. The probable stratigraphic relations of the salt and anhydrite of the Pecos Valley with the limestone formations exposed in the mountains of trans-Pecos Texas are shown in Figure 3. The condition to which was due the deposition of more than 1,000 feet of salt in one area and practically no salt 8 miles to the west was certainly unusual, but it indicates the maintenance, through a long period, of a remarkable balance between the more saline and less saline areas of the Permian waters of the region.

TONNAGE AND ECONOMIC VALUE

It is impossible to figure the quantity of salt present in this region with any degree of accuracy. On the reasonable assumption that the average thickness throughout the salt area of 70,000 square miles in Texas and New Mexico is 400 feet, there is about 50,000 billion tons of salt in these two States alone. Darton, employing different assumptions, has estimated the salt in the entire region of the South Central States, including Kansas and Oklahoma, at about 30,000 billion tons.

The salt from salt lakes was used by the Indians and early settlers and is still used locally for stock. In recent years salt has been mined by two plants near Colorado City, Mitchell County, Tex., from a depth of about 750 feet. So far as the writer is aware, this is the only record of commercial mining of Permian salt in the entire region.

With a total of 50,000 billion tons in Texas and New Mexico alone, it is evident that there is here a supply of salt which may, in time, prove of considerable economic importance. However, should salt prove to be the only minable product it is not probable that these States will in the near future become important producers of salt, for salt production in Michigan, New York, Ohio, and Kansas, where there is also an unlimited supply, has gained considerable headway. Once established in Texas and New Mexico, salt production will be profitable, for the semiarid climate is suitable to the use of the solar system of evaporating and refining. In a number of places in this region salt can be reached at a depth of 700 to 800 feet, and practically everywhere in the region it is within 1,500 feet of the surface.

POTASH

STIMULUS FOR THE SEARCH

The knowledge that an immense deposit of salt, formed from the desiccation of an old sea, exists in south-central United States, and that this deposit is geologically similar, both in age and in stratigraphy, to the famous salt and potash deposits of Germany, led geologists of both the United States Geological Survey and the Texas Bureau of Economic Geology and Technology to believe that potash of commercial quality and thickness might ultimately be found somewhere in this vast region. It certainly does not seem reasonable to assume that, with arid conditions suitable for the deposition of great thicknesses of salt prevalent over so extensive a region during Permian time, there was no place in all this region where evaporation continued to the point at which the more soluble potash salts were precipitated. Accordingly, investigations were begun which, after the first discovery of potash in 1912, assumed more definite character.

A few years later the United States Geological Survey and the Texas Bureau of Economic Geology and Technology began a cooperative search for potash. As the funds available have not been large, this search has not been as extensive and systematic as would be desirable, but potash of notable richness has been found in widely separated localities throughout the plains region of western Texas.

The discoveries prior to 1915 were made public by Udden.[8] Five press notices, issued by the United States Geological Survey, the first of which appeared June 7, 1921, have supplied information concerning more recent discoveries and the general potash situation in this region. More detailed discussions of the subject have appeared in papers by White,[9] Steiger,[10] and Mansfield.[11]

EARLIER DISCOVERIES OF NOTABLE AMOUNTS OF POTASH

To Dr. J. A. Udden belongs the credit for the first discovery of potash in western Texas. In 1912, in brine from the deep well drilled by Swenson & Sons near Spur, Dickens County (No. 13, Pl. III, and also Pl. XV), Udden found 5.4 per cent of potassium calculated as cloride. The brine had been standing undisturbed in the well for two months and was taken from a depth of about 2,200 feet.

Some crystals of red salt from a depth between 875 and 925 feet in a well drilled in 1915 at Boden, in western Potter County (No. 56C), contained 9.2 per cent of potash (K_2O). In the same year red salt taken from a depth between 1,500 and 1,700 feet in the Miller well, in western Randall County (No. 56E), yielded 6.1 per cent of K_2O and some colorless salt particles from a depth greater than 1,700 feet assayed 10.5 per cent of K_2O.

In view of these earlier findings and the fact that the potash supply of the world was then controlled by warring European countries, the United States Geological Survey drilled a test boring for potash, beginning in the winter of 1915–16, at Cliffside, 6 miles northwest of Amarillo, Potter County (No. 56B). The drilling was discontinued in 1917, at a depth of 1,703 feet. No significant amounts of potash were found in the entire thickness of salt beds penetrated, approximately 460 feet. It seemed probable, however, that had funds been available to continue drilling, salt would have been encountered for several hundred feet additional.

LATER DISCOVERIES FROM WILDCATTING

Since 1917 an observer has been maintained in the field to cooperate with drillers throughout western Texas and eastern New Mexico and to obtain samples of both cuttings and brines for analysis. Since 1920 potash in the form of the mineral polyhalite ($MgSO_4 . K_2SO_4 . 2CaSO_4 . 2H_2O$) has been found in cuttings from a number of wells in western Texas. These wells are widely scattered in an area

[8] Udden, J. A., The deep boring at Spur: Texas Univ. Bull. 363, 1914; On the discovery of potash in west Texas: Chem. and Met. Eng., vol. 25, pp. 1179–1180, 1921; Potash in the Texas Permian: Texas Univ. Bull. 17, 1915.

[9] White, David, Potash reserves in west Texas: Mining and Metallurgy, April, 1922.

[10] Steiger, George, Potash salts of western Texas: Chem. and Met. Eng., vol. 26, p. 175, 1922.

[11] Mansfield, G. R., The potash field in western Texas: Ind. and Eng. Chemistry, vol. 15, p. 494, 1923.

measuring approximately 130 miles from east to west and 110 miles from north to south.[11a]

The information from three of these wells was obtained from only a few individual cuttings, no continuous records being available. Thus, a single sample from a depth between 2,405 and 2,411 feet in the Bryant well, drilled by the States Oil Corporation in Midland County (No. 40, Pls. III and XI), was found to contain 8.94 per cent of K_2O in the soluble salts. A sample taken from a depth of 1,780 feet in the Burns well, drilled by the LaMesa Oil Co. in eastern Dawson County (No. 12A, Pls. XIII and XIV), was found to contain 11.95 per cent of K_2O, or 21.10 per cent in the soluble salts. Selected samples from cuttings taken from different depths in the Jones well, in eastern Borden County (No. 3), contained the following percentages of K_2O in the soluble salts: Depth 1,070–1,075 feet, 22.9 per cent; 1,075–1,083 feet, 17.68 per cent; 1,115 feet, 6.59 per cent. Other samples have been collected from this well to a depth of about 2,000 feet, but none have been found to contain significant percentages of K_2O.

From four wells more continuous records are available. They are the River well, drilled by the Arthur Pitts Oil Co. in southern Ward County (No. 67, Pl. XVI); the McDowell No. 4 well, drilled by the General Oil Co. in northern Glasscock County (No. 29, Pl. XI); the Means well, drilled by the Pinal Dome Corporation in northeastern Loving County (No. 37, Pl. XVI); and the St. Rita well, drilled by the Texon Oil & Land Co. in southwestern Reagan County (No. 57, Pl. III). The Means well has afforded the most detailed record of the salt beds, for samples were taken by the drillers at intervals of 5 to 10 feet. Plate IV, prepared by Mansfield, represents the records of these and other wells. The percentages of K_2O in the samples analyzed and in the soluble salts are shown opposite drillers' logs.

INTERPRETATION OF SAMPLES AND OF THEIR ANALYSES

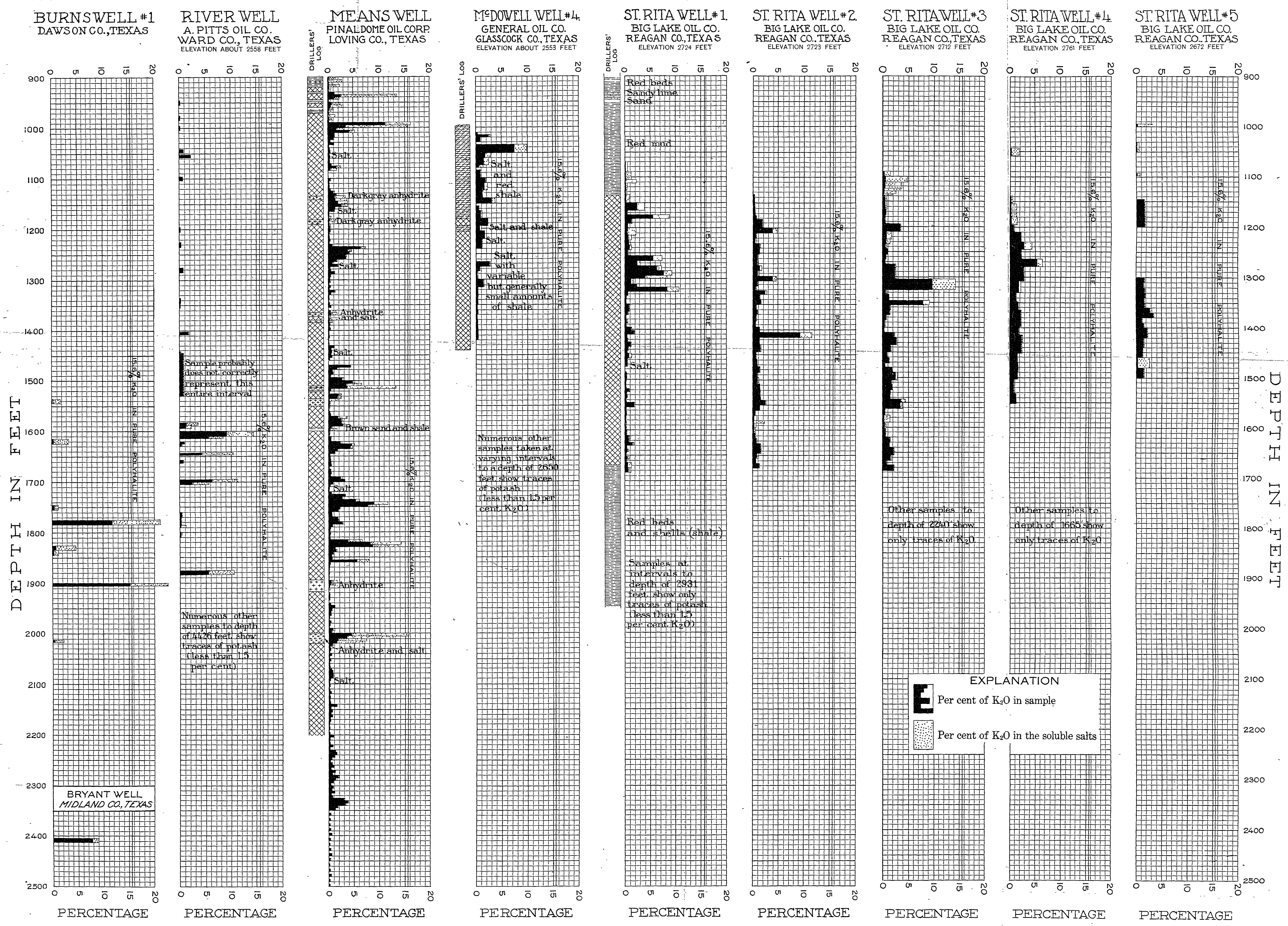
It should be emphasized that all samples found to contain potash were collected from wells drilled principally for oil, not for potash. All these wells except the Burns, which was drilled by rotary tools using a core barrel, were drilled with cable tools. All samples, except the single one from the Burns well, which represents a portion of a core, were obtained by bailing the cuttings from the well after drilling rock thicknesses ranging from 5 to 35 feet. From some of the wells complete sets of samples were saved; from others only occasional or even single samples were obtained.

[11a] In November, 1925, samples of cuttings from the McNutt No. 1 well, in sec. 4, T. 21 S., R. 30 E., 15 miles northeast of Carlsbad, N. Mex., were examined by R. K. Bailey, of the Geological Survey, and were found to contain notable amounts of sylvite (KCl), a new potash mineral for salt beds of the United States, besides considerable polyhalite.

It is evident that satisfactory information concerning the ricnness of the potash and the thickness of the individual potash-bearing layers can not be obtained from samples from wells drilled by cable or "standard" tools. Because speed is desired in the drilling of oil wells, it is customary with these tools to drill 6 feet, or in soft formations such as salt 10 or 15 feet, before pulling out the drill and running the bailer for a sample of the cuttings. The recognition of individual beds, especially thinner beds carrying potash, from samples obtained in this way is not possible, because the material is thoroughly mixed and represents the entire column drilled since the last bailing. For example, a sample representing the interval from 1,025 to 1,040 feet and testing 8 per cent of K_2O may come from a 15-foot bed all of which contains 8 per cent of K_2O or only a small portion of this interval may contain as much as 8 per cent of potash; or, again, the 15-foot interval may be composed entirely of potash-bearing material of which some is of poor grade but other portions are nearly pure polyhalite.

The dissolving effect of the drill water on these easily soluble salts and the possibility of caving from overlying beds must be taken into account, as either may cause enrichment or impoverishment of the sample. As polyhalite, the only potash mineral known to exist in western Texas, is somewhat less soluble than common salt, enrichment of the sample by solution appears to be more likely than impoverishment. However, as practically all the samples collected have been churned in the drill water for an average time of about two hours before being bailed from the well, it is not impossible that solution has impoverished the cuttings by removing all trace of extremely soluble salts, such as sylvite (KCl).

The results of chemical analyses shown graphically in Plate IV should therefore be regarded as only suggestive rather than as presenting any definite record of the number, quality, and thickness of the individual potash beds. With this limitation in mind, interesting suggestions may be had from a study of the results of these analyses. In the wells from which the samples were obtained little or no casing was used below the top of the salt-anhydrite series while this series was being penetrated. If no great amount of caving of polyhalite occcurred from overlying strata, and if the drilling was continuous, with no delays that allowed increased solution of sodium chloride at certain horizons, it would appear that in the drilling of most of the wells represented on the left of the chart definite beds were encountered that contain fairly high percentages of K_2O, in some beds probably pure polyhalite. A number of beds 10 to 15 feet thick are shown to contain as much as 8 per cent of K_2O in the total sample.



DEPTHS AT WHICH POTASH HAS BEEN FOUND IN WESTERN TEXAS, PERCENTAGE OF POTASH PRESENT AND CHARACTER OF MATERIAL PENETRATED

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ASSAY METHODS

Steiger[12] has called attention to the fact that in the assay of samples of potash from western Texas the ratio for the amount of sample to the amount of water used was arbitrarily taken as 1 to 100. He says:

If these salts become of industrial importance it may be advisable to adopt a ratio in their assay more nearly agreeing with that used in their commercial extraction. The necessity of stating the quantity of water used in dissolving these salts for assay is clearly brought out when the assay of pure polyhalite is considered. One gram of polyhalite contains 0.452 gram $CaSO_4$, 0.199 gram $MgSO_4$, 0.289 gram K_2SO_4, and 0.060 gram of water. While the presence of other salts will slightly change the figures, 100 cubic centimeters of pure water are capable of dissolving at 25° C. 0.208 gram of $CaSO_4$. This dissolved $CaSO_4$ added to the easily soluble $MgSO_4$ and K_2SO_4 in 1 gram of the mineral will total 0.696 gram, or 69.6 per cent of soluble salts. By calculation we find that the 15.6 per cent of K_2O in polyhalite becomes 22.4 per cent of K_2O in the soluble salts. This figure will vary accordingly if a larger or smaller amount of water is used.

The selected sample from the Jones well containing 22.9 per cent of K_2O in the soluble salts was evidently pure polyhalite.

SIGNIFICANCE OF THE POTASH-BEARING WELLS

The scattered wells near the south end of the Llano Estacado in which notable amounts of potash have been found are the only wells in an area of 20,000 square miles which have been drilled deep enough to encounter an appreciable thickness of salt, and from which samples have been collected and analyzed.

Although the fact that potash was found in all these wells is certainly suggestive of widespread and fairly continuous areal distribution of the potash, it can not be taken to mean that potash will probably be found to occur without interruption throughout this extensive area. The wells are too few in number to warrant such a conclusion, and they are not representative of a large part of the area. Furthermore, at the time of potash deposition the waters had been evaporated to a comparatively small volume and probably occupied low places irregularly distributed over the old sea floor. Extreme desiccation, however, was not necessary for the formation of polyhalite, and it appears likely, from the wide distribution of the wells mentioned, that although the concentrated waters probably occupied minor basins, these basins were broad and shallow and contained isolated lakes of shallow concentrated brine that individually covered somewhat extensive areas.

[12] Op. cit., pp. 175-176.

AREA PROBABLY CONTAINING ONLY INSIGNIFICANT AMOUNTS OF POTASH

The Kansas Geological Survey and the Division of State Chemical Research have in recent years carried on extensive investigations to determine if potash is present in the salt beds of this State. These investigations have revealed no commercial sources of potash.[13] Cooperative field observers of the United States Geological Survey and the Texas Bureau of Economic Geology and Technology, while stationed in the Panhandle, collected and tested samples from a number of wells in western Oklahoma and the northern and eastern parts of the Panhandle but found only traces of potash. Salt samples collected by the writer from a number of wells in the eastern part of the southern Llano Estacado region, in Scurry and Mitchell counties, Tex., and in Eddy County, N. Mex., near Carlsbad were equally barren.

Though it can not be denied that commercial deposits of potash may exist in these regions, it may be generally stated that the north half of the salt region of the south-central United States, together with the east and west borders of the Texas portion, probably does not contain potash in quality and thickness comparable to that of the southern Llano Estacado region.

THE MOST PROMISING AREA FOR COMMERCIAL POTASH

Although samples rich in potash have been obtained from several wells throughout a wide area in western Texas, at no place is it yet certain that commercial deposits have been found. All but one of the samples that contained significant amounts of potash were taken from the upper portion of the salt series, from depths less than 2,350 feet. If proved to be of commercial quality and thickness, these beds are all minable. The exceptional sample was taken from the Bryant well (No. 40), Midland County, at a depth of 2,405–2,411 feet.

According to Beede's correlation of the Permian of Texas and Kansas, referred to on page 41, there is considerable difference in the age of the salt beds of these two States. The salt of Kansas, occurring in the Wellington formation, is older than the salt in the Clear Fork and Double Mountain formations of Texas. Were it possible to point out definitely the location of the last deposited salt in this entire region, then it could be safely stated that there, or in that general area, would be a likely place for the occurrence of rich beds of potash. However, it can not be supposed that conditions were

[13] Moore, R. C., unpublished report on the salt beds of Kansas.

suitable for the precipitation of potash salts at only one time, and that these salts will be found in a restricted area above all other saline deposits. The fact that polyhalite has been found distributed throughout the upper 1,500 feet of the thickest of the known salt series proves conclusively that conditions conducive to potash precipitation persisted for a considerable period; and the wide distribution of this salt proves that the mother liquors were not confined to a single small basin. Polyhalite was deposited through a considerable period of time and over an extensive area. But where are the richest beds of this and other potash salts to be found? Certainly this question can not be answered from present data, but until proved otherwise such beds should be looked for in those places where other saliferous deposits resulting from desiccation are most abundant—in other words, where the salt beds are the thickest. Precipitation was concentrated at such places throughout the period of salt deposition, and unless the mother liquors shifted in position or were destroyed the later precipitation of the potash salts occurred there also. Whether the richest beds are found to be in the areas of greatest salt deposition or elsewhere, the greatest number of potash layers may there be expected.

Where, then, are the thickest salt beds? The greatest aggregate thickness yet reported is in the Means well, in northeastern Loving County (No. 37, Pls. III and XVI), where 1,391 feet of salt was penetrated. It might appear at first glance that the greatest thickness of salt occurs in this vicinity, for two other wells, the Toyah-Bell well, in southern Loving County, and the River well, in southern Ward County, have recorded over 1,000 feet. However, at 80 miles due east of the Means well 1,030 feet of salt was found in the Bryant well, Midland County (No. 40, Pl. XI); at 240 miles to the north-northeast 752 feet was penetrated in the Adrian well, southwestern Oldham County (No. 49A, Pl. III); and at 60 miles to the northwest 633 feet has been credited to the Andrews well, Eddy County (No. 17, Pl. XII). The abrupt thickening of the salt beds from the Pecos River east to the Andrews, Means, Toyah-Bell, and River wells makes it appear probable that the greatest thickness has not yet been found. Plate III shows the location and extent of the area believed to be underlain by 1,000 feet or more of salt, and in addition a more extensive area which may also be underlain by a similar aggregate thickness. Many but not all wells drilled within or just outside the borders of these two areas may be expected to encounter notable amounts of potash, which in places, it is believed, will prove to be of commercial quality and thickness.

SUGGESTIONS TO OPERATORS

Prospecting should not be undertaken in a haphazard manner even though the area appearing to be underlain by notable amounts of potash is large. No recommendations for the exact location of test wells can yet be given. Locations already selected in the longitude and latitude of Loving, Winkler, Ector, and Midland counties are probably favorable, and the drilling of wells farther south in Ward, Crane, and Upton counties should not be discouraged. In addition to being promising for potash, much of these areas is easily accessible by railroad. It is suggested that locations for additional test wells be selected near those wells which have already revealed the presence of layers of potash notably rich and apparently of considerable thickness. Of these, the Means (No. 37, Pl. III), in Loving County; River (No. 67), in Ward County; McDowell (No. 29), in Glasscock County; and St. Rita No. 1 (No. 57), in Reagan County, have the most promising records. Other wells that have contributed one or more samples rich in potash are the Bryant (No. 40), in Midland County; Burns (No. 12A), in Dawson County; and Jones (No. 3), in Borden County. The results of reliable exploratory test wells drilled in the vicinity of these old wells and in other areas underlain by thick salt deposits may serve as a basis for additional exploration, which, in general, should be extended toward regions where the salt is thicker.

It can not be expected that all wells drilled, even in the area believed to be most promising, will meet with success. The United States Geological Survey's boring at Cliffside, in Potter County, was believed to be favorably located, and the fact that no significant amounts of potash were found shows that barren areas interspersed with possibly productive areas may be expected. Gale[14] points out that when systematic exploration for potash began in Alsace more than 100 deep wells were put down, 95 of which penetrated rock salt, but only 17 found potash.

Explorations for potash in western Texas and eastern New Mexico should not be confined to wildcat wells, but should follow a definite program of operation. In view of the high value of potash, it is considered that the present indications warrant the expenditure of a sum of money sufficient to test thoroughly the most promising areas. The chances for success on an extensive scale are highly promising, and there is urgent need for early and definitely reliable information concerning the presence or absence of commercial potash in this region.

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[14] Gale, H. S., The potash deposits of Alsace: U. S. Geol. Survey Bull. 715, p. 19, 1920.

Core drilling should be universally adopted by all companies drilling wells in the salt-bed area of western Texas and eastern New Mexico, whether the objective is potash or oil. The use of a core drill permits adequate tests for both potash and oil, but information obtained from a well drilled with cable tools is inadequate and unreliable for the purposes here indicated. For potash, drilling below a depth of 2,500 feet will as a rule probably not be necessary.

Should cable tools be used in future drilling of wells in this region, however, it is urged that samples of both the cuttings and the drill water be taken at close and regular intervals, and that care be taken to bail the hole clean at each bailing. Samples should be carefully labeled as to depth and placed in the hands of a competent chemist, sent to the Director, United States Geological Survey, Washington, D. C., or placed in the hands of the Survey's local representative, whose name and address may be ascertained by writing to the Director at Washington.

SOME FIELD TESTS AND AN ASSAY OF TEXAS POTASH SALTS

By George Steiger

INTRODUCTION

The field tests and assay here described for the identification and analysis of natural salts to determine their potash content have been devised with special reference to the examination of the salts found in western Texas. The field tests may be carried out with little or no previous training in chemistry. The assay, however, requires a knowledge of the fundamentals of analytical chemistry.

In the salts of western Texas that have so far been examined potash occurs largely or wholly as the mineral polyhalite, and for this reason the physical characteristics and a special field test for this mineral are given in detail.

Polyhalite is a hydrous sulphate of potassium, calcium, and magnesium, and the pure mineral contains 15.6 per cent K_2O. The polyhalite found in the Texas salts is a compact, massive, brittle mineral, in texture resembling a fine-grained marble, some of the varieties being almost without grain and inclined to be pearly. It has about the same hardness as marble and is of about equal density (weight). Like marble it can be easily crushed with a knife blade or other hard instrument to a sandy powder. The color ranges in general from a dark brick-red to a light salmon, but some polyhalite is gray.

Anhydrite, a sulphate of calcium, which is abundant in the Texas salts, resembles polyhalite in texture, hardness, and density and produces a sandy powder on being crushed with a hard instrument. Its prevailing color is gray or white; that of polyhalite is almost invariably red.

Glauberite, a sulphate of sodium and calcium, was noted in the material from one Texas locality. This specimen was of a dark brick-red color, had about the same hardness and density as polyhalite, and on crushing gave a similar sandy powder. It responds to the test described below for polyhalite, but its glassy luster, lack of granular structure, and semitranslucent appearance serve to distinguish it.

FIELD TESTS

TEST FOR POLYHALITE

A fragment the size of a pea or larger, if available, is selected. After examination to see if its physical characteristics agree with those of polyhalite the specimen is broken in two, placed in 10 or 15 times its weight of water, and allowed to stand undisturbed over night. In the morning white needle-like crystals of gypsum will have been deposited on the broken surface, or it will be covered with a thin white to brownish chalky coating, which is much softer than the original mineral and can be easily scaled off with the point of a knife. Much of the Texas salt received at this laboratory has been in contact with water, either during drilling or in the slush pit; consequently many of the polyhalite fragments have this coating already formed. This coating is very characteristic of polyhalite and is one of the things to be kept constantly in mind when prospecting for potash in Texas. If all the salt available has been crushed to a sand or grit the coating may be recognized on the individual grains and removed by simply rubbing between the fingers. Removal of the brown coating reveals the color of the original polyhalite. The water test for polyhalite may be applied to small grains, with the same procedure as that used on larger fragments. Polyhalite grains may be replaced by a bunch of needle-like gypsum crystals radiating from a single point and large enough to be seen by the unaided eye; or the crystals may not be so numerous or may be so small as to be invisible without a magnifying glass. The varieties of polyhalite giving a coating are more difficult to detect than those producing needlelike crystals. It is important when working with either small grains or larger fragments to keep the vessel in which the experiment is conducted well covered to prevent undue evaporation. If time permits it is well to separate by hand the grains that most clearly resemble polyhalite before applying the test. Common salt has little or no effect on the formation of the gypsum crystals or the coating, but calcium sulphate has a retarding action.

GLAUBERITE, SYNGENITE, AND KRUGITE

Glauberite gives the same reaction as polyhalite, but its physical characteristics, as above described, make it easy to distinguish the two minerals. Syngenite and krugite would doubtless give the same result in the water test as polyhalite, but as both contain potassium it is sufficient for present purposes to class them along with polyhalite.

COBALTI-NITRITE TEST

In the cobalti-nitrite test for potash two reagents are used. To make solution A 113 grams of cobalt acetate is dissolved in somewhat less than 400 cubic centimeters of water, 100 cubic centimeters of glacial acetic acid is added, and the solution is diluted to 500 cubic centimeters with water. Solution B is prepared by dissolving 220 grams of sodium nitrite in water and diluting to 500 centimeters. To prepare for use, equal parts of A and B are mixed and set aside until the brown fumes formed by the reaction of the two solutions have escaped. This operation should be conducted where there is a good draft, as the fumes are poisonous.

Solutions A and B by themselves will keep indefinitely. After mixing the reagent slowly undergoes decomposition; it will stay in good condition for three or four weeks if kept in a dark place. Toward the end of this period it should be tested with a known potash solution.

To carry out the test, as much of the ground sample is taken as it is possible to scoop up with a 10-cent piece,[15] put into a 150 cubic centimeter beaker with 30 cubic centimeters of water, covered with a watch glass, and boiled at a lively rate for 10 or 15 minutes. At the end of this time the bulk of the solution should be 15 or 20 cubic centimeters. It is filtered into a test tube of 50 cubic centimeters capacity, 10 cubic centimeters of the cobalt reagent is added, and the contents of the tube are well mixed by shaking and are then allowed to stand undisturbed for several hours or, better, overnight; the bulk of the yellow precipitate is roughly proportional to the quantity of potassium present in the solution.

The operator must determine for himself by using standard solutions of a potassium salt the ratio between the bulk of the precipitate and the quantity of potassium. It is very important in carrying out this test that the procedure be always the same, even to the minute details. The temperature and the length of time the solution is allowed to settle are two of the most important details. If the samples to be tested are largely sodium chloride, it is well to add an equivalent amount of sodium chloride to the standard potassium solution used for comparison. If conditions vary in making this test on different samples, unreliable results may be expected. Tubes of special design, restricted in diameter at the bottom and roughly graduated, may be purchased from chemical dealers; such tubes are of great assistance in judging the bulk of precipitate.

A second procedure is to prepare a saturated solution by adding to water a sufficient quantity of the sample so that a portion of the soluble part will remain after thorough stirring. The test is applied as before, 5 or 10 cubic centimeters of the saturated solution and 10 cubic centimeters of the cobalt reagent being used. In samples containing small percentages of soluble salts it is very difficult to know when the point of saturation has been reached. Results obtained by this procedure denote the percentage of potassium in the "soluble salts," with no reference to the percentage in the sample taken as a whole.

THE FLAME TEST

The flame test detects potassium in any of its soluble compounds, requires a minimum of equipment, and is very rapid. It requires long experience, however, and even those who are expert can make only a mere approximation of the quantity of potassium present.

The apparatus required includes a piece of No. 24 platinum wire 4 or 5 inches long, hydrochloric acid, a Merwin color screen, and an alcohol lamp or, better, one of the various forms of the blue-flame gasoline blowtorch.

Procedure: Make a saturated solution of the salt and acidulate with hydrochloric acid. Remove a drop by means of the platinum wire, carefully dry over the flame of the lamp, finally ignite, and observe the flame through the Merwin color screen. If potassium is present the flame will be colored violet, and the depth and duration of the color will give a rough idea of the quantity present. The yellow of the sodium salts is entirely cut out by the Merwin screen, but the red of the calcium salts is only partly eliminated; this is a source of error which requires long experience to overcome.

ASSAY

In assaying Texas salts for potassium it is important that detailed instructions should be rigidly and consistently followed; otherwise wide variations may be expected, especially in the determination of "soluble salts."

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[15] If a balance is available 1 gram is weighed out.

Procedure: 2½ grams of the salt ground to pass an 80-mesh sieve is put into a 400 cubic centimeter beaker with 250 cubic centimeters of water and gently boiled for 30 minutes. Care should be taken that the bulk of the solution is not reduced more than 10 or 15 cubic centimeters during boiling. Without waiting for it to cool the material in the beaker is poured into a 250 cubic centimeter glass-stoppered graduated cylinder, enough water being used in transferring the insoluble residue to bring the contents of the cylinder up to the 250 cubic centimeter graduation mark. The cylinder and contents are vigorously shaken from time to time, and when the material is cooled to the temperature of the surrounding air water is added if necessary to bring the volume back to 250 cubic centimeters. It is then given a final shaking to mix the contents thoroughly and set aside overnight.

SOLUBLE SALTS

50 cubic centimeters of the solution is transferred with a pipette to a 3-inch porcelain evaporating dish, which has been previously weighed, and the solution is evaporated as far as possible on the steam bath. The dish is then placed in an air bath, heated for 1 hour at 180° C., cooled, and weighed. The residue so obtained is called "soluble salts."

POTASSIUM

50 cubic centimeters of the solution is transferred to a 3-inch porcelain evaporating dish, and 1 cubic centimeter of strong hydrochloric acid is added, together with slightly more than enough platinic chloride solution to form K_2PtCl_6 with the potassium present. The solution is then evaporated nearly but not quite to dryness on the steam bath, removed, cooled, moistened with a few drops of 95 per cent alcohol, and ground thoroughly with a pestle made by enlarging one end of a glass rod, 10 or 12 cubic centimeters of 95 per cent alcohol is added, and the solution is set aside for half an hour. At the end of this time it is filtered and washed until the washings give no test for chlorine with silver nitrate. Without waiting for it to dry, the residue is dissolved in hot water, and 5 to 10 cubic centimeters of 1–1 hydrochloric acid and a piece of metallic magnesium the size of a pea are added (in rich samples more magnesium and acid may be needed). When the magnesium has been entirely dissolved, heat being used to hasten solution, the precipitated platinum is filtered, washed with hot water until the washings are free from chlorine, ignited, and weighed. The weight of the platinum so obtained multiplied by 0.4826 gives K_2O, by 0.7639 gives KCl, and by 0.4006 gives K.

SURFACE FEATURES OF THE COUNTRY

The northern part of the region is the southern continuation of the Llano Estacado and is a high, nearly featureless plain that slopes south and southeast at the rate of about 10 feet to the mile. The highest altitude, near Lovington, N. Mex., is approximately 4,300 feet; the lowest altitude of the Llano Estacado, in northern Howard County, Tex., is about 2,500 feet.

This southern portion of the Llano Estacado contains no permanent streams. Here and there a shallow draw draining in a general southeasterly direction may be noted, together with numerous sinks and other circular or elongate depressions, many of which contain the salt playas common to the plains of western Kansas, Oklahoma, and Texas. These playas occur in the area of outcrop of the Triassic red beds but are more common in areas covered by a mantle of calcareous sand and gravel of Cenozoic age. The salt of these playas has been obtained from the long-continued evaporation of drainage waters that have leached small amounts of sodium chloride and other salts from the soil.

The depressions that can be identified as true sinks are small, ranging in area from less than an acre to 3 acres. They are common in the southern portion of the Llano Estacado, which in greater part is directly underlain by 50 feet, more or less, of Cretaceous limestones.

The eastern limit of the Llano Estacado is marked by "the breaks," a nearly vertical cliff 150 to 300 feet high, which runs in a general southerly direction from Randall County, in the north-central part of the Texas Panhandle, to Borden and Dawson counties, near the south end of the plains. From Randall County "the breaks" pass southeastward through Armstrong, Swisher, Briscoe, Motley, and Dickens counties and thence southwestward through Crosby and Garza counties. They enter the area under discussion near the northwest corner of Scurry County and extend southwestward through Borden and Dawson counties.

The "lower or eroded plains" described by Baker[16] lie to the east of the Llano Estacado and extend over most of Borden, Scurry, and Mitchell counties and the eastern part of Howard County. Alternating sandstone and soft clay of the Dockum group (Triassic, probably Upper Triassic) are exposed in this area and account for the rapid erosion and the gently rolling topography. The altitude ranges from 2,400 feet near the northwest corner of Scurry County to about 1,800 feet in southeastern Mitchell County.

The southwestern and western limits of the Llano Estacado are well defined. Concho Bluff, so named because of the shell limestone of which it is composed, is 40 to 100 feet in height and extends in a northwesterly direction from the northwestern part of Upton County through central Ector County to the northeast corner of Winkler County. The Lower Cretaceous limestones (Edwards and Comanche Peak), which form the upper part of this bluff, dip below loose surface sands in the southern edge of Andrews County. About 50 miles to the northwest, near Monument, Lea County, N. Mex., the Mescalero Ridge marks the western limit of the Llano Estacado. This ridge extends northwestward to a locality 35 miles west of Lovington, where it assumes a north-south course along the west line of Lea County. It consists of hard and soft sandstone with siliceous and calcareous cement, respectively, soft powdery limestone, gravel,

[16] Baker, C. L., Geology and underground waters of the northern Llano Estacado: Texas Univ. Bull. 57, p. 37, 1915.

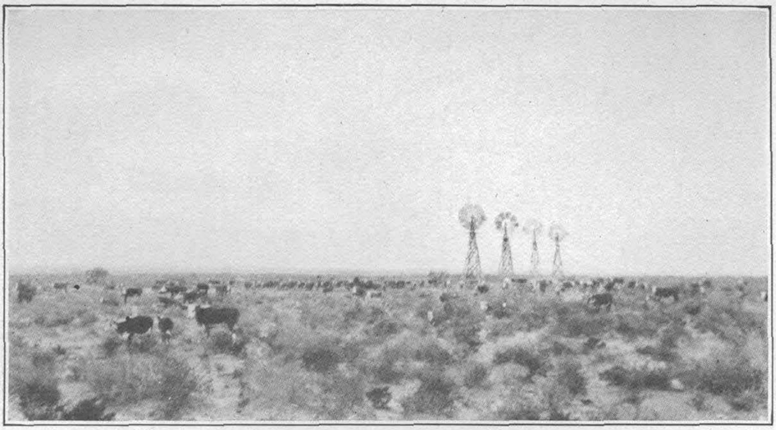
and boulders, which together are of Tertiary (?) and Quaternary age and have an exposed thickness of 75 to 100 feet; this material constitutes the "cap rock" of a large part of the Llano Estacado.

The broad, open valley of Pecos River lies directly west and southwest of the Llano Estacado. Where the river cuts its way through soft red beds in southeastern New Mexico and northwestern Texas the valley is from 60 to 75 miles wide and extends to the east as far as Mescalero Ridge and Concho Bluff. The present channel of the river near Pecos, Tex., is approximately 550 feet lower than the top of Concho Bluff, 60 miles to the northeast. A general view of this featureless country, which is largely devoted to cattle raising, is shown in Plate V, *A*.

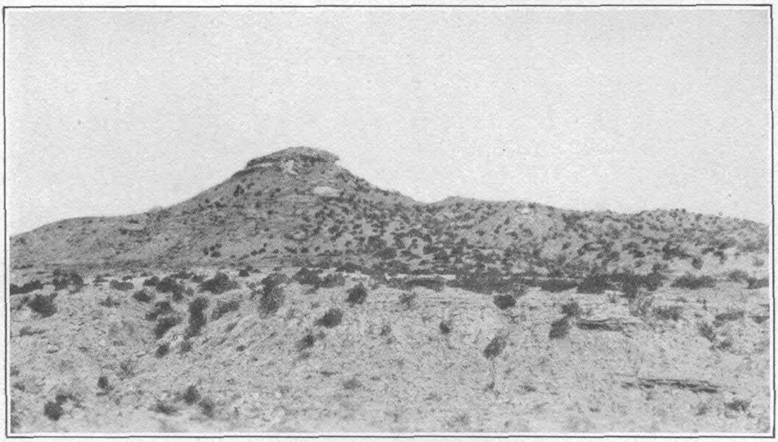
The surface of much of that part of western Texas and southeastern New Mexico lying between Pecos River and the western edge of the Llano Estacado is covered with wind-blown sand, which ranges in thickness from only a few feet to more than 200 feet. Irregular sand-dune topography with small relief is common to all this region. Where this surface sand exceeds 50 feet in thickness an abundant supply of fresh water is commonly found at its base, directly on top of Triassic red clay, which underlies much of this sand area. Where the surface sand is only a few feet thick it is usually necessary to penetrate the Triassic red clay to a depth of 500 to 750 feet, where fresh water is in many places encountered in sands within the Triassic.

The southern limit of the Llano Estacado, which is the northwestern limit of the Edwards Plateau, is in places marked by high northward-facing bluffs, 300 to 500 feet high, which are locally called mountains. Such bluffs occur southeast of Big Spring, in southern Howard County, and in central Upton County and southeastern Crane County. In the intervening Glasscock and Midland counties these high bluffs give place to low ridges and in some localities no outstanding topographic feature is evident, for the surface slopes gradually upward toward the southeast, to the Edwards Plateau.

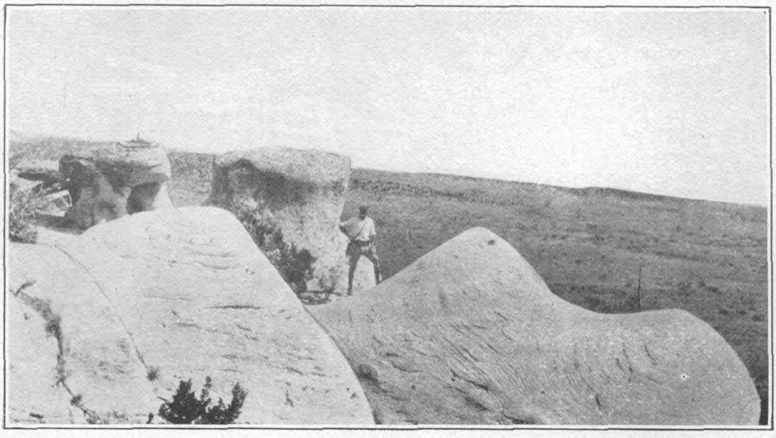
The Edwards Plateau lies to the south and southeast of the Llano Estacado and covers a large area in southwestern Texas. The occurrence of Edwards and associated limestones, with an aggregate thickness of about 600 feet, is typical of this region. These limestones constitute a resistant covering for softer formations and produce a surface commonly having a gentle slope coincident with the southeasterly dip of the rocks. The northwestern limit of the Edwards Plateau, in southern Upton County and northeastern Pecos County, is marked by high bluffs and mesas several miles in length, which are capped by Edwards and possibly overlying limestones but whose bases expose as much as 100 feet of the underlying Trinity sand and, in places, some of the red clays and sandstones of the Dockum group.



A. THE FLAT-LYING COUNTRY WEST OF CONCHO BLUFF, SOUTHERN ECTOR COUNTY, TEX



B. MUCHAKOOYO PEAK, BORDEN COUNTY, TEX.



C. GRAY CROSS-BEDDED SANDSTONE OF UPPER PART OF DOCKUM GROUP, EASTERN HOWARD COUNTY, TEX.

PREVIOUS GEOLOGIC WORK[17]

George G. Shumard, geologist on the Marcy exploring expedition of Red River, in 1852, viewed the eastern escarpment of the plains at the mouth of Palo Duro Canyon and followed it to the head of the canyon. He placed the strata of the Llano Estacado in the Cretaceous. The next year Jules Marcou traveled along the northern escarpment, in the Panhandle and northeastern New Mexico, and concluded that the rocks of the upper plateau were Jurassic.

William P. Blake reported upon the geology of the route traversed by Captain Pope in 1854 near the thirty-second parallel. Regarding the route between Big Springs and Pecos River, Blake says:[17a]

> The age of the overlying rocks of a lighter color is also obscure; but there is much reason to regard them as Cretaceous and Tertiary. The only fossils which I found in the collection from the Llano are Cretaceous and serve to indicate the development of that formation at the Big Springs of the Colorado and a point on the Llano 20 miles east of the sand hills.

A two-year trip was made by Shumard in 1855–56.

In 1890 W. F. Cummins gave a summary of previous work done on the Permian of Texas and divided the Permian in central Texas into three formations—the Wichita, Clear Fork, and Double Mountain.[18] Beds of conglomerate, sandstone, and red clay, resting unconformably upon the upper Permian near Dockum, at the foot of the Llano Estacado, were named Dockum "beds." The Tertiary strata that constitute the Llano Estacado were called by Cummins "Blanco Canyon beds" but are now known as the Blanco formation.

In 1891 Cummins gave more detailed descriptions of the Permian, Triassic, and Tertiary strata of the plains region and discussed their relations.[19]

The next season[20] Cummins followed the outcrop of the Triassic northward from Iatan, Mitchell County, to the Panhandle, crossed over the plains to Tucumcari, N. Mex., and traveled southward to Fort Sumner and along Pecos River to southern Crane County, Tex. The rocks were classified as Permian, Triassic, Lower Cretaceous, and Tertiary. N. F. Drake, a member of the party, made a special study of the Triassic throughout the area visited, and his report followed that of Cummins in the same volume. Vertebrate fossils collected from Texas, mostly from the upper Cenozoic and the Triassic, were identified and described by E. D. Cope.[21]

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[17] The account of the early explorations was taken from Cummins, W. F., Texas Geol. Survey, Third Ann. Rept., p. 134, 1892.

[17a] U. S. Pacific R. R. Expl., vol. 2, p. 17, supplement, 1856.

[18] Texas Geol. Survey First Ann. Rept., pp. 185–197, 1890.

[19] Texas Geol. Survey Second Ann. Rept., pp. 394–435, 1891.

[20] Texas Geol. Survey Third Ann. Rept., pp. 129–223, 1892.

[21] Idem, pp. 251–259.

In the field season of 1891 Cummins and his assistants, accompanied by Cope as vertebrate paleontologist, made further studies of the Tertiary, Cretaceous, Triassic, and Permian strata along the eastern edge of the Llano Estacado from Big Spring north to the Panhandle.[22]

The first detailed work dealing principally with the stratigraphy of the Texas Cretaceous was that of Taff in 1891–92,[23] though introductory studies had been made by Hill [24] and others. More detailed studies by Hill, the results of which were published in 1901, gave information on the distribution and character of these rocks,[25] in addition to underlying Carboniferous and older strata.[26]

The physical geology of Texas was discussed by R. S. Tarr in 1893.[27] In 1900 Hill compiled all available data on the physical geography of the Texas region,[28] eastern New Mexico, southern Oklahoma, and western Arkansas and Louisiana. This work was based, to a large extent, upon Hill's personal observations.

More recent work has been done on that part of the Llano Estacado lying to the north of the area under present discussion. W. D. Johnson, in 1899–1900, completed a study of origin, structure, climate, physiography, and water resources of the High Plains of western Texas, Oklahoma, and Kansas.[29] The investigations of Gould[30] in the Panhandle region contributed much to the knowledge of the Permian and Triassic of this part of Texas. The Permian and Triassic from Wichita Falls, Tex., west to Las Vegas, N. Mex., were discussed by Case,[31] whose investigations dealt mostly with the stratigraphy and vertebrate fauna of these beds. C. L. Baker studied the geology of the northern Llano Estacado, mainly in connection with the water resources of this part of the High Plains.[32]

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[22] Texas Geol. Survey Fourth Ann. Rept., pp. 179–238, 1893.

[23] Texas Geol. Survey Third Ann. Rept., pp. 269–363, 1892; Fourth Ann. Rept., pp. 241–336, 1893.

[24] Hill, R. T., A brief description of the Cretaceous rocks of Texas and their economic uses: Texas Geol. Survey First Ann. Rept., pp. 105–137, 1890.

[25] Hill, R. T., Geography and geology of the Black and Grand prairies: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, pp. 107–345, 1901.

[26] Idem, pp. 86–106.

[27] Tarr, R. S., Notes on the physical geography of Texas: Acad. Nat. Sci. Philadelphia Proc., 1893, pp. 313–347.

[28] U. S. Geol. Survey Topographic Folio 3, 1900.

[29] Johnson, W. D., The High Plains and their utilization: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 4, pp. 609-741, 1901; Twenty-second Ann. Rept., pt. 4, pp. 637-669, 1902.

[30] Gould, C. N., The geology and water resources of the eastern portion of the Panhandle of Texas: U.S. Geol. Survey Water-Supply Paper 154, 1906; The geology and water resources of the western portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 191, 1907.

[31] Case, E. C., The red beds between Wichita Falls, Tex., and Las Vegas, N. Mex., in relation to their vertebrate fauna: Jour. Geology, vol. 22, pp. 243-259, 1914; The Permo-Carboniferous red beds of North America and their vertebrate fauna: Carnegie Inst. Washington Pub. 207, 1915.

[32] Baker, C. L., Geology and underground water of the northern Llano Estacado: Texas Univ. Bull. 57, 1915.

Two papers by Udden have a direct bearing on the stratigraphy of the subsurface Permian of the High Plains of Texas and eastern New Mexico. The first[33] records the earliest and to date the only available detailed description of these beds as revealed by exhaustive study of cuttings taken from a well in Dickens County; and the second[34] discusses the distribution, thickness, and attitude of the salt beds with special reference to their known potash content.

Considerable work has been done on adjoining local areas. J. W. Beede and V. V. Waite examined in detail the geology of Runnels County,[35] and Beede and W. P. Bentley the geology of Coke County.[36] A paper by Liddle and Prettyman[37] on the geology of Crockett County included data on the stratigraphy and structure of the central Pecos Valley.

The mountainous parts of Texas, west of Pecos River, have received considerable attention, for it is here that upper Paleozoic rocks contemporaneous with deeply buried strata of the Texas Plains region may be studied. The first observations in the Marathon country, Brewster County, were made by Hill[38] in 1900. From 1904 to 1914 Udden measured a number of cross sections through the "Permo-Carboniferous" strata and collected many fossils.[39] The fossils were studied by Böse, who subdivided the enormous mass of the "Permo-Carboniferous" strata by their contained ammonoids and made correlations of beds in northern Texas with beds in Europe and Asia.[40]

A map by Liddle, published in 1920, showed the Sheffield terrace, a flexure of the Cretaceous rocks probably representing the northeastern extension of the Marathon disturbance, and in the accompanying text Liddle discussed the possible influence of this flexure on the accumulation of commercial quantities of petroleum.[41]

Considerable geologic work has been done in the trans-Pecos region, west and northwest of the Marathon country. As early as

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[33] Udden, J. A., The deep boring at Spur: Texas Univ. Bull. 363, 1914.

[34] Udden, J. A., Potash in the Texas Permian: Texas Univ. Bull. 17, 1915.

[35] Texas Univ. Bull. 1816, 1918.

[36] Texas Univ. Bull. 1850, 1921.

[37] Liddle, R. A., and Prettyman, T. M., Geology and mineral resources of Crockett County: Texas Univ. Bull. 1857, 1920.

[38] Hill, R. T., Physical geography of the Texas region: U. S. Geol. Survey Topographic Folio 3, 1900.

[39] Udden, J. A., Notes on the geology of the Glass Mountains: Texas Univ. Bull. 1753, 1917; A sketch of the geology of the Chisos country, Brewster County, Tex.: Texas Univ. Bull. 93, 1907.

[40] Böse, Emil, The Permo-Carboniferous ammonoids of the Glass Mountains, west Texas, and their stratigraphical significance: Texas Univ. Bull. 1762, 1917.

[41] Liddle, R. A., The Marathon fold and its influence on petroleum accumulation: Texas Univ. Bull. 1847, 1920.

1855 and 1856 George G. Shumard made geologic explorations of western Texas and southern New Mexico.[42] His party went from a point near Matagorda Bay to San Antonio and west-northwestward to Pecos River, continued up the Pecos to the mouth of Delaware Creek, just beyond the New Mexico line, turned westward to the Guadalupe Mountains, and continued on into southern New Mexico. Conclusions drawn by G. G. and B. F. Shumard from fossil collections obtained by this party were published in 1858 and 1859.[43] W. H. von Streeruwitz, in the first four annual reports of the Texas Geological Survey, published between 1889 and 1892, described the geology of parts of the trans-Pecos region. In the fourth report appeared also a report on the rocks of the region by Osann.[44] In 1892 the results of Tarr's investigations in the Guadalupe Mountains[45] were published, with notes on the geology of the southern Llano Estacado and the country to the east. R. T. Hill, in his "Physical geography of the Texas region," already cited, and in other papers, has made brief references to the trans-Pecos country. In 1901–1904 publications of the University of Texas Mineral Survey[46] gave information on the economic and general geology of parts of this region.

Richardson[47] in 1904 made a valuable contribution to the geology and underground water resources of this part of Texas. Work was also done by Baker and Bowman[48] in trans-Pecos Texas south of the Texas & Pacific Railway. In 1914 appeared the results of detailed work by Richardson in the the south-central part of northern trans-Pecos Texas.[49] Girty[50] and Lee,[51] in 1908 and 1909, discussed the paleontology and stratigraphy of the upper Paleozoic of this region.

[42] Shumard, G. G., A partial report on the geology of western Texas, pp. 53–145, 1886.

[43] Shumard, B. F., Notice of new fossils from the Permian strata of New Mexico and Texas: St. Louis Acad. Sci. Trans., vol. 1, pp. 290–297, 1858; Notice of fossils from the Permian strata of Texas and New Mexico: Idem, pp. 387–403, 1859.

[44] Osann, C.A., Report on the rocks of trans-Pecos Texas: Texas Geol. Survey Fourth Ann. Rept., pp. 123–138, 1893.

[45] Tarr, R. S., Reconnaissance of the Guadalupe Mountains: Texas Geol. Survey Bull. 3, 1892.

[46] See especially Phillips, W. B., Sulphur, oil, and quicksilver in trans-Pecos Texas: Texas Univ. Min. Survey Bull. 2, 1902. Hill, B. F., The Terlingua quicksilver deposits: Texas Univ. Min. Survey Bull. 4, 1902.

[47] Richardson, G. B., Reconnaissance in trans-Pecos Texas north of the Texas & Pacific Railway: Texas. Univ. Min. Survey Bull. 9, 1904.

[48] Baker, C. L., and Bowman, W. F., Geologic exploration of the southeastern front range of trans-Pecos Texas: Texas Univ. Bull. 1753, pp. 61–177, 1917.

[49] Richardson, G. B., U. S. Geol. Survey Geol. Atlas, Van Horn folio (No. 194), 1904.

[50] Girty, G. H., The Guadalupian fauna: U. S. Geol. Survey Prof. Paper 58, 1908.

[51] Lee, W. T., and Girty, G. H., The Manzano group of the Rio Grande valley: U. S. Geol. Survey Bull. 389, 1909.

Still later have appeared publications by Richardson,[52] Beede,[53] and Darton[54] on the paleontology, stratigraphy, and structure of the trans-Pecos region of both Texas and New Mexico.

A report by Udden, Baker, and Böse,[55] published in 1916 and revised in 1919, contains a condensed discussion of the geology of the entire State.

A complete record of the early writings on the geology of Texas will be found in the compilations of Hill[56] and Simonds.[57]

STRATIGRAPHY

The rocks exposed in this region are of Permian, Triassic, Comanche (Lower Cretaceous), Pliocene or Pleistocene, and Recent age. The lithologic character of still older rocks has been determined from the logs and samples of cuttings of wells that have been drilled for oil within and near the region. A number of the wells drilled in the eastern portion of the region have penetrated older Permian rocks than are exposed at the surface within the region, and it is probable that a few of them have penetrated the upper part of the Pennsylvanian. Records of wells drilled in Sterling, Tom Green, and Coke counties, to the southeast, as interpreted by Beede,[58] reveal the presence of several hundred feet of strata of probable Pennsylvanian age. Rocks believed by Udden[59] to be of upper Pennsylvanian age were encountered in the lower part of a deep well drilled in Dickens County,

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[52] Richardson, G. B., Stratigraphy of the upper Carboniferous in west Texas and southeast New Mexico: Am. Jour. Sci., 4th ser., vol. 29, pp. 325–337, 1910.

[53] Beede, J. W., Correlation of the Guadalupian and the Kansas sections: Am. Jour. Sci., 4th ser., vol. 30, pp. 131–140, 1910; Notes on the geology and oil possibilities of the northern Diablo Plateau in Texas: Texas Univ. Bull. 1852, 1920.

[54] Darton, N. H., A comparison of Paleozoic sections in southern New Mexico: U. S. Geol. Survey Prof. Paper 108, pp. 31–55, 1917; Permian salt deposits of the south-central United States: U. S. Geol. Survey Bull. 715, pp. 205–223, 1921; Geologic structure of parts of New Mexico: U. S. Geol. Survey Bull. 726, pp. 173–275, 1922.

[55] Udden, J. A., Baker, C. L., and Böse, Emil, Review of the geology of Texas: Texas Univ. Bull. 44, 1916; 3d ed. (revised), 1919.

[56] Hill, R. T., The present condition of knowledge of the geology of Texas: U. S. Geol. Survey Bull. 45, 1887.

[57] Simonds, F. W., A record of the geology of Texas for the decade ending December 31, 1896: Texas Acad. Sci. Trans., vol. 3, pp. 19–285, 1900.

[58] Beede, J. W., and Bentley, W. P., The geology of Coke County: Texas Univ. Bull. 1850, pp. 71–76, 1921.

[59] Udden, J. A., The deep boring at Spur: Texas Univ. Bull. 363, 1914.

to the northeast. The information made available by the records of other wells drilled along the eastern border of the region which probably encountered rock strata older than the Permian, will be discussed below.

Rocks exposed in a part of western Texas and southeastern New Mexico

Age	Group	Formation	Character	Thickness (feet)
Recent.			Stream deposits of sand, gravel, and clay	0–50±
			Wind-blown sand	0–200
			Caliche ("cap rock" of plains)	10±
Unconformity				
Pleistocene or Pliocene.			Sand, gravel, and clay, unassorted and poorly stratified.	50±
Unconformity				
Comanche (Lower Cretaceous).	Washita group	Georgetown limestone probably represented in southern part of area.	Undivided Georgetown and Edwards limestones are equivalent to Devils River limestone. Marly gray fossiliferous limestone of varying hardness. The greater part is commonly argillaceous and only moderately resistant, but interbedded strata are hard, crystalline, and resistant.	5–372
	Fredericksburg group	Edwards and Comanche Peak limestones undifferentiated.		
		Walnut limestone.	Yellowish-brown argillaceous limestone, in places very sandy.	3–10
	Local unconformity			
	Trinity sand.		Variegated sandstone, in places conglomeratic, cross-bedded, and usually having a loose sugar-like appearance.	26–142
Unconformity				
Triassic.	Dockum group.		Dark-red clay.	0–175
			Dark-red clay and gray cross-bedded and micaceous sandstone.	0–225
Unconformity				
Permian.	Double Mountain formation (southeastern Mitchell county.)		Red shale, sandstone, and thin beds of gypsum.	200±
	Red beds of Pecos Valley and Rustler limestone.		Dolomite, sandstone, red shale, and gypsum. Probably in part at least equivalent to Double Mountain formation and may be in part younger.	150–200±

PENNSYLVANIAN SERIES

CENTRAL AND NORTH-CENTRAL TEXAS

Rocks of Pennsylvanian age are not exposed within this region. One zone of their outcrop lies approximately 100 miles to the east, where they form a long belt 50 to 75 miles wide extending in a northeasterly direction. The extensive area of outcrop of the Texas Permian separates this belt from that of the Triassic, which borders the eastern edge of the Llano Estacado. The Pennsylvanian strata in central and north-central Texas have received the attention of many geologists and were first subdivided by W. F. Cummins in his report on the geology of northwestern Texas. The subdivisions now accepted are given in the table below. The total thickness of the Pennsylvanian in this part of Texas is about 6,500 feet.

Permian and Pennsylvanian formations of central and north-central Texas [a]

Age	Formation	Character	Thickness (feet)
Permian.	Double Mountain formation.	Red and blue sandstone, shale, and clay; some limestone, dolomite, and gypsum; contains much rock salt farther west in plains region.	2,200±
	Clear Fork formation.	Red and blue clay and shale; limestone, locally dolomitic; sandstone, gypsum, and clay-ball conglomerate; probably contains rock salt farther west in plains region.	750-1,975±
	Wichita formation.	Red and blue sandstone and shale, with some clay-ball conglomerate.	1,000-2,000±
Pennsylvanian.	Cisco formation.	Blue clay and shale, sandstone, conglomerate, and some thin beds of limestone.	750-1,000
	Canyon formation.	Limestone, blue clay, some reddish sandstone, conglomerate, and coal.	800-1,100
	Strawn formation.	Sandstone, some conglomerate and shale, few limestones, and some coal.	950-4,700±
	Smithwick shale.	Dark to black carbonaceous shale; some sandstone	225-600±
	Marble Falls limestone.	Bluish-gray to black limestone; limestone conglomerate or breccia at base.	450-650
Mississippian.	Barnett shale.	Black fissile shale, highly bituminous; some limestone.	150±
Unconformity—			
Ordovician.	Ellenburger limestone.		

[a] Taken mostly from Udden, J. A., Baker, C. L., and Böse, Emil, Review of the geology of Texas: Texas Univ. Bull. 44, 3d ed. (revised), 1919.

SOUTHERN TRANS-PECOS REGION, TEXAS

In the southern trans-Pecos region of Texas Udden[60] and Baker[61] have identified strata of Pennsylvanian age and have subdivided and mapped Pennsylvanian and Permian rocks which aggregate approximately 16,000 feet in thickness.

Permian and Pennsylvanian formations of Glass Mountain area, southern trans-Pecos Texas [a]

Age	Formation	Character	Average thickness (feet)
Permian.	Tessey formation.	Dolomitic limestone, partly oolitic.	1,400
	Gilliam formation.	Gray and reddish limestone and dolomite, commonly brecciated; some sandstone.	2,600
	Vidrio formation.	Dolomitic limestone or dolomite; some chert and very little sandstone.	2,000
	Word formation.	Gray, yellow, and reddish limestone, partly dolomitic, and sandstone; limestone contains chert concretions.	600
	Leonard formation.	Limestone, sandstone, chert, gray shale, and some conglomerate.	1,800
	-Unconformity-		
	Hess formation.	Limestone, some shale, and a basal conglomerate.	2,000
	-Unconformity-		
	Wolfcamp formation.	Gray to black shale and some limestone and sandstone.	500
Unconformity			
Pennsylvanian.	Gaptank formation.	Limestone, shale, and sandstone; conglomerate at base.	1,500
	Haymond formation.	Greenish sandstone, green and black clay, and conglomeratic limestone with marine fossils.	500
	Dimple formation.	Alternating beds of gray limestone, black chert, black shale, and some chert conglomerate. Marine fossils.	925
	Tesnus formation.	Dark-green and black shale, sandstone, chert, and some conglomerate. Fossils; a few land plants.	3,370
Unconformity			
Devonian.			

[a] Udden, J. A., Baker, C. L., and Böse, Emil, Review of the geology of Texas: Texas Univ. Bull. 44. 3d ed. (revised), pp. 49–51, 55–57, 1919.

[60] Udden, J. A., Notes on the geology of the Glass Mountains: Texas Univ. Bull. 1753, pp. 38–41, 1917.

[61] Baker, C. L., and Bowman, W. F., Geologic exploration of the southeastern front range of trans-Pecos Texas: Texas Univ. Bull. 1753, pp. 101–107, 1917.

NORTHERN TRANS-PECOS REGION, TEXAS AND SOUTHERN NEW MEXICO

The Hueco limestone, as developed in the mountains northwest of Van Horn, in southwestern Culberson County, and east and north of El Paso, Tex., and the Magdalena group of southern New Mexico represent the only known Pennsylvanian rocks of this region. The Hueco, which Girty[62] has identified as of Pennsylvanian age, has a total thickness of not less than 5,000 feet. It is now believed, by Darton, Girty, and others that the upper part of the Hueco is probably of Permian age; the lower part is of Mississippian age.

The Magdalena group is well developed in the mountains north and northeast of El Paso. Its thickness as given by Darton[63] is 1,000 to 2,500 feet.

Permian and Pennsylvanian formations of northern trans-Pecos region of Texas and southern New Mexico[a]

Age	Group and formation		Character	Thickness (feet)
	Rustler limestone.		Massive gray dolomite and dolomitic limestone, some sandstone, and brecciated limestone. Fossils rare.	(?) 500-1,000
	Castile gypsum.		Massive white gypsum; some limestone, dolomite, and gray, red, and green shale and marl. Relations to Capitan limestone not established.	1,000
Permian.	Guadalupe group	Capitan limestone.	Massive white limestone; changes toward the east and north to red shale and sandstone, gypsum, and rock salt of Pecos Valley.	1,800
	Guadalupe group	Delaware Mountain formation.	Bluish-gray limestone and white and brown sandstone; locally some shale. Thins rapidly northward.	2,300
	Unconformity			
Pennsylvanian and Mississippian.	Hueco limestone.		Mainly massive gray fossiliferous limestone, locally including beds of shale and sandstone. Upper part probably of Permian age and equivalent to Manzano group in whole or in part; lower part is of Mississippian age.	5,000

[a] Chiefly from Udden, J. A., Baker, C. L., and Böse, Emil, op. cit., pp. 51-52, 59-62; and Beede, J. W., Notes on the geology and oil possibilities of the northern Diablo Plateau in Texas: Texas Univ. Bull. 1852, pp. 5-33, 1920.

North of the Guadalupe Mountains, in New Mexico, the Manzano group (Permian, 1,200 to 4,000 feet thick) and the Magdalena

[62] Richardson, G. B., U. S. Geol. Survey Geol. Atlas, Van Horn folio (No. 194), p. 5, 1914.

[63] Darton, N. H., Geologic structure of parts of New Mexico: U. S. Geol. Survey Bull. 726, pp. 179-180, 1922; A comparison of Paleozoic sections in southern New Mexico: U. S. Geol. Survey Prof. Paper 108-C, p. 53, 1917.

group (Pennsylvanian, 1,000 to 2,500 feet thick) are present. The upper part of the Manzano group (Chupadera formation) is, according to Darton, equivalent to the Guadalupe group, but the lower part (Abo sandstone), which thins out to the south, is apparently older than the Guadalupe.

WELLS DRILLED INTO THE PENNSYLVANIAN ROCKS

Well at Spur, Dickens County.—Probably the first well in this region to encounter strata of Pennsylvanian age was one drilled by Swenson & Sons at Spur, Dickens County, Tex. (No. 13, Pls. III and XV). Samples of cuttings, taken at more or less close intervals from this well, were examined and described in detail by Udden.[64] The well started near the top of the Permian red beds and was drilled to a depth of 4,489 feet. The lower 389 feet, consisting of light-colored limestone and dark-colored shale, in part bituminous, is considered by Udden to be of upper Pennsylvanian age, probably equivalent to the upper part of the Cisco formation of central and north-central Texas.

Well northwest of Matador, Motley County.—Another well about 50 miles north of the Spur well and 15 miles northwest of Matador, Motley County, Tex. (No. 48, Pls. III and XV), was completed late in 1922 by the Minneapolis Oil Corporation, of Minneapolis, Minn. Its depth is more than 4,700 feet. Samples of cuttings from depths of 3,200 to 4,200 feet were furnished by Dr. A. C. Traweek, of Matador, for examination. These samples consist of dolomitic limestone, dolomite, and shale, with some interspersed fragments of white anhydrite, and are considered to represent the equivalent of the lower Permian (Wichita formation) in the Spur well as described by Udden. No samples from the 500-foot interval between depths of 4,200 and 4,700 feet were received, but according to Dr. Traweek[65] a sandstone containing considerable gas was encountered at 4,705 feet. It is considered likely that the lower 300 or 400 feet of this well also is upper Pennsylvanian (Cisco formation).

Cain No. 1 well, Tom Green County.—The Cain No. 1 well, drilled by the Southwestern Petroleum Syndicate near San Angelo, Tom Green County, reached a depth of 4,310 feet. Regarding the lower part of this well Beede[66] states:

> The base of the Wichita in the Cain well is probably about 3,000 feet below the surface. This can not be positively stated until the Fusulinae of the central Texas region are known. It certainly should be between 2,800 and 3,000 feet; probably much nearer the latter than the former figure. If this is the case, the whole of the Strawn and Canyon is wanting here, and if the driller's diagnosis

[64] Udden, J. A., The deep boring at Spur: Texas Univ. Bull. 363, 1914.
[65] Personal communication.
[66] Beede, J. W., The geology of Coke County: Texas Univ. Bull. 1850, p. 74, 1921.

of the top of the Smithwick shales is a correct one at 3,321 feet, the Cisco is reduced in thickness from 800 feet on the Colorado River in Coleman County to about 321 feet in the Cain well, or at the very most, 525 feet.

Richardson No. 1 well, Sterling County.—The Richardson No. 1 well, near the southeast corner of Sterling County (No. 65, Pls. III and XIV), was drilled by the Texas Elkhorn Oil Syndicate to a depth of 4,143 feet. Beede tentatively places the top of the Cisco here at 2,852 feet below the surface. Regarding the lower part of the well, he says[67]:

The base of the Cisco may be 3,185 feet, or a thickness of 333 feet. Whether or not the beds below this all belong to the Smithwick shales or to the Cisco is uncertain. The known Bend occurs at 3,735 feet and continues to the bottom of the well. Several oil horizons seem to have been struck in the lower part of the well.

Stroud No. 1 well, Coke County.—The Stroud No. 1 well, drilled by the Robert Lee Oil Co. to a depth of 3,286 feet, is in Coke County near Robert Lee. Beede[68] believes that the lower 400 feet, more or less, of this well is Cisco. The identifications for this and the Cain and Richardson wells were based largely, if not altogether, upon the lithologic character shown by the well logs and the samples of cuttings collected from the wells. Practically the only fossils yet found in cuttings of lower Permian and upper Pennsylvanian age of this region are *Fusulina* and other Foraminifera.

Kuteman No. 1 well, Nolan County.—The Kuteman No. 1 well (No. 49; Pls. III, XI, and XII) is in southwestern Nolan County, 15 miles north of the Stroud No. 1 well. Its depth is 4,447 feet. The top of the sandstone that occurs at 3,700 feet is the approximate equivalent of the sandstone found at a depth of 2,986 feet in the Stroud No. 1, which Beede considers the approximate top of the Cisco. This correlation gives thickness of 747 feet to the Pennsylvanian penetrated in the Kuteman well. Very probably the lower 300 feet or more, which contains an appreciable amount of shale, is older than Cisco and may, if the Canyon and Strawn are absent, as has been suggested, represent the Smithwick shale. (See diagrammatic log, Pl. XII.)

Other wells.—Other deep wells in Fisher and Mitchell counties have been drilled nearly to the top of the Pennsylvanian, but the lithologic character recorded in their logs and that of samples collected from some of them indicate that none of those in Mitchell County have passed through all of the Wichita (1922). (See diagrammatic log of Hodges No. 1 well, Pl. XIII, and those of wells in Mitchell County, Pl. XII.)

[67] Idem, p. 75.
[68] Idem, p. 76.

PERMIAN SERIES

The Permian strata form one of the most extensively developed geologic series of Texas, and they outcrop in north-central Texas in a belt that averages nearly 100 miles in width. A list of the formations, with a general statement of their character and thickness, is given in the table on page 63. Permian beds are also found in the northern part of the Marathon region in southern trans-Pecos, where they are exposed on the summits and slopes of the Glass Mountains. (See list of formations, p. 64.) The Permian is also well developed in the mountainous portions of northern trans-Pecos Texas and southern New Mexico. (See p. 65.)

In southern New Mexico the Manzano group makes up at least the lower portion of the Permian section. Farther north in southern New Mexico Darton[69] has divided the Manzano group into the Abo sandstone below and the Chupadera formation above, the latter comprising Lee's two subdivisions, the Yeso formation and the San Andres limestone.[70] No precise correlation of these lower Permian rocks of southern New Mexico with those across the Texas line south in the Guadalupe Mountains has yet been made. Udden, Baker, and Böse[71] believe that the lower series of limestone of the Guadalupe Mountains is equivalent, at least in part, to Lee's Yeso and San Andres formations, which as stated above are the same as Darton's Chupadera formation; Darton considers the Chupadera formation equivalent to the Delaware Mountain and Capitan formations.

PERMIAN ROCKS EXPOSED

Permian rocks outcrop in two belts within this region. One is the southwestern edge of the north-central Texas Permian, which is best exposed along Colorado River in Coke County, and northwest as far as southeastern Mitchell County. The other is the eastern edge of the Permian of northern trans-Pecos Texas and southern New Mexico, where they make up the rocks of the Pecos River valley. (See Pl. X.)

Red shale, sandy shale, sandstone, and some gypsum constitute the greater part of both belts, although dolomite is common in some parts of the western belt. These belts are about 200 miles apart, being separated by the south end of the Llano Estacado.

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69 Darton, N. H., op. cit. (Bull. 726), pp. 181-182.

70 Lee, W. T., and Girty, G. H., The Manzano group of the Rio Grande valley, N. Mex.: U. S. Geol. Survey Bull. 389, pp. 12-17, 1909.

71 Op. cit., pp. 59-60.

SOUTHEASTERN MITCHELL COUNTY

The Permian in southeastern Mitchell County is composed of sandy shale and fine-grained sandstone, predominantly dark red to brick-red. In many places the thin-bedded red shale is interstratified with beds of bluish-green sandy shale, half an inch to 4 inches thick, and is irregularly marked by bluish-green streaks. According to Dodson,[72] beds of gypsum 2 or 3 inches thick may be found in certain localities along Colorado River in southeastern Mitchell County.

These Permian red beds are a continuation of the "Eskota or Greer beds" as mapped by Beede[73] in Coke County, which there consists essentially of dark-red fine-grained sandstone and fine sandy shale, with many thick beds of gypsum.

Regarding these beds Beede[74] says:

> Recent work has shown that the gypsum formerly referred to the Greer is a southwestward continuation of the Blaine formation. * * * The gypsums of western Coke County, Tex., extend north and connect up with the Blaine gypsums, so far as our present information goes.

The "Greer" formation has recently (1924) been abandoned by the Federal Survey, by the Oklahoma State Survey, and by Oklahoma geologists generally, many of the gypsum beds included in it having been found to correspond to gypsum beds included in the supposedly older Blaine formation. There is, however, in western Oklahoma and the eastern Panhandle of Texas a thick bed of gypsum underlying the Quartermaster formation and overlying the Woodward group, for which the name Cloud Chief gypsum has recently been adopted by Oklahoma geologists.[75] This gypsum occupies the stratigraphic position formerly assigned to the "Greer" formation and has heretofore been included in the beds designated by that name. The Cloud Chief gypsum, however, is younger than any of the gypsum beds in Coke County, and Beede now questions its presence in any part of Texas south of Red River.

The unconformity at the top of the Permian in northwestern Coke County and southeastern Mitchell County is believed to represent the upper part of the stratigraphic interval occupied by the Quartermaster formation, the Cloud Chief gypsum, and the Woodward group of the upper Permian, all of which are younger than the Blaine gypsum.

Following up Colorado River the red beds of Coke County continue into southeastern Mitchell County to a point within about 10 miles of Colorado City.

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[72] Dodson, F. C., personal interview.

[73] Beede, J. W., op. cit. (Bull. 1850), pp. 29-38.

[74] Personal correspondence.

[75] Gould, C. N., A new classification of the Permian red beds of southwestern Oklahoma: Am. Assoc. Petroleum Geologists Bull., vol. 8, pp. 325-341, 1924.

The following sections were taken at several points from northwestern Coke County northwestward into Mitchell County.

Section of the west point of Stepp Mountain, a remnant of the Edwards Plateau in northwestern Coke County, Tex., one-half mile south of the Mitchell-Nolan County corner

	Feet
Comanche series (Lower Cretaceous):	
Fredericksburg group:	
Edwards and Comanche Peak limestones undifferentiated:	
Gray limestone, some yellowish brown; alternating soft, chalky, impure, and hard, semicrystalline. Fossils: *Gryphaea*, *Exogyra*, and *Pecten*. Base concealed	160
Walnut limestone (concealed)	(?)
Trinity sand: Variegated sand, medium grained, loose and friable	5
Unconformity (concealed).	
Permian series:	
Double Mountain formation:	
Red and green clay and sandstone	2
Dark-brown clay	12
Dark-brown sandstone, hard	1
Concealed	4½
Dark-brown sandstone, cross-bedded	2
Concealed	2
Dark-brown sandy clay, no bedding	22
Grayish-green sandstone, soft, medium grained, and cross-bedded	6
Dark-brown clay	4
Grayish-green sandstone, hard, medium grained, and cross-bedded	2½
Concealed	1½
Greenish-gray and brown sandstone, hard and massive	7½
Greenish-gray sandstone, soft	31
Conglomerate, with sandy calcareous matrix. Chert and quartz pebbles and fragments of brown earthy limestone up to 1 inch in diameter	7½
Concealed. All probably red clay, sandstone, and shale	115

Section of round-topped hill 1¼ miles west of section at Stepp Mountain, northwestern Coke County, Tex.

	Feet
Comanche series (Lower Cretaceous):	
Fredericksburg group:	
Edwards and Comanche Peak limestones undifferentiated: Gray limestone, earthy and not very resistant. *Gryphaea* abundant	8
Walnut limestone: Yellowish-gray limestone, earthy; fragments of *Exogyra* and *Gryphaea* present; sandy near base	5½
Trinity sand: Variegated sand, coarse grained, loose, friable, and soft	6

	Feet
Unconformity.	
Triassic system (?):	
Dockum group (?):	
Brown and green micaceous sandstone and red and green clay. Minute plant fragments in green clay noted	10
Conglomerate, coarse and massive; coarse sandy matrix with rounded pebbles of flint, chert, and quartz of various colors, black flint predominating. Lenticular layers of coarse sandstone interbedded with conglomerate	15±
Unconformity.	
Permian series:	
Double Mountain formation:	
Light-gray sandstone, medium grained, soft argillaceous, and cross-bedded	11
Light-red sandstone with seams of light-red shale; cross-bedded	5
Dark-brown shale; weathers to brick-red and purple	15
Dark-brown sandstone, cross-bedded, ripple-marked; contains bluish-green splotches	1
Greenish-gray sandstone; cross-bedded	½
Dark-brown clay shale; bedding poor	6
Reddish-brown sandstone and sandy shale; cross-bedded in upper portion	26
Greenish-gray sandstone	1
Brick-red shale	5

A massive conglomerate similar to that which marks the base of the Triassic (?) in the above section was found about 12 miles to the north on the main highway from Robert Lee to Colorado City, in the northeast corner of sec. 19 of the J. P. Smith survey, where it separates typical Permian red shales from overlying dark-red clay and greenish-gray sandstone that are believed to be Triassic.

Section on south bank of Silver Creek 2 miles south of Mitchell-Coke County line and 3 miles east of Colorado River

	Feet
Permian series:	
Double Mountain formation:	
Brown sandy clay shale, with bluish-green streaks; poorly bedded, with crystalline gypsum lining bedding planes	8
Pinkish-gray limestone or dolomite, thin bedded; weathers to platy surface	6
Brown sandy clay shale	2½
Light-blue sandy clay shale	½
Purple shale; thin, paper-like bedding	½
Light bluish-green sandstone, soft	½
Brown sandy clay shale and cross-bedded sandstone	9½

At 50 feet to the west and directly underlying these beds is 1½ feet of brown sandy clay shale, underlain by more than 6 feet of light-gray massive gypsum that weathers to greenish gray.

This section is stratigraphically lower than either of the two preceding sections and represents the oldest Permian seen in this vicinity. Still older Permian rocks form the walls of the Colorado River valley farther southeast, in Coke and Runnels counties, but in a trip northwestward into Mitchell County only the youngest Permian beds of this region are to be seen.

At the southwest corner of sec. 3, block 12, Houston & Texas Central Railway survey, Mitchell County, about 15 feet of thin-bedded brick-red shale is exposed. Beds of bluish-green shale, half an inch to an inch thick, are interstratified with the red shale.

At the southeast corner of sec. 11 of the same block 2½ feet of thin-bedded brick-red and bluish-green shale is exposed. From 1 mile to 3 miles to the north, bordering a creek on the southeast, is a series of low round-topped hills that are composed largely of brick-red to darker red shale and sandstone.

In a low hill at the southwest corner of sec. 40, block 12, the following Permian rocks are exposed:

Section at southwest corner of sec. 40, block 12, Houston & Texas Central Railway survey

	Feet
Dark brown clay, no bedding; contains irregular splotches and streaks of bluish-green color	18
Massive brown sandstone, medium coarse grained, cross-bedded throughout; changes laterally to gray within 40 feet	1
Brown shale with good bedding; base concealed	1±

A road exposure at the northwest corner of sec. 41 shows the following beds:

Section at northwest corner of sec. 41, block 12, Houston & Texas Central Railway survey

	Feet
Gray and red sandstone, massive; top 10 inches cross-bedded	3
Shale, mostly dark red but containing bluish-green beds half an inch to 2 inches thick; exceptionally well bedded, showing a distinct contrast to the red clay and clay shale of the Dockum group farther north	3½

Similar exposures were noted in the creek channel 500 feet to the south and on the highway along the south side of sec. 41.

The Permian as exposed farther northwest along Colorado River was not examined in detail. With the exception of the immediate valley of the Colorado and its tributaries, this part of Mitchell County is covered by the Dockum group (Triassic). In portions of eastern Mitchell and Scurry counties Permian rocks are probably exposed at the surface. Permian red shale and sandstone occur to the north, in the valley of the Double Mountain Fork of Brazos River, in south-central Kent County.

PECOS VALLEY, NORTHWESTERN TEXAS AND SOUTHEASTERN NEW MEXICO

GENERAL FEATURES

Along Pecos River on the west and in the river bed itself (see Pl. VI, *B*) are exposed Permian rocks consisting largely of gray dolomite, with numerous beds of gray and red sandstone, red shale, and grayish-white gypsum. These rocks all appear to belong to the Rustler limestone of northern trans-Pecos Texas, although the occurrence of thick beds of gypsum in their lower part suggests the presence of the underlying Castile gypsum, which has been mapped by Richardson within 4 miles of the river. The rocks described are of younger Permian age than Darton's Chupadera formation of southern New Mexico, which Darton has traced into the Capitan limestone and Delaware Mountain formation of trans-Pecos Texas.[76]

The Rustler limestone forms the prominent Rustler Hills, in northeastern Culberson County. The uneven topography produced by the unequal erosion of the alternating hard and soft strata of this formation extends northward along the west side of Pecos River at least as far as Carlsbad. Low-lying hills, capped by beds of dolomite, are to be found also in northwestern Reeves County for a distance of 10 to 15 miles south of the Texas-New Mexico State line.

The following section illustrates the character of a portion of these beds as they are exposed about 10 miles south of Malaga, Eddy County, on Red Bluff Arroyo near the station of Red Bluff. (See Pl. VI, *A*.)

Section of Rustler limestone at Red Bluff, Eddy County, N. Mex., 10 miles south of Malaga

	Feet
Yellowish-gray dolomite, in beds 2 inches to 2 feet thick	30±
Light-green clay; no bedding	1
Red sandy shale; poor bedding	2±
Grayish-white gypsum, massive	7±
Dark-red sandy shale; fair bedding with many bedding planes lined with gypsum	10±
Light-green sandstone; soft, of medium texture and cross-bedded	15+

Massive beds of sandstone are well exposed in the bed of Pecos River near the State line. East of the river, in this locality, few, if any, exposures are to be found except in the immediate vicinity of the river bed, for in this direction, both north and south of the State line, the surface is covered with loose residual and wind-blown sand.

[76] Darton, N. H., Geologic structure of parts of New Mexico; U. S. Geol. Survey Bull. 726, pp. 181-182, 1922.

Along Pecos River just east of Malaga, Eddy County, is a series of low bluffs exposing red beds composed largely of shale, sandy shale, and sandstone. Gypsum and limestone are less abundant than across the river to the west and southwest. Similar red beds are exposed to the northeast as far as the Eddy-Lea County line in T. 20 S., but here, where noted, the gypsum and limestone beds are entirely lacking. Some distance to the north, near Lakewood, Eddy County, Fisher[77] measured the following section just east of Pecos River:

Section near Lakewood, Eddy County

	Feet
Massive gray limestone	35
Gypsum and red sandstone in alternating layers, with a few limestone ledges	50
Gypsum with thin-bedded porous limestone and red sandstone arranged alternately, the gypsum predominating	150
Gypsum with thin layers of gray limestone	50
	285

STRATIGRAPHIC RELATIONS OF THE RED BEDS OF PECOS VALLEY

As the regional dip is east-southeast and as consecutively younger beds are exposed toward the east, it might seem that the disappearance of the limestone and gypsum in that direction is due to vertical change from lower strata consisting predominantly of limestone and gypsum with some red beds to higher red shale and sandstone. There is, however, strong evidence of lateral change.

Near Carlsbad, N. Mex., according to Beede,[78] 200 or 300 feet of limestone and other strata separate the underlying Capitan limestone from the red beds of Pecos Valley. The strata referred to apparently correspond to the Rustler limestone and possibly the Castile gypsum. It is certain that the dolomite and limestone of the Rustler and probably the massive Castile gypsum also grade laterally on the east and southeast into some part of a series composed largely of red shale, sandstone, gypsum, rock salt, and anhydrite. (See upper parts of logs of Bluebird and Andrews wells, Pl. XII; Andrews and Means wells, Pl. XVI; and Bell and Toyah-Bell wells, Pl. XI.)

The Rustler, as exposed at the surface from its type locality in the Rustler Hills northeastward to the Red Bluff section (p. 73), changes from a formation consisting predominantly of dolomite and dolomitic limestone, with only a few sandstone beds, to one containing a large amount of sandstone, gypsum, and red shale in addition to the still abundant dolomite.

These facts strongly suggest that the red beds exposed and buried east of Pecos River in Eddy County are equivalent, at least in part,

[77] Fisher, C. A., Preliminary report on the geology and underground waters of the Roswell artesian area, N. Mex.: U. S. Geol. Survey Water-Supply Paper 158, p. 7, 1906.

[78] Beede, J. W., The correlation of the Guadalupian and the Kansas sections: Am. Jour. Sci., 4th ser., vol. 30, pp. 132-133, 1910.

to the Rustler limestone west of the river, or to that part of the Rustler which has been removed by erosion. Just how much of these red beds is equivalent to the Rustler is not known. Some of them are probably younger, but all those east of Pecos River in the southern half of Eddy County are believed to be upper Permian or Triassic older than the Dockum group. The only fossils that have been found were taken from limestone near the river, none having thus far been reported from the red beds to the east. Fisher[79] found *Schizodus* and *Pleurophorus* in a limestone near what he considered to be the base of the Rustler northwest of Roswell. Near Lakewood Beede[80] found five or six species in a limestone that probably belongs to the upper part of the Rustler. He says:

They consist of *Cyrtodontarca? parallellidentata?*, *C.?* sp., another pelecypod, the cast of an ostracode, and some minute gastropods from 1 to 3 millimeters in length badly preserved as molds.

The thickness of that portion of the red beds of Pecos Valley herein considered to be Permian is at least 500 feet.

Beede[81] has correlated, by fossil and lithologic evidence, all beds above the Capitan limestone in the Pecos Valley with Permian beds that east of the Llano Estacado, in western Oklahoma and the Panhandle of Texas, overlie the Whitehorse sandstone of the Woodward group. This correlation would make the gypsum-bearing beds of the Rustler (and the Castile gypsum, if that formation should prove to be younger than the Capitan) roughly equivalent to the Cloud Chief gypsum and possibly a part of the overlying Quartermaster formation, which also contains thick beds of gypsum. If correlation is continued upward the upper part of the Permian red beds of Pecos Valley, consisting of red shale and sandstone, would possibly be the westward extension of the upper part of the Quartermaster. Richardson[82] says

that the red beds of Pecos Valley constitute a variable group, the base of which is not a definite horizon, the occurrence of the red color extending irregularly across the strike of the rocks; and that the upper part of the red beds of Pecos Valley is equivalent to the upper part of the Permian red beds of northwest Texas and Oklahoma.

It seems probable that the youngest Permian red beds of Pecos Valley in Eddy County, N. Mex., are in part equivalent to the upper Permian red beds of southeastern Mitchell County, Tex. According to Beede's recent work in correlating the gypsum directly underlying the beds of southeastern Mitchell and northwestern Coke

[79] Fisher, C. A., op. cit., pp. 7–8.
[80] Beede, J. W., op. cit., p. 136.
[81] Idem, pp. 131–140.
[82] Richardson, G. B., Stratigraphy of the upper Carboniferous in west Texas and southeast New Mexico: Am. Jour. Sci., 4th ser., vol. 29, p. 337, 1910.

County with the Blaine gypsum, which underlies the Woodward group farther north and is considered to correspond to about the middle of the Double Mountain formation,[82a] the Permian red beds of southeastern Mitchell County would appear to be in part equivalent to and in part older than the red beds of Pecos Valley, Eddy County.

SUBSURFACE PERMIAN ROCKS

GENERAL FEATURES

With the few exceptions previously noted in the discussion of the Pennsylvanian (pp. 66–67), all rock strata penetrated by wells drilled within this region are of Permian age or younger. It should be remembered that Permian rocks exposed in north-central Texas and in northern trans-Pecos Texas have a total thickness of over 5,000 feet, and in the Glass Mountains to the south, nearly 11,000 feet. Darton records the total thickness of the Manzano group in southern New Mexico as 1,200 to 3,900 feet, but in view of the greater thickness of the Permian a few miles south on the State line, it is probable that in the southernmost part of New Mexico it is at least 4,000 feet thick; although farther north, according to Darton's figures, it thins appreciably. Bordering the region here considered, then, on the east, south, and west are Permian strata with a thickness of 4,000 to 10,900 feet, which pass below the younger rocks that form the surface of the High Plains. As is suggested by the correlation of well logs in various directions across these plains (see Pls. XI, XV, XVI), the bordering Permian strata dip toward the center of a large geosyncline that underlies the southern part of the High Plains in western Texas. Wells drilled on the plains penetrate, first, either the surface sand and Pliocene (?) gravel, 25 to 50 feet thick, or, in the extreme southern part, the lowermost 50 feet, more or less, of the Comanche limestone and sandstone; second, 300 to 1,200 feet of red clay and red and gray fresh-water sand belonging to the Triassic (Dockum group); and third, Permian strata consisting of red and blue shale, sandstone, and gypsum in the upper 500 to 1,000 feet and red shale, sandstone, limestone, rock salt, and anhydrite in the succeeding 300 to 4,000 feet. This series containing salt and anhydrite is thinnest near the eastern and southeastern borders and thicker farther west. West of the south end of the plains, in the eastern part of the broad Pecos Valley, it attains a thickness exceeding 4,000 feet. Three deep wells near Pecos River in Loving and Reeves counties have penetrated all of this series and from 200 to 500 feet of underlying rocks consisting largely of sandstone but having a dark dolomitic limestone at their top. It is quite certain that all these rocks are Permian.

[82a] Gould, C. N., Index to the stratigraphy of Oklahoma: Oklahoma Geol. Survey Bull. 35, chart (compiled by U. S. Geol. Survey), 1925.

Wells drilled north of Pecos River and south of parallel 33° 30′ N., between meridians 102° and 103° W., will probably not penetrate the entire salt-anhydrite series at a depth less than 4,500 feet. It is more probable that in the longitude of Ector County and eastern Winkler County, where the overlying Triassic red beds are believed to have their maximum thickness, the base of this series will be found considerably below this depth. Exceptions to the two preceding statements will probably be found in southern Crane and Upton counties and northwestern Crockett County. The top of the Pennsylvanian in this region is believed to lie at a depth below 6,000 feet.

DEEP WELLS

In western Texas and southeastern New Mexico, as in other parts of the mid-Continent region, wells have been drilled for oil. In the eastern part of the area, in Scurry, Mitchell, and Howard counties and northern Glassock County, wells are more numerous than elsewhere and offer opportunity for subsurface correlations of a more reliable nature although even here, owing to the varying lithologic character of the underlying sediments, correlations can not be accepted as certain. Farther west and southwest wells are widely scattered, and a number of counties are altogether devoid of wells other than shallow ones drilled for water. In fact, there is a belt 100 miles wide and 200 miles long, extending along the eastern boundary of southern New Mexico and lying partly in New Mexico and partly in Texas, in which no deep wells have been drilled. This lack is due largely to poor transportation facilities and in less degree to the generally unpromising character of the underlying rocks as a source of petroleum. A number of wells have been drilled farther west, along Pecos River.

The location of all deep wells known to have been drilled within the region here described (1922) and also as far north as parallel 34° north in the same longitude are shown on the structure-contour map (Pl. XVII) and salt-thickness map (Pl. III). The locations of a few of the most representative wells in the Panhandle are also shown. A list of these wells, numbered in alphabetic order of the counties, is given on pages 116–118.

INFORMATION FROM WELL LOGS

METHODS OF CORRELATION

Diagrammatic logs of the most critical wells of the region are shown in Plates XI–XVI. Each plate represents the correlation of the records of wells drilled on or near a definite line, such as *A–A′*, *B–B′*, *F–F′*, shown on the structure-contour map (Pl. XVII). The records of wells that lie some distance off the correlation line have been projected at right angles to it by shifting them either up or down from their true position in accordance with the probable structure of the top of the salt beds of the region, which is shown by the structure contouring. This has produced an untrue representation of the structure of the overlying beds, which are unconformable upon the Permian.

STRATIGRAPHY

The separation of the Permian strata underlying the High Plains into stratigraphic divisions equivalent to those that have been made where Permian strata crops out is difficult. It appeared possible and quite worth while, however, to make tentative divisions of the logs of the easternmost wells in this region, identifying, as closely as possible, the strata that represent the divisions of the Permian of central and north-central Texas. The stratigraphic continuity or discontinuity of these divisions, as tentatively identified in the records of wells farther west, could then be studied.

Consequently, the logs of three wells near the eastern edge of the area have been divided tentatively, the divisions corresponding, in general, to those of the areas where the rocks are exposed. These wells are the Kuteman (Pls. XI and XII), in southwestern Nolan County; the Hodges No. 1 (Pl. XIII), in southwestern Fisher County; and the Richardson (Pl. XIV), in southeastern Sterling County.

The divisions of the Kuteman well are, from top to bottom, lowermost limestone of the Fredericksburg group, Trinity sand, Dockum group(?), Double Mountain and Clear Fork formations, Wichita formation, and Cisco formation. (See Pl. XI.) The lithologic character of the strata, as given in the well log, is the sole basis for this division. It is in general accordance with the character of the rocks where exposed in this region, as described by Beede,[83] Beede and Waite,[84] Wrather,[85] and others, and the divisions may be satisfactorily correlated with similar divisions made by Beede[86] in wells of Coke, Sterling, and Tom Green counties. The Canyon and Strawn formations of the Pennsylvanian may be present but are herein tentatively omitted in accordance with evidence presented by Beede. The separation of the upper Permian in the Kuteman well into the Double Mountain and Clear Fork formations has not been attempted, but the base of the Double Mountain is probably about 1,200 feet below the surface.

The Hodges No. 1 well, in southwestern Fisher County (No. 22, Pls. III and XIII), is on the outcrop of the upper part of the Double Mountain and penetrates strata which, to a depth of 3,070 feet, are probably all Permian. The lower 433 feet, consisting almost wholly of sandstone, limestone, and sandy limestone, is apparently the

[83] Beede, J. W., and Bentley, W. P., The geology of Coke County: Texas Univ. Bull. 1850, 1921

[84] Beede, J. W., and Waite, V. V., The geology of Runnels County: Texas Univ. Bull. 1816, 1918.

[85] Wrather, W. E., Notes on the Texas Permian: Southwestern Assoc. Petroleum Geologists Bull., vol. 1, pp. 93-106, 1917.

[86] Beede, J. W., and Bentley, W. P., op. cit., pp. 71 et seq.

equivalent of the lower part of the Kuteman well and is tentatively referred to the Cisco.

The divisions of the Richardson log, except those in the upper part, are Beede's. In correlating the salt beds and lower limestones of wells to the northwest (line *D–D'*, Pl. XIV) with the Richardson well, it has been concluded that the upper 500 feet, more or less, which appears to be the equivalent of the major part of the salt beds to the northwest, is probably Double Mountain instead of Clear Fork as tentatively classified by Beede. According to this correlation the gravel bed at the top of the well is then either a surface deposit of probably Recent age or a part of the Double Mountain. The "white lime" at 500 to 540 feet recorded in the driller's log may represent the Merkel dolomite of Wrather, and its top is tentatively considered the top of the Clear Fork.

Logs of wells along lines *A–A'*, *B–B'*, and *C–C'*, Plates XI, XII, and XIII, respectively, are correlated westward across the plains, from the Nolan and Fisher County wells to wells drilled along the Pecos Valley in southeastern New Mexico and western Texas. These wells, where closest together, are separated by an average distance of nearly 20 miles, and the correlations can be considered as only approximate. It is not the purpose of these subsurface cross sections to show correlations in detail, but to portray diagrammatically the lithologic character of the subsurface Permian and associated rocks revealed by records of drilled wells, to show an attempted correlation of major divisions of these rocks from east to west under the High Plains, and to disclose the possibilities of different correlations than the one herein represented.

Although it is believed that the identifications of the major divisions of the Permian (the Wichita, Clear Fork, and Double Mountain formations) in the Kuteman, Hodges, and Richardson wells are approximately correct, there can be no certainty that the correlation charts show the extensions of these divisions westward. In the eastern part of the region, where wells are more closely spaced, the thin salt beds were found to be fairly reliable for use as a key horizon in correlation. It seems reasonable to believe that the westward time equivalents of these eastern salt beds lie somewhere within the 5,000 feet of the salt, anhydrite, and red bed series near the southeast corner of New Mexico. The correlations indicated by the dashed lines represent only a possibility and are based on the suppositions that the highest salt beds are everywhere equivalent in age and that the rate of westward dip through Mitchell County does not abruptly increase farther west. These suppositions may prove to be erroneous, but as beds can be correlated only by a comparison of either their fossil content or their lithologic character and stratigraphic relations, and as practically nothing is known of the fossils from the subsurface

Permian beds of this region, lithology and stratigraphy must be the basis of any attempted correlation. Until the variations in the microscopic fauna of the Texas Permian and their significance are known, no unquestionable correlation can be made. The cross sections have their greatest value in revealing the character of subsurface rocks and the possibilities of correlation.

Although Permian rocks are not well exposed for a considerable distance west of Pecos River in Reeves County, their attitude in Culberson County suggests that the Delaware Mountain formation should occur at considerable depth east of the Pecos—probably in the lower part of the Toyah-Bell well (No. 38, Pls. XI and XVI) and the Means well (No. 37, Pl. XVI). The beds penetrated in the upper parts of these wells are probably equivalent to the Capitan, Castile, and Rustler formations. If the Rustler is equivalent to the beds above the Woodward group which correspond to the upper part of the Double Mountain, as suggested by Beede in 1910, the underlying Capitan limestone and Castile gypsum of northern trans-Pecos Texas, together with the Delaware Mountain formation, may be equivalent to the lower part of the Double Mountain, the Clear Fork, and the Wichita formations of north-central Texas.

Beede[87] in 1920 correlated the Wichita formation with the Chupadera formation of southern New Mexico. Darton has traced the Chupadera, the upper formation of the Manzano group, southward into the Capitan and Delaware Mountain limestones of the Guadalupe Mountains of Texas. On the basis of this work the Capitan and Delaware Mountain formations of northern trans-Pecos Texas would appear to be equivalent to at least the upper part of the Wichita formation. However, different correlations by Böse and Beede give different results. Böse's study of fossils from the Permian of north-central Texas and the trans-Pecos country has led him to consider the upper part of the Double Mountain probably equivalent to the Word formation of the Glass Mountains and to the Delaware Mountain formation of northern trans-Pecos Texas.[88] Beede,[89] in 1920, made similar correlations. If the recognition of the Delaware Mountain formation in the lower parts of the Toyah-Bell, Bell, and Means wells was certain, the former correlations by Beede and Darton would indicate that the correlation line representing the top of the Wichita (Pl. XI) has been carried too deep to the west, whereas the later correlations by Böse and Beede would mean that such correlation lines, especially the one representing the bottom of the Double Moun-

[87] Beede, J. W., Correlation of the upper Paleozoic rocks of the Hueco Mountain region of Texas: Science, new ser., vol. 51, p. 494, 1920; Notes on the geology and oil possibilities of the northern Diablo Plateau in Texas: Texas Univ. Bull. 1852, p. 30, 1920.

[88] Böse, Emil, Carboniferous ammonoids of the Glass Mountains: Texas Univ. Bull. 1762, p. 26, 1917.

[89] Op. cit. (Bull. 1852), pp. 31, 32.

tain, has not been carried deep enough to the west, and that all of the salt belongs to the Double Mountain formation.

In order to simplify the discussion of the Permian rocks underlying the southern part of the High Plains region of Texas they will be described as the probable westward equivalents of the major divisions of central and north-central Texas—that is, the Wichita, Clear Fork, and Double Mountain formations—but the boundaries between the formations are located only approximately and are therefore queried on the logs. Even though these tentative correlations are only approximate, the following descriptions will illustrate the type of variation which occurs from east to west in the subsurface Permian of western Texas.

This tentative correlation of approximate stratigraphic equivalents will not only prove useful in the present discussion but, it is hoped, will stimulate more detailed studies of the hidden stratigraphy of this region. Because of the present incomplete knowledge of the paleontology, lithologic continuity, and structure of western Texas, this attempt at an identification of known Permian formations in wells so widely separated may be viewed with skepticism. It is believed, however, that the correlations have not been carried to extremes, and it seems likely that in greater part they are approximately correct.

WICHITA FORMATION

The character of the beds classified as Wichita formation in the Kuteman well (No. 49, Pls. XI and XII) is similar to that of the section of the Wichita in Runnels County given by Beede and Waite.[90] With the exception of the upper 300 feet, which is largely shale, the beds consist of limestone. Their thickness is 1,530 feet, as compared with 1,690 feet in Runnels County. In the Hodges well (No. 22, Pl. XIII), 40 miles north of the Kuteman well, the beds tentatively assigned to the Wichita contain more sandstone and shale throughout, but limestone still makes up 75 per cent of the formation. This increase in the amount of sandstone and shale to the north is to be expected, for in north-central Texas the Wichita consists almost entirely of these clastic sediments. Udden's lower Permian in the Spur well (No. 13, Pl. XV) is largely dolomite and shale, with some sandstone and anhydrite. The thickness assigned to the Wichita in the Hodges well is 1,245 feet and shows a progressive thinning from Runnels County and the Kuteman well.

In the section along line *A–A′* (Pl. XI) the beds assigned to the Wichita show little change of character westward. In the Brennand well (No. 64, Pl. XI), northwestern Sterling County, they contain a little shale in their central portion, but in the McDowell well (No. 29,

[90] Op. cit., pp. 10–45.

Pl. XI), in northern Glasscock County, the beds penetrated are altogether dolomite or dolomitic limestone. In both these wells the dolomite or dolomitic limestone is bituminous, and in the McDowell well about 10 barrels of oil a day was for several months produced from the upper part. The bottom of the Bryant well (No. 40, Pls. XI and XV), Midland County, is believed to be near the top of the Wichita formation but may be stratigraphically higher.

The Toyah-Bell well (No. 38, Pl. XI), in southwestern Loving County, was drilled into 330 feet of strata consisting largely of sandstone but with a dark limestone at the top, which are wholly unlike the overlying Permian. The overlying series of red beds, salt, anhydrite, and anhydrite with dolomite is believed to be contemporaneous with the Rustler limestone, Castile gypsum, and Capitan limestone of the northern trans-Pecos region. The lower 330 feet, below 4,270 feet in depth, probably represents the Delaware Mountain formation.

In the section along line *B–B'* (Pl. XII), the limestone assigned to the Wichita is seen to change to a series of limestone, sandy limestone, sandstone, and shale, as shown by the logs of wells in Mitchell and Howard counties particularly the Morrison-T. & P. (No. 45), the Read (No. 33), and the Quinn (No. 32).

In the section along line *C–C'* (Pl. XIII) there is little change to be noted in the Wichita west from the Hodges well (No. 22). The bottom of the Snyder well (No. 62) is probably near the top of the Wichita; the Reynolds well (No. 4) is believed to be near the base.

The logs of two deep wells in the central part of the High Plains have been connected by lines of tentative correlation in section *D–D'* (Pl. XIV), to those of wells farther southeast and finally to that of the Richardson well in Sterling County. Only one of these two wells, the Bledsoe (No. 31), has been drilled into beds considered to be Wichita. Owing to the isolation of this well it is not possible, from the lithologic character recorded in the well log alone, to do more than guess at the position of the top of the Wichita and other divisions of the Permian. The writer has no record of much of the lower 600 feet. Probably the lower 1,000 feet, more or less, is Wichita. The upper part of this lower 1,000 feet consists of dolomitic limestone, anhydrite, and shale, with a minor quantity of rock salt.

To sum up, the Wichita formation of the Permian in Runnels County may be said to consist largely of limestone in the lower 1,250 feet and shale with some limestone in the upper 450 feet; as identified in wells to the west, in northern Sterling and Glasscock counties, a decrease in the amount of shale in the upper part is the only important change in the Wichita, though the base has not been penetrated; in southern Sterling County the lower part becomes very sandy; and to the northwest, in Mitchell, Howard, western

Borden, Scurry, and western Fisher counties, and as far northwest as Dickens County, sandstone, sandy limestone, and shale make up a considerable part of the Wichita rocks.

CLEAR FORK AND DOUBLE MOUNTAIN FORMATIONS

The Clear Fork formation as exposed in Runnels and Coke counties[91] and along the Texas & Pacific Railway in northern Taylor and Nolan counties[92] is a series of shale and clay, mostly red, with some sandstone, dolomite, and limestone. The Double Mountain formation, in Coke and Mitchell counties, consists of sandstone, sandy shale, and shale, mostly red, with numerous thick beds of gypsum.

In the Kuteman well (No. 49, Pls. XI and XII) limestone is abundant in the lower part of the beds referred to the Clear Fork and Double Mountain formations, and it would appear from the driller's log that only limestone and one bed of gypsum occur in the upper part. Most if not all of these upper strata, recorded as "white lime" and "gray flint shale" by the driller, are probably beds of anhydrite, and they have been so entered in the diagrammatic reproduction of this log and others. This assumption may be false for some of the logs, but repeated examinations of samples taken from a number of wells have proved that the driller is commonly not familiar with anhydrite and, because of its hardness and general limy appearance, enters it in his log as "lime," "white lime," "limestone," or "flint." Anhydrite, when broken up by the drill, has the appearance of fine sand and is sometimes classed as such by the driller.

In the Hodges well (No. 22, Pl. XIII) limestone is more abundant in the upper part of the Clear Fork, but with this exception and the one given above, the Clear Fork and Double Mountain part of the Permian in both the Kuteman and Hodges wells is similar to the surface section in Runnels and Coke counties. In the Richardson well (No. 65, Pl. XIV) there is no difference worthy of note.

When these upper Permian divisions are traced westward and northwestward from these wells in western Fisher and Nolan counties and eastern Sterling County the most noticeable feature is the appearance of strata of rock salt which come in first in that part referred to the Double Mountain. Intercalated with the salt are beds of anhydrite, red shale, sandy shale, sandstone, and conglomerate. Rocks referred to the Clear Fork contain much anhydrite and some rock salt in the upper part, and, if the correlation is followed westward to a point near the center of the south end of the western Texas geosyncline, both salt and anhydrite are found to be common to the entire thickness herein referred to the Clear Fork.

[91] Beede, J. W., and Bentley, W. P., op. cit., pp. 16-19.

[92] Wrather, W. E., Notes on the Texas Permian: Southwestern Assoc. Petroleum Geologists Bull., vol. 1, pp. 97-99, 1917.

This condition is best shown by the correlation along line *A–A′* (Pl. XI). The first change noticeable in the Clear Fork as it is thus traced westward is the increase in the amount of limestone over that of shale. (See logs of Brennand well, No. 64, and Cushing well, No. 28.) Farther west, in the McDowell well (No. 29), samples of cuttings show that most of the limestone has graded laterally into anhydrite or anhydrite with dolomite. The log of the Brunson well (No. 27) in major divisions is considered reliable but is only an approximation, for it was given from memory by Mr. Brunson. Red shale and salt form the beds regarded as equivalent to the Clear Fork. In the Bryant well (No. 40) much salt and what is probably anhydrite and limestone, together with red shale, sandy shale, and sandstone, are included in the Clear Fork.

Rock salt and anhydrite are characteristic of the Double Mountain in all parts of this western Texas region, but, so far as known, they are common to strata herein grouped as comprising the entire Clear Fork only in that part lying west of central Glasscock and Howard counties. In the Bryant well the thickness of strata considered to be Clear Fork and Double Mountain is approximately 3,100 feet, as compared with about 1,850 feet in the Kuteman well.

In the wells drilled farther northwest (see section *D–D′*, Pl. XIV) notable thicknesses of rock salt are apparently confined to the Double Mountain, but thin strata of salt and probably also considerable anhydrite occur in the Clear Fork.

THE BURIED SALT-ANHYDRITE SERIES OF THE PECOS VALLEY

Section *F–F′* (Pl. XVI) and Figure 3 show the thickness and general stratigraphic relations of the buried salt-anhydrite series of the Pecos Valley. To the southeast and to the northwest this series grades into strata consisting largely of limestone or dolomite, with minor quantities of sandstone and shale.

Except in northern Pecos County, Tex., and in two wells in New Mexico, one near Carlsbad, Eddy County (No. 16), and the other 13 miles north of Roswell, Chaves County (No. 8), no rock salt has been reported west of Pecos River. This is certainly remarkable in view of the fact that the thickest deposits of rock salt known in America, aggregating over 1,000 feet, have been encountered by wells within a few miles of the river on the east.

The west end of section *A–A′* (Pl. XI) reveals the abrupt disappearance of approximately 1,000 feet of salt in a distance of 8 miles. The Toyah-Bell well (No. 38) passed through 1,024 feet of salt interstratified with approximately 2,550 feet of anhydrite and anhydrite with dolomite. The Ira J. Bell well (No. 58), 8 miles west of the Toyah-Bell, encountered less than 15 feet of salt in its upper 2,600 feet and not much more in the next 1,900 feet. The information concerning the scarcity of salt in the Bell well is reliable, for a complete set of samples of the cuttings, taken at intervals of 2 to 10 feet to a depth of more than 2,600 feet, was carefully examined. The entire interval of 3,570 feet represented by salt, anhydrite, and anhydrite with dolomite in the Toyah-Bell well contains practically no salt in the Bell well, but instead is composed almost entirely of anhydrite in the upper part and of anhydrite with dolomite in the lower part.

The Toyah-Bell is only one of three wells just east of Pecos River which have encountered great thicknesses of salt. The River well (No. 67, Pl. XVI), in southern Ward County, penetrated about 1,130 feet of salt to a depth of 4,670 feet and was not yet through the series, and the Means well (No. 37, Pl. XVI), in Loving County, went through a total of 1,391 feet of salt. Samples of cuttings taken at 5 to 10 foot intervals through most of the salt-anhydrite series of both of these wells were examined.

The logs of the Andrews well (No. 17, Pl. XII) and the Bluebird well (No. 16, Pl. XII), near Carlsbad, N. Mex., indicate an abrupt westward thinning of salt similar to that from the Toyah-Bell to the Bell well 75 miles southeast. The Bluebird well, just south of Carlsbad, is 8 miles west of the Andrews well. It penetrated only 100 feet of salt, whereas in the Andrews well there is a total of 633 feet. Both wells passed through the salt series.

The salt, anhydrite, and red-bed series of Pecos Valley and the region to the east is believed to be equivalent, at least in part, to the Capitan limestone, Castile gypsum, Rustler limestone, and possibly the Delaware Mountain formation, of trans-Pecos Texas. That Darton considers this series in large part equivalent to his Chupadera formation of southern New Mexico is shown by his discussion of the Toltec well (No. 8), which penetrated 3,120 feet of strata consisting of dolomite, salt, anhydrite, gypsum, sandstone, and shale. He says:[93] "The deep boring 13 miles northeast of Roswell was probably in the Chupadera formation throughout. Probably, however, the top of the Abo sandstone was not far below its bottom."

From the foregoing statements and from Darton's correlations, previously referred to (p. 73), it appears that the Chupadera formation of southern New Mexico is the equivalent of the Delaware Mountain formation and Capitan limestone, and possibly also the Castile gypsum and Rustler limestone farther south in trans-Pecos Texas. Beede correlates the Chupadera and equivalent Manzano strata with the Wichita and correlates the Rustler with much younger rocks—the upper part of the Double Mountain formation.

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[93] Darton, N. H., Geologic structure of parts of New Mexico: U. S. Geol. Survey Bull. 726, p. 212, 1922.

It was not considered advisable to attempt to correlate the logs of any of the Pecos Valley wells with the Permian section as exposed in the Glass Mountains, regarding which Udden[94] says:

It is believed that the Vidrio, the Gilliam, and the Tessey formations are in part the equivalents of the Capitan limestone in the Guadalupe Mountains. Together they have a thickness of 3,800 feet, which is more than twice the known thickness of the Capitan limestone. The three formations are conformable and dip to the northwest with an angle of about 8°.

If this is so, then the three formations mentioned are probably also equivalent to a part of the salt, anhydrite, and red-bed series of western Texas. Beede has tentatively correlated the underlying Leonard and Word formations with his San Angelo formation and with the "Greer" (probably the Cloud Chief part of it) and Quartermaster.[95] Böse in 1917 had similar views, for he considered the Word formation and the Delaware Mountain formation to be equivalent to the upper part of the Double Mountain formation. Böse further considered the Wichita formation of the Permian of central Texas to correspond to the lower part of the Leonard formation, the Hess formation, the unknown strata destroyed by "Permo-Carboniferous" erosion, and the Wolfcamp formation, all of the Glass Mountains.[96]

TRIASSIC SYSTEM

GENERAL FEATURES

Triassic rocks that crop out along the eastern edge of the Llano Estacado were first described by Cummins[97] and were named Dockum "beds." Two years later Drake[98] divided the Triassic of Texas into three more or less definite beds characterized as follows:

A lower bed of sandy clay which is from 0 to 150 feet thick; a central bed or beds of sandstone, conglomerate, and some sandy clay which is from 0 to 235 feet thick; and an upper bed of sandy clay and some sandstone which is from 0 to 300 feet thick.

Gould,[99] working in the Texas Panhandle, made a different division as follows:

The Triassic red beds as exposed in the western part of the Panhandle of Texas consist of 150 to 300 feet of shale with interbedded ledges of sandstone and conglomerate. The beds as a whole may be referred to two well-differenti-

[94] Udden, J. A., Notes on the geology of the Glass Mountains: Texas Univ. Bull. 1753, p. 54, 1917.

[95] Beede, J. W., Notes on the geology and oil possibilities of the northern Diablo Plateau in Texas: Texas Univ. Bull. 1852, p. 31, 1920.

[96] Böse, Emil, The Permo-Carboniferous ammonoids of the Glass Mountains, west Texas: Texas Univ. Bull. 1762, pp. 26–27, 1917.

[97] Cummins, W. F., The Permian of Texas and its overlying beds: Texas Geol. Survey First Ann. Rept., pp. 189–190, 1890.

[98] Drake, N. F., Stratigraphy of the Triassic formation of northwest Texas: Texas Geol. Survey Third Ann. Rept., pp. 225–235, 1892.

[99] Gould, C. N., The geology and water resources of the western portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 191, pp. 21–29, 1907.

ated formations. At the base of the group are shales known as the Tecovas formation, while at the top are beds composed usually of three ledges of massive, more or less cross-bedded sandstone and conglomerate separated by red shales to which the name Trujillo has been applied.

The following section was taken by Gould:

Section on North Branch of North Canyoncito Creek, eastern Randall County, Tex.

System	Formation		Character	Thickness (feet)
Tertiary.			Sand and clay.	70
Unconformity				
Triassic.	Dockum group.	Trujillo.	Gray sandstone and conglomerate, cross-bedded, with fossil bones and plates (upper sandstone)	30
			Red and gray shales	35
			Gray cross-bedded sandstone and conglomerate, with fossil bones and plates (middle sandstone)	10
			Red shale with white bands of soft sandstone	60
			Massive cross-bedded sandstone, gray to brown, with shaly members, and conglomerate, locally three well-marked ledges with shale lentils between (lower sandstone)	75
		Tecovas.	Dark-red shale with white bands	140
			Yellow shales with iron concretions	20
			Maroon shales with iron concretions	20
			White to lavender shales	10
Unconformity				
Carboniferous (Permian).	Quartermaster.		Red shales with white bands and ledges of soft sandstone.	150

The region under consideration lies 150 to 200 miles south of the area discussed by Gould and includes only the southern portion of the exposed Triassic described by Drake.

The Triassic rocks rest unconformably upon the eroded surface of the Permian. Where they are not exposed they are probably in turn unconformably overlain by Comanche (Lower Cretaceous) sediments or by unconsolidated Cenozoic deposits.

SOUTHEASTERN LLANO ESTACADO

The Triassic beds along the eastern edge of the Llano Estacado to the south, in Borden, Scurry, Howard, and Mitchell counties, are herein considered as composed of units differing somewhat from those of either Gould or Drake. The Dockum here has a total thickness of 300 to 450 feet and consists largely of dark-red clay with interbedded layers of gray cross-bedded sandstone and coarse sandstone conglomerate. The sandstone is invariably micaceous, having bedding planes lined with small flakes, the largest about one-eighth of an inch across. The clay ranges in color from dark red to light brick-red, but the variegated shale of the lower part of Gould's Tecovas was not seen at any place within the entire area covered by this paper. Splotches and streaks of greenish-gray color are commonly abundant in the clay.

The lower part of the Dockum group near Colorado City, in Mitchell County, though predominantly red clay, contains numerous beds of massive gray cross-bedded sandstone. Toward the west, over the outcrop of the lower beds of the Triassic, the same conditions are found to exist throughout the lower portion of the group. At Signal Peak, 10 miles southeast of Big Spring, in Howard County, where the Dockum beds are capped by Lower Cretaceous sandstone and limestone, the upper 150 feet or more is made up of dark-red clay with one bed of red argillaceous sandstone 3 to 5 feet thick.

Section at Signal Peak, 10 miles southeast of Big Spring, Howard County, Tex.

Age	Group or formation	Character	Thickness (feet)
Comanche (Lower Cretaceous)	Edwards and Comanche Peak limestones.	Gray to grayish-pink semicrystalline and marly limestone	117
	Walnut limestone.	Yellowish argillaceous limestone	8
	-Local unconformity-		
	Trinity sand.	Soft, friable sandstone of variegated color	60–70
Unconformity (concealed)			
Triassic	Dockum group.	Concealed; residual surface material mostly dark-red clay	3
		Dark-red clay	52
		Dark-red argillaceous sandstone, cross-bedded, with abundant mica flakes	3–5
		Dark-red clay. No bedding and only very slightly sandy. (Valley below in dark-red clay.)	95+

Drake included within the Triassic at this locality 25 feet of the overlying sandstone, which is herein considered a part of the Trinity sand.

In northwestern Scurry County, at the edge of the Llano Estacado, where also the Triassic is capped by Comanche beds, the upper 150 feet consists entirely of red clay.

Section at edge of Llano Estacado about 20 miles northwest of Snyder, Scurry County, Tex.

Age	Group or formation	Character	Thickness (feet)
Pliocene (?).		Unconsolidated sand, gravel, and clay; unassorted and unstratified.	15
Unconformity—			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Gray coarsely crystalline and marly limestone.	158
	Walnut (?) limestone.	Concealed.	3–8
	Trinity sand.	Top concealed. Soft, friable purple sandstone.	6
Unconformity (concealed)			
Triassic.	Dockum group.	Dark-red clay; no bedding, and only slightly sandy. (More red clay with occasional beds of gray sandstone occur in stream valleys below.)	150±

It may be said, therefore, that the Dockum group in this region is divisible into two more or less distinct formations—a lower one with a maximum thickness of 275 feet, characterized by red clay and numerous beds of massive gray cross-bedded sandstone (see Pl. VII, *B*), and an upper one with a maximum thickness of 175 feet or more, consisting almost entirely of red clay. The lower formation includes the basal sandstones exposed in and near Colorado City, Mitchell County, in addition to Drake's "lower bed of sandy clay" and his "central bed or beds of sandstone" exposed near Iatan. The upper formation is approximately equivalent to Drake's "upper bed of sandy clay and some sandstone." Generally stated, these two units will hold for at least the major portion of this area. There are, however, local exceptions where rather thick beds of gray sandstone occur in the upper division and also where they are not so abundant in the lower division.

Section at Muchakooyo Peak (Pl. V, B), 4 miles southeast of Gail, Borden County, Tex.

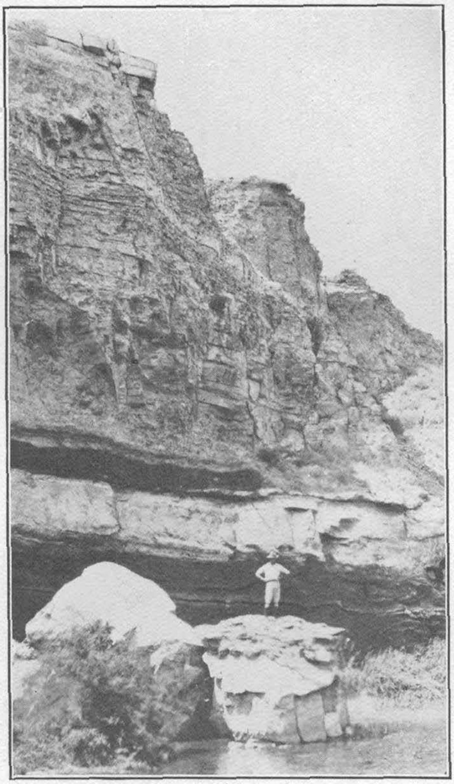
Age	Group or formation	Character	Thickness (feet)
Pliocene (?).		Unconsolidated sand, gravel, and clay; unassorted and unstratified	10±
Unconformity—			
Comanche (Lower Cretaceous.)	Edwards and Comanche Peak limestones.	Gray semicrystalline and marly limestone	115
	Walnut limestone.	Yellowish argillaceous limestone	4
	Trinity sand.	Soft, friable sandstone of variegated color; small gravel abundant throughout	35
Unconformity (concealed)			
Triassic.	Dockum group.	Dark-red clay Greenish-gray cross-bedded sandstone, very micaceous Dark-red clay with occasional beds of greenish-gray sandstone	60 10–18 100+

Section at Wild Horse Mountain, near center of east side of Howard County, Tex.

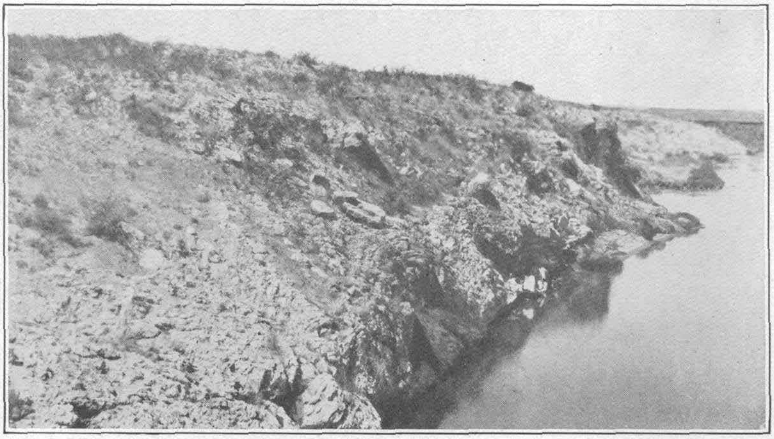
Age	Group or formation	Character	Thickness (feet)
Pliocene (?).		Loose, unconsolidated mass, consisting of sand and gravel with limestone boulders derived from erosion of Edwards and Comanche Peak limestones	10
Unconformity			
Triassic.	Dockum group.	Red clay	5
		Light greenish-gray sandstone of coarse to fine texture, beautifully cross-bedded. (See Pl. V, *C*)	10
		Coarse gray sandstone with quartz pebbles as much as 1 inch in diameter	2
		Light greenish-gray argillaceous sandstone; mica flakes abundant	3
		Dark-red clay with greenish-gray streaks; dinosaur bones, plates, and teeth	60
		Conglomerate of rounded fragments of sand and clay with some coarse sand grains	6
		Dark-red clay with greenish-gray streaks	27
		Light grayish-green sandstone, cross-bedded	3
		Red sandstone of medium coarse texture, thin bedded, argillaceous. (See Pl. VII, *A*)	36
		Dark-red clay with light-gray streaks	56
		Light-gray sandstone of coarse texture	11
		Conglomerate; contains fragments of gray limestone and pebbles 2 inches or less in diameter	2
		Light greenish yellow clay, rather sandy	2
		Dark-red clay	60+
		(Triassic below outcropping to the east contains massive beds of gray sandstone.)	

The Dockum group is of Triassic age, having been deposited after the underlying Permian red beds had probably undergone extensive erosion. As the sediments of Dockum time were thus probably laid down upon the uneven, eroded surface of the upper Permian, the thickness of the lower formation of the Dockum group may be expected to vary more or less irregularly throughout the region. After the Dockum beds had been deposited they were subjected to erosion and, no doubt, partly removed during Jurassic and early Trinity time. As a result, the upper formation varies considerably in thickness throughout the region.

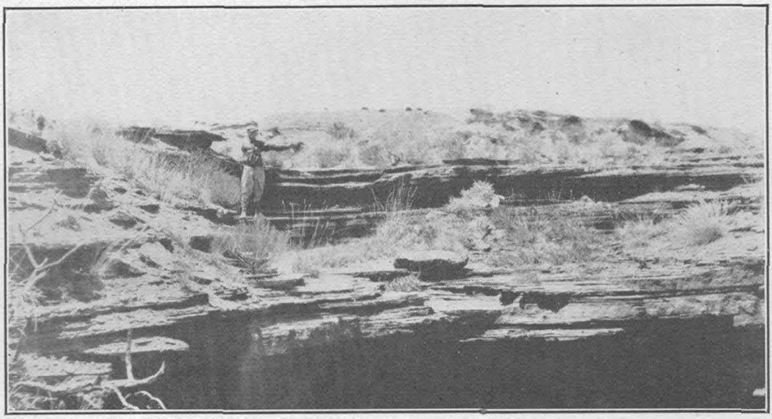
Terrestrial conditions prevalent during Triassic time did not allow for the widespread deposition of a definite division or formation having everywhere the same general lithologic characteristics. These conditions gave rise to the deposition of conglomerate and sandstone in an area near the source which grade laterally into clay. Evidence of this gradation is to be found in the rapid thickening, thinning, and lensing out of conglomerate and sandstone strata within the Dockum. It is probable, therefore, that should it become possible to make definite correlations from one locality to another, it would be found that the variation in the stratigraphic section from place to place is due partly to the lack of deposition or the removal of beds marked by the two unconformities, but principally to a lateral variation in the lithology of the beds; also, that Gould's section of the Dockum in the Panhandle region grades laterally into Drake's



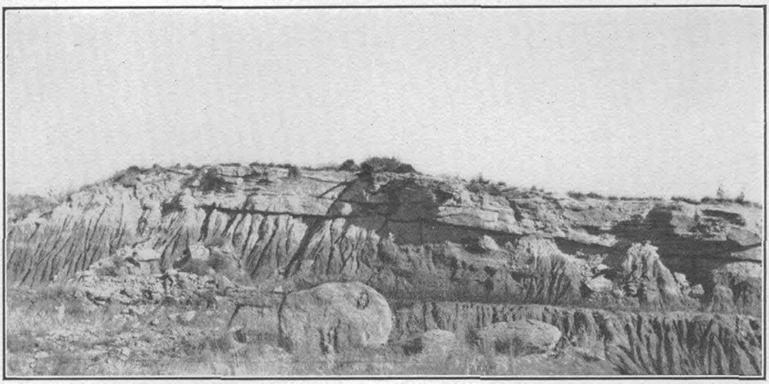
A. TYPICAL BEDS OF THE RUSTLER LIMESTONE EXPOSED AT RED BLUFF, SOUTHERN EDDY COUNTY, N. MEX.



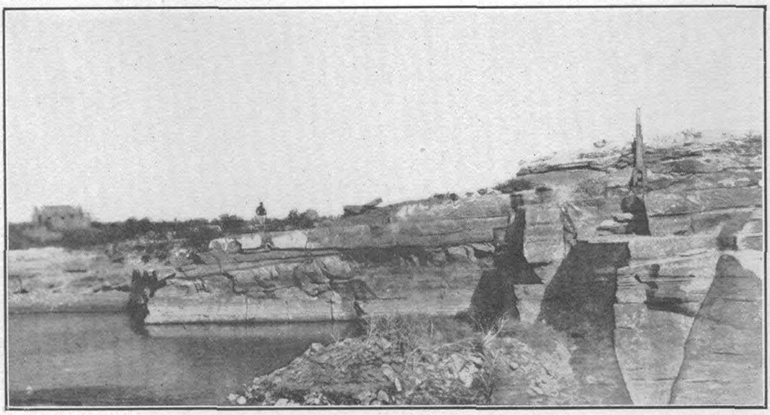
B. DOLOMITES OF THE RUSTLER FORMATION IN SOUTHERN EDDY COUNTY, N. MEX.



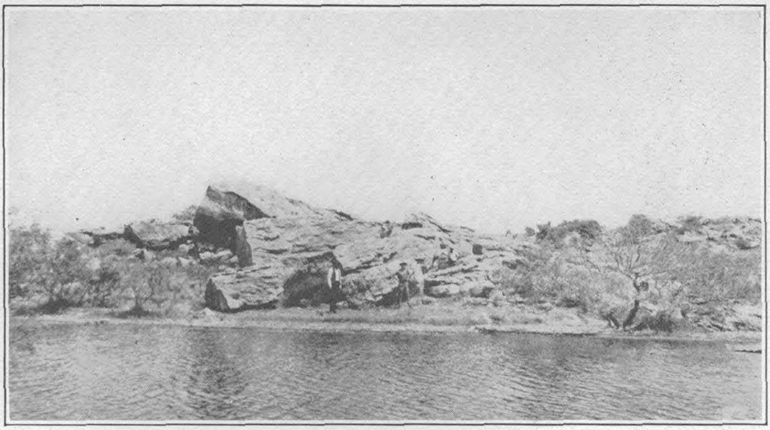
A. RED THIN-BEDDED SANDSTONE OF THE DOCKUM GROUP, WILDHORSE MOUNTAIN, EASTERN HOWARD COUNTY, TEX.



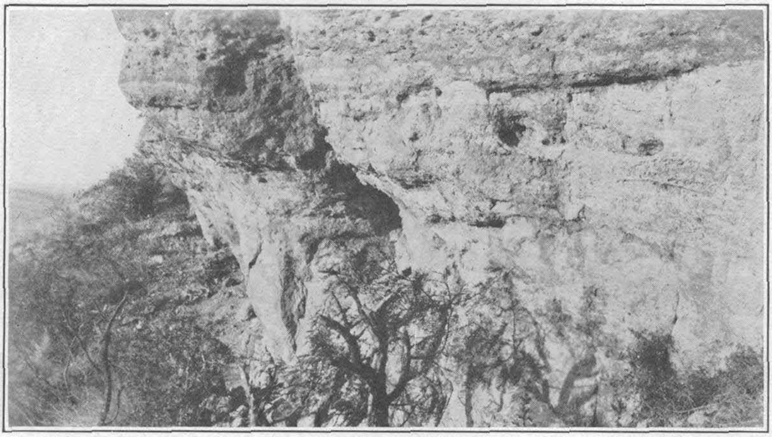
B. RED CLAY AND GRAY CROSS-BEDDED SANDSTONE OF LOWER PART OF DOCKUM GROUP NEAR IATAN, WESTERN MITCHELL COUNTY, TEX.



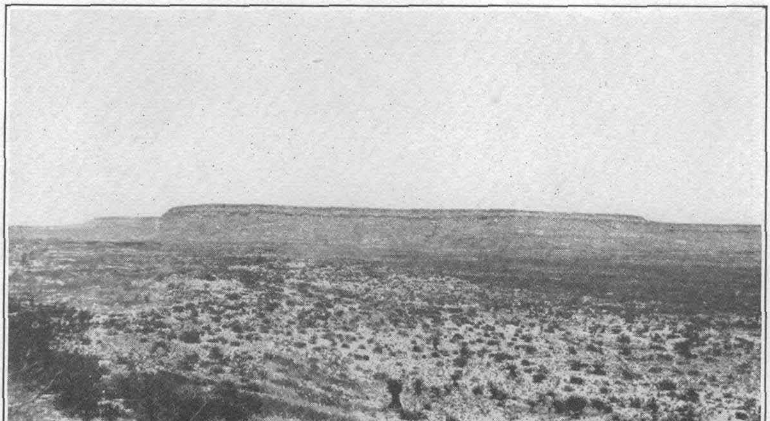
C. QUARRY OF SANDSTONE IN LOWER PART OF DOCKUM GROUP AT QUITO, WARD COUNTY, TEX.



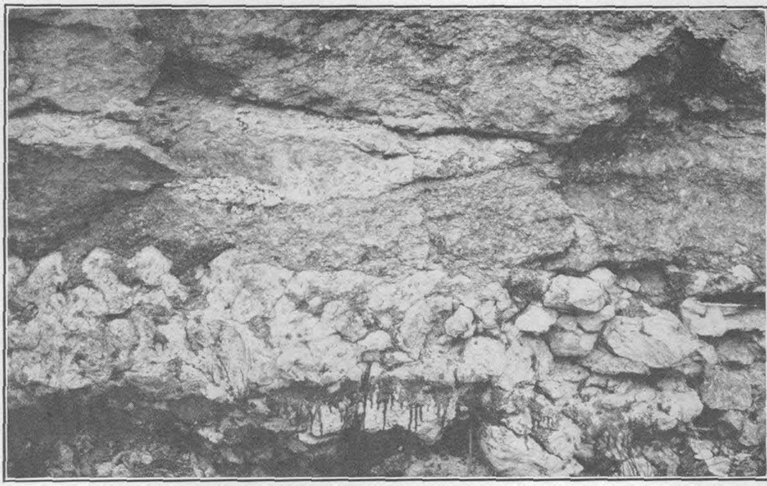
A. MASSIVE QUARTZITIC TRINITY SAND EXPOSED ALONG CONCHO BLUFF IN WESTERN ECTOR COUNTY, TEX.



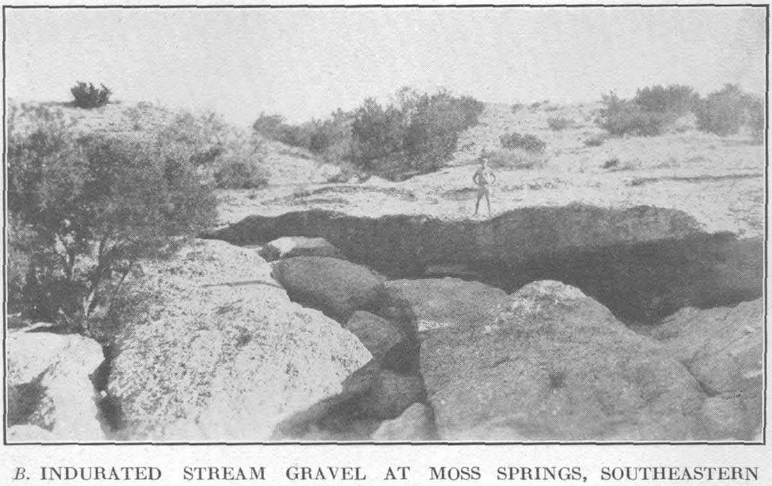
B. LOCAL UNCONFORMABLE RELATION OF THE TRINITY SAND AND WALNUT LIMESTONE, SIGNAL PEAK, SOUTHEASTERN HOWARD COUNTY, TEX.



C. WESTWARD-FACING BLUFFS CAPPED BY CRETACEOUS LIMESTONE, SOUTHEASTERN CRANE COUNTY, TEX.



A. UNCONFORMITY IN LOWER PART OF CRETACEOUS LIMESTONE, SOUTH-CENTRAL ECTOR COUNTY, TEX.



B. INDURATED STREAM GRAVEL AT MOSS SPRINGS, SOUTHEASTERN HOWARD COUNTY, TEX.

section in some areas and also into the section given above for the Scurry and Howard counties.

Fossils collected in part by the writer but largely by F. C. Dodson were submitted for identification to J. W. Gidley, of the United States National Museum, and T. W. Stanton, of the United States Geological Survey. Mr. Gidley made the following report on the vertebrate remains:

> This lot contains several teeth, a few vertebrae, and other fragments of reptilian remains determinable as follows:
>
> Cf. Phytosaurus sp., scutes and teeth.
> Palaeoctonus cf. P. orthodon Cope, teeth.
> Palaeoctonus dumblianus Cope, teeth.

Concerning the invertebrate material Mr. Stanton says:

> The invertebrates consist of several fragments of a large smooth species of *Unio* apparently differing from all the several forms of *Unio* described from the Dockum and other American Triassic formations. Unfortunately the specimens submitted do not show the beaks nor enough of the outlines of the form to serve as the basis of a specific description.

Except at one locality the Permian-Triassic contact is not, to the knowledge of the writer, exposed in this area. In southeastern Mitchell County and the extreme northwest corner of Coke County a massive basal conglomerate separates the red shale of the Permian from the overlying Triassic dark-red clay and massive greenish-gray sandstone. Although there is here presumably a considerable gap in sedimentation, no great angular unconformity exists. The Permian shale dips west-northwest at a rate averaging about 30 feet to the mile. Dips in the overlying Triassic are more or less erratic throughout. In some localities in eastern Howard County and western Mitchell County anticlinal and synclinal folding is evident, but with these exceptions the dip is in general east-southeast at a rate of about 10 feet to the mile.

PECOS RIVER VALLEY

The portion of the Pecos River valley here considered lies between the western breaks of the Llano Estacado on the east and the Guadalupe and Delaware Mountains on the west. The broad valley narrows abruptly to the south near the northwest corner of Crockett County, Tex., where the high bluffs composed of resistant Comanche limestones close in on the river from the east and the west. All Triassic exposures in this region are found northwest of this point.

Although much of the belt of outcrop of Triassic rocks is covered with unconsolidated Cenozoic material, records of water wells show the greater portion of the Triassic beds to consist of red clay. The gray micaceous cross-bedded sandstone previously described as being so common in the lower part of the Dockum of the eastern area is not so abundant in the Triassic exposed in the Pecos Valley. Sandstone is fairly common near the base and the top, however, and although some beds are gray, most of them are red, massive, of a medium texture, and well cemented with ferric oxide. Coarse conglomerate is interbedded with the red clay and sandstone throughout the Dockum group.

Just how much of the red beds of the Pecos River valley is Triassic is not yet known, for the Permian-Triassic boundary has not been definitely determined. Although diligent search was made for fossil evidence of the age of these beds, none was found. It is not possible to separate the Permian red beds from the Triassic on the basis of a marked difference in color, a method found useful by Gould in the Panhandle, for there is no distinct change in color at any place. The lithology of the beds apparently offers the best criterion for their separation.

Except at a few places the red beds of this region are concealed by loose residual, eolian, and alluvial material of much later age. In southern Lea County, N. Mex., in sec. 17, T. 25 S., R. 36 E., 7 miles northwest of the town of Jal, about 15 feet of brownish-red sandstone crops out at the base of a low ridge. The top of the ridge is capped by a hard siliceous material of probable Tertiary age. The brownish-red sandstone is poorly exposed, but was found to be cross-bedded and to contain small flakes of mica less than one-eighth of an inch across. About 2 miles northwest of this point a good exposure was found at Cluster Mountain.

Section at Cluster Mountain, sec. 12, T. 25 S., R. 35 E., 9 miles northwest of Jal, Lea County, N. Mex.

	Feet
6. Sandstone, light brown, well cemented; contains many small pebbles (Cenozoic)	15
5. Sandstone, light greenish gray, soft, cross-bedded; contains abundant rounded and subangular fragments of soft gray limestone; some mica noted	11
4. Clay shale, dark red, with splotches of light green; bedding poor	16
3. Shale, light bluish green, sandy	½
2. Sandstone, greenish gray, cross-bedded; contains some small flakes of mica	8
1. Clay shale, dark red, sandy, with fair bedding; contains bluish-green streaks	15+

The abundance in this section of brownish and greenish sandstones which are conspicuously cross-bedded and which contain considerable mica is considered evidence that the rocks belong to the Dockum group.

About 35 miles northwest of this locality, in the east-central part of Eddy County, N. Mex., are the Red Hills, so-called because of the red beds of which they are composed.

Section of bluff in eastern edge of Red Hills, sec. 36, T. 20 S., R. 30 E., Eddy County, N. Mex.

	Feet
8. Sandstone, red, massive, medium coarse, cross-bedded, and ripplemarked; contains inclusions of dark-red shale and some mica in small flakes	35
7. Clay, dark red, sandy; no bedding; partly concealed	12+
6. Sandstone, green; mica abundant; top concealed	1+
5. Clay shale, chocolate brown, sandy; bedding poor	15½
4. Sandstone, red, massive, medium coarse, with abundant small flakes of mica	10
3. Clay shale, reddish brown, and sandy; bedding poor	15
2. Sandstone, light green; mica abundant	¼
1. Clay shale, dark brown, sandy; bedding poor	2½+

The resistant red sandstone at the top of the bluff, which laterally changes to gray, is easily the most conspicuous stratum seen within the red beds of southeastern New Mexico, and it is unusually persistent. What appears to be the same sandstone is exposed 50 miles to the southeast, in northeastern Loving County, Tex., where a measured section is nearly identical to that given above.

Section on Means ranch, near well of Pinal Dome Corporation, in sec. 23, block C 26, northeastern Loving County, Tex.

	Feet
7. Sandstone, gray, massive, cross-bedded; contains many iron concretions	14
6. Sandstone, red, argillaceous, cross-bedded, and ripplemarked. (Probably equivalent of bed No. 8 of eastern Eddy County section)	36½
5. Clay shale, dark red, sandy; bedding poor	11
4. Sandstone, light green	1
3. Sandy clay shale and sandstone, dark red to brown; bedding poor	12
2. Sandstone, red, massive	10
1. Clay shale, dark red, sandy; base not exposed	2+

The prominent southwestward-facing bluff formed by this sandstone series in northeastern Loving County can be traced southeastward for more than 40 miles to Quito station, in Ward County, where a quarry has been opened near its base. (See Pl. VII, *C*.) In view of the general variable lithologic character of red-bed strata and the great distance separating the two sections last given, it can not be positively stated that bed No. 6 of the Loving County section is the same sandstone as bed No. 8 of the Eddy County section. However, in consideration of the facts that each bed in its locality is the only prominent relief-making stratum in the red beds and that the northwestward extension of the Loving-Ward County exposure of this sandstone (40 miles long) would pass in the near vicinity of the eastern Eddy County section, it is safe to say that these two beds are probably the same. That the lithology of this section, where traceable, does not change materially is shown by the following section, taken some 30 miles southeast of the Pinal Dome Corporation's well on the Means ranch:

Section 13 miles due north of Barstow, Ward County, Tex.

	Feet
8. Conglomerate; quartz, chert, and flint pebbles of all colors as much as 2 inches in diameter embedded in a sandy matrix (Cenozoic)	30
7. Sandstone, gray, massive, soft to hard; round concretions of iron abundant; cross-bedded throughout (equivalent to beds 6 and 7 of Means section in northeastern Loving County)	40
6. Clay, light gray; little or no sand; top and base concealed	4+
5. Sandstone, light brown, hard	6±
4. Clay, dark red; no sand and no bedding	11
3. Sandstone, dark brown, argillaceous, cross-bedded, ripple-marked	5½
2. Sandstone, gray, medium hard; changes laterally to reddish brown	1–1½
1. Sandy clay and sandstone, red, with light-green streaks near top, ripple-marked and cross-bedded near base; base concealed	15+

In Guadalupe County, N. Mex., according to Darton,[1] a resistant, massive sandstone, the Santa Rosa, lies near the base of 800 feet or more of red shale and sandstone representing the Dockum group. The sandstone series in eastern Eddy, Loving, and Ward counties above described may be the equivalent of Darton's Santa Rosa sandstone of Guadalupe County, N. Mex. It is considered to occur at or very near the base of the Dockum group of southeastern New Mexico and western Texas. This would place nearly all if not all the red shales exposed to the west east of Pecos River beneath the Dockum and probably in the upper Permian. These upper red beds below the Dockum are discussed on pages 73–76 and have been mapped as upper Permian.

The fact that these red shales are generally lighter in color than the overlying red sandstones and sandy shales, which are exposed in the above section and farther to the east, suggests their Permian age. Gould[2] states that the uppermost Permian shales in the western por-

[1] Darton, N. H., Geologic structure of parts of New Mexico: U. S. Geol. Survey Bull. 726, p. 183, 1922.

[2] Gould, C. N., Geology and water resources of the western portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 191, pp. 23–24, 1907.

tion of the Panhandle are of a brillant brick-red color, in vivid contrast to the overlying variegated sandy shales of the Triassic. Darton says that the shales underlying the Santa Rosa sandstone "are of undetermined age and may be either Triassic or Permian." He points out that no satisfactory evidence has been found as to the age of the series of red shales east of Pecos River in Eddy County, but considers them probably Lower Triassic.

Near the highway bridge that crosses Pecos River 3 miles southwest of Grant Falls, Ward County, a massive conglomerate 4 feet thick forms rapids. This conglomerate is composed largely of rounded igneous pebbles and fragments of gray limestone and sandstone embedded in a coarse sandy matrix. It is underlain by 5 feet or more of dark reddish-brown argillaceous sandstone. Both the conglomerate and the underlying sandstone show cross-bedding. The conglomerate grades laterally into a coarse brown sandstone. Although the stratigraphic position of this conglomerate could not be determined, it probably lies within the Triassic not far above the top of the sandstone series that extends southeastward to Quito, and it may be equivalent to a part of that series.

About 8 miles southeast of the bridge, at a ford crossing 5 miles northwest of Imperial, Pecos County, a conglomerate is exposed in the river bed. It has about the same thickness as the conglomerate under the Grand Falls bridge, is of very similar composition, is cross-bedded, and is underlain by dark reddish-brown sandy clay. Although at both localities the conglomerates dip southeast and may represent two different horizons within the Triassic, they may be the same bed.

In southern Crane County, just north of Imperial, dark reddish-brown sandstone and lighter-red sandy shale and clay shale are exposed along the north bank of Pecos River. Although shale showing good bedding is not common to the Triassic as identified in this paper, such shale occurs here in beds considered to be of Triassic age.

The only exposure of the uppermost Dockum beds found in the Pecos River valley is at Red Point, in southeastern Crane County, Tex. At this exposure, a section of which is given below, the Dockum beds are preserved from erosion by overlying Trinity sand and the lower limestones of the Comanche series.

Section at Red Point, southeastern Crane County, Tex.

Age	Group or formation	Character	Thickness (feet)
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Limestone, gray, mostly soft and marly, capped by hard, resistant layer	32
	Walnut limestone.	Yellowish argillaceous limestone	3
	Trinity sand.	Variegated sand, usually soft and nonresistant; basal member a fine-grained white silty sand containing considerable clay	147
Unconformity			
Triassic.	Dockum group.	Clay, red, sandy; contains bluish-green streaks	11-15
		Sandstone, light gray, massive, specked with yellow iron stain, cross-bedded; contains some mica	8
		Sandy clay and sandstone, dull red, soft; sandstone is cross-bedded	25
		Sandstone, grayish brown, medium hard, massive	6
		Sandstone, light brown, very massive, strikingly cross-bedded	5
		Sandstone and sandy clay, red; sandstone is cross-bedded	6
		Conglomerate with quartz pebbles as much as 2½ inches in diameter embedded in a matrix of red sandy clay	2
		Sandstone and sandy clay, light brownish red	8
		Sandstone, light red and gray, massive	4
		Sandy clay and sandstone, red with bluish-green streaks, soft; sandstone is cross-bedded	16+
		(Level of Pecos River valley.)	

It is difficult to draw a dividing line in the foregoing section between the Trinity sand and the underlying Dockum beds. Such a line is provisionally drawn at the top of the highest bed of red clay, for red clay is not known to exist in the Trinity sand elsewhere in this immediate region. This division places several massive beds of gray and light-brown sandstone that occur in the next 60 feet below within the Dockum beds.

The thickness of the Dockum group can only be estimated, for all the beds are not exposed for measurement. In the Bryant well, 9 miles south of Midland, Midland County, Tex., the base of a series of sandstones 260 feet thick occurs at a depth of 1,400 feet. The driller reported fresh water from the upper part of these sandstones and salt water from the lower 100 feet. It appears likely that at least the fresh-water sandstones belong to the Dockum beds and are the equivalent of the sandstone series that extends south to Quito station, described on preceding pages. The drill passed through approximately 100 feet of the Trinity sand at the top of the well. If all fresh-water sandstones are included, the Dockum beds have a thickness of about 1,200 feet in this vicinity. They thin out gradually to the east and south and probably also to the west. At the Wolcott well, in Martin County, 40 miles north of the Bryant well, the Dockum beds, similarly identified, apparently have a thickness of about 1,100 feet although they may be as thick as 1,200 feet. The identification of the base of the Triassic in these wells is altogether provisional.

COMANCHE SERIES

The character and distribution of the formations of the Comanche series (Lower Cretaceous) in Texas have been thoroughly discussed by Hill,[3] Taff,[4] and others. The area of exposure of this series in Texas is greater than that of any other like geologic division. It is exposed in a belt from 30 to 100 miles wide, extending from Red River in Montague and Cooke counties southward to a point near Austin, where the outcrop swings westward and widens to the north, west of the uplift in Llano and Burnet counties. The exposure is continuous westward to the Marathon fold in northern Brewster County and extends northwestward nearly to the southeast corner of New Mexico (see Pl. X), near the area where the series is concealed by unconsolidated Quaternary material. Scattered outcrops occur in the extreme western part of Texas in Presidio and El Paso counties, and a narrow belt borders the east side of the Llano Estacado in Borden, Dawson, and Scurry counties.

As commonly described, the formations of this series are divided into three groups which, in ascending order, are the Trinity, Fredericksburg, and Washita.

TRINITY SAND

The Trinity sediments were deposited in a sea which gradually encroached from the region of the Gulf of Mexico in a northerly and northwesterly direction over the Texas region. The landward portion of this encroaching sea was shallow and received from the mainland the sediments transported by streams. As the sea progressed, shore deposits were accumulating over areas that were progressively farther and farther inland from the old shore line, and the deposits were being continually reworked by waves and currents. As a result the base of the Trinity in Texas is marked by a stratum of clean quartz sand, which, because of its origin and stratigraphic position, has been called the "Basement sands." Considered alone, these sands, whose average thickness is little more than 100 feet, have the appearance of a single formation lying directly upon a Paleozoic floor in the greater part of Texas and upon Triassic beds in much of western Texas. They are, however, the shoreward extensions of a number of formations deposited farther east and southeast, which make up the lower part of the Comanche series. In other words, at the same time these sands were accumulating near shore in an interior region calcareous marl and limestone were being deposited seaward. This

[3] Hill, R. T., Geography and geology of the Black and Grand prairies, Tex.: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 7, 1901.

[4] Taff, J. A., Report on the Cretaceous area north of the Colorado River: Texas Geol. Survey Fourth Ann. Rept., pt. 1, pp. 241-354, 1892.

subject is discussed at length by Hill.[5] The preceding long period of erosion and the wide and continuous distribution of Trinity sand of no great thickness argue for a land region of very low relief.

In the region herein described the Trinity is composed entirely of sand, commonly conglomeratic, and the Trinity group, as the deposits to the east are called, here becomes the Trinity sand. It should not be understood, however, that the Trinity sand in this region is of earliest Trinity age. It is considerably younger than the basal Trinity sands in the region of Fort Worth and Waco and is, according to Hill,[6] equivalent in age to the Paluxy sand, the top formation of the Trinity group of that region.

The Trinity sand, which ranges in thickness from a possible 26 feet in northwestern Scurry County to 142 feet in southeastern Crane County, rests upon a floor of red Triassic clay intercalated with red and gray sandstones.

It is commonly overlain by the limestones of the Fredericksburg group, but in places these limestones have been removed by erosion, leaving the sand either exposed or covered only by loose Cenozoic material.

In general it consists of clean friable fine quartz sand of various colors, which is well compacted but contains little or no cementing material and which is therefore commonly called "pack sand." The sand is conglomeratic throughout but in many places not characteristically so near the base, as might be expected. Waterworn pebbles of quartz and flint from half an inch to 3 inches in diameter are common, the average being about 1 inch. Cross-bedding is abundant, and in many places the lines are marked by layers of quartz pebbles. The color of the sand is commonly white or yellow, but generally in a single exposure these colors grade both laterally and vertically into red, purple, lavender, and brown. The unusual porosity of this formation accounts for its importance as a source of underground water and makes possible the extensive cattle ranges of western Texas. After experimenting with sand collected from this formation at a number of localities to determine its absorptive power, Taff[7] states that "a cubic yard of the sand will absorb 80 gallons of water." The pore space of this sand is 40 per cent of its volume, a proportion which is exceedingly high. The supply of fresh water in water wells sunk to this horizon is seldom affected by the seasons of drought common to this region. In some localities the sand is highly cemented at its outcrop by siliceous material which has formed apparently as a result of the evaporation of Trinity waters carrying dissolved silica. In such places the sand appears as a very

[5] Op. cit., pp. 132–140.
[6] Idem, p. 133.
[7] Op. cit., p. 315.

hard sandstone or quartzite. This condition is common in western Ector County. (See Pl. VIII, *A*.)

With the exception of fragments of silicified wood. no fossils were found by the writer in the Trinity sand.

FREDERICKSBURG GROUP

Rocks of the Fredericksburg group of the Comanche series are the chief relief-making strata of the western Texas region. They are made up altogether of limestones, which, although they vary in their purity and hardness, are much more resistant to erosion than the underlying soft Trinity sand and the red beds of the Triassic and Permian. To these and associated limestones is due the preservation of the Edwards Plateau, which extends southeastward from this region toward Mexico and the Gulf. The topographic slope of the Edwards Plateau is in accord with the gentle south-southeasterly dip of the limestones. The basal portion of these limestones extends northward from the north end of the Edwards Plateau and forms a part of the "cap rock" for the south end of the Llano Estacado, at least as far north as latitude 33° north.

The rocks of the Fredericksburg group farther east in Texas are described by Hill under three formational names—in ascending order the Walnut clay, the Comanche Peak limestone, and the Edwards limestone. In western Texas all these formations are no doubt present, but owing to the similar lithology, paleontology, and topographic relief of the Comanche Peak and Edwards limestones, these two formations have not been separated in the present study. These two limestone formations are really a depositional unit and can not be separated without detailed study of their paleontologic characteristics. Fossils are abundant in these beds, and a great number of them range from the base of the Walnut limestone to the top of the Edwards limestone and are not diagnostic of definite horizons. *Exogyra texana* is more common to the Walnut and the lower portion of the overlying limestone, and *Gryphaea marcoui* is found agglomerated in beds from a few inches to several feet thick ranging through about 100 feet of limestone above the Walnut.

The sea in which the Fredericksburg limestones were laid down resulted from a continuation of the subsidence of the Texas region that began in earliest Trinity time. This sea, although widespread and covering the greater part of Texas, was probably not as extensive as those of later Cretaceous time, which covered more of the central interior of North America

WALNUT LIMESTONE

The Walnut limestone has hitherto been referred to as the Walnut clay, for farther east it is composed largely of clay, calcareous marl, and argillaceous limestone. As exposed in western Texas, however, it is nearly everywhere not a clay but a yellowish-brown argillaceous limestone, which is in places very sandy and which represents the transitional phase between the underlying Trinity sand and the overlying Comanche Peak limestone. Its thickness ranges from 3 to 10 feet.

The contact of the Walnut limestone with the Trinity sand is in places irregular and marked by an unconformity. (See Pl. VIII, *B*.) This break in sedimentation was probably local and not accompanied by any great amount of erosion. In other localities the change from the Trinity sand to the Walnut was observed to be gradual and without unconformity.

The Walnut limestone differs from the overlying limestone mainly in its content of argillaceous material and consequently in its color, which where it was noted is a yellowish brown, in contrast to the light-gray color of the Comanche Peak and Edwards limestones. This difference in color and argillaceous content is effected by a gradual change within a vertical distance commonly not exceeding 1 foot.

Fossils are abundant in the Walnut limestone, and the most common species is probably *Exogyra texana*. T. W. Stanton has identified some of the fossils taken from the Walnut, as follows;

Exogyra texana Roemer.
Holectypus planatus Roemer.
Ostrea sp.
Gryphaea marcoui Hill and Vaughan.
Pecten occidentalis (Conrad).
Protocardia sp.
Tylostoma sp.

These are the common fossils of the Walnut clay, but they also range up into the overlying formations of the Fredericksburg group.

COMANCHE PEAK AND EDWARDS LIMESTONES

It has not been found practicable in this area to separate the Comanche Peak and Edwards limestones without more detailed paleontologic and stratigraphic study. The combined unit is a light-gray to pinkish-gray dense to coarsely crystalline limestone, usually massive, although the lower portion, about 50 feet thick, is nodular in part and in places thin bedded. The greater part is composed of marly and chalky beds of limestone interstratified with thinner beds which are hard, durable, and resistant to erosion. The softer strata weather to steep slopes, in contrast to the vertical cliffs produced by the harder beds.

In the lower portion are hard, resistant beds, some of them more than 3 feet thick, which are composed almost entirely of the shells of *Gryphaea marcoui*. Other fossil forms are abundant, a few of which were collected and submitted to T. W. Stanton for identification. These are:

Ostrea crenulimargo Roemer?
Ostrea sp., small simple form.
Pecten sp., small smooth species.
Unicardium? sp.
Exogyra texana Roemer.
Turritella cf. T. seriatim-granulata Roemer.
Gryphaea marcoui Hill and Vaughan.
Cyprimeria texana (Roemer).
Tylostoma sp.
Cerithium bosquense Shumard.
Enallaster texanus (Roemer).
Protocardia sp.
Tylostoma sp.

Flint in irregular seams and nodules is abundant in the upper part and has been found sparingly in the lower part.

The thickness of the Comanche Peak and Edwards limestones ranges from a minimum of approximately 5 feet in northeastern Borden County to a maximum of 372 feet in the Castle Gap section of southeastern Crane County, Tex., but possibly part of the limestone in the thickest sections represents the Georgetown limestone of Washita age. Udden has shown that the Devils River limestone on Devils River and the lower course of the Pecos includes equivalents of both the Georgetown and the Edwards, though it has the lithology of the Edwards and has often been referred to that limestone.

WASHITA GROUP

The Washita group is known to be present in the southern part of the region discussed in this report, but it has not been certainly identified in any of the detailed sections described. It is reported that the Buda limestone, the Del Rio formation, and limestones of Georgetown age are present in the neighborhood of Fort Stockton.

On Devils River and the lower part of Pecos River limestones of Georgetown age constitute the upper part of Udden's Devils River limestone. It is possible that the upper part of the limestone in the Castle Gap section, in southeastern Crane County, is of Georgetown age.

SECTIONS OF COMANCHE ROCKS

Vertical sections of the Comanche formations were measured in suitable localities throughout the region of their exposure. The "breaks of the plains" along the east side of the Llano Estacado in

Scurry, Borden, and Dawson counties, and the "mountains" along the north edge of the Edwards Plateau, in Coke, Howard, Upton, and Crane counties, afford the best opportunities for the measurement of such sections. Sections were also taken at several points along Concho Bluff, the escarpment that forms the southwestern edge of the Llano Estacado in Upton, Crane, Ector, and Winkler counties. These sections will be given in geographic order beginning in Scurry and Borden counties and following southward around the south end of the Llano Estacado and the north edge of the Edwards Plateau.

SCURRY COUNTY

Comanche rocks are exposed along the south end of the eastward-facing "breaks" of the Llano Estacado in the northwest corner of Scurry County. These rocks were not found south of the town of Fluvanna, for erosion in this part of the plains has dissected and worked below the level of these harder rocks into the softer red beds of the Triassic. Beginning at a point about 2 miles northeast of Fluvanna, the exposure of the Comanche rocks follows the cliffs or "breaks" northwestward into the extreme northeast corner of Borden County. A section taken at a point about 4 miles northeast of Fluvanna, in or near sec. 602, is as follows:

Section 4 miles northeast of Fluvanna, Scurry County, Tex.

Age	Group or formation	Character	Thickness (feet)
Pliocene (?).		Unconsolidated sand and gravel	15
Unconformity—			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Massive gray limestone; contains a number of 1-inch clay bands	22
		Light yellowish-brown marl; fossils abundant	1
		Gray limestone, massive	8
		Yellowish-gray limestone; nodular in upper part and crystalline in lower	52
		Concealed	17
		Gray, impure limestone	22
		Calcareous mass of *Gryphaea marcoui*; resistant	1
		Concealed; probably impure limestone	10
		Yellowish-gray limestone; impure	24
	Walnut (?) limestone.	Concealed; probably partly Comanche Peak and Walnut and partly Trinity sand	20
	Trinity sand.	Light-purple sand; loose and clean	6–15±
Unconformity (concealed)			
Triassic.	Dockum group.	Dark-red clay; no bedding and only slightly sandy	150

This section represents the maximum thickness (157 feet) of the Edwards and Comanche Peak limestones in Scurry County. Outliers of these limestones are found several miles to the northeast, in southeastern Garza County and southwestern Kent County. In following the "breaks" northwest these limestones were found to thin out until only the lower 5 or 10 feet remain. In sec. 533, northeastern Borden County, for example, the entire thickness of these limestones and tho Walnut limestone does not exceed 10 feet.

The thinness of the Trinity sand in the above section is noteworthy, for in no other locality within the region is its thickness so small. Although the exact thickness here is questionable it probably does not greatly exceed 15 feet. In northeastern Borden County this sand is approximately 25 feet thick.

Except in southern Garza County, representatives of either the Fredericksburg or Trinity group of the Comanche sediments are not known to the writer to occur at any point in western Texas or eastern New Mexico north of 33° north latitude. It is believed that the position of the northwestern shore line of the Trinity-Fredericksburg sea was somewhere between southern Garza County and northeastern New Mexico, for in the latter region the Comanche is represented by only the Washita group.

BORDEN COUNTY

The Fredericksburg and Trinity rocks crop out in an irregular line in northern Borden County, for here, as usual, they follow the "breaks" of the Llano Estacado. Two widely separated outcrops were selected for measurement, one at Muchakooyo Peak, an outlier several miles from the edge of the plains, and the other near the west county line.

Section at Muchakooyo Peak, 4 miles southeast of Gail, Borden County, Tex., in secs. 7 and 8, block 30, T. 4 N.

Age	Group or formation	Character	Thickness (feet)
Pliocene (?).		Unconsolidated sand and gravel, calcareous	10±
Unconformity			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Gray limestone, impure and only moderately resistant	15
		Massive gray limestone; fossils abundant	20
		Gray limestone, impure; contains numerous thin bands of clay	12
		Massive light-gray limestone, crystalline in upper portion but argillaceous at base	17
		Gray limestone, impure	39
		Calcareous mass of shells, largely *Gryphaea marcoui*; hard, crystalline	1
		Yellow, impure limestone and marl	10
		Calcareous mass of shells, largely *Gryphaea marcoui*	1
	Walnut limestone.	Yellowish-brown argillaceous limestone	4
	Trinity sand.	Yellowish-brown sand, containing considerable clay	10
		Purplish-gray sand with abundant quartz pebbles; bed is soft and sand is loose and clean	25
Unconformity (concealed)			
Triassic.	Dockum group.	Dark-red clay; no bedding	6
		Greenish-gray cross-bedded sandstone, very micaceous	10-18
		Dark-red clay with occasional beds of greenish-gray sandstone	100+

The thickness of the Edwards and Comanche Peak limestones in this section is 115 feet, and that of the Trinity sand is 35 feet.

Section near county line in extreme east central part of Dawson County, Tex.

Age	Formation	Character	Thickness (feet)
Pliocene (?).		Unconsolidated sand and gravel, calcareous	25±
Unconformity			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Massive gray limestone; flint nodules abundant	11½
		Light-gray limestone, not as hard as bed above	23
		Light-brown argillaceous limestone; fossils abundant	12
		Calcareous mass of shells, impure but more resistant than overlying bed	2
		Light grayish-white limestone, soft	10
		Calcareous mass of shells, largely *Gryphaea marcoui* and *Exogyra texana*	1½
		Yellowish-gray limestone, impure and soft	3½
		Calcareous mass of shells, largely *Gryphaea marcoui*, impure	2
	Walnut limestone.	Yellowish-brown impure limestone and sandy clay with many fossils, the most abundant of which is *Exogyra texana*	5
	Unconformity		
	Trinity sand.	Light-purple sands with abundant quartz pebbles; fragments of silicified wood noted; base not exposed	10+

On account of unequal erosion of its upper surface, the limestone above the Walnut is only 65 feet thick in the foregoing section. Records of water wells drilled on the plains as far west as La Mesa, Dawson County, indicate that the Fredericksburg and Trinity beds underlie much of the southern portion of the Llano Estacado and that the water supply of this region is obtained largely from the Trinity sand at a depth ranging from 150 to 350 feet.

South of the locality of the section last given erosion has decreased the thickness of the resistant limestone. In southwestern Borden County and the northern two-thirds of Howard County the Comanche beds have been completely removed, but in much of this area a Cenozoic covering of calcareous sand and gravel conceals the Triassic red clay and gray sandstone that are so widely exposed in most of Borden County, the eastern part of Howard County, and the western part of Mitchell County.

HOWARD COUNTY

Two sections in Howard County are given below:

Section at west end of Big Spring "Mountains," near Hughes Lake, 1 mile south of Big Spring, Howard County, Tex.

Age	Group or formation	Character	Thickness (feet)
	Edwards and Comanche Peak limestones.	Light-brown limestone, hard, massive, and finely crystalline	15
		Light-brown limestone, soft and impure; contains three beds 2 to 3 inches thick of shell agglomerate	19
		Gray limestone, nodular and only fairly resistant	20
		Poorly exposed; occasional exposure of gray nodular limestone	21
		Gray calcareous shell bed, composed largely of *Gryphaea marcoui*	2½
		Concealed	14
		Gray nodular limestone, earthy and sandy	8
		Concealed	14
Comanche (Lower Cretaceous).	Walnut limestone.	Light yellowish-brown impure limestone, soft	9½+
	Trinity sand.	Light bluish-gray sand, soft, loose and friable; contains abundant quartz and chert pebbles as much as half an inch in diameter	5
		Sand, light brown with irregular variations to purple, lavender, and pink; clay bands half an inch to 2 inches thick and abundant pebbles as much as 1 inch in diameter; beautifully cross-bedded	38
		Yellowish-brown sandstone with iron oxide cement; quartz and chert pebbles; cross-bedded	2
		Clay, maroon to brown, sandy	2½
		Purple sand; small pebbles	1-2
		Yellowish-brown sandstone, of medium texture, cross-bedded; contains some clay	1-5
		Sand, purple, yellowish-brown, and gray, cross-bedded; containing lenticular gravel beds 2 to 24 inches thick	17
Unconformity (concealed)			
Triassic.	Dockum group.	Dark-red clay	50+

Section at Signal Peak, 10 miles southeast of Big Spring, in sec. 33, block 31, T. 1 S., Howard County, Tex.

Age	Group or formation	Character	Thickness (feet)
Comanche (Lower Cretaceous)	Edwards and Comanche Peak limestones.	Grayish-brown limestone, massive and finely crystalline in upper part and soft and earthy in lower part	25
		Limestone mass of shells, mostly *Gryphaea marcoui*	1
		Yellowish-brown limestone, soft and impure	3½
		Light-brown limestone, hard and massive	4
		Yellowish-brown limestone, soft and earthy	8½
		Gray limestone, massive and hard alternating with soft and earthy	29
		Limestone mass of shells, hard and resistant	1
		Gray limestone, alternately hard and soft, nodular; contains earthy bands	35
	Walnut limestone.	Yellowish-brown limestone, argillaceous throughout and sandy in lower 2 feet	8
	Unconformity		
	Trinity sand.	Light-brown sand, soft, loose; cross-bedded in upper part with quartz pebbles as much as one-half inch in diameter along lines of cross-bedding; streaks of yellow clay in lower part	12
		White sand, soft, loose, with finer texture than above; few pebbles	3
		Light-blue sand, fine texture, soft and loose; a few pebbles	9
		Massive brown sandstone, coarse, with few pebbles, partly cemented by ferrous iron	3-5
		Sand, white and light blue, with irregular purple coloring; fine texture	20
		Brown sandstone, incompletely cemented by iron oxide and more resistant than bed above	2
		Sand, white, purple, blue, and brown, soft, medium-textured and loose; quartz pebbles as much as 1 inch in diameter	5
		Concealed	3½
		Sand, bluish-gray, soft and loose	1
		Concealed. Base marks approximate base of Trinity sand	10
Unconformity (concealed)			
Triassic.	Dockum group.	Concealed, probably red clay	3
		Dark-red clay, with a few light-gray streaks	52
		Dark-red sandstone, hard, of medium texture, cross-bedded; small flakes of mica	3-5
		Dark-red clay; no bedding	95+

As may be noted from these two sections, the Edwards and Comanche Peak limestones in southern Howard County are represented by an average thickness of 110 feet. The unusually regular thickness of 70 feet of the Trinity sand in this area is considerably greater than in Borden and Scurry counties, where the thickness of this formation was found to range from 15 to 35 feet. In this distance of 40 to 50 miles the Trinity sand has thickened 35 to 55 feet.

These sections were taken along the north edge of the Edwards Plateau, which extends southward from this locality to the Rio Grande.

NORTHWESTERN COKE COUNTY

The Callahan Divide, in Taylor, Nolan, and northern Coke counties, which is separated from the Edwards Plateau proper by the Colorado River valley, is capped by a considerable thickness of resistant Edwards and Comanche Peak limestones.

Section of the west point of Stepp Mountain, a remnant of the Edwards Plateau in northwestern Coke County, one-half mile south of the Mitchell-Nolan County corner

Age	Formation	Character	Thickness (feet)
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Gray limestone, nearly white, alternately hard and chalky, lower portion earthy	22
		Gray limestone, massive; weathers to vertical cliff	33
		Gray limestone, upper part nodular	48
		Yellowish-brown limestone, earthy; fragments of *Gryphaea* and *Exogyra* shells abundant	14
		Bluish-gray limestone, sandy, earthy, and soft	9½
		Concealed	1
		Blue clay	½
	Walnut (?) limestone.	Concealed	33
	Trinity sand.	Light-blue sand, of medium texture, soft and loose	2½
		Yellowish-brown sand, soft and loose	½
		Concealed	1
		Bluish-gray sand, soft and loose	1½
Unconformity (concealed)			
Permian.	Double Mountain formation.	Clay, shale, and sandstone (see p. 70 for description)	230+

The exact horizon of the Walnut limestone in this section is doubtful, for, as may be noted, at the horizon at which it is believed to occur the rocks are concealed by float from overlying beds. It is possible that this concealed bed, 33 feet thick, and the next two above may represent a part of the Trinity sand; the Walnut would then lie at the horizon of at least a part of the "bluish-gray limestone" bed, 9½ feet thick. If this is the true condition, the Trinity sand has a thickness of nearly 40 feet, rather than 5½ feet shown in the above section. It is certain, however, that the Trinity sand is 30 feet and possibly as much as 64 feet thinner in northwestern Coke County than in the southern part of Howard County.

STERLING, MITCHELL, AND GLASSCOCK COUNTIES

The north edge of the Edwards Plateau cuts across the northeast corner of Sterling County into southern Howard County. From Big Spring it curves back to the south and southwest and cuts off the northwest corner of Glasscock County. The Edwards and Comanche Peak limestones (Pl. X) are at the surface over most of Sterling and Glasscock counties, the southwest corner of Mitchell County, and the south-central part of Howard County. Both the

Trinity sand and the upper part of the Triassic red beds are exposed along the base of the high, nearly vertical cliff that marks the edge of the Edwards Plateau as far northwest as Big Spring. From this point southwestward nearly to Upland, in central Upton County, this cliff is reduced to a prominent bluff, and, except at isolated localities where patches of the Trinity sand are exposed, formations older than the Comanche Peak are concealed by a covering of Cenozoic sand and gravel. Small exposures of the Triassic, such as that 1 mile south of Sterling City, occur in the northern part of the Edwards Plateau, where stream erosion has cut below the level of the Comanche rocks.

MIDLAND AND MARTIN COUNTIES

The southern two-fifths and practically all of the extreme western part of Midland County is underlain by the lowermost part of the undifferentiated Edwards and Comanche Peak limestones, approximately 50 feet thick. In this portion of the county numerous small sinks or dry lakes are bordered by exposures of *Gryphaea* limestone in place. In the central part of the county, south and southeast of Midland, brown sandstone belonging at the horizon of the Trinity sand is exposed at several localities. The greater part of northeastern Midland County is covered by loose sandy soil and is underlain by the Triassic.

In Martin County the surface is covered almost entirely by a calcareous sandy soil and by irregular deposits of white pulverulent to platy limestone of post-Cretaceous age. What is believed to be the lower part of the Trinity sand is exposed near the top of an eastward-facing bluff 3 miles northeast of Stanton, in southeastern Martin County. Triassic red clay and greenish-gray sandstone are exposed at the base of this bluff. From the facts that Comanche rocks crop out in northwestern Midland County, in southeastern Gaines County, near Seminole, and in eastern Dawson County, and that these rocks underlie the greater part of Dawson County, it seems probable that they also underlie the post-Cretaceous deposits of a part of western and northern Martin County. There is nothing in the topography or known structure of the region to warrant the belief that excessive erosion has removed these formations from this area.

UPTON, CRANE, ECTOR, AND WINKLER COUNTIES

The "mountains" that form the edge of the Edwards Plateau in west-central and southwestern Upton County are in reality broad mesas 300 to 500 feet high, capped by Georgetown (?), Edwards, and Comanche Peak limestones. (See Pl. VIII, *C*.) The westernmost extension of these higher topographic features, a good representative of which is Castle Mountain, enters Crane County at about the middle of the east side.

Section at Castle Mountain, in southeastern Crane County, Tex., in about sec. 2, block X, Corpus Christi, San Diego & Rio Grande Narrow Gage Railroad survey

Age	Formation	Character	Thickness (feet)
Comanche (Lower Cretaceous).	Georgetown (?), Edwards, and Comanche Peak limestones.	Brownish-gray limestone, massive, crystalline	10
		Yellowish-gray limestone, soft, marly	40
		Brownish-gray limestone, hard, massive, crystalline, with iron nodules near base	18
		Yellowish-gray limestone, not so hard and resistant as overlying bed	206
		White to yellowish-gray limestone; contains variety of fossils with ammonites conspicuous	20
		Gray limestone	7
		Gray limestone mass of shells, largely *Gryphaea marcoui*	1
		Yellowish-gray limestone, argillaceous and only fairly hard	24
		Yellowish-gray limestone, massive; contains argillaceous layers; hard and soft alternately	30
		Yellowish-gray limestone, earthy and soft	8
		Brownish-gray limestone, part of which is a fossil mass; crystalline	5
	Walnut limestone.	Yellowish-gray limestone, argillaceous and alternately hard and soft; *Exogyra texana* abundant	8
	Trinity sand.	Sandstone, brown, purple, and red, medium to coarse grained, from loose and friable to hard, quartzitic	6
		Sandstone, white and variegated colors, medium fine, mostly soft and friable	16
		Sand, white and pink, very fine, with chalky appearance; soft and loose.	6
		Sandstone, light gray, medium grained, somewhat soft and argillaceous but mostly a hard quartzitic sandstone.	9
		Sandstone, brownish gray, soft, with abundant minute specks of yellow iron stain	10½+

The total thickness of the Comanche limestones in this section is 369 feet, the greatest measured thickness of these limestones within the area. The dip of the limestones in this region is approximately 18 feet to the mile in a south-southeasterly direction. The slope of the surface throughout the Edwards Plateau is in the same general direction but at a slightly less rate than the dip of the surface beds, a difference which accounts for the gradual thickening of the Comanche limestones to the south and southeast.

The total thickness of the Trinity sand is not revealed at this locality, but a complete section of it was found about 3 miles to the northeast, at Red Point. A measured section at Red Point is given on page 96; here the Trinity sand is 147 feet thick, 67 feet thicker than at any other locality within the area where the thickness was measured.

The resistant Comanche limestones have been removed from the vast area to the west and northwest by erosion of Pecos River. The broad Pecos Valley is now covered by a mantle of sand and gravel, largely of Recent age, which is underlain by the soft, nonresistant red beds of the Triassic and Permian.

No "mountains" occur north of west-central Upton County, for the higher topographic features of the Edwards Plateau lie to the south. The lower 50 feet, more or less, of the Comanche limestones, however, extends to the north and forms the floor for portions of the south end of the Llano Estacado as far north as the southern boundary of Garza, Lynn, and Terry counties. These lower limestones, together with underlying Trinity sand, crop out in a southwestward-facing bluff that extends northwestward from west-central Upton County to the northeast corner of Winkler County. Because of the abundance of *Gryphaea* and other shells in the limestone, this bluff has been named Concho Bluff. Sections measured at several points along Concho Bluff in Ector and Winkler counties follow.

Section at Dawson Wells, in southeastern Ector County, Tex., about sec. 46, block 43, T. 3 S.

Age	Formation	Character	Thickness (feet)
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Gray limestone, platy and semicrystalline	25
	Walnut limestone.	Brown limestone, earthy, very sandy, and hard; fossils abundant, especially *Exogyra texana*; some lignite in basal foot	8
	Trinity sand.	Purple sand; red and orange-colored streaks near top; medium grained, soft and loose	9½
		Gray sand; same as above but showing uneven bedding	3
		Purple sand, dark, medium grained, soft and loose; contains calcareous nodules of sand 1 to 3 inches in diameter; cross-bedded	5+

Section taken at Dead Man's Cut, south-central Ector County, Tex., 14 miles southwest of Odessa on Texas & Pacific Railway

Age	Formation	Character	Thickness (feet)
Cenozoic (?)		White limestone, platy and containing wavy, irregular lines of "bedding"; inclusions of angular fragments of limestone and rounded quartz pebbles; no fossils	12+
Unconformity			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestones.	Limestone mass of shells, largely *Gryphaea marcoui*, yellowish gray, hard, and massive	3
		Gray limestone, soft, with few fossils	1
		Limestone mass of shells, largely fragments of *Gryphaea*	¼-½
		Gray limestone	1
		Limestone mass of shells, largely *Gryphaea marcoui*, yellowish gray, hard, and massive	2-2½
		Unconformity. (See Pl. IX, *A*.)	
		Gray limestone, hard, nodular, semicrystalline	4+
		Concealed (gap in the cut)	10±
		Gray limestone, nodular	8
	Walnut limestone.	Yellowish-brown limestone, earthy; fossils abundant	3
	Trinity sand.	Brown sandstone, dark, hard, massive	1¼
		Sandstone of variegated color—brown, blue, purple, and red, medium to fine grained, mealy, friable, and soft; contains small quartz pebbles	14+

The unconformity in the Edwards and Comanche Peak, shown in Plate IX, *A*, is evidence that at least a part of these lower limestone beds were laid down in shallow water.

The age of the white limestone at the top of the section is questionable. Similar platy, concretionary limestones were noted at numerous localities throughout the region, and everywhere they occur at the surface, overlying all other rocks. They contain no fossils except waterworn fragments of Comanche forms, and in structure and general appearance they are entirely different from any part of the Edwards and Comanche Peak limestones. They are believed to be of Recent age. Their probable origin is discussed on page 113.

Unlike the soft, loose sands listed in foregoing sections of the Trinity, the uppermost sandstone bed in the above section is extremely hard. This was found to be true of practically all the exposed Trinity sands in west-central Ector County, where beds 15 to 20 feet thick are exposed as hard, quartzitic sandstones. (See Pl. VIII, *A*.)

Section at Blue Mountain, in northeastern Winkler County, Tex., in block 46, T. 1 N.

Age	Formation	Character	Thickness (feet)
Recent.		Soil and loose limestone fragments	10±
Unconformity			
Comanche (Lower Cretaceous).	Edwards and Comanche Peak limestone.	Limestone mass of shells, largely *Gryphaea marcoui*, yellowish gray, hard, fairly massive	2-2½
		Gray limestone	1
		Limestone mass of shells, largely *Gryphaea marcoui*, yellowish brown, hard	¾
		Light-gray limestone, nodular; contains irregular beds of *Gryphaea* as much as 6 inches thick	18
		Gray limestone, hard and crystalline	1½
	Walnut limestone.	Light-brown limestone, soft and earthy	4
		Brown sandstone, calcareous and platy; contains fossils	2½
		Light-brown limestone, hard, with many gastropods	½
	Trinity sand.	Sandstone, variegated color, soft and loose, medium to fine grained; contains abundant quartz pebbles and irregular beds as much as 1½ feet thick colored yellow by ferric iron	45+

The above section is essentially the same as the section taken at Dead Man's Cut. At no place in this region is the entire thickness of the Trinity sand exposed, for its lower portion is concealed by the covering of loose sand and gravel that extends to the west and north.

The lower part of the undifferentiated Edwards and Comanche Peak limestones, where present in Andrews County, is concealed by the surface covering of wind-blown sand and limestone gravel that is so widespread over this county. It is doubtful if these surface deposits of any but the southeastern and eastern third of Andrews County are underlain by Comanche rocks, for water wells drilled in the west-central part of the county have encountered nothing but surface sand and red clay. These wells are from 500 to 750 feet deep and obtain their water from sands probably within the Triassic.

A single exposure of Edwards and Comanche Peak (?) limestones is known to occur to the north, in Gaines County, 10 miles southeast of Seminole.

Section 10 miles southeast of Seminole, Gaines County, Tex., at J. B. Thompson's ranch house, sec. 19, block C43.

Age	Formation	Character	Thickness (feet)
Comanche (Lower Cretaceous).	Edwards and Comanche Peak (?) limestones.	Brownish-gray limestone, hard and soft alternately; fossils abundant	10½
		Limestone mass of shells, largely *Gryphaea*; weathers to yellowish gray; upper foot is hard; remainder is softer and argillaceous	5½
		Brownish-gray limestone; *Gryphaea* and *Exogyra texana* abundant together with sea urchins and *Turritella*-like gastropods	3
		Gray limestone, medium hard and nodular	½+

Although it is impossible to make a definite correlation, the limestone shell bed in this section is of the same general composition and appearance as the one occurring near the top in each of the two preceding sections. It is also very similar to the *Gryphaea* shell bed exposed around the edges of sinks or dry lakes in southern and western Midland County and eastern Ector County.

PLIOCENE OR PLEISTOCENE ROCKS

An unconsolidated, heterogeneous layer of sand, gravel, and clay occurs at or near the surface over the greater part of the Llano Estacado. Its thickness, which is less at the south end of the High Plains, ranges from a few feet to more than 100 feet. It rests unconformably upon all underlying rocks, which may be either Triassic or Comanche and, near Canadian River in the Panhandle, probably also Permian.

The gravel, where noted, consists of granite, felsite, and other igneous rocks, together with considerable quartzite, flint, limestone, and sandstone. Waterworn forms of fossils common to the Lower Cretaceous are scattered throughout the formation.

RECENT DEPOSITS

The deposits of Recent age in this region are of three types—(1) stream deposits of sand, gravel, and clay found along the immediate channel of Pecos River, Colorado River, and minor drainage lines; (2) deposits of loose sand, mostly, if not altogether of eolian origin, which cover a belt averaging 40 miles in width bordering Pecos River on the east and which range in thickness from a few feet to more than 200 feet; and (3) a deposit consisting of caliche and similarly formed siliceous material, which forms the "cap rock" of much of the Llano Estacado and which ranges in thickness from 1 foot to more than 20 feet.

An example of the last-named deposit is given at the top of the section at Dead Man's Cut (p. 110). It appears in most localities as a white calcareous deposit, similar to an ordinary limestone but having wavy concretionary lines instead of the ordinary planes of bedding and containing gravel, sand, and fragments of limestone and sandstone.

It is generally agreed that caliche is formed as a result of the evaporation of ground water brought to or nearly to the surface by excessive evaporation in areas of dry climate. If this water contains dissolved calcium carbonate, as it commonly does, this compound is deposited where evaporation occurs, at or within a few feet of the surface. If silica is the dissolved mineral compound, the deposit resulting is hard and siliceous. Whatever its composition, it always includes material, such as gravel and sand, that occurs at or near the surface at the time of evaporation. Plate IX, *B*, illustrates an outcrop of stream gravel which has become indurated by thorough cementation, probably by the process just described.

STRUCTURE

The region of the High Plains of Texas, western Oklahoma, and western and central Kansas is a broad but comparatively shallow structural basin. That a basin of generally similar features was present in late Permian time is proved by the presence and wide distribution of great thicknesses of salt, deposited from a sea which, in its stages of desiccation, must have occupied the lowest portion of a basin.

Proof of the present existence of this geosyncline is to be found not only in the subsurface correlations herein presented and those given by Udden[8] but also in the general regional dip of the rock strata exposed in those parts of western Texas and eastern New Mexico that are now known to occupy the limbs or sides of this geosyncline. The Permian beds east of the Llano Estacado dip to the west at a rate of 30 to 35 feet to the mile, and those west of the Llano Estacado dip to the east at approximately 40 feet to the mile.

In the preparation of the cross sections showing subsurface correlations it was necessary, before well logs could be accurately projected to the correlation lines, to determine with as much accuracy as possible the structure of the region. In the selection of a stratigraphic key bed that could be identified in most of the well logs and

[8] Udden, J. A., Potash in the Texas Permian: Texas Univ. Bull. 17, pp. 47-52, 1915.

would therefore be useful in the construction of a structure-contour map, the top of the salt beds that occur so extensively throughout the region promised to give the most satisfactory results. It is realized, however, that salt deposition very probably did not stop in all parts of the Permian sea at the same time and therefore that the top of the salt beds probably does not represent a single stratigraphic horizon. The marked differences between the altitude of the highest salt bed in both the Neal well, in Glasscock County (No. 30), and the Scoggin well, in southwestern Kent County (No. 36), and the altitude of the highest salt in wells near by to the west of each serve to show that these altitudes are probably taken on two different salt strata, one several hundred feet below the other. The youngest and last deposited salt beds, under normal conditions, would be expected to occur near the center of the Permian basin, where were collected the last remaining waters of the evaporating sea. Also later folding, accentuating the original synclinal structure of the basin, and subsequent erosion may have resulted in the removal of the youngest salt strata from the borders of the basin. The highest salt bed encountered at different localities throughout the region would not then be at the same horizon but would represent progressively younger strata toward the center of the syncline. In case the accuracy of the structure map is affected by the fact that either or both of the two processes mentioned have occurred, the result is the same—that is, the syncline is deeper and more accentuated than the map indicates.

In Mitchell and Howard counties wells have been drilled sufficiently close together to permit correlations of beds at other horizons than the salt, and thus to check the relation which the top of the salt bears to the structure. This is shown in cross section *B–B′* (Pl. XII). A similar check, although not so conclusive, is given by wells in Scurry and Borden counties (cross section *C–C′*, Pl. XIII). It will be noted that the top of the salt is inclined westward at an angle which as a rule is slightly less than that of underlying strata, but nowhere does there appear any marked variation.

The reliability of the top of the salt beds in revealing the structure in the areas where these beds are thinnest, the great thickness of single salt beds (200 to 300 feet) in other areas, and the extensive distribution and apparent lack of abrupt folding of the salt series argue strongly for the reliability of the structure map. Moreover, of the 83 well logs that were selected for use in constructing the map only six were found that would not fit into the structure as plotted from the remaining logs. Of these six logs two are considered unreliable, one representing the result of rotary drilling and the other not having been recorded until long after drilling was completed.

The six questionable well logs (listed below) have not been used in the construction of the structure-contour map, and the map is considered reliable in portraying the general structural character of most of the region. However, because of the possibility that the same salt bed has not been used throughout and that the syncline is more accentuated than the map shows, it should be understood that the structure indicated is tentative.

In the preparation of this map the logs of all wells within the area that penetrated rock salt (see list on pp. 116–118) were studied. In computing the altitude of the top of the highest salt bed in a number of the wells it was necessary to use estimates of the surface altitude. Accurate altitudes were available for some wells, and the approximate altitude of many others was determined by an aneroid barometer.

A few wells penetrated little or no salt, and it was necessary to determine, from the log or cuttings of samples, the horizon believed to be equivalent to the top of the salt.

The data from the following six wells could not be used, because of either inaccuracy of the logs or local conditions of deposition or structure as yet undeterminable:

7. Arroyo ranch well, 25 miles east of Roswell, Chaves County, N. Mex.
15. McKnight well, southwestern Ector County, Tex.
20. Turkey Track ranch well, northeastern Eddy County, N. Mex.
30. Neal well, east-central Glasscock County, Tex.
35. Sandhill well, central Howard County, Tex.
36. Scoggin well, southwestern Kent County, Tex.

In at least the eastern part of the southern Panhandle there appear to be two distinct series of salt beds, to which Udden[9] has called attention.

The altitude of the top of the upper series was used in the construction of the map. As the wells near Childress (No. 9) and near Shamrock (No. 71) penetrated only the lower series, the former altitude of the top of the upper series was estimated from correlations with wells in Motley and Hall counties.

In eastern Pecos County the altitudes of all wells have been either estimated or obtained from other sources. The approximate altitudes given for the White & Baker well (No. 56) and the Reilly well (No. 55) are considered fairly reliable; those given for other wells in this vicinity are questionable. The position of the horizon equivalent to the top of the highest salt bed in the Bethlehem-Texas well (No. 50) is uncertain, as two samples of cuttings covering depths from 145 to 300 feet and from 300 to 690 feet were composed entirely of blue shale and gypsum, but from correlation with the Reilly well this horizon has been estimated to lie at a depth of approximately 350 feet, but may be somewhat lower.

[9] Op. cit. (Bull. 17), p. 49.

The position of the horizon equivalent to the top of the salt in the Bell well (No. 58), in eastern Reeves County, has been estimated to to be approximately 680 feet below the surface.

Wells whose logs were used in the construction of cross sections and maps

Map No.	Location	Name	Operating company	Depth of well (feet)	Depth to salt (feet)	Thickness of salt (feet)	Altitude of well (feet)
	Andrews County, Tex.:						
1	West-central part	Water well		700	(?)	(?)	3,200±
	Armstrong County, Tex.:						
2A	Sec. 145, block B3, Houston & Great Northern Ry. survey.	Goodnight No. 1	Goodnight Oil Co.	3,665	1,020	330±	3,145±
	Borden County, Tex.:						
3	Southeastern part, sec. 130.	Long	Jones and others	1,975	840	425±	2,300±
4	Southeastern part, sec. 55, block 25, Houston & Texas Central Ry. survey.	Reynolds	Vincennes Oil Co.	3,825	725	85±	2,225±
	Chaves County, N. Mex.:						
5	Sec. 15, T. 15 S., R. 26 E.	Lake Arthur		2,966	--------	0	3,400±
6	Sec. 15, T. 12 S., R. 25 E.	Orchard Park		2,295	--------	0	3,450±
7	25 miles east of Roswell, sec. 5, T. 11 S., R. 28 E.	Arroyo Ranch well.		2,943	850	2	3,700±
8	13 miles northeast of Roswell, sec. 31, T. 8 S., R. 24 E.	Toltec	Toltec Oil Co.	3,120	1,033	526	3,600±
	Childress County, Tex.:						
9	Childress	Fort Worth & Denver.	Fort Worth & Denver Ry. Co.	1,263	848	315	1,877
	Coke County, Tex.:						
10	Sec. 13, block 2, Houston & Texas Central Ry. survey.	Sauls	Transcontinental Petroleum Co.	3,776	--------	0	1,950±
11	Near Robert Lee	Stroud		3,270	--------	0	2,020±
	Crockett County, Tex.:						
12	Sec. 25, block C. D.	Henderson		5,908	--------	0	2,700±
	Dawson County, Tex.:						
12A	Near east line	Burns No. 1	La Mesa Oil & Gas Co.	1,865	1,510	95±	2,550±
	Dickens County, Tex.:						
13	Near spur	Spur	Swenson & Sons	4,489	570	374±	2,250
	Ector County, Tex.:						
14	2 miles northeast of Odessa.	Newnham	Farmers Oil Co.	927	(?)	(?)	2,950
15	Southwestern part	McKnight		700±	700±	(?)	2,800±
	Eddy County, N. Mex.:						
16	Sec. 18, T. 22 S., R. 27 E.	Bluebird	New Mexico Drilling & Refining Co. of Los Angeles.	2,127	485	100	3,106
17	8 miles east of Carlsbad.	Andrews		2,820	482	633	3,118
18	Sec. 15, T. 24 S., R. 27 E.	Canix	Nix, Etter & Cain	1,320	--------	0	3,016
19	Sec. 23, T. 18 S., R. 26 E.	Dayton	Dayton Petroleum Co.	1,126	--------	0	3,200±
20	25 miles east of Artesia, northwest corner of T. 16 S., R. 30 E.	Turkey Track ranch		501	231	270+	3,500±
	Fisher County, Tex.:						
21	Sec. 12, block 5, Texas & Pacific Ry. survey.	Barron	Wilcox Oil & Gas Co.	3,532	--------	0	2,062
22	Sec. 119, block 3, Houston & Texas Central Ry. survey.	Hodges	do	3,503	--------	0	2,153

Wells whose logs were used in the construction of cross sections and maps—Contd.

Map No.	Location	Name	Operating company	Depth of well (feet)	Depth to salt (feet)	Thickness of salt (feet)	Altitude of (feet)
23	Foard County, Tex.	Herring		3,115		0	(?)
	Garza County, Tex.:						
24	3 miles east of Justiceburg.	Boren		1,835	575	80±	2,318
25	3 miles southwest of Justiceburg.	Payne	Post City Oil & Development Co.	3,000	690	175−	2,369
26	Northwestern part	Post City	Double-U Co.	1,674	1,314	10+	2,700±
	Glasscock County, Tex.:						
27	Sec. 8, block 35, T. 3 S.	Brunson	Associated Producers & Refiners Corporation.	2,920	1,275	600±	2,550±
28	Northeastern part	Cushing	Cushing Production Co.	2,900+		0	2,560
29	Sec. 34, block 34, T. 2 S.	McDowell No. 4.	General Oil Co.	3,780	1,010	430	2,533
30	Sec. 31, block 33, T. 3 S.	Neal	do	2,810	1,880	235	2,656
	Hale County, Tex.:						
31	Southern part, sec. 17, block X.	Bledsoe	Bledsoe Oil & Gas Co.	3,855	1,760	315±	3,200±
	Hall County, Tex.:						
31A	5 miles south of Memphis.	Memphis		1,908	550	450−	1,950±
	Hardeman County, Tex.:						
31B	Near Quanah	Quanah		1,160		0	(?)
	Howard County, Tex.:						
32	Sec. 21, block 24, T. 1 S.	Quinn	Big Spring Production Co. (Rotary tools.)	3,610	1,205	25+	2,470±
33	Sec. 38, block 30, T. 1 N.	Read	General Oil Co	3,284	1,035	130±	2,250±
34	Sec. 24, block 32, T. 1 S.	Roberts	do	2,950	1,024	452	2,453
35	Sec. 35 block 32, T. 1 N.	Sandhill	General Oil Co. (Rotary tools to 1,656 feet.)	3,510	2,470	(?) 110	2,500±
	Kent County, Tex.:						
36	Western part, near Scoggin.	Scoggin		1,960	880	81±	2,100±
36A	Lea County, N. Mex.	Water well		700		0	(?)
	Loving County, Tex.:						
37	Sec. 23, block C26	Means	Pinal Dome Corporation.	5,208	921	1,391	3,000±
38	Sec. 80, block 1	Toyah-Bell No. 2.	Ramsey Oil Co.	4,599	700	1,024	2,685±
	Lynn County, Tex.:						
38A	Near Tahoka	Tahoka		2,710	1,932	415	3,110±
	Martin County, Tex.:						
39	Sec. 249, block 38, T. 3 N.	Wolcott	Cox Realization Co.	1,990	(?)	(?)	2,800±
	Midland County, Tex.:						
40	Sec. 9, block 39, T. 3 S.	Bryant	States Oil Corporation.	4,478	1,760	1,030±	2,780
	Mitchell County, Tex.:						
41	Northwestern part	Coleman No. 1	Flesher Petroleum Co.	3,095	1,220	123	2,300±
42	Sec. 21, block 28, T. 1 S.	Conway No. 1	Reno-Tex Land & Oil Co.	3,238	1,260	15	2,250±
43	Sec. 43, block 29, T. 1 N.	Foster No. 1	Colorado-Texas Oil Co.	2,655	1,310	52±	2,212
44	Sec. 88, block 25, T. 1 S.	Landers No. 1	Travellers Oil Development Co.	2,583	705	25±	2,300±
45	Sec. 33, block 28, T. 1 N.	Morrison No. 2	Underwriters Production & Refining Co.	2,970	823	75	2,119
		Texas & Pacific No. 2.	United Production & Refining Corporation.	3,175			
46	Sec. 33, block 27, T. 1 N.	Smith No. 1	Carey and others.	1,990	748	90±	2,090
47	2 miles southeast of Colorado City.	Salt works		750±	750±	(?)	2,175±
	Motley County, Tex.:						
48	15 miles north-northwest of Matador.	Echols	Minneapolis Oil Corporation.	4,707	700	40+	2,700±

Wells whose logs were used in the construction of cross sections and maps—Contd.

Map No.	Location	Name	Operating company	Depth of well (feet)	Depth to salt (feet)	Thickness of salt (feet)	Altitude of (feet)
	Nolan County, Tex.:						
49	Sec. 79, block X, Texas & Pacific Ry. survey.	Kuteman	Wichita Nolan Oil Co.	4,447		0	2,612
	Oldham County, Tex.:						
49A	2 miles southwest of Adrian.	Adrian	Adrian Oil & Gas Co.	2,825	690	752	4,050±
	Pecos County, Tex.:						
50	Sec. 51, block 2	Bethlehem-Texas,		2,740	350±	10±	2,400±
51	Sec. 23, block Z, Houston & Texas Central Ry. survey.	Buena Vista		1,114	962	(?)	2,400±
52	Sec. 25, block 127	Circle	Circle Oil Co.	3,951	600±	(?)	2,500±
53	Sec. 208, Burleson survey.	Devlin	Pinal Dome Corporation.	3,955	1,658	440±	2,791
54	Sec. 51, block C4	Menzie		3,000	962	523	2,760
55	Sec. 4, block 193, Texas & Mexican Ry. survey.	Reilly	Reilly Texas Co.	3,050	590?	27+	2,115
56	Sec. 11, block Z	White & Baker	Texas Oil Top Co.	3,225	714	150±	2,400±
	Potter County, Tex.:						
56A	Sec. 59, block 2, Adams, Beaty & Moulton survey.	Tanner	Miller Oil & Refining Co.	3,941	1,050±	345±	3,609
56B	6 miles northwest of Amarillo.	United States Geological Survey.	United States Geological Survey.	1,703	665	460	3,408
56C	Western part	Boden		2,000	640	560	(?)
	Quay County, N. Mex.:						
56D	8½ miles southeast of Tucumcari.	McGee No. 1		4,014	1,100	70	4,200±
	Randall County, Tex.:						
6E	18 miles southwest of Amarillo.	Miller No. 1	W. A. Miller & Sons.	2,575	940±	680±	3,680±
	Reagan County, Tex.:						
57	Southwestern part, sec. 3.	St. Rita No. 1	Texon Oil & Land Co.	1,945	1,137	533	2,725
	Reeves County, Tex.:						
58	Sec. 20, block 2, Houston & Texas Central Ry. survey.	Bell No. 1	Dixieland Syndicate.	4,507	680?	15+	2,690±
59	Western part	Huling-Ross		4,100		0	(?)
60	Sec. 17, block 4, Houston & Great Northern Ry. survey.	Laura	Sunshine Oil Corporation.	2,000+		0	2,630
	Scurry County, Tex.:						
61	2 miles southwest of Hermleigh.	Hermleigh	Hermleigh Oil & Gas Co.	1,200+	900	35±	2,331±
62	Snyder	Snyder	Snyder Oil & Development Co.	2,510	655	145+	2,310±
63	2 miles east of Dunn	Dunn		600	?600+	(?)	2,260±
	Sterling County, Tex.:						
64	Sec. 130, block 2, Houston & Texas Central Ry. survey.	Brennand	Sterling Petroleum Co.	3,300	885	45+	2,494
65	Sec. 127, block 6, in southeast corner.	Richardson	Texas Elkhorn Syndicate.	4,140		0	2,200±
	Upton County, Tex.:						
66	Upland	Upland		1,300+	1,300±	(?)	2,665±
	Ward County, Tex.:						
67	Sec. 25, block 33, on Pecos River.	River No. 2	Arthur Pitts Oil Co.	4,426	950	1,130±	2,558±
68	Sec. 187, block 34, Houston & Texas Central Ry. survey.	Soda Lake	do	1,977	(?)	(?)	2,608
69	3 miles north of Barstow.	Trans-Pecos	Trans-Pecos Oil Co.	1,700	(?)	(?)	2,625
70	Sec. 6, block 34, Houston & Texas Central Ry. survey.	Valley	Arthur Pitts Oil Co.	1,620	(?)	(?)	2,550±
	Wheeler County, Tex.:						
71	Near Shamrock	Shamrock		2,027	935	155±	2,281±

Post-Permian tilting of the basin toward the east, evidence of which has been presented and discussed by Udden,[10] apparently has been preceded and possibly also accompanied or followed by accentuation of the original synclinal structure and the development of other irregular structural features within the major geosyncline.

If it is assumed that the highest salt beds are everywhere approximately of the same age the degree of eastward tilting of the basin has been marked, as shown by the relative altitude of the upper salt beds east and west of the High Plains. The top of the highest salt bed in eastern Scurry and Mitchell counties ranges from 1,431 to 1,595 feet above sea level, whereas in the Pecos Valley region, over 200 miles due west, the highest salt bed has an altitude of more than 2,600 feet.

Widespread precipitation of salt probably does not occur in very deep water. To permit continuous deposition of 4,000 feet of salt and anhydrite the basin probably underwent progressive downwarping as strata accumulated. As illustrated by the tentative correlations of well logs (Pls. XI–XVI), this process resulted in more sharply synclinal structure in the deeper beds. Mild post-Permian accentuation of this structure may have occurred as a result of continuation of this basin downwarping, or uplift of lands to the east and west, or possibly a combination of these processes.

As discusssed on page 122, most of the irregularities in the outline of the major geosyncline were probably developed before salt was deposited.

The structure-contour map shows the major geosyncline extending nearly due north and south and the deepest portion, or axis, lying roughly along the west sides of Midland, Martin, and Dawson counties. The trend of the basin as represented is approximately correct, but its axis may not lie where it has been drawn. The lowest altitude above sea level at which the top of the salt has been encountered in all this region is 1,020 feet, found in the Bryant well (No. 40, Pl. XV), Midland County, but the Wolcott well (No. 39, Pl. XV) has been drilled 210 feet lower, to an altitude of 810 feet, and has not yet encountered salt. The axis of the geosyncline has been tentatively drawn near these two wells, but it may lie either considerably farther west or as much as 20 to 25 miles farther east. From a study of the map it appears much more likely that if the axis is not correctly shown it lies some distance to the west, rather than to the east. There is no reliable information concerning the altitude of the top of the salt for a distance of 80 miles west of the Bryant well, and in Andrews, Gaines, and Lea counties and eastern

[10] Op. cit. (Bull. 17), pp. 50–52.

Eddy County, no wells, to the knowledge of the writer, have been drilled deep enough to encounter salt.

The outline of that part of the basin where well data are more abundant is irregular, and there are evidences of minor basins and broad anticlinal folds. The geosyncline does not continue northward indefinitely but turns abruptly northeastward at about the corner of Hockley, Lamb, Hale, and Lubbock counties and enters southwestern Oklahoma just north of Red River. This bend is due to Permian and post-Permian geanticlinal folding in the Panhandle region near Amarillo. The folding has been attributed by Powers[11] and Pratt[12] to differential compacting of strata deposited around and over an eroded mountain system. According to these writers a hill of granitic rock has been found to underlie every dome of large size in the Texas Panhandle. Recent operations in Beckham County and other places in southwestern Oklahoma indicate that similar anticlinal folds, with underlying crystalline rocks, occur there also. There can be little doubt that these folds, which trend in a generally westerly direction, are a westward continuation of the Wichita-Arbuckle Mountain uplift; there may be a similar connection with Lee's "ancestral Rocky Mountains" of northern New Mexico.[13]

Another anticlinal irregularity in the major geosyncline, as indicated by meager data, apparently occurs in Cottle, Motley, and Floyd counties. The mapping of the structure of this part of the region is based on information from only four widely separated wells and therefore is not to be considered entirely reliable. The fold appears as a broad plunging anticline with its axis trending slightly north of east. Owing to the insufficiency of the data, the axis is only tentatively located, and the indicated trend is probably inaccurate. As the fold is mapped a line drawn through the axis and continued to the east would pass between the Wichita Mountains and the Electra and Burkburnett oil fields, the latter on the Red River uplift, 100 miles east of the region here described. It is not impossible that this fold represents either a spur from the Wichita Mountains or the westward continuation of the Red River uplift. Liddle[14] called attention to the fact that "in Foard County * * * the Carboniferous is known to be at least 500 feet above its normal undisturbed position." The possible relation of this condition to the Marathon fold, the Sheffield terrace, and the structural features of Coke County were discussed. He added: "It is possible, however, that the elevation

[11] Powers, Sidney, Reflected buried hills and their importance in petroleum geology: Econ. Geology, vol. 17, pp. 252-258, 1922.

[12] Pratt, W. E., Oil and gas in the Texas Panhandle: Am. Assoc. Petroleum Geologists Bull., vol. 7, pp. 239-243, 1923.

[13] Lee, W. T., Concerning granite in wells in eastern New Mexico: Am. Assoc. Petroleum Geologists Bull., vol. 5, pp. 163-167, 1921.

[14] Liddle, R. A., The Marathon fold and its influence on petroleum accumulation: Texas Univ. Bull. 1847, p. 15, 1918.

of the Carboniferous in Foard County is associated with the Red River uplift."

From the facts that the Red River uplift and the anticlinal fold shown in Hale, Floyd, and Motley counties are practically coextensive, and that a pronounced uplift in Carboniferous strata has been recognized in Foard County directly between these two structural features, it appears very probable that a continuous line of disturbance extends westward from north-central Texas along parallel 34° north to some locality near the axis of the Llano Estacado geosyncline. If such a flexure is present, surface evidences should appear east of the High Plains in the outcrop of the Double Mountain and Clear Fork beds and should be looked for in eastern Motley, eastern Hall, Childress, Cottle, Foard, Hardeman, and Wilbarger counties, in Texas, and in the part of Oklahoma bordering Red River west of Burkburnett.[14a]

The most pronounced synclinal irregularity perceptible in the outline of the major geosyncline is to be found in Howard, Mitchell, southern Scurry, and Borden counties. This is the area in which wells are most abundant and for which the structure-contour map is most reliable. Even for this area detailed structural features are not shown on the map, for the contour interval and the distances between wells are too great. The production of approximately 250 barrels of oil a day (1923) in northwestern Mitchell County comes from minor folds within this large synclinal basin.

In mapping the structure of eastern Pecos County the logs of five wells were used, though the determinations of their surface altitude and of the position of the horizon equivalent to the top of the salt in one of the wells (No. 50) are not without question. Because of the scarcity of data the correlations are not entirely reliable, but it seems likely that an anticlinal fold is present in this area. The exact proportions and the trend of this fold can not be shown, but its relation to the Glass Mountains, which form the northwestern flank of the Marathon fold, 50 miles to the southwest, is evident. Detailed work by Liddle and Prettyman[15] has resulted in the mapping of the Sheffield terrace, a flexure of the surface rocks which extends 20 miles northeastward from eastern Pecos County and whose longer axis is coincident with the trend of the Marathon fold. The subsurface fold in eastern Pecos County herein outlined makes an angle of about 50° with the Sheffield terrace and, if proved to be present by more detailed work, is probably also a northeastward continua-

[14a] The structure map, prepared in 1923, shows a less prominent anticlinal nose in southern Garza County. In 1924 (Oil Weekly, Oct. 17, 1924, p. 59) it was stated that the B. V. Blackwell well, drilled on the J. M. Boren lease, 4 miles east of Justiceburg, encountered oil between 1,960 and 2,005 feet. On January 9, 1925 (Oil Weekly), this well was reported to be pumping 25 barrels of oil daily.

[15] Liddle, R. A., and Prettyman, T. M., Geology and mineral resources of Crockett County, with notes on the stratigraphy, structure, and oil prospects of the central Pecos Valley: Texas Univ. Bull. 1857, pp. 66–67, 86–90, 1920. See also Liddle, R. A., The Marathon fold and its influence on petroleum accumulation: Texas Univ. Bull. 1847, pp. 9–16, 1920.

tion of the folding of the Marathon country. Local folding of the surface rocks has been noted not far from Pecos River in northwestern Crockett County and southwestern Upton County, north of wells Nos. 54 and 56, and it is possible that the subsurface fold of eastern Pecos County, if actually present, continues farther north-northeastward than has been shown.

Information concerning the presence of salt in southwestern Pecos County and southern Reeves County is lacking, for no deep wells, so far as the writer knows, have been drilled in this area. The south end of the major geosyncline is believed to have occupied during Permian time western Pecos County and eastern Reeves County and possibly also a small part of northeastern Jeff Davis County and northern Brewster County, west of the Glass Mountains. This end of the geosyncline has, no doubt, been affected by the later disturbances that produced the Barilla and Davis mountains and elevated the Marathon region. That the Permian basin did not extend far south of eastern Pecos County is suggested by the presence of only thin deposits of salt in most of the eastern Pecos County wells. The only deep well in northern Crockett County (No. 12) of which a log is available encountered no salt.

There is little irregularity to be noted along the western border of the major geosyncline. However, the contouring for 200 miles northward from Loving, Winkler, and Ector counties is highly hypothetical, for in this area there is a nearly complete lack of data.

Comparison of Plates III and XVII discloses a very striking relation between the structure of the region and the thicknesses of reported salt. In general, the structurally low areas are those of greater thickness of salt and the structurally high areas are areas in which smaller amounts of salt have been recorded. This relation strongly suggests that the structural features of the basin of deposition in Upper Permian times were much like those of to-day—that is, the present structurally high areas were high and the low areas were low, thus permitting greater thicknesses of salt to accumulate in areas that remained more continually submerged beneath strongly saline water.

CONDITIONS DURING PERMIAN AND TRIASSIC TIME

In the following attempt to describe conditions prevalent in western Texas and adjoining regions directly before, during, and after the time of salt deposition it is assumed that the correlations indicated in the cross-section charts are correct.

In early Permian time marine conditions existed over probably all of western Texas and eastern New Mexico. The rocks of the Permian Wichita formation, although differing considerably in detail, are not greatly unlike the underlying Pennsylvanian rocks in all parts of Texas where they are both exposed, and apparently there was no marked change in conditions at the end of the Pennsylvanian epoch. The main body of the Permian sea was to the southwest, and an arm of this sea covered most of western Texas and eastern New Mexico and extended northeastward into western and central Oklahoma and central Kansas. Along its east shore, in north-central Texas, terrestrial and near-shore deposits, largely of red color, were deposited, while farther west, southwest, and south, in the Llano Estacado, in the trans-Pecos region of Texas and southern New Mexico, and in Coke and Runnels counties, Tex., strictly marine formations, consisting largely of limestone with some sandstone and shale, were accumulating. Marine conditions were also prevalent farther north in northern Oklahoma and Kansas. Although this northern sea was probably not entirely disconnected from Texas marine waters, it is believed that mountainous areas in southern Oklahoma and the Texas Panhandle prevented widespread connections during most of early Permian time. Later in the Permian epoch the conditions that brought about the deposition of the terrestrial and near-shore sediments which now constitute the red beds spread northward from southern Oklahoma and westward and southward over western Texas.

In Clear Fork time shales, mostly red, with some sandstones, limestones, and beds that now comprise dolomites were laid down in the longitude of Coke and Runnels counties, while farther west in Sterling County and eastern Glasscock County the conditions were suitable for the accumulation of considerable thicknesses of limestone, which was contemporaneous with anhydrite and rock salt deposited still farther west, in the more central portions of this shallow inland part of the Permian sea.

The amount of water removed by evaporation from this northeastward-extending arm of the Clear Fork seas was in excess of that supplied by the influx of sea water, rains, and inflowing streams. Hence, the climate was arid, but there was sufficient rainfall to produce erosion of the bordering lands and to develop streams sufficiently large to supply the muds that made up the near-shore red beds. Salt was deposited in areas of restricted circulation, in general some distance from shore, where the more highly concentrated waters were collected. The climate gradually became even more arid, and the land to the east and northeast probably became eroded to a lower level; the streams were fewer and sluggish; the salinity of the sea gradually increased, and with excessive evaporation and near-shore deposition the sea gradually became smaller. No positive statement concerning the exact positions of the eastern shore line during Clear Fork time and the succeeding Double Mountain epoch can be made, for if the beds of those epochs were deposited in central Texas, they have been removed by erosion. With increase in the salinity of the sea water and decrease in the diluting power of the inflowing streams, salt deposition became more widespread in Double Mountain time, and except in a belt of varying width bordering the shore (the eastern near-shore belt apparently was just east of Mitchell and Scurry counties) it occurred throughout the extent of the sea in western Texas and eastern New Mexico, east of Pecos River.

Although salt was not precipitated in the eastern near-shore belt, because of dilution by stream water, gypsum was deposited in dry periods near shore, interbedded with the clastic sediments. That the normal process of evaporation and deposition in the offshore portions of the isolated arm of the sea continued without interruption is unlikely, for interbedded with the salt and alternating with it are thick beds of anhydrite. Conditions on the west side of the salt basin in the trans-Pecos region were similar to those described above for the eastern near-shore belt. It is interesting to compare the relative amounts of anhydrite and salt in the Means well (No. 37), in northeastern Loving County, the Toyah-Bell well (No. 38), in southern Loving County, and the Bell well (No. 58), in northeastern Reeves County. Below the top of the highest bed of salt in the Means well there are about 4,080 feet of strata deposited solely by precipitation from highly saline waters, of which 1,390 feet (34 per cent) is salt; in the Toyah-Bell well there are 3,565 feet of precipitates, of which 1,024 feet (28.7 per cent) is salt; and in the Bell well not more than 5 per cent is salt. There is a marked increase of anhydrite over salt from northeastern Loving County southwestward to the country just west of Pecos River. Farther west, in northern trans-Pecos Texas, the Capitan limestone, Castile gypsum, Rustler limestone, and possibly also the Delaware Mountain formation are believed to be the equivalent of the buried salt, anhydrite, and red-bed series east of the river. It seems apparent that the open sea was in the direction of trans-Pecos Texas and that the beds of anhydrite alternating with salt in the Means and Toyah-Bell wells and the increase of anhydrite over salt progressively southwestward toward the open sea are due to intermittent influx of sea water to the inland sea possibly over some low barrier that may have existed not far west of Pecos River. The sandy nature of the Rustler limestone near the Texas-New Mexico line and the presence of considerable sand and fine gravel in the cuttings from the upper part of the Bell well suggest the presence of land not far distant. Gradual subsidence, continuation of intermittent influx of sea water, and an arid climate provided the necessary conditions for the accumulation of this thick and widespread mass of salt and anhydrite.

As desiccation approached completion within the large isolated basin of western Texas and eastern New Mexico, the mother liquors containing the more highly soluble salts were gradually driven to the minor basins formed by low places in the old sea floor. No evidence has yet been found that complete desiccation occurred, for the extremely soluble salts common to all sea water have not been discovered in this region. It is known, however, that polyhalite ($2CaSO_4.MgSO_4.K_2SO_4.2H_2O$) was deposited in several localities scattered throughout western Texas. In discussing the phenomena that attended the formation of the beds of gypsum, anhydrite, salt, and polyhalite at Stassfurt, Germany, Clarke[16] says:

> For a long time only gypsum was deposited; but later, as the concentration of the bay increased, salt also was laid down, and by its action the gypsum was converted into anhydrite. From this point onward, for a considerable period, the calcium sulphate derived from the influx of sea water above fell through a deep layer of concentrated brine and was deposited directly as anhydrite, in alternating layers with the salt. When, however, so much salt had been precipitated that the supernatant solutions had become bitterns rich in magnesium salts, the calcium sulphate united with these salts, and polyhalite was formed. The polyhalite region at Stassfurt is essentially a bed of rock salt, containing, with other impurities, from 6 to 7 per cent of the new mineral.

There is no apparent reason to believe that conditions in western Texas were greatly unlike those that attended the deposition of the Stassfurt beds.

In consideration of the areal extent of Permian salt deposition in the south-central part of the United States, the small number of wells drilled, especially those from which complete sets of samples of cuttings have been saved, and the vast territory which is as yet wholly untested, it can not be said that the more highly soluble salts are absent in this region. Indeed, it is reasonable to believe that somewhere, in some of the minor isolated basins, desiccation was complete and these salts were deposited.

After this period of extreme aridity the climate became more humid, and streams from the land, which may have been somewhat elevated, carried much sediment. The sea probably continued to have intermittent access to parts of the region. A series of red beds, composed mostly of shale and sandstone, with some gypsum and thin limestones, was deposited throughout the region. Such conditions probably existed throughout late Permian time.

Near the end of the Permian epoch gentle folding probably occurred, and as a result the region was apparently subjected to erosion in early and middle Triassic time. The Llano Estacado geosyncline, which was becoming more pronounced throughout the epoch of salt deposition, probably underwent mild accentuation at

[16] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 221-222, 1920.

this time. Swiftly flowing streams became more numerous and transported their load from the higher lands on the east and west to the lower parts of the Triassic basin. The red sediments, consisting of mud, sand, and gravel, which went to make up the Dockum beds, accumulated to a thickness which as herein identified ranges from a few feet near the edges of the basin to about 1,200 feet near the center. The accumulation of these beds produced a nearly featureless Triassic plain, on which subsequent erosion, which is considered to have occurred throughout Jurassic time, was not rapid. These conditions prevailed until the region was again inundated by the transgressing Trinity sea.