University of Texas Bulletin

No. 2801: January 1, 1928

CONTRIBUTIONS TO GEOLOGY, 1928

Bureau of Economic Geology

J. A. Udden, Director E. H. Sellards, Associate Director

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The benefits of education and of useful knowledge, generally diffused through a community, are essential to the preservation of a free government.

Sam Houston

Cultivated mind is the guardian genius of democracy. . . . It is the only dictator that freemen acknowledge and the only security that freemen desire.

Mirabeau B. Lamar

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The "Contributions to Geology" includes shorter papers of which in addition to other Bureau publications, usually, one volume per year will be issued, this volume being the first of the series. Each volume of the "Contributions" bears a bulletin number and is thus a part of the series of University of Texas bulletins issued from the Bureau of Economic Geology.

E. H. SELLARDS.

THE ECONOMIC IMPORTANCE OF SALT DOMES

BY DONALD C. BARTON

INTRODUCTION

The salt domes, considering their importance in both pure and economic geology, have been rather curiously neglected by geologists who have not come immediately in contact with them, and as a result competent discussions of them and their importance are practically wanting in the textbooks in English. For example: the famous Leadville, Colorado, which has had a total production of a value of some 425 million dollars has been the subject of two voluminous monographs in addition to numerous shorter articles in the professional journals; but Sulphur, La., which quietly produced one-third as many dollars worth of sulphur from only seventy-six acres has been described only in brief papers in the journals, and the origin of its sulphur has never been made the subject of careful study. Salt domes, inclusive of salt ridges, are found widely scattered throughout the world. The United States has over one hundred salt domes: Eighty-two known salt domes in Texas and Louisiana; over thirty-two domes recently discovered mostly by the seismograph in Texas and Louisiana, and not yet drilled, but accepted by the Gulf Coast geologists as proved; and some few probable salt domes or salt ridges in Utah. Mexico has fifteen known salt domes. Roumania has at least sixty known salt domes in Old Roumania and at least fifteen known salt domes in Transylvania.[1] Germany has some fifty known salt domes and salt ridges.

Manuscript submitted September 1, 1927; published July, 1928. Given in part as lectures at the University of Texas in 1927.

[1]Voitesti states that there are 200 known salt domes but the writer suspects that he counts different portions of the same dome as separate domes. Voitesti, I. P., Geology of the Salt Domes in the Carpathian Region of Roumania, Bull. Am. Assoc. Petr. Geol., Vol. IX, 1925, p. 1165. Reprinted in Geology of Salt Dome Oil Fields, Am. Assoc. Petr. Geol., p. 87, 1926 .

Salt domes are known also in Spain, in northern Siberia, to the south of the Ural Mountains, in Algeria, in Egypt, and in Persia.

Salt domes are interesting purely as geologic structures. The extreme type of a salt dome is an intrusive sedimentary mass which has been intruded for thousands of feet into overlying formations as truly as have volcanic stocks. Such salt domes virtually stand midway between normal folding in sedimentary rocks and certain types of igneous intrusions. As the salt series in some places itself has a definite stratigraphic section that is recognizably preserved in those salt domes, the structure and flowage that have taken place in the salt domes can be worked out. All types of salt domes present a study of the extreme degree of mobility and plasticity of sedimentary rocks under deformation.

The economic importance of salt domes is perhaps greater than their importance in theoretic geology. Seventy-five per cent of the world's production of sulphur is from salt domes. Some 35 per cent of the world's production of potash is from salt domes and salt ridges and yet the value of the oil produced is greater than that of either the sulphur or the potash. Any one of several salt mines or salt domes in several countries has an easily minable reserve of salt to supply the world's demand for a thousand years and if an estimate is made of the readily available salt reserve of the salt domes, it is best given in terms of cubic kilometers.

SALT DOMES DEFINED

A salt dome in the generic sense of the term is an anticline in which there is abnormal axial thickening of a salt formation to form an axial core of salt. The thickening of the salt in the anticline in some localities is known, and in all localities is assumed, to be concomitant with corresponding thinning of the salt formation in the adjacent area off the salt dome. The salt domes of the world show a complete series of types: From one that is a normal anticline with a very faint axial thickening of the salt, to one in which the salt has been erupted through the crest of the anticline and has been intruded for thousands of feet—we know that in many places it is over five thousand feet—into the overlying sediments.

The origin and method of formation of salt domes are best seen in the German salt dome district. Over most of northern Germany, in the Zechstein times of the Permian, a thick salt series was deposited, which in the salt dome area has a characteristic and persistent stratigraphic section; a thin clay zone carrying marine fossils, for example, occurs in the middle of the salt series, is extremely persistent, is constant in character, and makes an exceptionally good key bed on which to work out structure. As the salt series contains members composed of potash salts, the potash mines with their shafts and galleries have allowed the interior structure of many salt domes and ridges to be worked out in detail. Numerous exploratory diamond drill holes and in places numerous oil wells taken with good surface exposures give good information in regard to the flank beds and outer form of the salt domes and ridges.

The deformation of the salt series in Germany ranges from the normal types of geologic structures such as gentle arches, folding, and faulting in such areas as the Thuringia Basin, to the intrusive salt stocks of the North German coastal plain. In the broad Thuringia Basin, the whole sedimentary series including the salt series is only very gently deformed. In the Madgeburg-Halberstadt Basin, the salt series has been rather sharply deformed with the concomitant formation of numerous salt domes and salt ridges. From the upper (southeast) end of the Basin northwestward out into the North German (coastal) plain, there is a complete sequence and gradation in type of the salt domes and ridges, from simple anticlines with a very faint axial thickening of the salt core (Stassfurt type, Fig. 2a) through sharp anticlines with a highly thickened axial core of salt but with the overlying beds still concordant with the surface of the salt (Asse type, Fig. 2b) to the salt stocks where the salt core has broken through the crest and

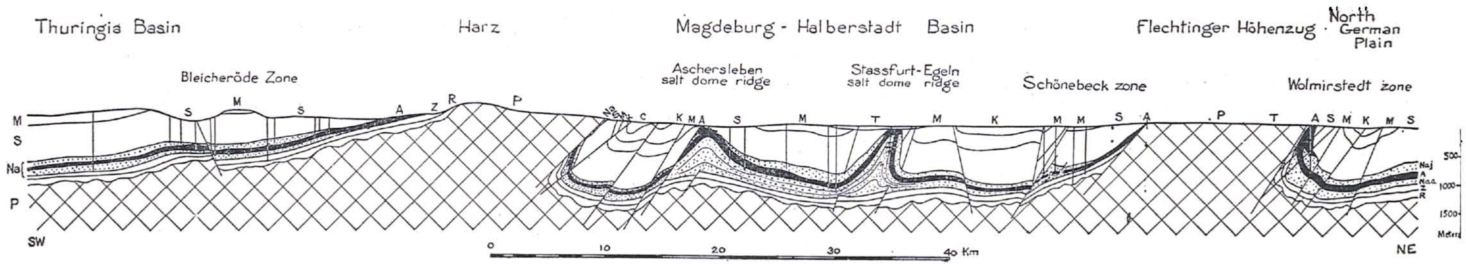

Fig. 1. General cross section of the north German potash-bearing salt deposits showing the contrast of the very slightly deformed beds of the Thuringia Basin with the sharply deformed beds of the Magdeburg-Halberstadt Basin. (After Everding, Geinecke, Schunemann, and Seidl.) The potash-bearing zone lies in the stippled zone immediately below the broad black band representing the "Main" anhydrite. T=Tertiary, C=Cretaceous, K=Keuper, M=Muschelkalk, S=Buntsandstein, Na=Salt Series (Na-j, the "Younger" Salt Series; A, the "Main" anhydrite; and Na-a, the "Older" Salt Series), R=Rotliegendes, P=Pre-Permian.

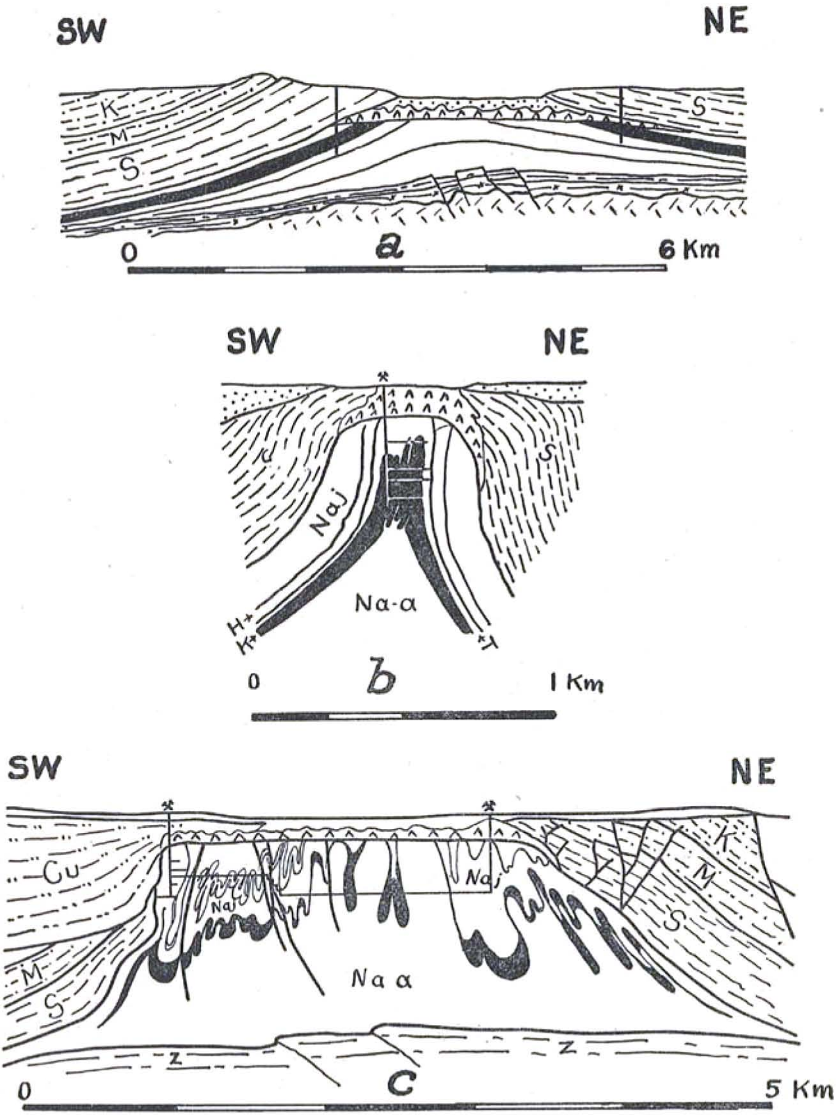

Fig. 2. Cross sections of the Schmücke-Finne salt dome ridge: *a*, Stassfurt type ridge; *b*, of the Stassfurt salt dome ridge at a point at which it is an Asse type ridge; and *c*, of the Benthe salt dome, a Hannoverian type salt dome. (After Schlafke, Stille, Seidl.) Cu = Lower Cretaceous, K = Keuper, M = Muschelkalk, S = Buntsandstein, Na-j = "Younger" Salt Series, Na-a = "Older" Salt Series, Z = Lower Zechstein. In Figs. 2a and 2c the black band represents the "Main" anhydrite; the "Older" or main potash-bearing zone lies immediately under it; in Fig. 2b, H = the "Main" anhydrite, and K = the "Older" potash-bearing zone; in Fig. 2c, the much-contorted light black lines above the letters "Na-j" represent the zone of the "Younger" potash-bearing zone of the Hannover District.

has been intruded into the overlying sediments (Hannoverian type, Fig. 2c).

The formation of those salt domes and ridges by plastic deformation and flowage of the sedimentary Zechstein salt series has been worked and definitely proved by the use of the recognizable stratigraphic section of the salt series in the area of the domes. The salt series has apparently flowed more or less as a whole and the movement of the salt has not been by transfer through solution and redeposition. The structure of the American, of the Roumanian, and of some of the Mexican salt domes indicates definitely that the salt has been intruded for thousands of feet up into sediments in which it does not belong. The structure of the salt as revealed in the Roumanian and Louisianan salt mines shows that the salt has had the same high degree of plasticity that is manifested by many gneisses and schists. The sedimentary origin of the salt of the Roumanian salt domes is indicated by the interstratified clayey zones, and of the American salt domes by the algae in a core from 4,800 feet in the Rycade Oil Corporation's Gray No. 1 on the Markham salt dome in Texas.[2]

The motive force which has caused the plastic flowage of the salt and its intrusion in many cases into the overlying beds is still a question of dispute. It must probably be some sort of thrust; one school attributes it to tangential orogenic thrust and another school to the static thrust of the overlying beds.

The American salt domes of Texas and Louisiana represent extreme phases of the Hannoverian type of dome. The domes are circular to sub-circular in plan; the salt core has an area of from one to six square miles (2 to 16 sq. km.) and has flanks dipping 60 to 90 degrees. The salt core in most domes is surmounted by a cap of anhydrite, gypsum, and limestone which in a few cases extends part way down the flank of the salt. The salt core has been

[2]Barton, Donald C., The American Salt Dome Problems in the Light of the German and Roumanian Salt Domes, Bull. Am. Assoc. Petr. Geol., Vol. IX, 1925, pp. 1227–1268. Reprinted in Geology of Salt Dome Oil Fields, Am. Assoc. Petr. Geol., 1926, pp. 167–208.

intruded up for at least 8,000 feet (2,400 meters) and probably over 13,000± feet (4,000 meters)[3] into a series of Tertiary and perhaps Cretaceous sediments in the case of the coastal group of domes.

The Roumanian domes, like the Texas-Louisiana domes, represent extreme phases of the Hannoverian type of dome. The petroliferous domes of Old Roumania have been intruded for thousands of feet into Tertiary sediments. But being in a region in which there have been strong horizontal compression and overthrusting, the domes are much elongated perpendicularly to the direction of thrust. No cap rock is present in the Roumanian salt domes.

The Mexican salt domes seem to show the complete range of types of salt domes. Throughout the salt dome area, there seems to be a mother salt formation at only moderate depth. It in places has arched the overlying beds into gentle elliptical domes resembling the Stassfurt type of salt dome ridges and in other places it has been intruded into the overlying beds and forms a salt stock of the Hannoverian type. A cap is present in many of the domes.

PETROLEUM

GEOLOGY

Petroliferous salt domes are found in the United States, Roumania, Germany, and Mexico.[3a] The production from

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[3]Drilling shows a Tertiary-Recent section without salt beds at least 6,000 feet thick; the seismic method of geophysical prospecting with which the Gulf Coast has been fairly thoroughly covered indicates no salt beds above 8,000 feet and a few abnormally long shots have given results that seem to indicate no salt down to a depth of some 13,000 feet, except in salt domes.

[3a]Also in Russia. The Dossor oil field in the Ural Emba district is on a known salt dome. Novobogatinsk is also a known salt dome, and Makat is suspected of being a salt dome. The production for the past few years has been of the magnitude of 1½ million barrels per annum. In 1924, the Dossor oil field was the only one of the fields operated. Little seems to be known about these fields. Development goes slowly on account of their inaccessibility. There would seem to be a good possibility of the existence of large reserves on these salt domes.

Cf. interview with J. N. Strigeoff by J. Logan, *Oil Weekly*, March 30, 1928, p. 61; B. B. Zavoico in "Russian Oilfields in 1924–25" and "Russian Oilfields in 1925–26," in "Petroleum Development and Technology in 1925" and corresponding volume for 1926, published by the American Institute of Mining and Metallurgical Engineers.

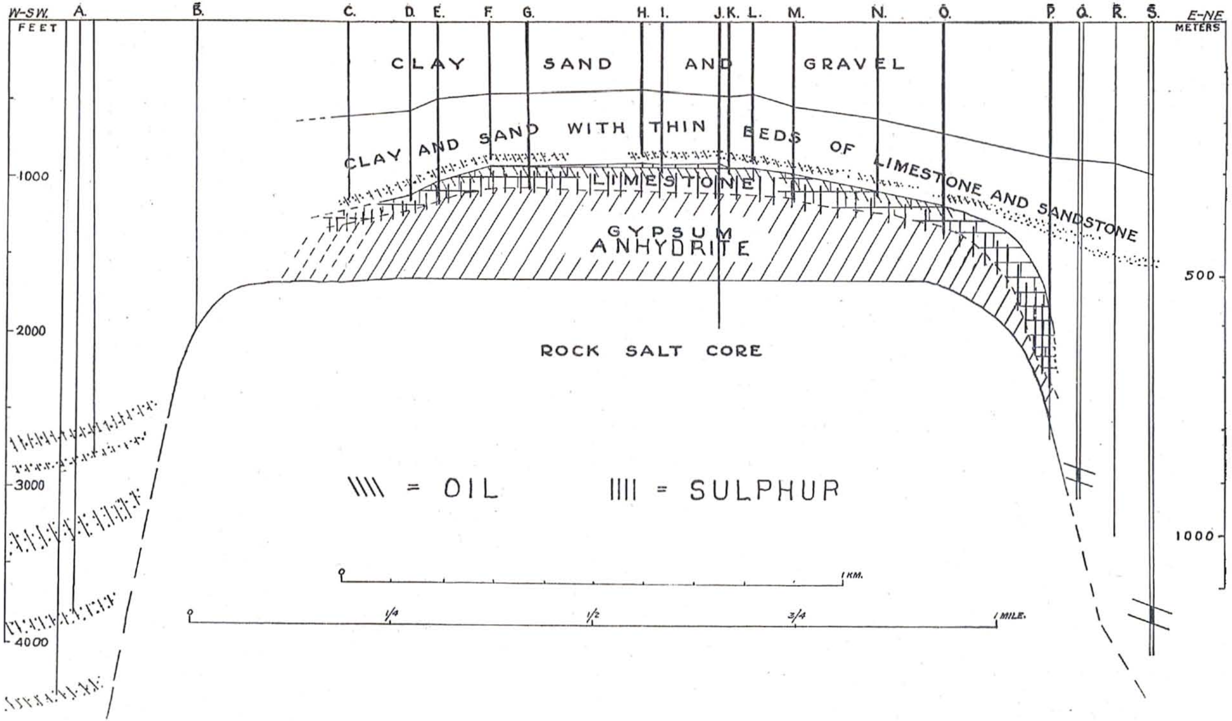

Fig. 3. Diagrammatic section of a salt dome of the Texas-Louisiana Gulf Coast showing the occurrence of the oil and of the sulphur. The section and the occurrence of the oil are essentially those of the Spindletop salt dome. The cap has been modified slightly after the Bryan Heights salt dome in order to represent the occurrence of the sulphur, as Spindletop is not a sulphur dome. Wells A=the 3,000–5,000-foot (900–1,500-meter) wells producing from the lateral sands of the southwest flank of Spindletop. Wells C, F, H, L=shallow oil wells producing from the super-cap sands. Wells D, I, K, N=oil wells producing from the limestone of the cap. Wells E, G, M, O, P represent sulphur wells. Wells Q, R, S= actual dry holes on the east side of Spindletop.

the salt domes of the United States and Roumania is of the first class;[4] that from the German salt domes, of the third class; and that from the Mexican salt domes, of the fourth class. Practically all the petroleum produced in Roumania and Germany comes from salt dome oil fields. The oil of salt dome oil fields has no genetic connection with the salt, but according to certain theories of the generation of petroleum, the intrusion of the salt might have favored the generation of the petroleum. The main function of the salt dome has been to provide situations structurally favorable for the accumulation of oil.

Three types of oil fields are found on salt domes: The super-cap (super-salt type), the cap-rock type, and the lateral sands or flank types. (See Fig. 3.)

In the super-cap (super-salt) type, a sand bed or lens that extends wholly or partly across and above the salt core, has been arched but not broken by the upthrust of the deeper lying salt mass. The structural form of the "sand," therefore, is that of a bed in a simple anticlinal dome and the accumulation of the petroleum in that sand or sands is merely a case of simple anticlinal accumulation. The Saratoga oil field is a salt dome oil field wholly of the super-cap type. The super-cap (super-salt) oil fields of the world in general are not as prolific as the cap-rock and lateral sand oil fields.

In the cap-rock type, the oil is found in the top of the limestone of the cap. The latter in the American domes is composed of anhydrite (or gypsum) below and limestone above with the anhydrite (or gypsum) predominant. The limestone of the cap may be wanting or very thin. The origin of the limestone is not clear; Goldman believes that it is secondary; the character of the limestone changes

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[4]The writer's usage of the terms first, second, third, and fourth class as applied to oil fields is as follows:

First Class: An oil field which has produced or can produce 5,000,000 barrels of oil (700,000 tons) or more in one year.

Second Class: Between 1,000,000 and 5,000,000 barrels (135,000 to 700,000 tons) in one year.

Third Class: Between 150,000 and 1,000,000 barrels (20,000 and 135,000 tons) in one year.

Fourth Class: Less than 150,000 barrels (20,000 tons in one year).

from dome to dome, but nearly everywhere it is porous; in some places it is permeated by a ramifying network of minute solution channels; in other places there are numerous large solution caverns, or numerous fissures, in which the bit may drop several feet suddenly; in some cases the limestone is granular and has considerable intergranular porosity. The cap-rock oil is found filling all these types of cavities and spaces.

The source of the oil has not been proven. There is no evidence or possibility of the petroleum's being indigenous to the limestone or having any genetic relation to it. The function of the limestone seems merely to have been that of a very favorable reservoir rock for the accumulation of the oil. It has been thrust up into the Plio-Miocene clays, which have acted as a relatively impermeable seal for it. On some domes, it is apparently so well sealed off that it is barren, although productive sands are present, as for example on the Nash salt dome. The porous limestone cap of some domes seems to have been in contact either with source beds or oil sands from which it must have imbibed its oil. At Humble, the limestone cap is practically in contact with the Jackson black shale, which seems to be a favorable source rock, and at Spindletop the southwest edge of the limestone cap is only a few hundred feet horizontally and vertically from the inner edge of the upper lateral productive oil sands. No careful study has been made of the character of the oil to determine whether or not it is a derivative of the oil of the Jackson black shale at Humble. The cap-rock oil at Spindletop is not oil that has seeped in recently from the lateral sands; the cap-rock oil is quite different in character from the oil of the lateral sands.[5] Although both the cap rock and the lateral sands types of oil belong definitely to the naphthene (wax-free) class of oils, the cap-rock oil has a high sulphur content (2.31 per cent), is deficient in the gasoline, naphtha, and kerosene fractions, and has an A.P.I. gravity of 19.7 (Sp.

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[5]Kraemar, A. J., and Grandone, Peter, Analyses of Spindletop, Texas, Crude Oils, U. S. Bureau of Mines, Serial No. 2808, May, 1927.

Gr. of 0.936) ; and the oil of the lateral sands, whether from the shallower sands at a depth of 2,700 feet (510 meters), the intermediate sands, or the deeper sands at a depth of 5,000 feet (1,500 meters), has a very low sulphur content (0.15 to 0.30 per cent), contains considerable gasoline and naphtha fractions (5 or 20 per cent), and has an A.P.I. gravity of 25 to 31 (Sp. Gr. of 0.901 to 0.874). The cap-rock oil contains about three times as much asphalt as the lateral sand oil. If the oil of the cap-rock field came originally from the same source as the oil of the lateral sands, it must have been so very long ago that since then it has had time to undergo very considerable alteration.

The American cap-rock oil fields are prolifically productive; the cap-rock oil field at Humble has produced some 45,000,000 barrels (6,650,000 tons) of oil; the cap-rock oil field at Spindletop has produced some 50,000,000 barrels (7,000,000 tons) of oil from 265 acres and has a record of a per-acre production of 190,000 barrels (64,000 tons per hectare).

In the lateral sands, or flank, type of salt dome oil field, the oil is found in sand beds or lenses in the sediments that flank and dip away from the salt core. The beds of which the oil sands are a part have been dragged up, strongly tilted, and pierced by the upthrust of the salt mass. The oil sands of the flank normally terminate upward against the edge of the salt core or against faults parallel and close to it, but in a few cases terminate against tangential faults farther out. The upward sealing off of the oil sands must be due to the plastering of the upper end of the oil sands by plastic gumbo[6] and shale dragged upward in the fault plane or in some cases to the faulting of the upper end of the oil sand against impervious plastic gumbo and shale. The structure of the lateral sands type of salt dome oil field is actually a "downthrow on the down dip side" type of fault, a structural situation which, according to a rather general belief of oil geologists, is extremely unfavorable to the accumulation of oil. Some of the salt

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[6]Gumbo is a driller's term much used in oil geology for a stiff sticky clay.

dome oil fields of the lateral sand type are extremely prolific, as for example Moreni-Gura-Ocnitei in Roumania, and Spindletop and West Columbia in America. The lateral sands field at Spindletop produced some 34,000,000 barrels of oil from some 40 acres in 1926 and 1927 and had a record for those years of per-acre production of some 850,000 barrels (280,000 tons per hectare); and the old or southeast field at West Columbia has a per-acre production of over 125,000 barrels (41,000 tons per hectare). The flank sands production on some domes, however, is so poor as not to be commercially profitable.

The salt dome production of Texas and Louisiana comprises the three types. The production on some of the domes is predominantly of one type and on other domes of two different types. The production at West Columbia is wholly from lateral sands. The prolific production at Humble and at Spindletop is both from the cap rock and from lateral sands, with small production from super-cap sands. The production at Jennings and Saratoga is wholly from super-cap sands.

The production in Roumania is almost wholly from lateral sands on salt domes. At Runcu and one or two other places a small amount of production comes from super-salt sands. The German production is almost wholly from lateral sands on salt domes. The Mexican salt dome production is of all three types but the best of the production to date has been from the cap rock.

The age of the oil sands on the salt domes ranges from Cretaceous to late Pliocene. In the United States the stratigraphic distribution of the production is roughly as follows: Lower Miocene, 55 per cent; Middle Oligocene, 20 per cent; Middle Miocene, 15 per cent; Upper Miocene, Pliocene and Eocene, 10 per cent; Upper Cretaceous, one well, the discovery well for production on the interior group of salt domes. The salt dome production in Roumania is almost wholly Pliocene with a small amount from the Eocene, Oligocene, and Miocene. The Mexican salt dome production is Pliocene and Miocene. The German salt dome production is mostly from the Cretaceous. As the age of the salt dome cap rock is unknown, no age can be assigned to the cap-rock production.

The function of the salt and the salt dome in the formation of the oil pools has been mainly that of providing favorable situations for the accumulation of oil. Mrazec and the Roumanian school of petroleum geologists tend to emphasize a genetic connection between the oil and the salt in the conditions under which the salt was laid down. But to American petroleum geologists, who are more familiar with oil fields not associated with salt deposits than with them, the Roumanian view seems provincial. In the salt dome oil fields district of southeast Texas and southwest Louisiana, such large oil fields as Goose Creek and Orange have not been shown either by the drill (to about 5,500 feet) or by the seismograph to be associated with salt domes or salt deposits. But the recent discovery of salt at about 4,000 feet at Edgerly, which was apparently a characteristic "Goose-Creek" type of oil field with no indication of salt dome material in the several wells below 5,000 feet, suggests that further drilling and more detailed geophysical work will indicate the presence of salt domes at (possibly tangent to) the Goose Creek, Orange, Welsch, and Lockport oil fields. The heat and pressure consequent upon deformation, according to one theory of the origin of oil, tend to cause an acceleration of the formation of oil by causing a slow distillation and partial conversion of organic matter of the sediments into petroleum. According to that theory, the pressure and heat caused by the intrusion of the salt and the accompanying deformation of the sediments have caused or greatly accelerated the generation of petroleum from organic material in the sediments around the dome. Although that theory is possible, the function of the salt dome definitely can be seen to be to provide structurally favorable situations for the accumulation of the oil and possibly for the migration of oil from shale into sands.

The source of the petroleum of the salt dome oil fields is not well known and has not been studied thoroughly. In the

United States, the Jackson with its black shales very commonly has been regarded as the source formation. It is the most richly organic formation encountered in the area of the coastal salt dome oil fields, and although not important as a producing horizon, it is petroliferous nearly everywhere on the domes. On a considerable number of the domes, as for example Humble, Hull, West Columbia, prolific production comes from basal Miocene sands where they are in fault or unconformable contact with Jackson black shales, and on that account Deussen[7] postulates that the oil originated in the Jackson black shales and migrated into the Miocene sands. On account of the widespread prolific production from the basal Miocene without regard to its relation to the Jackson, on account of the intercalation of some thousand feet of poorly productive Oligocene sands and shales between the prolific Miocene sands and the Jackson at Orange, Goose Creek and Edgerly, and on account of the parabolic increase of Beaumé gravity of the oil with depth at Orange, the writer tentatively favors the view that the oil is indigenous approximately to the horizons in which it is now found,[8] although there has been much migration for a short distance on many of the salt domes.

Although the oil of the main Roumanian salt dome oil fields is postulated by Voitesti to be Paleozoic or Pre-Cambrian, the opinion of one school of Roumanian geologists seems to be that the oil is of Meotic (Pliocene) age and that, if now found elsewhere, it has migrated from the Meotic, in many cases along or in the edge of the salt and back into the sands in which it is now found. The Oligocene is said to be productive only where it is in contact with the Meotic. The opinion of another school is that the oil is derived from the Oligocene. The migration of oil up in or along the edge of the salt under such pressure that it could back the water for many hundred feet down a steeply

[7]Deussen, Alexander, The Humble Oil Field, Bull. S. W. Assoc. Petr. Geol. (now Am. Assoc. Petr. Geol.), Vol. I, pp. 60–81, 1917.

[8]Barton, D. C., The Gulf Coast Oil Fields of S.E. Texas and S.W. Louisiana, Internationale Bergwirtschaft Jahrgang I, Hefte 9–10, 1926.

dipping sand bed, as is postulated for Moreni and others of the domes, seems rather improbable.

PRODUCTION

The production of the salt dome oil fields of the Texas-Louisiana Gulf Coast with the totals inclusive of the associated non-salt dome oil fields of the Goose Creek type in parentheses, is given in Table 1.

Table 1. Production of the Salt Dome Oil Fields of Texas and Louisiana

	Millions of—			
	Barrels		Metric Tons	
1901	3.6		0.5	
1902	18.1		2.6	
1903	18.3		2.6	
1904	28.5		4.1	
1905	37.9		5.4	
1906	20.7		3.0	
1907	15.7		2.2	
1908	14.1		2.0	
1909	10.8		1.5	
1910	9.6		1.3	
1911	11.0		1.6	
1912	8.2		1.2	
1913	8.2	(8.5)	1.2	(1.2)
1914	12.9	(13.1)	1.9	(1.9)
1915	20.4	(20.5)	2.9	(2.9)
1916	21.3	(21.7)	3.1	(3.1)
1917	17.0	(24.3)	2.4	(3.5)
1918	14.6	(24.0)	2.1	(3.4)
1919	20.2	(27.5)	2.8	(3.9)
1920	26.1	(31.8)	3.7	(4.5)
1921	33.3	(39.6)	4.7	(5.7)
1922	28.7	(39.4)	4.1	(5.7)
1923	24.5	(36.2)	3.5	(5.2)
1924	21.4	(30.1)	3.0	(4.3)
1925	25.3	(34.5)	3.6	(4.9)
1926	37.1	(45.4)	5.3	(6.5)
1927	47.4	(54.5)	6.8	(7.7)
Total	555	648	79	92

The total production to January 1, 1928, of the more prolific fields is given in Table 2.

Table 2. Total Production of the More Prolific Gulf Coast Oil Fields

	Millions of—	
	Bbls.	Met. T.
Humble	99.4	14.2
West Columbia	65.7	9.4
Spindletop	83.7	12.0
Goose Creek*	61.7	8.8
Jennings	39.3	5.6
Sour Lake	71.1	10.2
Hull	56.9	8.1
Batson	33.8	4.8
Saratoga	24.8	3.5
Orange*	26.9	3.8

*Not yet known to be a salt dome.

The per-acre production of some of the fields is as follows: Spindletop, old or cap-rock field, 190,000 barrels (68,000 tons per hectare); new or lateral sands field, 850,000 barrels (over 280,000 tons per hectare) in one year; Jennings, 209,000 barrels (75,000 tons per hectare) for the whole field, and 306,000 barrels (110,000 tons per hectare) for the main productive area; Saratoga, 34,000 barrels (12,200 tons per hectare).

The production in Roumania, about 97 per cent of which is from salt domes, is given in Table 3.

Table 3. Production in Roumania

	Millions of			Millions of	
	Bbls.	Met. T.		Bbls.	Met. T.
1857–1909	64.5	9.2	1918	7.0	1.0
1910	9.0	1.3	1919	6.5	0.9
1911	11.0	1.6	1920	7.5	1.1
1912	13.5	1.9	1921	8.5	1.2
1913	12.5	1.8	1922	9.0	1.3
1914	12.5	1.8	1923	10.5	1.5
1915	11.0	1.6	1924	12.5	1.8
1916	6.5	0.9	1925	16.6	2.4
1917	5.0	0.7	1926	23.5	3.4
Total				247.1	35.3

About 52 per cent of the total Roumanian production in 1924 came from the several oil fields of the elongated Moreni-Gura-Oceitei salt dome.

Although oil has been produced from the German salt domes since 1875, only a very modest production has been developed. The amounts of the production for the past few years are given in Table 4.

Table 4. German Production 1919–1926

	Thousands			Thousands	
	Bbls.	Met. T.		Bbls.	Met. T.
1919	260	37	1923	355	51
1920	245	35	1924	415	59
1921	265	38	1925	555	79
1922	315	45	1926	665	95

The total production of the German domes from 1875 to the present has been about 12,000,000 barrels (1,750,000 tons). The production in 1926 had a total value of about 9,300,000 Renten marks ($2,210,000).

The production from the Mexican salt domes to date amounts to a very few million barrels, probably less than 10,000,000 barrels (1,300,000 tons), of which San Cristobal produced 1,700,000 barrels. The production of the Mexican salt domes has been as follows:

	Thousands			Thousands	
	Bbls.	Met. T.		Bbls.	Met. T.
1923	200	29	1926	1,300	186
1924	250	35	1927	2,800	400
1925	270	39			

At the present time, Filisola is reported to be producing about 6,000 barrels per day from a fault line oil field well out on the flank of the dome.

RESERVES

The petroleum reserves on salt domes can be estimated with no greater accuracy than a rough guess. A fairly reliable estimation can be made of the reserves of an oil field which has been fairly well outlined and whose production has become fairly well settled. Estimates of the reserves of undiscovered oil fields or of salt dome oil fields only slightly developed can, at the best, be merely shrewd guesses. The writer's estimates for the oil reserves of the several countries are:

United States.—The reserves of the salt dome oil fields of the coastal domes are (inclusive of Goose Creek, Orange, and others of similar type):

Recoverable by present methods of production, i.e., those now in use in those oil fields:

In sight, 520 million barrels (75 million tons); yet to be discovered, 1,800 million barrels (260 million tons [±50 per cent]).

Unrecoverable by present methods:

Recoverable by mining within the next generation, 175–350 million barrels (25 to 50 million tons).

Partially (20± per cent) recoverable within the next generation, 1,000 to 3,500 million barrels (150 to 500 million tons).

The methods of production in this country are probably just in the beginning of an era of rapid improvement in the transition from the present practical man's art to an engineering science. Methods of extraction of the oil not recoverable by the present standard methods are being studied and experimented with; water-flooding has been used for some years at Bradford, Pennsylvania; and repressuring of the oil sands with gas or less preferably with air has been tried out in the Mid-Continent shallow fields during the past year, and apparently has a very great future; extraction of the oil through shafts to shallow oil sands has been carried on successfully at Pechelbronn, Alsace, for a decade and more recently at the Wietze salt dome oil field north of Hannover, Germany. In the present stage of their development, it is impossible to predict how fast and to what extent such methods will develop, and whether or not or to what extent they will be applicable commercially to the salt dome oil fields. The prediction is safe, however, that there will be some development of such method or methods that will be applicable in the Gulf Coast salt dome oil fields within the next quarter-century and very probably within the next decade. But on the basis of our present knowledge it is impossible to predict how much of the reserve listed under the heading "Unrecoverable by present methods" will become available during the next decade and quarter-century.

The probable reserves of the two interior groups of salt domes are very problematic. The single producer that was completed in March, 1927, gave indications of having a capacity of several thousand barrels per day, but was almost immediately shut in, and when tested later showed much water. The results of the exploration during the summer and autumn have been unfavorable and the well may have been merely a flash in the pan, but the amount of exploration to date is in no way sufficient to condemn the interior Texas domes in the face of the amount of oil shown by that well at the time of its completion. The interior salt domes will probably be either essentially barren or else extremely prolific. The writer's estimates of the reserves of the interior salt domes are:

Recoverable by present methods of production:

1 to 10 million barrels (0.1 to 1.5 million tons), or 500 to 800 million barrels (70 to 100 million tons).

Not recoverable by present methods of production:

7 to 70 million barrels (1 to 10 million tons), or 2,000 to 3,000 million barrels (300 to 700 million tons).

Those estimates are made on the supposition that the interior domes in Louisiana will be productive as well as the interior domes of Texas. The supposition is equally warranted that only one of the two groups will be richly productive and in that case, a third group of estimates would be warranted of half the magnitude of the larger estimate.

The Utah salt ridges probably have some oil reserves but the amount of their reserves is not estimable even by shrewd guess at the present time. Although no commercial well has been completed as yet, considerable quantities of high-grade oil have been encountered on the Cane Creek and Shafter salt anticlines, and gas has been encountered on the Gibson and Cedar Mesa domes. As most of the tests have been isolated, as the salt domes and ridges are of good size, as good oil shows have been encountered in the few wells drilled, and as reservoir beds seem to be present, it seems probable that ultimately production will be established on the Utah salt domes, but the data to date do not warrant even a guess as to the probable reserves of those domes and ridges.

The petroleum reserves of the salt domes of Roumania must be large but no accurate estimate can be made, largely for three reasons: First, drilling is still relatively shallow; a 1,000-meter well is still a deep test in Roumania; and, therefore, the potentialities of deeper production are not known. Second, the number of undiscovered salt domes lying concealed in the plain in front of the known salt domes or among the known domes cannot be guessed until considerable geophysical reconnaissance has been done, preferably with the seismograph. Third, the Transylvanian salt domes are a largely unknown factor. Considerable drilling has been done on some of them and gas has been found in considerable quantity. The complex faulting and squeezing of the flank beds, the steep dip of the beds, and the narrowness of the productive zone cause serious complications in the discovery of flank production. In Texas and Louisiana five correctly placed wells on top of the dome and some twenty well placed 3,500 to 5,500-foot (1,000 to 1,600 meters) tests are necessary to condemn a single dome. Although the failure of exploration to find enough oil at least to make two or three small producers must be held as reducing the odds in favor of production being found there, the exploration has not been extensive or thorough enough to warrant the condemnation of the Transylvania domes.

The writer's estimates (guesses) in regard to the oil reserves of the Roumanian salt domes are:

Old Roumania:

Recoverable by present methods of production:

800 to 1,500 million barrels (120 to 200 million tons).

Not recoverable by present methods of production:

3,000 ($\pm$60 per cent) million barrels (400[$\pm$60 per cent] million tons).

Transylvania:

Recoverable by present methods of production:

A few million, or several hundred to many hundred million barrels.

Not recoverable by present methods of production:

Two or three times the preceding.

The oil reserves of the German salt domes are an unknown quantity and there seems to the writer a very good possibility that those reserves may be enormously larger than the German petroleum geologists suspect. The production up to date comes from domes relatively near the inner edge of the north German plain and somewhat comparable to the interior domes of Texas and Louisiana. North of the domes now productive, there is the wide expanse of the Tertiary portion of the north German plain, apparently very similar to the gulfward half of the Texas-Louisiana coastal plain and with a considerable number of known salt domes and an unguessable number of concealed ones. Gas seeps are reported and at Neuengamme near Hamburg, a gas well was completed at 820 feet (247 meters), which produced about 0.8 million cubic feet per day for some four years. Although test wells sunk near the gas well failed to find oil, and although gas is not necessarily associated with oil, that gas well and the reported gas seeps are favorable indications. The testing to date has not been deep; a 1,000-meter test is still a very deep test, and few of the tests in the northern part of the north German plain seem to have gone anywhere near to that depth. As shown by the Pierce Junction salt dome where the oil was discovered by the fifty-fifth well in an area of three square miles (8 square km.) around the dome, or by the West Columbia salt dome where the forty-first well in an area of about the same size was the discovery well, the first few wells on a salt dome do not necessarily discover the production. If the salt dome production of Texas and Louisiana had not been discovered, exploration equivalent in character and amount to that of the salt domes of the northern half of the north German plain might easily fail to discover production, although it is probable that it would encounter more shows than the exploration has in Germany. The present-day modest production from the salt domes of the Hannover district will probably be very considerably increased by more complete exploration of the periphery of the dome, by deeper drilling, and by increasing knowledge of the manner of occurrence of the oil on the domes, and by increasing knowledge of the form of the domes.

The best estimate that can be made of the potential oil reserves of the German salt domes is that there is a good possibility of enormous reserves, very possibly as much as 2,500 million barrels (400 million tons) recoverable by the present methods of production and 5,000 million barrels (700 million tons) unrecoverable by the present methods of production. There is, however, the definite alternative possibility that the reserves recoverable by the present methods of production are of the order of magnitude of only some 150 million barrels (20 million tons) and that the reserves not recoverable by the present methods of production are of the order of 350 million barrels (50 million tons).

The reserves of the Mexican salt domes seem probably not to be large. The salt domes and the salt dome area have been worked extensively with the torsion balance for four years. An extensive and scientifically controlled drilling campaign of the domes has been carried on for over six years. The results of the exploration have been extremely disappointing, although a modest and increasing production is being built up, and in 1927 twenty-four producers were completed out of thirty-three wells drilled and although the total production for the year was the largest that it has ever been. Although petroliferous beds seem to be widespread, and shows and small production are found on many salt domes, "sands" favorable for prolific production seem to be absent. The exploration to date has not been extensive enough totally to condemn the salt domes, but it has been extensive enough to make them look very unfavorable. The reserves recoverable by the present methods of production would seem probably to be of the order of some 50± million barrels (7± million tons) and the reserves unrecoverable by the present methods double that amount. The discovery of a good and fairly thick oil sand on a single dome might itself upset that estimate and necessitate the doubling of the figures.

The Persian salt domes, located on the coast of the southwestern part of the Persian Gulf, would seem to have distinct possibilities for oil production but not enough is known about them to warrant estimates or even guesses as to their probable potential oil reserves. Richardson[9] describes eight domes and states that others are known but

[9]Richardson, R. K., Die Geologie und die Salzdome in Südwestlichen Teile des Persischen Golfes. Verh. d. Naturhist. Medizin Vereins zu Heidelberg, N. F. Bd. XV, 1926.

does not discuss the oil possibilities of the salt domes. The stratigraphic section seems not unfavorable for the presence of source beds; in the upper 4,000 feet of the section, sands are present to act as favorable reservoir rocks; in the yet lower part of the section, limestones would have to be depended upon for reservoir rocks and might or might not afford reservoir space for the accumulation of oil. A small amount of high-grade oil was found on the Kishm Island salt dome. The exploration to date cannot have been sufficient to condemn the salt domes. The oil reserves may amount to anything from a few million barrels (several hundred thousand tons) to a few or many hundred million barrels (a few hundred million tons).

The Algerian salt domes seem to have distinct possibilities for the presence of oil in commercial quantities. The Algerian domes are in two groups, an interior group which pierces Cretaceous and Jurassic beds, and a coastal group which pierces Tertiary beds in some places as late as Pliocene. Probable source beds in the salt dome areas are found in the Triassic, in the lower Eocene, and in the Miocene. With some variation from area to area, possible reservoir beds are found in the Jurassic, Cretaceous, Miocene, and Pliocene, with the best development in the latter two. Oil shows and gas seeps seem not uncommon in Algeria. The two small Miocene oil fields of the Tliouanet district are not far from some of the coastal domes and are on the edge of the Miocene basin in which they occur. Gas seeps and oil seeps are reported from various domes. There would seem to be a reasonable probability that some of the domes will be productive and there is a possibility that some of the coastal group of domes will be prolifically productive. The exploration up to the date of Dalloni's report, 1922, had been scanty and the tests had not gone to any considerable depth. The data in regard to the exploration since that date are not available to the writer. Whatever exploration there has been, has been probably on the more easily recognized domes, which are the poorer prospects, and on which the difference of a few hundred feet in the location of the test may cause the oil to be missed. The data available are not sufficient really to warrant a quantitative estimate of the potential reserves. There would seem to be a reasonable probability that they are not less than 100 million barrels (15 million tons) and there is a possibility that they may be anything up to twenty times that amount.

The oil reserves of salt domes in other areas are totally unestimable. The data available at the present time to the writer does not warrant even a guess as to the approximate order of magnitude of possible oil deposits on them. It seems not improbable, however, that the salt domes in some of those areas ultimately will prove productive and may have reserves of very large size.

Two salt domes have been discovered in Alsace recently and presumably there is a considerable number of undiscovered domes. The report of the discovery of the domes does not mention any indications of the presence of oil, but with the presence of oil at Pechelbronn and the slight amount of exploration to date, there is a possibility of production from these two or other domes in Alsace or Baden.

POTASH

GEOLOGY

The function of the salt domes in connection with the potash deposits is merely that of bringing the potash-bearing beds within minable depth. The potash deposits are not genetically related to the salt domes, although the latter are genetically dependent on the salt series of which the potash-bearing beds are a part. In Germany the Zechstein salt series has the following stratigraphic section in the Leine Valley district, the Madgeburg-Halberstadt Basin (Stassfurt district), and the Hannover district:

Table 5. Stratigraphic Section German Zechstein Salt Series

	Feet	Meters
Upper Zechstein Clays		
“Youngest” rock salt	100 to 200	30 to 60
“Pegmatite” anhydrite, a graphic intergrowth of anhydrite and salt	3 to 8	1 to 2.5
“Red” salt clay	35	10
“Younger” salt, Stassfurt and Leine Valley districts	160 to 570	50 to 170
“Younger” salt, Hannover Dist.: Salt	200	60
“Younger” salt, Hannover Dist.: “Younger” potash zone	85	25
“Younger” salt, Hannover Dist.: Salt	230	70
“Main” anhydrite	135	40
“Gray” salt clay	25	7
“Older” potash zone	100	30
“Transition” zone (rock salt with Kieserite)	35	10
“Older” rock salt	500	150
“Basal” anhydrite (Lower Zechstein)	250 to 350	70 to 100
Limestone (Lower Zechstein)	13 to 35	4 to 10

This salt series apparently was laid down in a desiccating marine basin in which evaporation exceeded the inflow of water; with increasing concentration, precipitation and deposition of salts took place in the following order: anhydrite, salt with a little anhydrite, salt with kieserite (magnesium sulphate), and finally the very soluble potassium and magnesium salts—sylvite (KCl), carnallite ($KCl \cdot MgCl_2 \cdot 6H_{20}$), kainite ($MgSO_4 \cdot Kcl \cdot 3H_2O$), kieserite ($MgSO_4H_2O$)—and less common salts. There then came a change of conditions which led to temporary influx of sea water and the deposition of a thin bed of clay with a dwarf marine fauna. The cycle then began over again. In the Hannover district, the concentration finally went to the extreme phase again and potash salts again were deposited. Elsewhere the concentration did not become high enough for the precipitation of the potash salts. Another change led to an incursion of fresher water, which was followed by the deposition of the “Red” salt clay. The cycle started over again; a thin anhydrite bed was deposited and then a thin rock salt bed and then conditions changed permanently.

The potash-bearing zones of the salt series lie within minable depth of the surface around the eastern edge of the Thuringia Basin, around the eastern and southern edges of the Magdeburg-Halberstadt Basin, in the Werra and Fulda districts, and in the salt domes and salt dome ridges, and in all those areas are reached by the shafts of the potash mines. Around those edges of the two basins, the Zechstein outcrops, although the salt itself has been dissolved out immediately at the outcrop; in the Werra and Fulda districts, the Zechstein, including the salt series, has been broadly arched up. Out in the Thuringia Basin, the salt series lies more deeply buried and is not reached by the mining shafts.

Out from the edges of the Magdeburg-Halberstadt Basin, the salt series normally would be at or just below the limit of depth at which the potash could be mined commercially. In the Hannover district and farther north in the north German plain, the salt series normally would lie at very great depths, far below the reach of mining shafts, but through the upwelling of the salt domes and ridges, the included rich potash zones have been brought within easy reach of the surface.

The potash deposits have not been appreciably affected by their participation in the upthrust of the salt domes and ridges except by their participation in the common complicated folding that the whole series has undergone in the Asse and Hannoverian types of stocks and ridges. The paragenesis of the suite of compounds now present in the potash deposits apparently necessitates considerable alteration and rearrangement of composition since the deposition of the beds; thus, the common hartsalt, a combination of sylvinite and kieserite, apparently necessitates thermometamorphism under a temperature of at least 72° C. Although it might be accelerated by the conditions prevailing during the upthrust, the metamorphism apparently is not dependent upon the formation of the domes and is accounted for by Stille merely by the depth of the burial of the salt series before its uplift in the salt stocks and salt ridges.

The complication of the structure of the potash beds by complex folding is extreme in the Hannoverian type of stocks and ridges and is considerable in the others. The beds in many of the Hannoverian type of domes are complexly convoluted folds, many of which are overturned. A single shaft and several of the galleries of a mine may pass through the same bed many times. Individual beds are compressed and thickened in some places and stretched and thinned in others.

Potash-bearing salt domes are found also in Spain and the United States. In Spain, three potash-bearing salt ridges of the Asse type are known in Catalonia, at Suria, Cardona and Callus. In the United States, only one salt dome is known to be potash-bearing: The Markham salt dome at which a single core of potash salt was obtained at 4,800 feet in Rycade Oil Corporation's Gray No. 1.

PRODUCTION

The German salt domes and ridges have been mined for potash since 1858. The first shaft was sunk to the salt for rock salt at Stassfurt in the early eighteen-fifties. Mining of the salt began in 1857 and in the following year mining of the potash salts was started in the fear that their deliquescenct would endanger the production of the salt. The value of the potash salts as fertilizer was shown by Schutz-Lupitz's experiments in 1860 and the mining of the potash salts for the potash began in 1861.

The production of potash from the German mines is given in Table 6.

Table 6. Production of Potash in North Germany

	Millions of Metric Tons	
	Crude Potash Salts.	K_2O
1861–1870	1.26	----
1871–1880	5.74	----
1881–1890	10.97	----
1891–1900	18.91	----
1901–1910	51.7	----
1911	9.7	0.94
1912	11.2	----

	Millions of Metric Tons	
	Crude Potash Salts	K_2O
1913	11.6	1.1
1914	8.0	0.9
1915	6.9	0.68
1916	8.7	0.88
1917	8.9	1.1
1918	9.4	1.1
1919	7.8	0.89
1920	11.4	1.3
1921	9.3	1.1
1922	13.1	1.4
1923	9.1	0.99
1924	8.0	0.84
1925	12.04	1.2
1926	11.0	1.1
The world production of potash was:		
1925	13.7	2.0

The figures for the years 1910 to 1917, inclusive, include the production from the Alsatian mines. The production in Alsace began in 1910 and in 1913 amounted to 0.04 million tons of K_2O, about 4 per cent of the total German production. The Alsatian production is not from salt domes.[10]

The figures cover production both from mines on salt domes and salt ridges and from mines not on them. The allotted quota of active mines on salt domes and ridges, according to data given by Fulda in 1926, is 48 per cent of the total quota of active mines. The yearly production from salt stocks and ridges is, therefore, of the order of 5 million metric tons of crude potash, or 0.5 million tons of K_2O. As the value of the total German production of potash in 1926 was 150 million Renten-marks (about $35,700,000), the value of the potash mined from the salt domes and ridges was about $17,000,000.

The production from the Spanish salt domes is negligible and amounts to only a few thousand tons per year.

RESERVES

The reserves of potash in the salt domes and salt dome ridges and in the shallower portions of the area underlain

[10]Two salt domes are reported to have been found in the Alsatian salt district.

by the potash-bearing Zechstein salt series are enormous. An estimate made in 1910 by the German Geological Survey put the German potash reserves at 10,790 million cubic meters containing 20,000 million tons of crude potash salt and about 2,000 million tons of K_2O.[11] Meisner of the German Geological Survey in a more recent estimate gives the world reserves at 25,000 million tons of crude potash salts, or 2500 to 2800 million tons of K_2O, of which 70 to 80 per cent is in Middle and North Germany.[12] The data are not at hand to show just how those estimates were arrived at; unless the existence of a considerable number of undiscovered domes out in the North German plain was postulated, the estimates are probably somewhat too low; the seismic method of geologic exploration may reveal an unexpected wealth of unsuspected salt domes in the North German plain, just as it has done recently in Louisiana. The total reserve of potash on the salt stocks and salt ridges is probably not quite half of the total German reserves, that is, about 1,000 million tons of K_2O. As the present world consumption of potash is about 2 million tons per year, the German salt domes and ridges could supply the present world demand for 500 years and could supply a very considerably increasing world demand for several hundred years.

The development of the potash deposits on seaboard salt domes might have a very important effect on the development of the Texas potash deposits. At present, the German potash, which has a moderate rail haul to reach tidewater, could probably be laid down at the Atlantic seaboard in United States more cheaply than potash from Texas. If, as is distinctly possible, potash mines should be developed near Hamburg and could operate at the same costs as the present mines, it is distinctly possible that, with simply the water transportation and no rail haul, the potash could be laid

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[11]Friedenburg, F., Kalivorkommen ausserhalb des deutschen Reiches. Kali, Vol. 6, p. 572, 1912.

[12]Meisner, M., Weltmontanstatistik 1860–1922, Preuss. Geol. Landesanstalt. Teil I, 1925.

down even at Houston, Texas, more cheaply than could the potash from West Texas.

The extent of the Spanish potash deposits is not well known and they have been only partially prospected, mostly in the Suria district. Marin is quoted by Jung[13] as making an estimate of a reserve of 268 million tons of K_2O in the Suria district. Beckman[14] gives a reserve of 3,700,000 tons of carnallite and sylvinite in Cardona. The potash reserves on the Spanish salt domes are apparently very much smaller than the German but yet are sufficiently large potentially to be an important factor in the world potash situation.

Whether the Texas-Louisiana salt domes have any reserves is an open question. The single rich potash core from the Rycade Oil Corporation's Gray No. 1 at Markham shows that potash salts were laid down in the mother salt series in the Gulf Coast. Although a very considerable number of wells have been drilled into the salt, some of them for a very considerable distance, there is no report of potash in any other well than Gray No. 1. Although cores were taken rather sparingly, the total number of cores of salt that have been taken and that have been examined by geologists is fairly large. Although the salts of the potash series are not necessarily pink, the potash zones of the world rather commonly contain pinkish minerals; the sylvite from Gray No. 1 was pinkish. A core of pink salt would be sufficiently abnormal to cause it to be brought to the attention of the geologists. No potash salt has been found in the salt mines on Avery, Jefferson, and Weeks Islands. The data to date are insufficient to warrant the conclusion that the Texas-Louisiana domes have no commercial reserves, but do warrant the conclusion that the chances are slightly more unfavorable than favorable for the existence of commercial reserves. The chances in favor of the presence of potash are sufficiently good to warrant prospecting some of the shallower domes. It is impossible,

[13]Jung, J., Le Basin potassique de Catalogne. Revue de l' Industrie Minera'e, 15 Oct., 1926.

[14]Beckmann, J. W., Mineral Industry, Vol. 24, p. 586, 1915.

however, to make any guess in regard to possible reserves that would have any real significance.

In Roumania there are fairly extensive salt mines, both in the domes of Transylvania and in those of Old Roumania. In some of the oil fields, as for example, Moreni, wells have to drill through the salt; but no information is available as to whether any care has been taken to watch for potash. No report is available to date of the occurrence of potash salts on the Roumanian salt domes. The Roumanian salt domes, like the American domes, should be regarded as more unfavorable than favorable, but as yet should not be definitely condemned as potash prospects.

On the Mexican salt domes, a few wells have been drilled into the salt and no report is available of the discovery of potash salts in any of them, but the testing of the salt cores has probably not been sufficient to warrant any conclusion in regard to their potash possibilities.

The potash possibilities of the other salt domes of the world are practically entirely unknown.

As the recently discovered salt domes of Alsace are in the same salt basin as the Alsatian potash mines, there would seem to be a good possibility of production from salt domes in Alsace and Baden, and domes on either side of the Rhine in that area may have considerable reserves of potash; but the present data are insufficient to make any estimate of the reserves.

SULPHUR

GEOLOGY

The sulphur deposits of the Texas-Louisiana Gulf Coast are found exclusively in association with the limestone of the salt dome cap rock.

The salt dome cap of the American domes is a disc-like mass of rock which caps the top of the salt core and which in a few domes extends for a distance down the flanks. The cap ideally can be said to consist of three members: a false cap of calcareous sandstone and sandy limestone, the limestone cap proper, and the gypsum-anhydrite cap.

The anhydrite forms the portion of the cap resting directly on the salt and extending down the flank of the salt core and in most domes composes the greater part of the cap-rock mass. It is a homogeneous saccharoidal anhydrite of medium grain that is very constant in character throughout the area.

The gypsum is an alteration phase of the anhydrite, and is found more commonly in the shallower domes and at the upper edge of the anhydrite. It ranges from micaceous gypsum to coarsely crystalline selenite.

The limestone cap proper forms a cap to the anhydrite-gypsum mass. It in a few domes extends down the flank as far as the anhydrite. It extends over the top in most of the domes but in a few it is most strongly developed on the flank at the shoulder of the dome. At the Nash dome, that situation prevails and seems to be due to planing off of the cap down into the anhydrite. The limestone is not as constant in character from dome to dome as is the anhydrite. One common phase of it is finely crystalline but irregular in texture. Some of it is granular. At Bryan Mound much of it is a confused, apparently non-crystalline mass with much included sand and clay. This perhaps corresponds to a slightly developed phase forming the top of the true cap at Nash, and being apparently much younger than the main limestone mass. The limestone is younger than the anhydrite or the gypsum.

The false cap is composed of Pleistocene sands and gravels, or Plio-Miocene sands, that have been cemented by the deposition of lime. Around the dome, especially close above the cap, there seems to be a tendency towards the deposition of lime in the sands or weak calcareous sandstones in the Miocene, the sands of the Pliocene, or the sands and gravels of the Pleistocene.

The origin of the anhydrite-gypsum cap and limestone cap proper is unknown. They have apparently not been formed at their present horizon but have been uplifted from lower depths. Various theories have been proposed to account for them but the evidence is scanty and unsatisfactory.[15]

The sulphur is found in a zone at the contact of the limestone and of the gypsum-anhydrite. The top of the limestone cap commonly is barren of sulphur, and the barren zone, if present, is spoken of by the sulphur miner as the "cap rock." The barren zone merges rapidly downward into the sulphur-bearing zone. The transition is marked merely by the increase in the content of sulphur and not by a change in the character of the enclosing limestone. In the lower part of the the sulphur-bearing zone there is a more or less gradual transition from lime carbonate to sulphate. At Big Hill, Matagorda, there are barren lenses of anhydrite in the base of the limestone zone. The transition zone of limestone, gypsum, sulphur and residual anhydrite grades by increasing percentage of anhydrite into massive barren anhydrite. Thin veinlets of sulphur may be found deep in the barren massive anhydrite and a few grains of sulphur were present in a core from several hundred feet within the salt mass at Nash.

The sulphur is native sulphur, secondary and younger than the limestone, gypsum, or anhydrite, and is found filling various types of cavities in them. It is found in massive form in irregular layers along shear planes and fissures and in irregular masses filling the irregularly ramifying network of small solution channels in the limestone, in vugs of various sizes, in veinlets, in bunches and specks, and as an impregnation of granular phases of the limestone. In the anhydrite, it is found only in thin veins. Crystals of sulphur are found lining incompletely filled cavities. The crystal form is the simple pyramid modified by the basal pinacoid and by a second pyramid or brachydome. The color of the sulphur is yellow, ranging from bright resinous

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[15]See Goldman, Marcus, Petrography of Salt Dome Cap Rock in "Geology of Salt Dome Oilfields," Am. Assoc. Petr. Geol., pp. 50–86, 1926, and Barton, D. C., The Salt Domes of South Texas, in "Geology of Salt Dome Oilfields," Am. Assoc. Petr. Geol., pp. 748–757, 1926.

canary yellow to waxy yellow, brownish-yellow and greenish-yellow. The sulphur is pure with a very high degree of purity.

The richness of the sulphur impregnation varies greatly in the same well, from well to well in the same local area on the dome, from place to place on the dome, and from dome to dome.

Although the range of the sulphur content is such that the mean value has little significance, the sulphur content is about 10 to 40 per cent in the productive areas. To be commercially profitable for mining, the content of sulphur must be higher than 10 per cent and the amount of the sulphur present in any given vertical prism must be equivalent to a mass of solid sulphur at least six feet high and with the same cross section as the prism. On the Sulphur, (Louisiana) dome, the whole of the cap was richly productive. At Big Hill, Matagorda, the cap is productive over the top of the dome but relatively barren at the edge of the dome. At Bryan Heights, the top of the dome is relatively barren and the production comes from the cap at the edge of the dome. At Damon Mound, the sulphur is localized in a small area on top of the dome near the north edge. Although the limestone cap is present over the rest of the dome, it is nearly barren. At Nash, the sulphur is found only on the upper part of the flank of the dome, and the top of the dome is entirely barren.

The amount of sulphur present on a dome ranges from the rich deposit of the Sulphur salt dome to the small "shows" of sulphur that are common in the coastal group of salt domes wherever the limestone cap is present. The relation holds that a considerable deposit of sulphur is found only on domes having a thick limestone cap, but the presence of a thick limestone cap does not necessarily imply the presence of considerable sulphur.

The occurrence of the sulphur seems to be limited almost exclusively to the limestone of the cap rock of the salt domes of the coastal group of Texas and Louisiana. Although sedimentary limestones ranging up to some two hundred feet in thickness are present on the flanks of some of the salt domes of the coastal group, sulphur has not been reported from them. In the interior group of domes, sulphur has not been found, although a thick limestone cap is present in some of the domes, as for example, Winfield. In the Mexican salt domes, a very few shows of sulphur are reported to have been found. In the domes of the other countries, with the exception of Persia, sulphur has not been found, or at least has not been reported.

The origin of the sulphur has not been clearly explained. The geology of its occurrence shows definitely that it is a secondary mineral deposit in the cap rock, indicates strongly that limestone of the cap is in some way genetically connected with its formation, and suggests that possibly the time of its formation in the main, at least, was before the uplift of the cap into its present position. Various theoretical chemical reactions have been proposed to account for the formation of the sulphur.

The secondary character of the sulphur is shown by its occurrence as a filling in veins, fissures, and solution channels in the limestone. Some genetic connection between the sulphur and the limestone of the cap seems to be indicated by the facts that the sulphur is found only where the limestone cap is present and that it is present in considerable quantity only when the limestone of the cap is fairly thick.

The evidences for the deposition of the sulphur before the uplift of the dome to its present position are two: The first is the occurrence of a small amount of sulphur in what seems to be a rotten clastic fragment of cap-rock limestone in a core of Miocene gumbo from the flank of the Nash salt dome. The second is the absence of sulphur from the limestones which occur at the same general depths as the sulphur deposits and closely adjacent to the salt core. The localization of the sulphur essentially in the lower part of the limestone and across the contact between the limestone and the gypsum-anhydrite suggests a genetic connection between the three. The abundant H_2S of the natural gas of the coastal domes offers a source for sulphur in a form in which it could very readily be reduced to native sulphur.

The subject of the theoretical possibilities and probabilities of the method of formation of the sulphur is complicated, has not been satisfactorily solved as yet, and cannot be satisfactorily handled in a paragraph or two. The best discussions of the subject to date are those by Goldman[16] and Wolf.[17]

The more likely theoretical suggestions in regard to the origin of the sulphur are:

1. *a.* $$\left.\begin{array}{l}\text{The anhydrite—}\\ \text{gypsum}\\ \textit{i.e.}\text{, } CaSO_4\end{array}\right\} + \left\{\begin{array}{l}\text{Carbon in some form}\\ C\\ CH_4\\ C_mH_m\end{array}\right\} = CaCO_3 + H_2S$$

   b. and $H_2S + O = H_2O + S$

2. $$\left.\begin{array}{l}\textit{a. } H_2S \text{ according to } 1a\\ \textit{b. } \text{Exogenous } H_2S\end{array}\right\} \text{reduced by anaerobic bacteria} = S_2$$

3. Exogenous $H_2S + O = H_2O + S$

PRODUCTION

Four salt domes have been commercially productive to date, Sulphur, Bryan Heights, Big Hill, Matagorda County, and Hoskins Mound. At Sulphur, Frasch finally perfected his unique process for mining the sulphur by melting it, early in this century and commercial production was started in 1903. The mine was exhausted and abandoned with the end of the year 1924. During the twenty years of its life, the Sulphur salt dome produced between 9½ and 10 million tons of sulphur with a gross value of some 155 million dollars. As the cost of production was well below $5 per ton, the net profits from the mine, therefore, must have been more than 140 million dollars. The area of the dome is 75 acres; the recovery per acre was 127,000 tons; and the net profits must have been of the order of $1,870,000 per acre. The production at Sulphur was wholly controlled by

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[16]Goldman, M. I., Petrography of Salt Dome Cap Rock, Bull. Am Assoc. Petr. Geol., Vol. IX, No. 1, pp. 42–78, 1925. Reprinted in Geology of Salt Dome Oilfields, Am. Assoc. Petr. Geol., pp. 76–86, 1926.

[17]Wolf, A. E., Big Hill Salt Dome Texas, Bull. Am. Assoc. Petr. Geol., Vol. IX, No. 4, pp. 711–737, 1925. Reprinted in Geology of Salt Dome Oilfields, Am. Assoc. Petr Geol., pp. 707–711, 1926.

the Union Sulphur Company. Commercial production was started at Bryan Heights in 1914, at Big Hill, Matagorda County, in 1919, and at Hoskins Mound in 1923. The production at Big Hill is controlled by the Texas Gulf Sulphur Company, that at Bryan Heights and Hoskins Mound by the Freeport Sulphur Company.

The world and the American production of sulphur are given in Table 7.

Table 7. Production of Sulphur in Hundred Thousand Tons

	U. S.	World
1903	0.3	5.7
1904	1.8	7.0
1905	2.0	7.5
1906	2.3	7.7
1907	2.7	7.3
1908	2.1	7.3
1909	2.7	6.9
1910	2.5	6.9
1911	2.0	6.3
1912	7.9	12.0
1913	4.9	8.9
1914	4.2	8.3
1915	5.2	9.1
1916	6.5	9.9
1917	11.3	14.3
1918	13.5	16.1
1919	11.9	14.4
1920	12.6	15.0
1921	18.8	21.5
1922	18.3	20.0
1923	20.4	23.5
1924	15.4	30.9
1925	14.1	25.5
1926	18.9	21.5

Of the American production 98 per cent comes from the salt domes. The total production from the American salt domes to the end of 1926 has been about 19 million (metric) tons with a value of some 280 million dollars.

RESERVES

The sulphur reserves of the Gulf Coast salt domes are large but are not inexhaustible. The amount of sulphur at Bryan Heights, Big Hill, and Hoskins Mound has been blocked out by extensive prospecting but the figures have not been released by the respective companies. The reserves, however, are very nearly of the following magnitudes:

Big Hill—5 to 7 million tons.

Bryan Heights and Hoskins Mound—10 to 14 million tons.

The Long Point and Boling salt domes show earmarks of having large commercial deposits of sulphur but the prospecting to date has not been sufficient to warrant an exact estimate of the size of the deposits. An estimate can be made that together they contain between 50 and 100 million tons.

The Palangana, Big Creek, Damon Mound, South Liberty-Dayton, Belle Isle, and Allen salt domes have been rather thoroughly prospected within the past few years and have been shown to have small deposits that could not be mined commercially at the present time, or are not worth the attention of the large sulphur producing companies. The Nash salt dome has a deposit that has been prospected only slightly but that is too deep for the sulphur to be mined profitably at present. The aggregate amount of sulphur on those domes is probably about 5 million tons, more or less.

The reserves of sulphur in sight on the Gulf Coast salt domes, therefore, amount to some 90 ($\pm$50 per cent) million tons definitely available and 5 ($\pm$50 per cent) million tons ultimately available in considerable part. The present world consumption of sulphur is about 2 million tons per year, of which the Texas-Louisiana salt domes produce about 70 per cent. The reserve in sight will suffice for some 50 ($\pm$25 per cent) years of production at the present rate.

The undiscovered reserve cannot be estimated, although shrewd guesses can be made in regard to maximum and minimum limits. Twenty of the coastal group of domes can be classified at once as improbable prospects for sulphur on account of the absence of a sufficient limestone cap, or on account of the excessive depth to the cap. Nine domes are impossible as sulphur prospects under the present conditions, as the depth to the top of the cap is slightly greater than the maximum depth at which sulphur can be mined commercially at present, but those domes may possibly become commercial prospects before another quarter of a century. Eight domes known to have thick limestone caps close to the surface have not been drilled sufficiently to be condemned. Old wells on several of them are reported to have had shows of sulphur. There are some twenty domes newly discovered by the seismograph about which little authentic is known. How many domes may yet be discovered is of course unknown. It seems probable that in southeastern Texas all the domes have been discovered which come close enough to the surface to be possible sulphur prospects. There is a distinct possibility that domes possible as sulphur prospects will be discovered in South Texas, and a distinct probability that a considerable number of domes possible as sulphur prospects will be discovered in the coastal swamp region of southwestern Louisiana, in the area of the Mississippi Delta, and in the area extending eastward into Mississippi. The guess is made by the writer that in those areas some 15 domes will be discovered. The assumption is made that the domes of the Mississippi Delta and to the east will be similar in all respects to the known domes of southeast Texas and southwest Louisiana. From the eight domes that are known to be distinctly possible prospects, one or possibly two may prove to be sulphur deposits of the first class with a reserve of 5 to 10 million tons each, and two or more may have small deposits with an aggregate reserve of some 10 million tons probably not commercially minable at present.

Of the twenty domes recently discovered and of the fifteen domes to be explored, two-thirds will probably be condemned by the first drilling. From the remaining nine, the guess may be made that two contain commercial deposits, each with a reserve of 5 to 10 million tons, and three or more contain small deposits not commercial at present with an aggregate reserve of from 5 to 10 million tons. There is also the distinct possibility of the discovery of another extremely rich sulphur dome such as Boling with a reserve of 50 or more million tons. The shrewd guess may be made, therefore, that the undiscovered sulphur reserve amounts to at least 20 and possibly to 90 million tons available under present conditions of production and some 10 to 30 millions tons available ultimately. The probability seems to be better that the figures of the maximum estimate are too low by 50 per cent than that the figures for the minimum estimate are too low by 25 per cent.

The sulphur reserves of the Texas-Louisiana salt domes, therefore, amount to:

140 ($\pm$30 per cent) million tons available under present conditions of production.

40 ($\pm$30 per cent) million tons ultimately available.

These reserves afford about 90 ($\pm$30 per cent) years supply of sulphur at approximately the present rate of production. The chances seem greater that these estimates are too conservative than that they are too liberal.

The Persian salt domes possibly have some sulphur reserves. Sulphur is reported by Richardson to occur in the gypsum of the Upper or the Gypsum-Effusive Rocks division of his Hormuez formation. This division seems to have a structural position and relation to the salt core somewhat similar to the cap of the American salt domes. The sulphur occurs in narrowly restricted areas, as an impregnation of the gypsum in small veins, and in layer-like zones of enrichments. The sulphur is reported from two domes, Kishm Island dome and the Khamir dome. A small amount of sulphur is won by the natives by primitive methods. The deposits exposed on those two domes do not seem to be of commercial size but apparently are somewhat similar to the American sulphur deposits and suggest the possibility of larger deposits on some of the other domes.

There is, however, the possibility that the sulphur is connected with the volcanic activity which produced the effusive rocks and is not connected with the salt domes.

The world reserves of sulphur, exclusive of the reserves in Texas and Louisiana, are estimated by Mansfield to be, on a conservative estimate, 30 million and, on a liberal estimate, 37 million tons.[18]

SALT

PRODUCTION

Salt domes are an important source of supply of common salt and offer enormous reserves of salt, sufficient to supply any possible world demand for tens of thousands of years. Economically, however, the production of salt from salt domes is not very important, as salt is widespread and is a cheap commodity.

In the United States, salt is mined from salt domes on the Avery Island, Weeks Island, and Jefferson Island salt domes in Louisiana; a shaft is being sunk for a salt mine on the Blue Ridge salt dome in Texas; and salt is being produced by the brine method on the Grand Saline and Palestine salt domes in Texas and at the Anse la Butte salt dome in Louisiana. The production of salt from the salt domes of Texas and Louisiana amounts to about 370,000 metric tons with a value of about $2,000,000, out of a total production in the United States of about 6,000,000 metric tons with a value of $28,000,000.

In Germany, a very considerable part of the salt mined is a by-product of the potash mines, although a few mines produce only salt and there is also some production of salt by the brine method. The data are not available by means of which to determine what part of the German production of salt is from salt domes and salt ridges. The German production of salt amounts to some 2 million tons per year, of which perhaps some 40 per cent comes from salt domes and salt ridges.

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[18]Mansfield, G. R., Report of a paper read before the Institute of Politics, Williamstown, Mass., Engineering and Mining Journal, Vol. 123, No. 14, pp. 567–570, 1927.

The salt production of Roumania is almost wholly from the salt domes. Salt is produced on six salt domes in Old Roumania and on six salt domes in Transylvania. In the Slanic salt dome in Old Roumania, in the Maros salt dome in Transylvania, and in several other of these domes, there are extensive salt mines. In Spain, salt is mined in salt domes.

RESERVES

The reserves of rock salt are so stupendous as to be inexhaustible for all human purposes. Each of many domes in many countries has an easily minable reserve sufficient to supply the world demand for over 500 years and an ultimate reserve sufficient to supply the world demand for over 1,500 years. The reserves of some of the American domes are given in Table 8.

Table 8. Rock Salt Reserves of Some Texas-Louisiana Salt Domes

	Cubic Kilometers of Rock Salt: Available above 2500 Ft. (750m)	Cubic Kilometers of Rock Salt: Available above 5000 Ft. (1500m)
Weeks Island, Louisiana	7	16
Avery Island, Louisiana	7	16
Jefferson Island, Louisiana	1 (Possibly 7)	6 (Possibly 16)
Anse la Butte, Louisiana	0.3	1
Spindletop; Hull, Big Hill—Jefferson County; High Island, Pierce Junction; Nash, West Columbia; Hoskins Mound, Bryan; Heights, Big Hill—Matagorda, Texas, and Pine Prairie, Louisiana	Each about 0.7; Total 9	2.5; 30
Blue Ridge, Texas	0.8	2.6
Grand Saline, Texas	2.0	4.5
Palestine, Texas	2.0	4.5
Kings, Louisiana	1.+	2.5+
Rayburn, Louisiana	1.+	2.5+

The total reserves above a depth of 2,500 feet (750 meters) amount to about 40 cubic kilometers. The total reserve above 1,000 feet (300 meters)—the mines in Southern Louisiana go to about 700 feet (200 meters)—is about 10 cubic kilometers. The total reserves above a depth of 5,000 feet (1,500 meters) where the salt comes to within 2,500 feet (750 meters) of the surface amount to 100 to 150 cubic kilometers. As the world consumption of rock salt at the present amounts to less than 0.01 cubic kilometer per year, the very easily minable reserve of the Texas-Louisiana salt domes would suffice for the world demand for 1,000 years and the easily minable reserve would suffice for 4,000 years. The Weeks, Avery, and Jefferson Island mines have in sight easily minable reserves for 25,000 years at their present rate of production.

The reserves of the German and Roumanian salt domes are comparable to those of the Texas-Louisiana domes. The reserves of the Mexican and Spanish salt domes are considerably less.

SUMMARY

The value of the annual production from salt domes amounts to:

Petroleum	70 to 110 million dollars
Potash	17 to 20 million dollars
Sulphur	25 million dollars
Salt	5 million dollars
or a total of	120 to 160 million dollars

In terms of percentage of the annual world production, salt domes produce:

75 per cent of the sulphur
35 per cent of the potash, and
4 per cent of the oil.

In terms of percentage of the annual production in the United States, salt domes produce:

99 per cent of the sulphur
3 per cent of the oil, and
5 per cent of the salt.

The world reserves of the salt domes amount to:

Oil	
Recoverable by the methods now in use	6,000 (±35 per cent) million bbls. (900 million tons)
Not recoverable by methods now in use	12,000 (±35 per cent) million bbls. (1,700 million tons)
Potash (K_2O)	1,100+ million tons
Sulphur (native)	
Readily minable	140 (±30 per cent) million tons
Ultimately minable	40 (±30 per cent) million tons
Salt	
Readily minable	300 (±50 per cent) cu. km.
Ultimately minable	1,000 (±50 per cent) cu. km.

In terms of the known world reserves, the salt dome reserves amount to approximately:

Potash	30 per cent
Sulphur (native)	65 per cent
Salt	5 per cent
Oil	Not estimable

In terms of the present world consumption, the reserves on the salt domes could supply the world with:

Oil	for	6 to 12	years
Potash	for	500+	years
Sulphur	for	80	years
Salt	for	150,000	years

In Texas, the reserves on the salt domes amount approximately to:

	Per Cent of World Reserves	Per Cent of U.S.A. Reserves	Years Supply at Present Rate of Production
Oil			
Recoverable by present methods—1,250 million bbls. (±40 per cent)	?	?	40
Unrecoverable by present methods—2,500 million bbls. (±40 per cent)	?	5	80
Potash ?	?	?	?
Sulphur (native)			
Readily minable—90 million tons (±30 per cent); Ultimately minable—15 million tons (±30 per cent)	50	75	35
Salt			
Very readily minable—14 cu. km.			640,000
Total minable—75 cu. km.	1–2	3–10	3,000,000

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The data of this paper are derived from the following sources of information:

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A NEGLECTED FIELD IN STRATIGRAPHY

BY J. A. UDDEN

The science of geology is only a little more than a hundred years old. We call Lyell the father of geology. His Principles of Geology was first published in 1830. In spite of the fact that geological data must be gathered from the entire surface of the earth, the bottom of the sea included, this science has had an enormous growth. Less than one-fourth of the entire area of the continents can be said to yet remain unexplored. The science itself has been segregated into different subdivisions. Mineralogy is perhaps the oldest. Then came stratigraphy, paleontology, and petrography of crystalline rocks, not to mention such minor divisions as glacial geology and physiography. We also speak of historical geology, which deals with the physical and the biological changes that can be made out for the earth's past from the data secured by geologists. By the aid of paleontology, structural geology, and latest by the study of diastrophism we have arrived at a stage in which the relative age has been ascertained not only of most larger and some smaller stratigraphic units, but also the approximate time of disturbances which have taken place during the making of the long sedimentary record. During the latest ten or fifteen years we have also begun to study the petrography of sedimentary rocks, and it is believed that with the new data to be revealed in this line of research, important facts will become better known concerning the manifold physical conditions under which sediments have been laid down in the past and are laid down at the present. Quite early in the study of geology, the chemical composition of sediments was observed and has to the present time continued to be made a subject of investigation. This is true not only of so-called chemical sediments but also of strictly mechanical sediments, such as arenites and argillites. Considerable attention has also been given to various

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kinds of bedding and to characteristic markings incidental to bedding, such as ripples, cross-bedding, raindrop prints, mud cracks, and so forth. The main motive in all studies of sedimentary rocks by the present and the past generations of workers has been correlation and the making out of the general physical conditions prevailing at the time and in the place where they were lain down. This will so remain, perhaps, always. It is perfectly natural that it should. The geological column is known, as yet, only from roughly hewn blocks. Sedimentation and sediments now being deposited have also received attention. The Challenger Expedition was, and yet remains, the greatest undertaking of this kind. At present there is going on some intensive and detailed work on sediments now forming in littoral parts of the sea, in lakes, and in rivers.

But it seems to me that one of the most important as well as one of the most promising lines of study of the stratified rocks, at least from a strictly scientific point of view, is the study of stratification itself as recorded in sediments the world over. How does it come that so little work has been done on the main distinctive feature of this class of rocks, their stratification? We know and can understand that the thinnest layers marked off in bedded rock, as well as the thickest, are caused by interruptions, or by changes in the physical forces at work. The records of these forces are everywhere in evidence, records that extend back for some hundred millions of years. We do not know for how long.

Even the earlier geologists learned of the records of great cycles in past times, sometimes called the sedimentary cycles. The beginning of an age is marked by the deposition of coarse mechanical sediments, as a rule, such as conglomerates and sands. Then follow shales and limestones, and sometimes precipitates, such as salt and gypsum. These cycles have forced themselves on our attention. Within these great cycles, other smaller cycles have also been noted in many cases, as for instance in the coal measures. Some one has said that each coal bed can be looked upon as an unconformity. Some observations have also been made on the extremely brief cycles represented by thin laminations shown by some sediments, probably caused by seasonal periods.

What has been done to investigate the breaks in sedimentation ranging in size between these two extremes? Hardly anything. The great number of cycles or accidental sedimentary divisions to be observed between the two extremes of entire formations on one hand and thin laminae on the other, still remains unmeasured and unknown. What is a sedimentary unit? A layer, a seam, a ledge, a formation or what? Who knows? Has any one tried to find out? Perhaps there is no such thing. Perhaps there are several kinds of units. Most likely. It would be well to know. Here is an open field, preëmpted by no one. It is coextensive with the distribution of sedimentary rocks, from the Archean to the Recent. We have so far been busy with describing local sections for the purpose of correlating them correctly with each other, and assigning them to their true and proper place in the geologic column and in order to make out structures, and the physical conditions of the past, so far as this has been possible with the general understanding we have of paleontology and general stratigraphy. In doing this we have drifted necessarily toward increasing detail in our stratigraphic notes, thus beginning to gather important data of what we might call a quantitative study of sedimentation. Such a line of investigation, it is my belief, should soon become important. The quantities I have in mind are the thicknesses of strata deposited under uninterrupted and uniform physical conditions.

From a study which I have made of some of the most detailed local sections described and published in this country by some of our most experienced and most careful and able geologists, it is evident that the descriptive units used are not the ultimate, thinnest units that it might have been possible to make out in the sections examined. They cannot be such. In our local sections of areal geology we use what we may call descriptive units, units consisting of rock that can conveniently be described with sufficient detail to be identified in other exposures. If we are to study the stratification of sedimentary rocks with the object of learning the nature and the history of the origin of these rocks, it is evident that more accurate and more detailed observations have to be made with that special end in view.

In the study referred to I took the measurements of 1,639 descriptive units as distinguished by six different geologists in some of their published reports. I found that the average thickness of these units was 44.8 feet. If I left out one case, which was hardly comparable with the rest of the series, the average was 10.5 feet. I also found that each geologist had a personal average, so to speak, perhaps in some measure, though certainly not entirely, due to personal characteristics. Some men like details. As such I take to have been Mr. Wm. Kennedy, of Texas, and Mr. H. E. Freeman, of Illinois, whose units averaged respectively 6.4 feet and 5 feet. In measurements of this kind it is evident that many circumstances affect the figures. The time allotted to the work, and the nature of the formations themselves are evidently the most important of these factors. But any one familiar with field conditions will know that even the smallest averages mentioned cannot truly represent the smallest natural units of stratification in sedimentary rocks. Even in such a rough study as this some interesting facts appear nevertheless. An average of more than a thousand measurements for different kinds of sediments shows that sands and sandstones are thickest. Next come marls, then clays and shales which have about the same measure as limestones. Lignites, coals, and fire clays average thinnest among all the descriptive units adopted.

A most important element in history is time, and not only relative time but time in cycles and periods of known duration. I am convinced that we make a mistake if we say that anything less than this should be looked for. Not that I believe that we can ever attain to measuring the number of years or larger time units in geology, but we ought to come much nearer to accomplishing this than we are at the present time. We can hardly claim to yet have made a beginning in this line of research.

It is generally recognized that coarse mechanical sediments accumulate at a more rapid rate than the calcareous lime and precipitates that form limestones. There are also differences in the rate of accumulation in different localities where each of the several kinds of accumulations is being formed. There are many different kinds of limestones, and of sandstones, of gravels, and of shales, each of which must have had its own rate of accumulation. Who can wonder that there has grown into the minds of us, the idea that we can deal with only relative age in geology? A bed of rock, underlying another bed, is older than the overlying bed. A bed of a certain kind of limestone measuring two feet in thickness has taken a longer time to be deposited than has another bed of limestone of the same kind, if it measures only two inches in thickness. This is relative time. Is this as far as we can go, and no farther? It has come to be almost a doctrine that such is the case. It is a doctrine that serves no good or stimulating purpose in our work.

Who has tried, so far, to interpret in years, or in other cycles of time, the immensely variable thicknesses of sedimentary beds? We have, as it were, been stunned by the size of the task and have remained inactive in the complacent belief that it cannot be done, that it is impossible.

Let us take a glance at the many discouraging circumstances that present themselves at the very beginning in the work which must be done to enable us to correctly interpret the most common phenomenon that the sedimentary rocks present: their stratification. Lamination represents the simplest process, perhaps; the accumulation of layer after layer of small thickness, a succession of thin layers of subequal thickness, due evidently to the repetition of some definite cycle of relatively short duration. Such lamination has been observed in glacial clays around the Baltic Sea. DeGeer and others have demonstrated that these laminae represent the annual cycle, and by a close study of a number of correlated beds he has been able to fix some definite dates in the late glacial history of Scandinavia.

But lamination is a rather unusual feature in our sediments. Why are not all fine-textured sediments laminated? It is not inconceivable that localities may exist in the bottom of the sea where deposition may go on continuously for long periods of time where no cyclic interruptions occur and where accidental changes seldom take place. Sediments produced under such conditions might show no lamination or stratification for the length of time represented by such conditions. Such conditions are probably quite exceptional. But there are other causes which efface lamination and stratification. Those most generally present of these causes, and in all probability the most effective, are the fauna and the flora which inhabit the sea bottom, and in the case of land deposits, the plants and animals in the soil. This explains the lack of stratification in most of our loess, and also accounts for its vertical cleavage. The animals and plants which burrow in, and penetrate and, in some cases, feed on the mud in the bottom of most waters, without doubt generally obliterate all thin laminations resulting from cyclic sedimentation. Lamination, in fact, is to be expected chiefly in sediments accumulated in waters that have been either too cold or too highly mineralized to be inhabited by either plants or animals. The laminated glacial clays in Scandinavia retain their original laminations because the waters, derived from glaciers, were too cold to permit any flourishing benthos life. Some unusually clear laminations in anhydrite found in the Permian in Texas have very likely been preserved because of the absence of life in parts of the seas of this age, due to the high concentration of more or less soluble salts in the waters of the seas. "Paper shale" is a new term in descriptive geology. It appears to have originated among petroleum geologists in the west. I have seen it used in the description of exposed sections in the Permian. No doubt the layers in this kind of shales represent cycles in sedimentation. But how long cycles? The elucidation of such a little problem might be an important item in the study of stratified rocks.

Another difficulty already alluded to is caused by secondary changes. These may have either obliterated or materially changed the stratification of the original and unaltered sediment. As a common instance of this kind may be mentioned the change of limestones into dolomite or marble. Layers in dolomite are often blurred and they are reduced in thickness from those in the original limestone. In marble the original stratification may be entirely obliterated, and layers may have been thickened or thinned by pressure.

But the greatest difficulty of all that we will meet in correctly interpreting the time values shown in stratification of sediments is the fact that the distinguishable units which can be measured are the results of more than one cycle, perhaps of several cycles affecting each other. And these are affected, no doubt, by many purely accidental happenings in progressing sedimentation. We may take some lamination of shales, clays, and some other rocks as having been produced by the annual cycle. There is no doubt in my mind that it is this cycle which is represented in a thickness of 1,600 feet of anhydrite in Culberson County in Texas. This cycle appeared first in the shale immediately underlying the base of this anhydrite and is continuous in the two formations. It is to be noted that the laminations in this shale were about half as thick as those in the anhydrite above it. Thus it is evident that deposition of the shale in this case was only about half as rapid as the deposition of the later anhydrite, bulk for bulk. I may add that the thin laminations in this shale are not unlike the laminations seen in our "paper shales," straight and trenchant. Can we find places where "paper shale" shows larger stratified divisions due to longer cycles? If so, we might measure the years it has taken to deposit such large units by merely counting the number of the smaller units in each of the larger. And can we find some locality where "paper shale" laminations grade into laminated limestone? Such occurrences must be rare. Thinly laminated limestones are scarce. For reasons already referred to most limestones have had their thinnest sedimentary units destroyed and blurred by mixing. But we should look for them. In some places they may have been preserved, and might yet be seen and measured.

It is evident that the sedimentary unit representing the annual cycles in different deposits is too small for measuring conveniently the sedimentary history throughout the ages. It is also evident that annual laminations have so rarely been preserved that they would not carry us far in the sedimentary column. The longest record yet known is in the anhydrite of the Castile formation of Texas. We have there an anhydrite that originally was some 1,600 feet in thickness and consists of some 300,000 layers, estimated to have an average thickness of 1.63 of a millimeter. But 1,600 feet of a rapidly accumulating precipitation of calcium sulphate represent evidently only a brief interval of Permian time.

If we wish to measure sedimentary history, if only roughly, in years, it is evident that we must at the very beginning find some larger unit of measurement than that of the annual layers produced by the annual cycle. We must also find a unit that is more frequently in evidence in the sedimentary strata, that can be observed and measured. What longer cycles can we look for? The answer to this question had better be deferred. We should approach the problem of interpretation with an open, unbiased mind and devote ourselves to correct observation of facts and to the collecting of data that may bear on the subject, even if this should give us work for a generation. Much of this work can be done in the course of our most common field work. We must adopt more perfect, accurate and detailed methods of noting, describing and measuring stratigraphic units, large and small. And we must give particular attention to what we might call the ledge unit. Here we have a long neglected object of study. We have failed because it is so common. It is a feature that is everywhere in evidence: the ledges that are seen in every limestone and marble quarry and in sandstone and quartzite quarries.

Every quarry man knows them. The layers worked in shale and clay pits are likewise units of this kind. Laborers in the stone and clay industries often are familiar not only with the measurement of these, but also with their physical peculiarities. Geologists, too, have taken notes on them, to be sure, but mostly only for economic or for correlation purposes. Who has studied them with the object of learning the cause or causes that produced them? They remain unexplained. The seams that separate the ledges should be made objects of study. In limestones we speak of shaly partings or seams sometimes. How many have made a study of these breaks in sedimentation to learn how their materials differ from the materials in the ledges above and below them? Various causes for such discontinuities in the sedimentary processes suggest themselves, such as climatic changes of shorter or longer duration, changes in the currents of the sea due to elevation or to lowering of the bottom of the waters, to the accumulation of local sediments themselves, no doubt, and to contemporaneous erosion of the bottom in other places, sometimes here and sometimes there. It is believed also that earthquakes may have served to produce seams in sediments. There can be no doubt that earthquakes will stir the loose muds and slimes that lie unconsolidated on the violently-rocking bottom of the sea, when an earthquake wave suddenly arrives and affects areas of thousands of square miles. Huntington and Visher have shown there is a corresponding frequency in earthquakes and sun-spots and it is possible that this circumstance may some day aid in finding yet unknown sedimentary cycles. Evidently there is more than one, perhaps many, cycles. Such being the case, it is clear that we cannot expect often to find trenchant repetitions of the same or of any one sedimentary cycle in the stratification of our sediments. But what we might look for is that now and then, perhaps at distant intervals, one cycle should dominate in influence over the others to such an extent that there is plain evidence of its influence.

In my own work I have encountered only four instances of what I believe have been repetitions of the same cycle in sedimentation. The first of these was the laminations in the Carlinville, also called the Shoal Creek, and the Curlew limestone in the Pennsylvanian in Illinois and Indiana. All geologists who have described this limestone have noted its thin beds of subequal measure. It has a tendency to weather into layers two and one-half to three inches in thickness. A laminated stiff black shale underlies this limestone, and if these laminations could be detected extending up into the Carlinville limestone we might be able to determine the length of the larger cycles in the limestone in units of what is probably the annual cycle in the black shale. It is on fortunate finds of transitions of this kind that we must depend for the correct interpretation and the measurement of all larger sedimentary cycles. Another case of what appears to me to be the result of cyclic deposition of limestone is what I found in a "thin bedded zone" in the Cibolo Creek section in Presidio County in Texas. Much of this limestone is bedded in uniformly thin beds measuring about four inches in thickness. This formation is also in the anthracolitic series. This is variable in its nature, and in some places it is argillaceous and weathers into slaty thin layers, which may represent the annual cycle. Here we may find a chance to reduce the smaller units to a more convenient denomination, approaching that of the ledge.

In my observations on the Comanchean in Texas I have found at least at one place a perfectly clear instance of cyclic deposition. This involves some layers of limestone and some marly material, measuring from one-half to three inches in thickness, and differing in texture and in fossil contents. These follow each other in a certain order, and the same order is thrice repeated. In each case the order is the same. This occurs in an otherwise apparently quite irregular succession of what we sometimes refer to as alternating beds and is near the middle of the Comanchean group of sediments. The dominant cycle was perhaps able to hold its own only for three rounds in this case, while other cycles, or vicissitudes, were strong enough to overcome it, both before and after it made its record.

The longest and the clearest record to my knowledge ever found so far of cyclic sedimentation in America is the laminated anhydrite in the Castile formation already briefly mentioned.[2] This contains some 300,000 cycles shown in 1,640 feet of the deposit, and there is no doubt in my mind that these are annual cycles. At some places in the section a larger cycle is clearly also in evidence. These larger cycles range in size so as to include from some four to fourteen of the annual layers, and average a little more than six of them. What was the cause of these six or seven years cycles? Some day, perhaps, we may know. At present we can hardly make a guess.

All beginnings are difficult. Meanwhile there are several reasons why we may profit by taking up the work of looking for sedimentary cycles. In the first place we will gain alertness in observing a new set of sedimentary features in the stratified rocks, some characteristics which have hitherto been largely neglected, and which must be of decided importance. In the second place we are apt to discover significant facts with regard to the relation between bedding and texture of sediments. And what is of still more importance, we will gain in making more accurate and more detailed measurements of our geological sections in general. No doubt advance in this line of investigations will require a large amount of measurements made anew and made for the one special purpose intended. It will require the efforts of real amateurs, in the best sense of the word, of people who can and will take the time for the scientific interest that is inherent in the work itself. It should be done somewhat in the same manner as the work of the paleontologist, the work of the collector and student of fossils. In the case of the paleontologist, the collected fossils give a great and constant stimulus to the worker. In the same manner, I think, the new stratigrapher might profit by collecting, sectioning and studying microscopically all different kinds of laminae and strata that he measures. Such observations will certainly appear in new light,

[2]Udden, J. A., 1924, Laminated Anhydrite in Texas. Bull. Geol. Soc. Amer., 35, 347–354, pls. 7–10.

when made in association with stratigraphic work of the kind here proposed, and collections of thin sections of this kind may furnish just as much inspiration to the one who makes them as a collection of fossils does to the paleontologist. Studies in stratification should be carried on hand in hand with studies in rock texture.

VERTEBRATE FAUNAL HORIZONS IN THE TEXAS PERMO-CARBONIFEROUS RED BEDS

BY ALFRED S. ROMER

INTRODUCTION

The study of the primitive land vertebrates of the "Red Beds" of Texas has resulted in the publication of a large amount of exceedingly valuable morphological, evolutionary, and taxonomic information by Cope, Case, Williston, and others. However, the faunal succession within these beds and its possible implications have received scant mention.

Cummins in 1908[1] attempted a comparison of Wichita and Clear Fork faunas. His information concerning collecting localities is of considerable value, but his conclusions are vitiated by two facts: (1) No definite boundary had been established between these two groups in the region concerned. (2) The taxonomy of the forms discussed was then in great confusion, Case's revisions of the Texas vertebrates not having been completed.

Case later[2] published a comparison of the two groups, species by species, in tabular form. This furnished an accurate summary of our knowledge at that time, but the results are limited in value not only by the lack of a definite Wichita-Clear Fork boundary, but also by the attempt at specific determinations. Species in these beds are of dubious value for the most part, as Williston has repeatedly stated.[3] Further, granting their validity, most of the specific distinctions rest upon characters of only one or two portions of the skeleton. Since most specimens from these beds are fragmentary, such a tabulation is, of necessity. confined almost entirely to the types themselves.

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[1]Cummins, W. F., Jour. Geol. 16 (1908), 737–745.
[2]Case, E. C., Carnegie Inst. Pub., 207 (1915).
[3]For example, Jour. Geol. 23 (1915), 253–255.

The present study attacks the problem from a somewhat different angle and with a different factual basis.

1. No attempt is made to differentiate between species, for the reasons cited above; the genus is used as a unit. The amount of material available for the purposes of this study is thus vastly increased; but on the other hand the possibilities of determining evolutionary changes within the limits of the formations are thereby unfortunately greatly diminished.

2. A larger amount of material is used; in addition to the collections available to Cummins and Case, the present study has made use of the later collections of the University of Chicago and those of a number of other American and foreign museums, the total comprising about 2,000 specimens.

3. Definite stratigraphic horizons are now available. At the time of previous discussions, no detailed geologic work had been done in the area under discussion. More recently, exploration for oil has resulted in an examination of the region from a stratigraphic point of view, and some of the results obtained are presented and utilized here.

4. A series of faunal zones is established. It seems probable, on *a priori* grounds, that the faunas of two related and conformable groups, as the Wichita and Clear Fork, would not exhibit a clear-cut faunal distinction at their boundary. We shall here divide the formations into a number of zones, most of them delimited by means of traceable stratigraphic markers, making a five-fold rather than a dual division of the fossil-bearing beds.

I shall attempt (1) to summarize present knowledge of the geology of the region, (2) to present, in tabular form, with commentaries, the vertical distribution of the vertebrate remains, (3) to interpret these findings.

With regard to the geology, I wish to thank Mr. W. E. Hubbard, of Wichita Falls, for much valuable information which I have incorporated here; and Messrs. F. B. Plummer, of Fort Worth, and W. E. Wrather, of Dallas, for their interest and encouragement; the former and Mrs. J. F.

Kemp, of Seymour, for the many kindnesses shown Mrs. Romer and the writer during the 1926 field season.

Dr. E. C. Case, of the University of Michigan, Dr. Barnum Brown, of the American Museum of Natural History, Dr. Ferdinand Broili, of Munich, Dr. F. von Huene, of Tubingen, and Dr. C. W. Gilmore, of the National Museum, were so kind as to furnish me with data regarding the collection of the Texas material in their charge. Dr. Case's criticisms have proved of especial value. Mr. Paul C. Miller, of Walker Museum, has given me the benefit of his knowledge of the terrain gained in many years of collecting, while Mr. W. F. Cummins, of El Paso, and Mr. C. H. Sternberg, of Pasadena, have aided in the interpretation of field records. Mr. R. L. Moore, of Vernon, the A. D. Kerr Company, of Seymour, and Mr. A. D. Sanders, of Dundee, have furnished me with information regarding doubtful localities.

GEOLOGY

In this paper only that part of the Texas "Red Beds" included in Baylor and Archer counties will, in general, be considered, most vertebrate specimens having been obtained from this district. Case in 1915[4] gave an excellent summary of the earlier geological work in this region. Since that time papers bearing on the area have been published by Wrather and by Hubbard and Thompson; the studies of Plummer and Moore and of Beede in the "Albany" region are of value for purposes of correlation.

The surface formations of the region are (from east to west) the Cisco group of the Pennsylvanian, and the Wichita and Clear Fork, customarily regarded as Permian. The general line of strike of the beds is northeast-southwest, with a dip to the north of west computed as from 20 to 45 feet to the mile in different portions of the area by various writers.[5] To the north the line of outcrops swings, in general, toward the east, with a more northerly and slighter

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[4]*Op. cit.*, chap. 1.

[5]Gordon, C. H., Jour. Geol., Vol. XIX, p. 115, 1911; Cummins, W. F., 2d Ann Rept. Texas Geol. Surv., pp. 430 ff., 1891. The lower figure is probably more nearly correct, for the eastern part of the area, at least.

dip, related to the presence of a broad north-plunging arch in Archer County.[6]

South of the area to which this report relates, the strata consist principally of limestones and light-colored shales of the Cisco and "Albany"; only above the latter, in the Clear Fork, do red beds occur. In Baylor and Archer counties, however, red bed conditions generally prevail; the limestones found farther south thin out and disappear when followed northward, and the strata consist mainly of red or variegated clays and shales with sandstones and conglomerates.[7] In the southeastern portion of Archer County the strata are of a lighter color, while in the central and eastern portions of Baylor County the limestones of the upper "Albany" persist and cross the region from southwest to northeast.

In the sequel an attempt will be made to divide the area into faunal zones, and the geology may perhaps be best treated under these headings.

Zone O. Cisco group; to the Coleman Junction Limestone (Putnam Formation).—In Archer County, because of the absence of traceable limestones, a boundary between Cisco and Wichita proved impossible of determination by the earlier workers. Farther south, however, where limestones are present, the boundary was established by Cummins[8] and Drake[9] as below the Coleman Junction limestone or Coleman Junction beds. Wrather[10] places the boundary tentatively below a somewhat lower limestone called the Sedwick by Plummer and Moore.[11] The latter writers, in the map accompanying their report indicate their Putnam Formation, lying between the Sedwick and Coleman Junction limestones, as questionable in position, but in their text definitely assign it to the Cisco, and place the boundary at the top of the easily traceable Coleman Junction.

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[6]Hubbard, W. E., and Thompson, W. C., Bull. Am. Assoc. Petr. Geol., Vol. X, p. 471, 1926.

[7]Udden, J. A., Univ. Texas. Bull. 246, pp. 15 ff., 1912; Case, E. C., Bull. Amer. Mus. Nat. Hist., Vol. XXIII, pp. 659–664, etc., 1907.

[8]Geol. Surv. Texas, 3d Ann. Rept., p. 357, 1892.

[9]Drake, N. F., Geol. Surv. Texas., 4th Ann. Rept., p. 421, 1893.

[10]Wrather, W. E., Bull. Am. Assoc. Petr. Geol., Vol. I. p. 94, 1917.

[11]Plummer, F. B., and Moore, R. C., Univ. Texas Bull. 2132, p. 179, 1921.

They state that it is impossible to draw a sharp line of demarcation; but that the boundary should not be placed higher, since ammonites of a Permian type are found only a short distance above this.

In Cummins' reports[12] only a small area in Archer County is assigned to the Cisco (roughly the Trinity drainage area in the southeastern corner). The line was apparently drawn here because of a change in the character of sedimentation, red beds being present north but not south of the line chosen. Although Adams[13] called attention to the now generally recognized fact that the change from marine to red beds sediments in the plains region does not imply a stratigraphic distinction, Gordon followed Cummins in drawing this boundary, but granted the Cisco a somewhat larger area in 1911[14] than did Cummins, and a smaller area in his 1913 report.[15]

More recent studies of this region enable us to give a more definite line of separation, for the Coleman Junction limestone has been traced northward to the southwestern corner of Archer County. Here it disappears, but its horizon can be followed to the northeast through Archer County.[16] As a result it is found that a much larger area is to be included in the Cisco than had been previously recognized, the line passing several miles to the west of Archer City.

To the south the Cisco consists of sandstones, shales, and thin limestones, with several coal seams. In the region of this report as described by Hubbard,[17] its upper portion is typically a red beds formation, without limestone members except at the extreme southwest.

The recorded Cisco vertebrates are found in the upper 200 feet in Archer County. These localities are probably to be included in the Putnam Formation of Moore and

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[12]Geol. Surv. Texas, 2d Ann. Rept., Pl. XVIII, 1890.

[13]Adams, G. I., Bull. Geol. Soc. Amer., 14, pp. 191–200, 1903.

[14]Gordon, C. H., *op. cit.*, p. 111.

[15]Gordon, C. H., U. S. Geol. Surv. Water Supply Paper 317, Pl. I, 1913.

[16]Hubbard and Thompson, *op. cit.*, pp. 463–464.

[17]*Op. cit.*, p. 463.

Plummer. However, Case has recorded the finding of fragments near Windhorst, at a considerably lower horizon.

Zone 1. Lower Wichita; to Godwin Creek; Admiral Formation?—Proceeding westward in Archer County there is encountered a series of typical red beds, consisting of clays, sandstone and shales, mostly red in color, and devoid of limestones,[18] with an estimated thickness of 350 feet.[19] At about the horizon of Godwin Creek limestones begin to appear. I am not aware of any traceable limestone member in this region, but from evidence given below, a line drawn northeast and southwest roughly approximating the course of Godwin Creek marks a definite faunal boundary.

These beds occupy the middle portion of the Wichita as Cummins conceived of it; but they are now seen to occupy the lower part of this group. This zone is approximately equivalent to the Admiral Formation of Plummer and Moore,[20] although no definite correlation can be made at present.

Zone 2. Middle Wichita; to the Beaverburk Limestone; Belle Plains Formation?—Beyond the horizon of Godwin Creek is found a series of beds about 200 feet in thickness, of a transitional character,[21] in which thin and impure limestones are occasionally present. (Udden's section 25[22] gives a picture of the upper portion of these beds somewhat farther north.) They are terminated above by the first continuous limestone in this region, found in an escarpment following the west side of the Godwin Creek Valley from the region of Rendham northward.[23] It appears in the valley of the Little Wichita south of Fulda, where it is frequently mentioned by Case,[24] and sometimes referred to as "6-inch limestone."

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[18]Gordon, C. H., Jour. Geol., Vol. XIX, p. 113, 1911; Udden's description of Wichita sediments applies largely to this zone.

[19]This and other figures cited were furnished me by Mr. W. E. Hubbard.

[20]*Op. cit.*, p. 192.

[21]Case, *op. cit.*, pp. 45–47.

[22]*Op. cit.*, p. 12.

[23]See Case, *op. cit.*, pp. 35–36, secs. 16, 17, 19.

[24]*Op. cit.*, pp. 35 (secs. 16, 17, 19), 45, and Bull. Am. Mus. Nat. Hist. 23, p. 662, 1907.

In Wichita County, Udden[25] has described the Beaverburk limestone, running from near Burk Station in a general southwesterly direction, and capping the bluffs on either side of the Big Wichita at the present diversion dam near the intersection of the county lines. Its course across the valley of the Big Wichita has not been followed in detail; Cummins' sections 28 and 29, on the south side of the river, just west of the county line, have the Beaverburk at the top;[26] see also Case's section 19.[27] I have not traced this limestone across the divide between the Big and Little Wichitas, but its horizon is that of the limestone near Fulda, and the two appear to be identical, as implied by Case,[28] Gordon,[29] and Hubbard and Thompson.[30]

To the south this limestone could be easily traced and brought into relation with the "Albany" sections. Cummins[31] states that he has done this, but does not give details. Quite possibly it is equivalent to the top of the scarp-forming Bead Mountain limestone; and the beds below it may be equivalent to the Belle Plains Formation of Plummer and Moore.[32]

This limestone is without doubt that stated by Cummins to be at the base of the Clear Fork,[33] and is the only point of demarcation indicated by him between Wichita and Clear Fork (since he did not at first realize the equivalency of the Albany and Wichita). Case and other workers in the vertebrate field have also considered the Wichita-Clear Fork boundary to lie at approximately this horizon,[34] and the evidence presented below shows that on faunal grounds

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[25]*Op. cit.*, sec. 25, p. 12.

[26]*Op. cit.*, pp. 402–403; his later statement (4th Ann. Rept.) that sec. 28 = Military Crossing is obviously incorrect, since that locality is twelve miles west of the county line.

[27]Carnegie Inst. Pub., 207, p. 35, 1915.

[28]*Op. cit.*, pp. 12, 47, and Pl. I.

[29]*Op. cit.*, pp. 114–115, and U. S. Geol. Surv. Water Supply Paper 317, pp. 17, 24, 1913.

[30]*Op. cit.*, p. 464, and map, p. 460; confirmed by Hubbard, *in litteris*..

[31]Texas Acad. Sci. Trans. 2, p. 97 (the second limestone mentioned), 1897.

[32]Plummer and Moore, *op. cit.*, p. 195.

[33]Cummins, W. F., Geol. Surv. Texas, 2d Ann. Rept., pp. 402–403, secs. 28, 29, ff., 1891.

[34]Case, E. C., *op. cit.*, pp. 12, 28, map, etc.

the division should not be placed above this position. However, upon lithologic grounds Gordon and later geologic writers have tended to place the boundary at a higher position in the series, and this usage is here followed despite the fact that it is not in agreement with the paleontological findings.

Zone 3. Upper Wichita; to the Lueders Limestone; Clyde Formation?—While the limestones of the lower members of the "Albany" disappear before reaching this area, those of the upper portion persist, and form a belt crossing the eastern portion of Baylor County from south to north and extending into Wilbarger and western Wichita counties.[35] This zone is approximately 230 feet in thickness, consisting of limestones, often impure, with blue and red shales.[36] It is topped by a scarp-forming limestone known locally as the Maybelle limestone, which crosses central Baylor County from the Big Wichita near the Kemp Lake dam to the Salt Fork about ten miles below Seymour. The canyon of the Salt Fork is cut through this and lower members of the limestone belt; on the western side the outcrop passes up the valley of Miller Creek and is found to be continuous with the Lueders limestone of the "Albany"-Clear Fork sections to the south.[37]

In the valley of the Big Wichita the outcrop of the Lueders may be traced west past Moonshine and Pony creeks;[38] it disappears under the lake level at Gray's Creek, but could formerly be seen in the region of the crossing of the Wichita on the old Seymour-Vernon road somewhat farther west.[39] On the north bank it attains its general line of outcrop near Whiskey Creek and turning north into Wilbarger County crosses Beaver Creek[40] and has been traced by Wrather[41] to a point south of Harrold.

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[35]Adams, G. I., *op. cit.*, p. 194; Gordon, C. H., Jour. Geol. 19, pp. 115–119, 1911.

[36]Gordon, C. H., Water Supply Paper 317, p. 68, 1913, gives a section of the upper portion.

[37]Wrather, W. E., *op. cit.*, p. 94.

[38]Broili, F., Paleontographica 51, pp. 3–4, 1904: Gordon, C. H., Jour. Geol. 19, p. 115 (east of Seymour-Vernon road), 1911.

[39]Gordon, *op. cit.*, Case, *op. cit.*, p. 36 (sec. 20), Bull, Am. Mus. Nat. Hist. 23, p. 662, 1907.

[40]Gordon, *op. cit.*, p. 112.

[41]*Op cit.*, p. 94.

This limestone series is quite probably equivalent to the Talpa and Paint Rock members of Drake[42] and Beede,[43] and approximately corresponds to the Clyde Formation of Plummer and Moore.[44]

In the region under consideration the limestone series is a distinct unit, and might be placed with equal propriety in either the Wichita or Clear Fork groups. Cummins distinctly assigns it to the latter, as does Case; on the basis of its vertebrate fauna it is to be associated with the Clear Fork.

Farther south, however, the line of separation between the "Albany" and the Clear Fork had been placed by Drake[45] at the Lueders limestone. Cummins later recognized the general equivalency of the "Albany" and Wichita,[46] but failed to reconcile their conflicting upper boundaries, although he mentions tracing a limestone which is apparently the Lueders northward and a second, apparently the Beaverburk, southward.[47] Gordon[48] chose the general line of the Lueders, and included the limestone series in the Wichita, although recognizing the fact that this was not in agreement with Cummins' original definition. Wrather,[49] working in the "Albany" section, chooses the Lueders, or rather a somewhat higher horizon, on lithological grounds, and Hubbard *(in litteris)* also considers that even in the northern area the limestone series should be included in the Wichita.

I have here adopted the current geological interpretation of the proper group division, although somewhat under protest, since the faunal relationships of the vertebrates in the limestone series are with the Clear Fork rather than the Wichita.

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[42]*Op. cit.*, pp. 428–429.
[43]Beede, J. W., Univ. Texas Bull. 1816, 1918.
[44]*Op. cit.*, p. 197.
[45]*Op. cit.*, pp. 428–429.
[46]Cummins, W. F., Texas Acad. Sci. Trans. 2, pp. 93–98, 1897.
[47]*Op. cit.*, pp. 96–97; the Lueders="Escarpment capped by a bed of hard limestone"; the Beaverburk=the second escarpment mentioned.
[48]*Op. cit.*, pp. 122–123.
[49]*Op. cit.*, p. 94.

The total thickness of the Wichita group, as thus defined is, in this region, approximately 780 feet. Farther south, in the "Albany" region, it is somewhat thicker, about 1,100–1,200 feet.

Zone 4. Lower Clear Fork; Arroyo Formation (and Vale Formation?).—Above the Lueders limestone are first some lighter-colored beds[50] which further south contain traces of limestone.[51] In this region no limestones are present and a transition to pure "red beds" conditions soon appears, the strata consisting principally of red clays, with small amounts of sandstone and conglomerates. The vertebrate remains are confined to approximately the lowest 250 feet or so of the Clear Fork; although they have been repeatedly searched for,[52] they have not been found west of Baylor County, and we need not discuss here the higher levels of the Clear Fork, or later Permian groups.

The vertebrates are principally in beds corresponding to the Arroyo Formation of Beede;[53] possibly a few of the higher localities are in his Vale Formation (the Abilene and Tye Formations of Wrather.[54])

VERTEBRATE COLLECTIONS

In the course of the present study I have attempted to gather and tabulate all available collections and records of Texas "red beds" vertebrates. Through the kindness of those in charge of these various collections, I have been able to enter in the table given herewith the specimens in the American Museum of Natural History, New York, the Museum of the University of Michigan, Walker Museum, University of Chicago, the Museum of the Alte Akademie, Munich, the Museum of the University of Tübingen, and the U. S. National Museum, Washington. The total number of specimens in these museums exceeds 2,000, and comprises, I

[50]Case, E. C., *op. cit.*, p. 48.
[51]Wrather, *op. cit.*, p. 97.
[52]*Cf.* for example, Sternberg, C. H., "Life of a Fossil Hunter," pp. 213–217, 236 239, 1909.
[53]*Op. cit.*
[54]*Op. cit.*, table opp p. 96

believe, at least 95 per cent of all collections made from these beds. Deducting several hundred which lack either identification or locality record, some 1,600 specimens remain for consideration. These, I feel sure, afford a fairly comprehensive picture of the vertebrate life of these beds.

HISTORY

It has been found impossible to interpret the collector's records without some understanding of the history of collecting in this region.

The first discoveries were made here for Cope in 1878 by Professor Jacob Boll, of Dallas, assisted by Isaacs, who had previously been employed by Cope in other fields. Entering the region from the Red River, they collected in the vicinity of Mount Barry, Wichita County. Turning west, they met with little success, and finally camped near the three forks of the Little Wichita in Archer County, where another collection was made. With a few known exceptions, all the material gathered on this trip was obtained from Zones 0 and 1. A few specimens without data as to localities appear to have been collected by Boll later in 1878 and in the following year. In 1880 a second large collection was secured by Boll, from the Little Wichita, various points on the Big Wichita, and the lower part of the Beaver Creek Valley. It appears that none of the specimens came from horizons higher than Zone 3; Cummins, *in litteris*, states that Boll did not go farther west than the "Military Crossing" mentioned below.

In 1880 W. E. Cummins began a series of collecting trips for Cope. Like those of Boll, his collections were mainly from the lower and middle divisions of the Wichita group; but he also visited localities to the north and west (including southern Indian Territory) and in 1882 first discovered remains from the Clear Fork beds at Coffee Creek.

C. H. Sternberg was the third to collect in these deposits. The story of his first trip (for the Museum of Comparative Zoology, Harvard) in 1882–1883, his fruitless search in the barren Double Mountain and Upper Clear Fork, and his final location of the Lower Clear Fork beds found by

Cummins in the previous season, is interestingly told in his autobiography.[55] Between 1896 and 1902 he frequently visited this region, collecting (principally in the Clear Fork at the Coffee Creek "boneyard" and other places) for Cope and later for the Alte Akademie (Munich) and American Museums. In 1917 he again visited Texas and excavated the Craddock Bone Bed, which had been discovered by Walker Museum,[56] his finds there being now principally in New York and Washington. In 1895 and 1897 he collected from the Coffee Creek region only; except for a short stay at Godwin Creek in 1902, his collections were made entirely from the upper beds of Zone 4. Hatcher, an experienced and successful collector, had prospected these beds for Marsh in 1885 and had reported them as valueless.

Case's important work on the Texas fauna began with collecting trips for the University of Chicago in 1895 and 1903. The results of later trips, in 1906 and 1908, for the American Museum, were incorporated in his revisions of the Texas fauna. In 1912 and 1913 he collected for the University of Michigan, the material being chiefly derived from the newly discovered and very productive Briar Creek bone bed.[57] Case's work has been done mainly in Zones 1 and 2.

In 1908 exploration in this field was begun by the University of Chicago, and has continued during the greater number of the field seasons for the past twenty years. The collecting, done almost entirely by Paul C. Miller, and mainly from Zones 3 and 4, has resulted in the discovery of a large amount of material, much of it new, described by Williston and his students. The Craddock and Cacops bone beds[58] were among the new localities discovered in the course of this work.

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[55] *Op. cit.*, pp. 205–264

[56] See Williston, American Permian Vertebrates pp. 5–7, 1911.

[57] Case, E. C., Carnegie Inst. Pub. 207, pp. 157–176, 1915.

[58] Williston, *op. cit.*, pp. 4–7.

LOCALITIES

Cope customarily gave locations as merely "from Texas," and in some cases (especially in the earlier years) no locality records are available. Section corners and other exact means of localization are not often available in this region; the most common form of record is the citation of the creek or other natural landmark, or ranch, near which the specimen was gathered. This would at first sight seem quite unsatisfactory since, for example, many of the creeks have a length of ten or fifteen miles. However, familiarity with the terrain shows that in most cases the exposures along each creek are quite limited both in extent and horizon, and in most cases the topographic determination can be made to within a mile or so while (in this region of little disturbance of strata) the vertical determination can be made to within 50 feet, on the average, which for our present purposes is usually sufficient.

Cummins[59] has published valuable notes on localities, including a number which would otherwise be impossible of identification at the present time. Following is a list of localities arranged by zones. (See also Table I.)

Zone 0. 1. Cottonwood Creek, a tributary of the south fork of the Little Wichita, 10 miles southwest of Archer City; about 200 feet below the top of the Cisco. 2. Elm Creek, stated by Cummins to be 12 miles southwest of Archer City; its exact position is uncertain, probably about 100 feet below the Coleman Junction. 3. The mouth of Onion Creek, northeast of Archer City; about 90 feet below the top of the Cisco. 4. The "Fireplace," on the south fork, near the mouth of Cottonwood Creek, not far below the Cisco-Wichita boundary. 5. Three Forks of the Little Wichita, northwest of Archer City, close to the line of the Coleman Junction. 6. "Shell Point," a Boll locality whose exact position is unknown, but which was probably not far from the Three Forks. 7. Long Creek, which empties into the north side of the Little Wichita due north of Archer City (not northwest of the copper mines, as stated by

[59]Jour. Geol. 16, pp. 737–745, 1908.

Cummins). If the locality was near the mouth, as was probably the case, it would be just below the Wichita-Cisco boundary.

This region is mostly well grassed over and the outcrops are relatively poor. None of these localities has been worked during the past forty years.

Zones 0 or 1. 8. North Fork of the Little Wichita. A number of specimens collected by Boll and Cummins are known to have been obtained from the lower portion of the course of this stream, but cannot be exactly located. 9. "Boll 1878." As noted above, Boll's collection of that year was obtained almost entirely from Zones 0 and 1, and specimens without a definite location are entered here. They are probably from either the Mount Barry district or the neighborhood of the "Three Forks."

Zone 1. 10. Middle Fork of the Little Wichita, 4 miles west of Archer City; on the east bank, near the old Archer-Seymour (now Archer-Megargel) road, about 50 feet above the Coleman Junction. 11. Case's notes for 1906 show that a number of specimens were collected south of Holliday and near the Little Wichita, but the exact location cannot now be ascertained. This region would be about 70 feet above the base of the Wichita. 12. Mount Barry, 10 miles west of Wichita Falls, from which Boll and Cummins collected, is undoubtedly in this zone, although no exact stratigraphic determination can be made. Many of Cope's types are from this region. 13. Briar Creek, a rich locality, the collecting ground being mainly on the east side a few miles from the mouth, near and in the bone bed discovered by Case; about 190 feet above the Coleman Junction. 14. Godwin Creek. Unless otherwise specified, specimens bearing this label appear to have come from the southeast side of this creek. The horizon is about 250–300 feet above the base of the formation.

Zones 1 or 2. 15. "North Fork of the Little Wichita." This entry includes specimens which appear to have come from the upper portion of this fork; the collecting beds here lie in Zones 1 and 2, and probably most of the specimens are from localities 17 and 19. 16. Case recorded a number of specimens from Scalen's ranch. This was situated somewhere to the south (and probably to the east) of Dundee; its location is not known to me.

Zone 2. 17. Cox's Camp (Cummins); Wooderum's pasture (Case). Exposures on the north side of the Little Wichita about opposite the mouth of Godwin Creek, about 350 feet above the base of the Wichita. This is at about the faunal boundary previously suggested. 18. "Head of Godwin Creek." Specimens so labeled are from the exposures below the Beaverburk on the west side of the Godwin Creek Valley, near Daggett Creek etc. They are at about the same horizon as the next locality. 19. Numerous exposures occur in the valley of the Little Wichita south and southeast of Fulda, about 450–500 feet above the Coleman Junction limestone, and not far below the Beaverburk. (The same is true of the next two localities.) The specimens are variously labeled "Little Wichita below Fulda," "Hackberry Creek," "North Side, Little Wichita," "South Side, Little Wichita," "North Side of Godwin Creek," "South of Fulda." (It is not impossible that a few of these, from Cassil Hollow, were slightly above the limestone.) 20. Slippery Creek is a tributary of the Little Wichita on the north side. Along its course, nearly due south of Dundee, is a series of breaks. Lyle's, Pearce's, and Young's localities of Case were in this neighborhood. 21. Tit Mountain or Corn Hill, an elevation just northeast of Dundee, about 500 feet above the Coleman Junction. 22. Camp Creek, 4 miles west of Tit Mountain, and 23, "Big Wichita" locality, are two collecting places of Cummins' on the south side of the Big Wichita River, and the locations where his section 28 and 29, previously referred to, were taken. The writer is not personally familiar with them; they appear to have been situated just below the Beaverburk limestone (which is found at the top of the sections) with a probable elevation above the Coleman Junction of about 525 feet. 24. A number of specimens collected by Boll are stated by Cummins to have been obtained near the mouth of Beaver Creek and hence in this zone; but it is not impossible that some specimens may have come from Zones 1 or 3.

Zone 3. Fossils are scarce in the limestone series. 25. A single specimen has been obtained from the lower portion of this series northeast of Fulda. 26. Udden[60] reports a collection from the "Bluff Bonebed" in western Wichita County, 65 feet above the Beaverburk. The specimens are not available to the writer, but they have been included in the tables. 27. Coal Creek. A single specimen has been found near the mouth of this creek southeast of Maybelle. The location is about 100 feet above the Beaverburk. 28. The most interesting locality in this horizon is that situated near Mitchell and Timber creeks, northeast of Maybelle in the old Bar X pasture. Williston has described a number of new or rare forms from this locality. It is about 150 feet above the Beaverburk. 29. Whiskey Creek. On the north side of the Big Wichita, not far below the Lueders; about 200 feet above the Beaverburk. 30. Moonshine Creek. On the south side, farther west, at about the same horizon. 31. Military Trail. This trail crossed the Big Wichita about a mile east of the present Kemp Lake dam. South of this it ran in Zone 3, and the same is true for several miles to the north; but while the finds are probably in this zone, the exact horizon cannot be stated.

Zones 1 to 3. 32. "Big Wichita" of Boll. As Cummins has noted, Boll used this locality record (in 1880) for various points along the course of this river. Some specimens are known to be from the Mount Barry region; others from eastern Baylor County, and no more definite localization is usually possible.

Zone 4. 33. "Sternberg 1896." In this year Sternberg collected in the neighborhood of Brush, Gray, Pony, and Hog creeks on the south bank of the Big Wichita, and Crooked, Indian, and Coffee creeks on the north side. Specimens of this date can thus be assigned to Zone 4 under this head in default of a better record. 34. Coffee Creek. Discovered by Cummins, and worked extensively by all later collectors, this locality has been one of the most prolific in Texas. At the highest, the beds here are probably not much over 100 feet above the Lueders limestone; the lowest

[60]Udden, *op. cit.*, pp. 36–41.

portion may possibly have lain below it, but this region is now covered by the waters of Kemp Lake. 35. Pony Creek. A tributary of the Big Wichita on the south side, north of Seymour; the collections were made near the head of the creek, probably about 100 feet above the Lueders. 36. Indian Creek adjoins Coffee Creek on the west. The collections are mainly from the region near its mouth. A large proportion of the specimens recorded from here are from the Cacops bone bed. The localities are about 100 to 150 feet above the Lueders limestone. 37. Gray's Creek. 38. Craddock's ranch, Brush Creek. About seven miles north and somewhat west of Seymour lies Craddock's ranch, an area of 6 square miles, drained by Gray's Creek on the east and Brush Creek on the west. Numerous "breaks" are present in this region; they were worked extensively by Sternberg and later with great success by Miller. A large proportion of the remains recorded under entry 38 are from Craddock bone bed. The beds average about 150 feet above the base of the Clear Fork. 39. Hog Creek. The next creek west of Brush Creek, with exposures at approximately the same horizon. 40. Table Top Mountain. A remnant of a former peneplain, rising to the south above Craddock's ranch and Brush Creek. The beds perhaps average 200 feet above the Lueders. 41. Crooked Creek. On the north side of the river, west of Hog Creek. The beds are apparently at about the horizon of those of Table Top Mountain. 42. Beaver Creek, Wilbarger County. The upper reaches of this stream have yielded a few remains. The localities are, I believe, all above the Lueders limestone, and quite probably correspond to the beds to the south at Coffee Creek. 43, 44. Dead Man's Creek, Soap Creek. Still farther west, on the south side of the Big Wichita. Only fragmentary remains have been found here; but they are of interest as being the highest horizon in which Permian vertebrate remains have been found in Texas.[61] They are probably 250 to 300 feet above the base

[61]The Paint Creek locality of Cummins is probably at about the horizon of Craddock's ranch (Geol. Surv. Texas, 4th Ann. Rept., p. 233, 1893).

of the Clear Fork, although the horizon cannot be stated with certainty.

TAXONOMIC USAGES

As noted, I have not attempted to use specific differences in this discussion; also closely related genera have been grouped together when isolated skeletal elements cannot be easily differentiated. In many instances it is quite probable that fragmentary remains assigned to known genera properly belong to related but as yet undescribed forms, of which a considerable number doubtless still remain. Fish remains, except for pleuracanthid spines and teeth, are too rare occurrences to be of aid.

Epicordylus and *Rhachitomus* are included in *Eryops*.[62] A number of plates of the *Aspidosaurus* type are assigned to that genus; but, as Case and Williston have noted, this disposition may be incorrect in some cases. Various limb bones of dissorophids from the Craddock bone bed are generically indeterminate and have been grouped under the family heading. *Zatrachys* has been confined to the known portions of the anatomy (mainly the skull) although, as previous workers have noted, some of the *Aspidosaurus* remains may possibly belong to this genus.

Pariotichus is confined to the type, the common forms once placed in this genus now being assigned to *Captorhinus*. *Varanops* and *Varanosaurus* are grouped together (since their limb bones are practically indistinguishable) as are *Theropleura, Diopaeus* and *Therosaurus*. *Clepsydrops* and *Dimetrodon* are placed under one head. They are at present distinguishable only by size and length of the spines, and it is impossible to tell small or immature *Dimetrodon* bones from those of *Clepsydrops* although, as Dr. Case has pointed out to the writer, the types of sphenacodont limb bones found at Briar Creek show differences great enough to be of a generic nature. *Edaphosaurus* and *Naosaurus* are considered jointly, as are *Bolosaurus* and *Ophiodeirus*.

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[62]For those unfamiliar with the vertebrates, Case, *op. cit.*, chap. 6, gives a useful summary with sketch restorations.

TYPES

In many cases the geographic or stratigraphic origin of type specimens from these beds has never been published. Below I give a complete list of the type localities, so far as they exist in museum records, supplemented by the records or memories of the collectors. Unless otherwise noted, these are holotypes. Genotypes are starred. In many cases original but now obsolete generic references have been retained. Only Texas and South Oklahoma forms are listed; other "Permian" localities are readily accessible in the literature. The localities are numbered as in the preceding list.

AMPHIBIA

Cricotus crassidiscus 8, *C. hypantricus*, Deep Red Run, Indian Territory.
**Eryops megacephalus* 9, *E. anatinus* 12, *E. latus*, no record.
**Rachitomus valens* 12.
**Anisodexis imbricarius* 34.
**Parioxys ferricolus* 12.
**Epicordylus erythrolithicus* 9.
**Acheloma cumminsi* 34, *A. casei*, 34.
**Dissorophus multicinctus (=D. articulatus)* 34.
**Alegeinosaurus aphithitos* 34.
**Otocoelus testudineus* 37, *O. mimeticus* 33.
**Aspidosaurus chiton*, type and paratype 34, *A. glascocki* 17, *A. crucifer*, no record.
**Cacops aspidephorus* 35.
**Broiliellus texanus* 28, *B. peltatus* 38.
**Trematops milleri* 38.
**Zatrachys serratus* 9 (type lost), neotype 13, *Z. microphthalmus*, type and paratype 34, *Z. conchigerus* 34.
**Trimerorachis insignis* 9, *T. alleni* 17, *T. bilobatus* 21, *T. medius* 19. *T. mesops* 34, *T. conangulatus* 35.
**Tersomius texensis* 19.
Diplocaulus limbatus 34, *D. magnicornis* 34, *D. pusillus* 38 *D. copei* 40.
**Platyops parvus* 38.
**Goniocephalus willistoni* 38.
**Gymnarthrus willoughbyi* 42, paratype 19.
**Cardiocephalus sternbergi* cotypes 34.

COTYLOSAURIA

**Seymouria baylorensis* 34.
**Desmospondylus anomalus* 34.
**Conodectes favosus* 37.
**Diadectes sideropelicus* 12, *D. biculminatus* 12, *D. latibuccatus* 6, *D. phaseolinus* 8, *D. huenei* 34, *D. maximus* 38.
**Diadectoides cretin* 42.
**Empedias alatus* 12, *E. fissus* 14, *E. molaris* 9, neotype 8.
**Bolbodon tenuitectus* 34.
**Chilonyx rapidens,* type and paratype 9, neotype 30.
**Pariotichus brachyops* 8, neotype 34; *P. isolomus,* type and paratypes 34, *P. aduncus* 35.
**Ectocynodon ordinatus* 9, *E. aguti* 34, *E. incisivus,* no record.
**Isodectes megalops* 35.
**Captorhinus angusticeps* 34.
**Hypopnous squaliceps* 34.
**Labidosaurus hamatus* 34, *L. broilii* 34.
**Pantylus cordatus,* type and paratype 32, *P. coicodus* 34.
**Ostodolepis brevispinatus* 34.
**Archeria robinsoni* 13.
**Helodectes paridens* 32, *H. isaaci* (type lost) 32.

PELYCOSAURIA

**Poliosaurus uniformis* 9, neotype 8.
**Poecilospondylus francisi* 34.
**Varanosarus acutirostris* 40.
**Varanops brevirostris* 35.
**Glaucosaurus megalops* 28.
**Mycterosaurus longiceps* 28.
**Theropleura retroversa,* type and paratype 9, paratype 12, *T. triangulata* 9, *T. grandis* cotypes (record doubtful) 12.
**Diopaeus leptocephalus* (=*Theropleura retroversa* neotype) 23.
**Therosaurus watsoni* 19.
**Tetraceratops insignis* 34.
Clepsydrops limbatus 9, *C. natalis* 12.
**Dimetrodon incisivus* 6, neotype 8, *D. gigas* 9, neotype 32, *D. longiramus* 21, paratype 9, *D. rectiformis* 12, *D. macrospondylus* 21, *D. obtusidens* 32, paratype 24, *D. semiradicatus* 32, *D. gigashomogenes* 34, *D. dollovianus,* Deep Red Run, Indian Territory, neotype 34, *D. platycentrus,* Deep Red Run, Indian Territory.
**Embolophorus fritillus* 9.
**Metarmosaurus fossatus* 12.
**Edaphosaurus pogonias* 34, *E. microdus* 23, neotype 24.
**Naosaurus claviger,* type and paratype 34, *N. cruciger* 8.
**Trichasaurus texensis* 38.
**Casea broilii* 35.

"PROTOROSAURIA"

**Bolosaurus striatus*, type and paratype 12, *B. major* 12.
**Ophiodeirus casei* 14.
**Araeoscelis gracilis* 38.

INCERTAE SEDIS

**Bathyglyptus theodori* 42
*"*Tomicosaurus* sp." 12.

INVERTEBRATE AND PLANT LOCALTIES

Some information regarding the relative position of invertebrate and plant localities has been gathered in the course of this work.

Girty's[63] localities 14 and 15 (south of Spring Creek) and 23 (Fane Mountain), 12 and 13 (Spring Creek) and 22 (west of Woodson) are close to the Coleman Junction limestone. The Antelope plant locality is also Cisco.[64] Localities 11 and 1* of Girty, the Godwin Creek invertebrate locality of I. C. White[65] are in Zone 1. The plant localities of David White[66] are close to the Beaverburk at the top of Zone 2 and that of I. C. White ("head of Godwin") is probably at the same horizon, although Cummins' statement[67] that it lies on the south bank suggests that it may lie at the top of Zone 1. Girty's locality 10 is in Zone 2, and Camp Creek of I. C. White at the top of 2 or the base of Zone 3. Localities 1 and 2 of Girty (the Bar X crossing and ranch house were situated at the head of the present diversion lake, about 4 miles west of the Archer County line on the Big Wichita) are near the base of Zone 3 or possibly at the top of Zone 2. The Camp Creek locality is at nearly the same horizon. The Bluff Bonebed of Udden[68] (plants and invertebrates) is 65 feet above the Beaverburk. Girty's locality 21 is in Zone 2 or Zone 3. His localities 3, 4, 6, 7,

[63]Girty, G. H., Jour. Geol. 19, pp. 125–134, 1911.
[64]White, I. C., Bull. Geol. Soc. Amer. 3, pp. 217–218, 1892.
[65]White, I. C., Amer. Nat. 23, pp. 109–128, 1889, U. S. Geol. Surv. Bull. 77, p. 16, 1891.
[66]White, D., Jour. Geol. 19, pp. 130–131, 1911, U. S. Nat. Mus., Proc. 41, 1912.
[67]Cummins, W. F., Jour. Geol. 76, 1908.
[68]Udden, J. A., Univ. Texas Bull. 246, pp. 36–41, 1912.

17–19 are in Zone 3, mainly near the top. The military crossing to which several of his localities refer, and from which I. C. White also collected, was about one mile east of the present Kemp Lake dam. His localities 5, 8, 9, 20, 24–26 appear to have been close to the Lueders limestone. The forms described by Leuchs[69] from Pony and Rock creeks are from the top of Zone 3.[70]

TABLES

In Table I are listed all vertebrate specimens known to me which have a locality record and which have been identified, with the exception of one specimen (probably with the wrong locality) noted below. In a few instances specimens somewhat doubtfully identified have been included, but only when the form has been identified without question from the same locality.

The number of specimens of each group from each locality has been recorded in order that some idea of the relative frequency of the forms may be afforded. This is in some respects misleading since, in the case of the larger forms *(Dimetrodon, Eryops,* etc.) single bones are often given separate museum numbers, whereas with smaller forms (as *Lysorophus, Trimerorachis,* etc.) a large number of specimens is often lumped under one number, giving the appearance in the table of a relatively greater infrequency than was actually the case.

The identifications of all specimens have been made by competent authorities. The writer has in addition checked over nearly all the material except the small proportion in foreign museums in order to discover, if possible, isolated instances of unusual distribution.

Below the main table are listed forms represented by one or two specimens, the numbers following giving the localities from which collected (only one specimen unless otherwise noted).

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[69]Leuchs, K., Centralbl. f. Min., etc., pp. 684–690, 1908.
[70]For localities, *cf.* Broili, F., Paleontogr. 51, pp. 3, 4, 1904.

Table II gives a summary by zones of the more common forms, arranged in taxonomic order. In Table III the same material is presented in a stratigraphic arrangement.

DISCUSSION

ADEQUACY OF MATERIAL

The available data, as displayed in the tables, appear to be sufficient to insure a representative section of the fauna. Zone 0 is sparsely represented in the material; it appears to have been similar to Zone 1 in content. From Zones 1 and 2 there is abundant material. From Zone 3 (as would be expected from the large proportion of limestones) we have only a small number of specimens; a number of them are of forms found elsewhere only in Zone 4. This last zone, because of the greater amount of work done in these beds, is very well represented.

Except then for Zones 0 and 3 it would seem that the material available is sufficient to determine the presence or absence in these horizons of the more common forms. But it is not at all improbable that the range of some of the rarer types may be found, upon further collecting, to be greater than that now known.

Both these statements, however, must be qualified. For example, *Diplocaulus*, very common at the top of the beds, would be recorded as absent in Zone 1 were it not for two fragmentary specimens; and in other cases the absence of common forms from certain zones may mean merely their comparative rarity. On the other hand, our material has apparently been sufficient to enable us to detect the presence of certain of the rarer types (as *Zatrachys*) in almost every zone.

DIAGNOSTIC FORMS

Three forms—*Cricotus, Bolosaurus,* and *Archeria*—are not known with certainty above Zone 1. Of these *Cricotus*, at least, is so abundant that it is probable that it is really confined to these beds.[71] *Bolosaurus* is known only from Zone 1 with certainty; but the small number of specimens renders this fact of comparatively little significance. *Theropleura* is abundant in the lower zones, but represented by only one specimen in Zone 3 and is not identifiable in Zone 4.

Four common and well-known forms are represented in every zone—*Eryops, Diadectes, Dimetrodon, Edaphosaurus.* That specific changes took place during this time interval from Zone 0 to Zone 4 in this group is exceedingly probable; and here specific diagnoses properly established would be invaluable.

In addition *Trimerorachis* is common to all zones (except 0). *Zatrachys* and *Aspidosaurus,* among the less common forms, also appear to have had a wide range. *Diplocaulus* is exceedingly numerous in Zone 4, but very scarce below, although present to some extent in Zones 1 and 3.

In the upper beds, four forms, three of them common, are to be found in Zones 3 and 4—*Captorhinus, Labidosaurus, Pantylus,* and *Broiliellus.* Some eight forms, of which *Seymouria* is the most widely distributed, are known only from Zone 4; but considering the scarcity of remains in Zone 3, it is not improbable that certain of these will eventually be found in the latter as well.

"WICHITA" AND "CLEAR FORK" FAUNAS

The two most characteristic zones are 1 and 4. With the former 0 is apparently to be grouped; with the latter, Zone 3. Zone 2 is, in general, of a neutral character, for with the exception of one or two rarer types it possesses only forms common to most of the beds.

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[71]Two instances of the occurrence of *Cricotus* in Zone 4 have been reported. One of these specimens (in Munich) consists of two small isolated ring-shaped centra which might equally well be assigned to an immature cotylosaur (cf. "*Desmospondylus*"). The second specimen, in the American Museum (collected by Sternberg), is identifiable as *Cricotus*. But the absence of any other identifiable specimens of this form among the 800 or so specimens known from these beds renders it probable that a mistake in the locality records has occurred; this is especially so since Sternberg in the same year collected from the known *Cricotus* horizon at Godwin Creek. Further, neither Mr. Miller, who worked in these beds for ten seasons, nor Dr. Case has ever seen the slightest indication of *Cricotus* there. For these reasons the specimen has been omitted from the tabulations.

Zone 1 may be held to be the locus of the typical Wichita vertebrate fauna; Zone 4 of the typical Clear Fork. If, however, we attempt to fix a line of division between the faunas, it will be found that this does not coincide with the accepted line of division between these groups. The line should be placed below Zone 3 and above Zone 1; the Beaverburk limestone is an acceptable marker, lying as it does above the neutral Zone 2.

The "Wichita" vertebrate fauna is thus confined to the Middle and Lower Wichita (and the upper Cisco); the "Clear Fork" vertebrate fauna is characteristic of the Upper Wichita as well as the Lower Clear Fork.

In this region the presence of *Cricotus* seems especially diagnostic of the lower fauna; the presence of captorhinomorphs *(Captorhinus, Labidosaurus)*, *Seymouria,* and a number of other forms gives a criterion for the upper fauna.

CHANGES OF AN EVOLUTIONARY CHARACTER

Faunal distinctions between portions of a series such as this might be attributed to one of three factors: (1) actual evolutionary advances in the fauna, the appearance of newly evolved types, and the disappearance of archaic ones, (2) changes in the environment within the area studied, (3) the inward migration of forms already present or evolving elsewhere.

It was hoped that considerable evidence of true evolutionary nature would be discovered. As is suggested by the remarks in the last section, this is unfortunately true to only a very limited extent.

The extinction of *Cricotus,* a primitive amphibian, and the poorly known *Archeria,* apparently a very primitive reptile, at the end of Zone 1 may be of this nature; this may also be true of the diminution in numbers and disappearance of *Theropleura,* a rather primitive type of pelycosaur. The deployment of the dissorophid amphibians may represent a truly evolutionary process. Specialized or advanced forms which appear late in the series, and which may represent the advance into this region of newly evolved types, include *Pantylus, Captorhinus, Labidosaurus,* and *Casea.*

However, *Seymouria* representing the supposed ancestral type of reptile, appears only in the highest beds. *Lysorophus* and its probable relatives seem to represent an ancient group, but appear only at the top of the series; *Diplocaulus,* of like antiquity, is sparsely represented except in the uppermost zone. These instances show an actual reversal of the evolutionary sequence.

The forms or groups which persist throughout the beds give little evidence of evolutionary change. A careful study of specific characters would, I believe, show progressive modifications within the common genera; but unfortunately this study is imossible at the present time.

Among the Rhachitomi, *Eryops,* which may be regarded as a primitive form, is common in even the lowest beds, but the more highly specialized types *Zatrachys, Acheloma, Trimerorachis* and the Dissorophidae *(Dissorophus, Broiliellus, Cacops, Aspidosaurus, Alegeinosaurus)* appear almost as early, although the dissorophids deploy only in the upper zones. Of the cotylosauria *Diadectes* is the earliest form to appear, and it is far from being a primitive reptile in many points.

Of the pelycosaurs, the Poliosauridae *(Poliosaurus, Poecilospondylus, Varanosaurus, Varanops* and perhaps *Mycterosaurus* and *Glaucosaurus)* are found from near the base of the series to Zone 4; but while generic changes appear in the group, these are not interpretable as progressive in nature. *Theoropleura,* a rather primitive type, is found at the bottom of the series, is rare above, and disappears before Zone 4 is reached. But, as previously noted, the long-spined *Dimetrodon* and *Edaphosaurus,* the two most specialized members of the fauna, are found to be already present in the very lowest zone. It may be remarked that although "spinescence" is regarded as a sign of racial old age, *Dimetrodon* persists to the highest levels and is almost everywhere the most abundant of all types.

Araeoscelis and *Bolosaurus* (unpublished evidence confirms their relationship) are perhaps the two most "advanced" forms among Texas reptiles. The former is found only in the top of the beds; but *Bolosaurus* is already present in Zone 1.

To summarize: while a few features apparently are of an evolutionary nature, many of the more specialized and advanced forms are already present at the beginning of the known bone-bearing Texas deposits. The space of time occupied by the deposition of these beds appears insufficient to show us any major features of evolutionary change, and the lowest beds are not by any means old enough to show us the beginnings of the fauna; its evolution must have begun much earlier.

DISTINCTIONS DUE TO ENVIRONMENTAL CHANGES

The general conditions relating to red beds deposition have been discussed by Case and others.[72] Many fluctuations in local environmental conditions which may have occurred during the time of deposition of the Texas red beds cannot perhaps be evaluated at present. But one major feature has long been recognized. The Upper Cisco deposits of the area in question are a terrestrial and near-shore phase of deposition, and the same is true of the Lower Wichita. In the Middle Wichita, however, the sea encroached upon the coastal plain from the south and (as shown by the limestone series of eastern Baylor County) soon advanced far to the north and covered much of this territory during the time of deposition of the beds of Zone 3. Above the Lueders follows a short transition zone, and above this are terrestrial red beds with an entire absence of limestones. It would seem that Zone 1 should show a large proportion of inland land forms and aquatic or semiaquatic types inhabiting fresh water streams or lakes; Zone 2 should show a reduction of these forms, with an increase of forms probably to be associated with brackish coastal lagoons or the seashore; and this change should be emphasized in Zone 3, while Zone 4 should show a return to the

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[72]Case, E. C., *op. cit.*, pp. 147–149 ff.

general conditions of Zone 1. The evidence favors these assumptions.

Table IV presents the percentages of relative abundance of the more common forms found in Zones 1 to 4. Except for Zone 3, the figures are probably large enough to be significant. Of these forms *Dimetrodon* is the most surely terrestrial type; except under unusual circumstances this animal probably spent all its time on land. It will be noted that this form is much more abundant in Zones 1 and 4, where it is the most common form found. *Edaphosaurus* is considered by Case to be an upland form; the figures, however, do not present clear evidence on this point. *Diadectes* is generally regarded as having been molluscivorous in habit; very possibly its habitus was the shores of the sea and estuaries where this type of food would be plentiful. In agreement with this we find that it is relatively more abundant in Zones 2 and 3 than elsewhere. The amphibian *Eryops* was apparently at home either on the banks or in the water, but it is generally believed to have been mainly a pool and lagoon denizen; it is much more abundant in Zone 2 than in either 1 or 4. *Trimerorachis* is without doubt an aquatic form, with little or no power of locomotion on land. It increases enormously in number in Zone 2, is abundant in Zone 3 and in the lowest transitional beds of Zone 4, after which it decreases.

Of all Texas animals, *Araeoscelis* was considered by Williston and Case to be the most purely terrestrial—perhaps even arboreal. It is found only in Zone 4; the related *Bolosaurus* in Zone 1; no traces of a similar type are to be found in Zones 2 or 3. The poliosaurids are usually considered as terrestrial forms. They are found in most zones, but are most abundant in 4. *Casea* and *Seymouria* are also generally believed to be terrestrial types; they are confined to Zone 4.

Of purely water living forms, *Trimerorachis* was considered above. There remain *Cricotus, Diplocaulus, Lysorophus,* and their relatives. With the exception of one instance of the occurrence of *Diplocaulus* farther to the north and presumably closer to the main land mass, these forms are not present in Zones 2 or 3. *Diplocaulus* and *Lysorophus* are, from their structure, obviously fitted for life in quiet pools; their distribution tends to indicate that these were inland, fresh water pools. With *Cricotus*, absence in Zones 2 and 3 may be due to the disappearance of an archaic type. But Case has noted the absence of fish remains in his collections from the productive Briar Creek bone bed, and further search there has yielded only one *Diplodus* tooth and one spine. It is possible that *Cricotus* was an inhabitant of inland waters, which the pleuracanth sharks rarely reached; the origin of the amphibians has been assumed with reason to have taken place in fresh water; and Watson has ably argued for the primitive position among the amphibia of the group of which *Cricotus* is one of the last survivors.

There remain for consideration among common forms *Captorhinus*, *Labidosaurus*, and *Pantylus*. The last has a conchifragous dentition; *Captorhinus* was probably an invertebrate feeder, including hard-shelled forms in his diet; *Labidosaurus* was so to a lesser degree. Case believed the last two to have been somewhat amphibious; the skeleton of *Pantylus* is unknown. It is probable that these forms may have been littoral in their habitat; we might expect them in Zones 2 and 3 and the lowest beds of Zone 4. They are not present in Zone 2; but in Zone 3 they constitute, taken together, a third of all known specimens. In Zone 4 *Pantylus* is known only from the lowest locality, Coffee Creek. At this same place *Captorhinus* and *Labidosaurus* are extremely abundant; above, they become rare. This distribution agrees well with the habits postulated.

It is not improbable that the skeleton of *Pantylus*, when found, will be somewhat aquatic in nature.

The findings from the distribution are thus seen to be in general agreement with those expected from the known changes in the environment.

CHANGES DUE TO MIGRATION

In Zones 3 and 4, especially the latter, are to be found a number of forms which are not present in lower beds, in which conditions seems to have been favorable for their existence. In a few instances, as in the case of the dissorophids and poliosaurids, we have merely the replacement of one form by a closely related one, or the addition of closely related genera to those already existing; in some instances this may possibly be considered as due to evolutionary changes occurring in this general region. But in many cases no such explanation can be offered. In *Lysorophus* and its allies we have the appearance for the first time in these beds of a Pennsylvanian group which must have been flourishing in other regions of this continent at the time of the deposition of the "Wichita" beds. *Seymouria* is a form generally assumed to represent the most primitive reptiles, a stock which must long antedate the appearance of highly specialized reptiles in the lowest Texas zone. *Captorhinus, Labidosaurus,* and *Pantylus,* appearing near the top of Zone 3, and *Casea,* in Zone 4, are highly specialized forms for which no antecedents are to be found in the Texas beds; their evolution must have occurred elsewhere, and their entry into this region may mark the establishment of a new land connection, probably with regions to the north and east.

SUMMARY OF THE GENERAL FAUNAL HISTORY

The Lower Wichita shows a comparative abundance of terrestrial or fresh water forms (as *Dimetrodon, Bolosaurus* and *Cricotus).* With the advance of the sea these become less numerous *(Bolosaurus* and *Cricotus* disappear, and even the presumably somewhat amphibious *Thereopleura* diminishes in numbers and finally vanishes). Shore dwellers (as *Diadectes)* and inhabitants of the coastal lagoons (as *Eryops* and *Trimerorachis)* are abundant. As the sea begins to retreat in the Upper Wichita, new forms *(Captorhinus, Labidosaurus* and *Pantylus)* follow the strand line south into this region. In the Lower Clear Fork, with the resumption of terrestrial conditions, land forms (as *Dimetrodon)* increase greatly in numbers, the shore-dwellers or coastal marsh types (as *Diadectes, Eryops, Trimerorachis)* decrease; new terrestrial types (as *Casea, Seymouria,* various poliosaurids and especially *Araeoscelis)* and fresh water forms (as *Lysorophus* and *Diplocaulus*, in a renewed invasion) appear. The sequence, land—sea—land, is reflected in the fauna.

"PERMIAN" TYPES IN THE CISCO

Although remains of this fauna have been reported from the Pennsylvanian in one other locality with certainty and doubtfully in others, the Texas finds have hitherto been universally regarded as being from the Permian Wichita and Clear Fork; Cummins believed the oldest remains to be Middle Wichita.[73] We have here shown that a number of localities are situated below the usually accepted top of the Cisco (Pennsylvanian); a fact prophesied by Beede some years ago.[74] Wrather and Beede would place the Cisco-Wichita boundary somewhat lower, resulting in the inclusion of all or nearly all these localities in the base of the Wichita; however, Case's notes record the finding of fragments at a considerably lower horizon in east Archer County. It is not improbable that the fauna will be found in the Cisco wherever suitable "red beds" conditions are met.

Tomlinson has recently presented evidence tending to show that the Pennsylvanian-Permian boundary in Texas is at present placed considerably higher than in Kansas and North Oklahoma; but that boundary (Neva limestone) is also an arbitrary one.

Case believes that the red beds fauna accompanied red beds conditions, that red beds conditions advanced progressively from east to west, as a corollary, suggests that the fauna had an east to west migration.[75] With the first of these conclusions I have no reason to disagree. But the red beds of Texas occur at a horizon probably as low as the Monongahela; those of Oklahoma may be as early in date as the lowest red beds in the eastern states,[76] and the

[73]Cummins, W. F., *op. cit.*, p. 739.
[74]Beede, J. W., Geol. Soc. Amer. Bull. 33, 1922.
[75]Case, E. C., Carnegie Inst. Washington Pub. 283, pp. 187–193, ff., 1919.
[76]Beede, J. W., *op. cit.*, p. 685.

vertebrate beds of New Mexico are not improbably older than those of Texas.[77]

COMPARISON WITH OTHER REGIONS

It was hoped that the results of this study might prove applicable to the correlation of terrestrial Permian deposits in North America. But since (as we have seen) many of the zonal differences are to be attributed to local environmental factors, they can be applied to only a limited area or with considerable qualifications. They may prove of aid in the determination of the stratigraphy of the "red beds" of uncertain relationship in Oklahoma south of the Wichita Mountains. With regard to northern Oklahoma and Kansas, there is little to add to the writer's previous discussion;[78] the presence of *Captorhinus* at Pond Creek and of *Cricotus* at Orlando is in agreement with the current correlations by Gould of the Stillwater with the Wichita and the Wellington with the Clear Fork, keeping in mind, however, that the faunas do not coincide with the formations.

New Mexican Permian.—Certain New Mexican forms have no very close relatives in Texas. Others, including *Eryops, Aspidosaurus,* diadectids, *Edaphosaurus,* and *Platyhistrix* are not useful in correlation since they or their relatives occur throughout the Texas beds. The absence of *Cricotus* would seem to suggest that the beds were later than Lower Wichita times. However, *Ophiacodon* (related to *Theropleura)* suggests that they were pre-Clear Fork. *Captorhinus* and *Labidosaurus* are absent, while *Limnoscelis* is apparently a primitive member of their group, suggesting the Middle Wichita or earlier; the absence of *Dimetrodon,* with the presence of a more primitive related type, suggests a correlation with pre-Wichita times. Altogether, the opinions of Williston and Case *(op. cit.)* concerning the early date of these beds seem confirmed, despite Darton's correlation of these beds (Abo) with the Wichita.[79]

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[77]Williston and Case, Jour. Geol. 20, pp 1–12, 1912.
[78]Jour. Geol. 33, pp. 179–182, 1925.
[79]Darton, N. H., Bull. Am. Assoc. Petr. Geol. 10, pp. 820–821, 1926.

Illinois.—The stratigraphic position of the bed at Danville bearing "Permian" vertebrates has been disputed; it has been regarded as a stream channel of later date than the normal local sediments (Cope, Case) or as possibly part of the late Pennsylvanian sediments of this area (Williston).[80] The point cannot now be determined; recent search by parties from the University of Chicago and the University of Illinois has failed to relocate this deposit. Besides one or two forms not present elsewhere, the fauna includes a relative of *Dimetrodon (Clepsydrops)*, which is not distinctive; *Cricotus*, characteristic of the Wichita fauna; and *Lysorophus* and *Diplocaulus*, abundant in the Texas Clear Fork. With regard to the last two, however, it has been pointed out that they are to be expected in other localities in lower horizons, and that their absence or rarity in the lower beds of Texas is probably a local condition only. *Captorhinus* has been reported from this locality on the basis of a femur; but the identification seems doubtful. The evidence as a whole points to the early age of these beds; it is not impossible that they are really to be attributed to the late Pennsylvanian.

AGE OF THE RED BEDS FAUNA

The discovery of fragmentary remains in the Round Knob formation (Pittsburgh shale) of the Conemaugh in 1908 led Case to conclude that the red beds fauna was of considerable antiquity, and should be treated as Permo-Carboniferous rather than Permian in nature. From this isolated find of a few fragments his conclusions might have been questioned. The present study, however, brings ample confirmation of them. No matter what the decision as to the Pennsylvanian-Permian boundary in Texas may be, it is apparent that some of the most specialized and advanced forms of the fauna are present in Texas at the very bottom of the Permian. No short period of time will suffice for their evolution. The fauna has its roots deep in the Pennsylvanian.

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[80]Case, E. C., Carnegie Inst. Washington Pub., 207, pp. 77–78, 1915.

Relying only on evidence from other regions, Case has repeatedly stated (and the writer as well) that from the point of view of the vertebrates the present line of division between Pennsylvanian and Permian is an unnatural one. The facts here presented tend further to strengthen this contention. The red beds vertebrate fauna is a Permo-Carboniferous, and not a purely Permian one. Other lines of geological and paleontological inquiry, also, suggest that a discussion of the factors concerned might lead to the adoption of a division of the later Palaeozoic into units more satisfactory than are those now current.

TABLE I

	Zone 0							Zones 0–1		Zone 1					Zones 1–2	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
AMPHIBIA																
Cricotus				1	1	1		1		1		1	39	1	1	1
Eryops	1	3		1	2	1	11	6	8	2	3	7	56	11	13	2
Dissorophus																
Aspidosaurus													2			
Cacops																
Broiliellus																
Dissorophidae																
Zatrachys					1								1			
Trimerorachis								1		1		2	3	5		1
Diplocaulus									1				1			
Platyops																
Lysorophus																
COTYLOSAURIA																
Seymouria																
Diadectes						1	5	3	3			5	3	7	6	1
Captorhinus																
Labidosaurus																
Pantylus																
Archeria													4			
PELYCOSAURIA																
Poliosaurus									1						1	
Varanosaurus																
Theropleura			1			1				1	1	6	25	1	1	
Dimetrodon		3			2	3	3	3		1	4	8	164	24	6	5
Edaphosaurus							1			1			21		4	
Casea																
"PROTOROSAURIA"																
Bolosaurus									1			8	7	4		
Araeoscelis																

TABLE I *(Continued)*

	Zone 2								Zones 1–3	Zone 3						
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
AMPHIBIA																
Cricotus																
Eryops	14	6	37	10	12	1	3	2	8		3		1	2	2	1
Dissorophus																
Aspidosaurus	1				1											
Cacops																
Broiliellus													2			
Dissorophidae																
Zatrachys				1												
Trimerorachis	1		30	1	12	1					2		3	1		
Diplocaulus											4					
Platyops																
Lysorophus																
COTYLOSAURIA																
Seymouria																
Diadectes	5		18	5	1	1	1	1	2		2				1	2
Captorhinus													11			
Labidosaurus													1	1		
Pantylus									2				9			
Archeria																
PELYCOSAURIA																
Poliosaurus			1													
Varanosaurus							1						1			
Theropleura			3				1	1	4	1	5		2		1	1
Dimetrodon	6	3	38	4	13	1	2	1	1	1	2	1	2	1	4	
Edaphosaurus			4			1										
Casea																
"PROTOROSAURIA"																
Bolosaurus																
Araeoscelis																

TABLE I *(Continued)*

	Zone 4											
	33	34	35	36	37	38	39	40	41	42	43	44
AMPHIBIA												
Cricotus												
Eryops	4	14	12	6		12	3	2				1
Dissorophus	1	3			1		1					
Aspidosaurus		2				1						
Cacops			21									
Broiliellus						1						
Dissorophidae						5						
Zatrachys		7				1				1		
Trimerorachis		8	4			9	1	1	1			
Diplocaulus	2	72	5	14	2	31	6	8	3			1
Platyops						2		6				
Lysorophus		54				4	2				1	
COTYLOSAURIA												
Seymouria		7	1		1	5		1				
Diadectes	1	24	3			5		2	1			
Captorhinus	1	37	7	1		2	1	2				
Labidosaurus		40	7	1			2					
Pantylus		4										
Archeria												
PELYCOSAURIA												
Poliosaurus								2				
Varanosaurus			99									
Theropleura	2	20	4	10		151	5	1	4	1	1	1
Dimetrodon	1	15	2	3		3	3			1		
Edaphosaurus			5			2						
Casea												
"PROTOROSAURIA"												
Bolosaurus						6						
Aracoscelis												

The localities to which the numbering refers are as follows: I, Cottonwood Creek; 2, Elm Creek; 3, Onion Creek; 4, Fireplace; 5, Three Forks; 6, Shell Point; 7, Long Creek; 8, N. Fork, Little Wichita; 9, Boll, 1878; 10, Middle Fork; 11, S. of Holliday; 12, Mt. Barry; 13, Briar Creek; 14, Godwin Creek; 15, N. Fork, Little Wichita; 16, Scalen's; 17, Cox's Camp; 18, Head of Godwin; 19, S. of Fulda; 20, Slippery Creek; 21, Tit Mountain; 22, Camp Creek; 23, Big Wichita, Cummins; 24, Beaver Creek; 25, Big Wichita, Boll; 26, N. E. of Fulda; 27, Bluff Bonebed; 28, Coal Creek; 29, Mitchell Creek, 30, Whiskey Creek; 31, Moonshine Creek; 32, Military Trail;

33, Sternberg ('96); 34, Coffee Creek; 35, Indian Creek; 36, Pony Creek; 37, Gray's Creek; 38, Brush Creek; 39, Hog Creek; 40, Table Topt Mt.; 41, Crooked Creek; 42, Beaver Creek; 43, Dead Man's Creek;; 44, Soap Creek.

The following are represented by one specimen at the localities cited, unless otherwise noted. Amphibia: Parioxys 12, Tersomius 19, Alegeinosaurus 34, Anisodexis 34, Acheloma 34 (2) and ? 13, Cardiocephalus 34 (2), Goniocephalus 38 (2), Gymnarthrus 42, 19, Trematops 38; Cotylosauria: Diadectoides 42, Isodectes 35, 36, Pariotichus 8, Helodectes 32, Ectocynodon 9, Hypopnous 34; Pelycosauria: Metarmosaurus 12 (2), Glaucosaurus 28, Mycterosaurus 28, Tetraceratops 34, Trichasaurus 38, Poecilospondylus 34; Incertae sedis: Tomicasaurus 12, Bathyglyptus 42.

TABLE II

Summary by Zones

	Zone 0	Zones 0–1	Zone 1	Zones 1–2	Zone 2	Zones 1–3	Zone 3	Zone 4
AMPHIBIA								
Cricotus	3	1	42	2				
Eryops	19	14	79	15	85	8	9	54
Dissorophus								6
Aspidosaurus			2		2			3
Cacops								21
Broiliellus							2	1
Dissorophidae								5
Zatrachys	1		1		1			9
Trimerorachis		1	11	1	45		6	24
Diplocaulus		1	1				4	144
Platyops								8
Lysorophus								61
COTYLOSAURIA								
Seymouria								15
Diadectes	6	6	15	7	32	2	5	36
Captorhinus							11	51
Labidosaurus							2	50
Pantylus						2	9	4
Archeria			4					
PELYCOSAURIA								
Poliosaurus		1		1	1			
Varanosaurus								101
Theropleura	2		34	1	4		1	
Dimetrodon	11	3	201	11	67	4	10	200
Edaphosaurus	1		22	4	8	1	11	28
Casea								7
"PROTOROSAURIA"								
Bolosaurus		1	19					
Araeoscelis								6

TABLE III

	Zone 0	Zones 0–1	Zone 1	Zones 1–2	Zone 2	Zones 1–3	Zone 3	Zone 4
Archeria			4					
Bolosaurus		1	19					
Cricotus	3	1	42	2				
Poliosaurus		1		1	1			
Theropleura	2		34	1	4		1	
Eryops	19	14	79	15	85	8	9	54
Diadectes	6	6	15	7	32	2	5	36
Dimetrodon	11	3	201	11	67	4	10	200
Edaphosaurus	1		22	4	8	1	11	28
Zatrachys	1		1		1			9
Diplocaulus		1	1				4	144
Trimerorachis		1	11	1	45		6	24
Aspidosaurus			2		2			3
Pantylus						2	9	4
Broiliellus							2	1
Captorhinus							11	51
Labidosaurus							2	50
Dissorophus								6
Lysorophus								61
Casea								7
Dissorophidae								5
Cacops								21
Varanosaurus								101
Seymouria								15
Platyops								8
Araeoscelis								6

TABLE IV

Comparative Percentages of Five Common Forms in Zones 1–4

	Zone 1	Zone 2	Zone 3	Zone 4
Eryops	24	36	22	15
Trimerorachis	3	19	14	7
Diadectes	4	13	12	11
Dimetrodon	61	28	25	59
Edaphosaurus	8	4	27	8

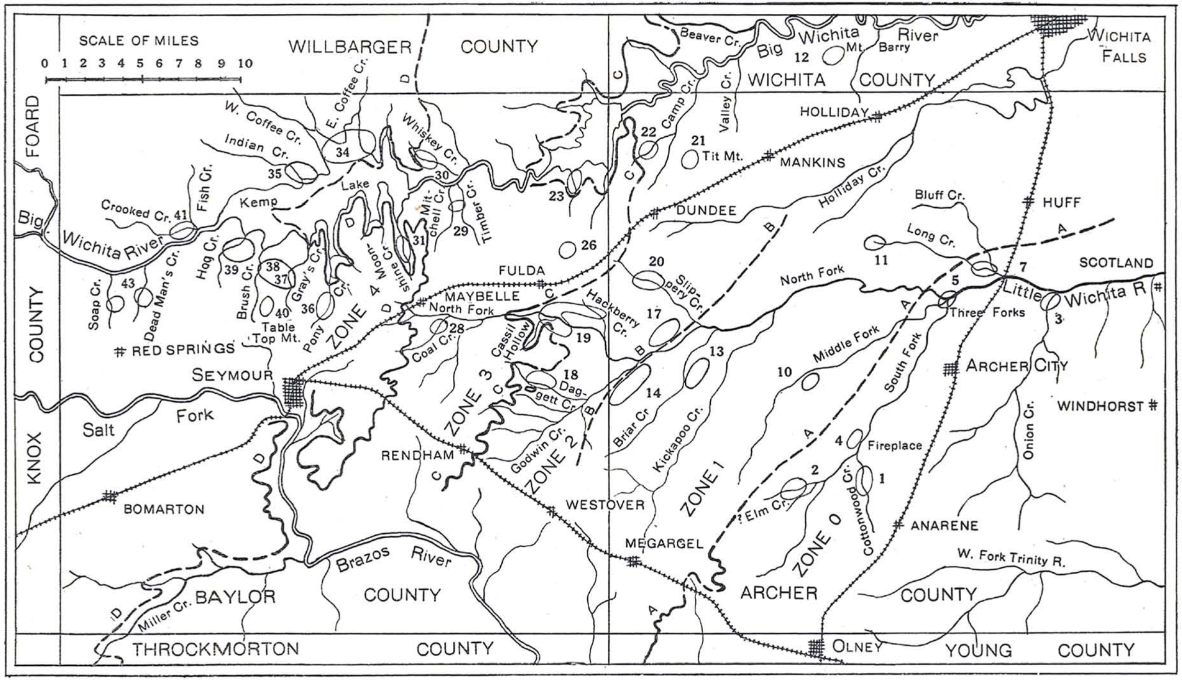

Fig. 7. Map of Baylor and Archer counties, Texas, to show the stratigraphy of vertebrate deposits. A=Coleman Junction limestone horizon, B=Approximate faunal boundary at horizon of Godwin Creek, C=Beaverburk (Rendham) limestone, D=Lueders (Maybelle) limestone. Zone 0=Upper Cisco, Zone 1=Lower Wichita, Zone 2=Middle Wichita, Zone 3=Upper Wichita, Zone 4=Lower Clear Fork. Numbered areas are vertebrate localities.

THE PENNSYLVANIAN AND PERMIAN STRATIGRAPHY OF THE GLASS MOUNTAINS

BY PHILIP B. KING AND ROBERT E. KING

INTRODUCTION

This paper is a preliminary statement of part of the results of nine months' field work done by the writers in the Glass Mountain area during the summers of 1925, 1926, and 1927. During this time, two fifteen-minute quadrangles, the Altuda and Hess Canyon, were surveyed in detail, and bordering areas were mapped in varying degrees of detail and reconnaissance. In advance of a more detailed report upon all phases of the geology of this area, it was thought advisable to prepare this preliminary account of the stratigraphy of the Pennsylvanian and Permian formations, in order that the information might be placed at the service of geologists working in that part of the State.

The writers are indebted to Professor Charles Schuchert, of Yale University, and Dr. E. H. Sellards, of the Bureau of Economic Geology of the University of Texas, for their encouragement to carry on the work after the first field season had been completed. The two succeeding seasons of field work were performed under their auspices, and with the benefit of their help and advice.

The first work in this area was done by Dr. J. A. Udden and his associates in 1915 to 1916, at which time the formations were named and delimited. The value of Udden's foresight in recognizing the fundamental importance of the Permian section of the Glass Mountains, and his continued interest in the region have been amply justified by the developments of the last few years. Notwithstanding the complexity of the Permian stratigraphy, his formational units have in the main proved to be practicable and natural. Later studies have served to amplify the knowledge which Udden obtained under more difficult conditions,

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and to carry on the investigation along the lines which he originally laid out.

The following list contains papers published on the Glass Mountain area. The paper by Schuchert summarizes the Carboniferous stratigraphy of the Glass Mountains and discusses the general relationships.

Udden, J. A., Notes on the Geology of the Glass Mountains, Univ. Texas Bull. 1753, pp. 1–59, 1917.

Baker, C. L., and Bowman, W. F., Geologic Exploration of the Southeastern Front Range of Trans-Pecos Texas, Univ. Texas Bull. 1753, pp. 61–177, 1917.

Böse, Emil, The Permo-Carboniferous Ammonoids of the Glass Mountains, West Texas, and Their Stratigraphical Significance, Univ. Texas Bull. 1762, 1917.

King, P. B., The Geologic Structure of a Portion of the Glass Mountains of West Texas, Bull. Amer. Assoc. Petr. Geol., Vol. X, pp. 877–884, 1926.

Keyte, I. A., Blanchard, W. G., and Baldwin, H. L., Gaptank-Wolfcamp Problem of the Glass Mountains, Texas, Jour. Pal., Vol. I, pp. 175–178, 1927.

King, P. B., The Bissett Formation; a New Stratigraphic Unit in the Permian of West Texas, Amer. Jour. Sci. (5), Vol. XIV, pp. 212–221, 1927.

Schuchert, Charles, The Pennsylvanian-Permian Systems of Western Texas, Amer. Jour. Sci. (5), Vol. XIV, pp. 382–401, 1927.

PENNSYLVANIAN

TESNUS FORMATION

The Tesnus formation was named by Baker, its type locality being at Tesnus station on the Southern Pacific Railway, in the eastern part of the Marathon Basin. It is the basal Carboniferous formation of the Marathon region. The Tesnus is extensively developed in the southeast, east, and northeast portions of the Marathon Basin, where it flanks the central area of early Paleozoic rocks. The formation was studied by the writers only in the northern part of this area. Being quite generally composed of soft sandstones and shales, it occupies the low places on the plains, and is widely mantled by wash. Good exposures are found in the vicinity of the Dimple Hills, and north of Haymond on the Marathon-Sanderson highway. Strata from 3 to 10 miles west of Marathon, called Tesnus by Baker,[1] have been found on the basis of fossils to belong largely to the Gaptank, and in part to the Haymond formation.

The Tesnus formation has a thickness of about 3,370 feet in a section measured by Baker,[2] and observations by the writers tend to confirm this measurement. It consists, in the eastern part of the Marathon Basin, of fine-grained, massive quartzitic sandstone in thin and thick beds, alternating with green and blue shale exhibiting various degrees of induration. The sandstones are greenish when fresh, and weather rusty-brown, giving a characteristic color to the exposures of the formation. The thicker sandstone beds are several hundred feet in thickness and are separated by more shaly members of equal thickness. Baker has called the lower third of the formation the Rough Creek shale member; this lower portion was not studied by the writers.

The Tesnus formation rests unconformably on the Caballos novaculite, of possible Devonian age.[3] The upper contact seems to be a conformable one, as the formation grades through a transition zone upward into the Dimple. The only known fossils are very fragmentary land plants and several species of foraminifera. David White[4] states that plant specimens from the Tesnus examined by him are suggestive of Pottsville age. Shale samples collected 16 miles east of Marathon, on the Marathon-Sanderson highway, have yielded foraminifera which Bruce H. Harlton[5] states are of "lowermost Pennsylvanian age." From these imperfect data we can do little more than assign a Pennsylvanian age to the Tesnus, although as the formation is evidently overlain by

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[1]Baker, C. L., and Bowman, W. F., Geologic Exploration of the Southeasternmost Front Range of Trans-Pecos Texas, Univ. Texas Bull. 1753, pp. 103-105, 1917.

[2]*Ibid.*, p. 102.

[3]Baker reports over 300 feet of Caballos to the south of Marathon, whereas north of the latitude of Marathon its thickness has nowhere been found to exceed 100 feet, a fact which is suggestive of pre-Tesnus erosion.

[4]Letter to R. E. King, 1927; see also Powers, Sidney, The Solitario Uplift, Bull. Geol. Soc. Amer., Vol. XXXII, p. 423, 1921.

[5]For this and other information regarding the microfossils of the Marathon region, the writers are indebted to Messrs. Sidney Powers and Bruce H. Harlton, of the Amerada Petroleum Corporation. Later on these data will be published.

3,000 feet of pre-Canyon beds, it would seem to belong very early in that period.

DIMPLE FORMATION

The Dimple formation was named by Udden for the Dimple Hills in the northeast part of the Marathon Basin, 6 miles south of Gap Tank. Being composed of massive and generally resistant limestones, it outcrops in long low ridges, most of them monoclinal, which stand above the waste-mantled plains of the northern Marathon Basin. Excellent exposures are found in the road cuts on the Marathon-Sanderson road 15 and 18 miles east of Marathon.

The Dimple is largely composed of limestone in moderately thick beds. Most of the limestone beds are gray, granular, and somewhat sandy, with occasional seams of chert pebbles; other beds are dense and highly bituminous. At the base and top, much shale and bedded chert are interbedded with the limestone, forming transition zones with the Tesnus below and the Haymond above. The top and base of the formation are drawn at the highest and lowest limestone beds. The lower transition zone has a thickness of about 70 feet, and the upper of about 200 feet. Including the transition zones, about 1,100 feet of the Dimple formation was measured on the south side of the Dimple Hills. The top of these hills is made up of the interbedded limestones, shales, and cherts of the upper transition zone. At several localities north of the Marathon-Sanderson road and about 15 miles east of Marathon, these transition beds grade upward into the sandstones and shales of the Haymond formation.

Baker records the finding of fossils in the Dimple 1.5 miles south of Marathon, and on San Francisco Creek west of Haymond. The forms listed prove little more than the Pennsylvanian age of the formation. Foraminifera, other than Fusulinidæ, of Pennsylvanian age, are reported by Harlton from the Dimple Hills and in the Dimple exposures 18 miles east of Marathon. Udden[6] has pointed out certain

[6]Udden, J. A., and Waite, V. V., Some Microscopic Characteristics of the Bend and Ellenburger Limestones, Univ. of Texas Bull. 2703, p. 7, 1927.

lithologic similarities between the Dimple limestones and those of the Bend. The fact that the Bend series and its known correlatives are separated by a well-marked unconformity from the beds above, whereas the Pennsylvanian of the Marathon region appears to be a conformable sequence would seem to argue for a post-Bend age of the Dimple formation. In the present state of our knowledge, however, it is not possible to make any safe correlation of the Dimple with Pennsylvanian formations in other regions.

HAYMOND FORMATION

The Dimple formation is clearly overlain by the Haymond formation, but nowhere has a complete and uninterrupted sequence from the base to the top of the latter been seen. The type locality of the Haymond is in the synclines near Haymond station, on the Southern Pacific Railway, east of Marathon. The formation was named by Baker, who later expressed some doubt as to its existence, suggesting that it is in reality Tesnus overthrust upon Dimple.[7] The present investigation has demonstrated, however, that the Haymond formation is a valid one, and that it overlies the Dimple. An examination of the region north of Haymond led to the conclusion that the geology is essentially correct as originally mapped by Baker, and field work farther to the northeast, in the neighborhood of Gap Tank and the Dimple Hills, has shown that the same formation is extensively developed there. The Haymond beds are well exposed about 3 miles south of the Dimple Hills, where they lie in the trough of a syncline between bounding outcrops of Dimple; and again from 2 to 8 miles southeast of Gap Tank, where they outcrop down dip from Dimple exposures, and underlie the Gaptank formation.

The Haymond formation is a succession of sandstones, with some interbedded shale, very much like the Tesnus in general character. Some of the shale is black. The thickness of the formation is unknown; Baker reports 500 feet near Haymond, but greater thicknesses are present elsewhere, and 1,800 feet of beds were measured beneath the

[7]Baker and Bowman, *op. cit.*, p. 107.

Gaptank formation 4.5 miles S. 70° E. of Gap Tank, with the base not exposed. In this region the formation consists of thick-bedded, friable, medium-grained, buff sandstone, whose quartz grains are mingled with kaolin and scattered flakes of biotite. Small amounts of shale and thin-bedded flaggy sandstone are interbedded. Four hundred feet below the top is a 30-foot bed of conglomerate which has been traced for over four miles; it is made up of angular fragments derived from Caballos novaculite, Maravillas chert, and fossiliferous Ordovician limestone. West of Marathon, sandstones and shales that lie beneath limestone containing *Chætetes milleporaceus,* and along the axies of strongly folded anticlines, are tentatively placed in the Haymond formation.

The contact between the Dimple and the Haymond formation is a gradational, and apparently a conformable one. It is well exposed at several places north of the Marathon-Sanderson highway, about 15 miles east of Marathon. The upper contact is likewise apparently gradational and conformable; the Gaptank has no basal conglomerate, and its basal member, the *Chætetes* limestone, rests directly upon the thin-bedded Haymond sandstone, as is well shown on the Marathon-Fort Stockton road 2 miles S. 10° W. of Gap Tank.

Only a few fossil remains have been found in the Haymond formation. A few wood imprints were found in the sandstone 4.5 miles S. 70° E. of Gap Tank, and Schuchert[8] reports gastropod trails in the uppermost Haymond southwest of Gap Tank and also west of Marathon. The base of the Gaptank is known to be the approximate equivalent of the base of the Canyon, and thus the Haymond can be correlated with some part of the Strawn of central Texas.

GAPTANK FORMATION

The Gaptank formation was named by Udden from the tank called by that name in Stockton Gap, on the Fort Stockton-Marathon road, 23 miles northeast of Marathon.

[8]Schuchert, Charles, Pennsylvanian-Permian Systems of Western Texas, Amer. Jour. Sci. (5), Vol. XIV, p. 386, 1927.

The Gaptank is the youngest Pennsylvanian formation and the last to be involved in the strong folding of the Marathon region. The formation outcrops only in the northern part of the Marathon Basin, while in the area to the south only the older formations remain, and the Gaptank has been removed by erosion. The formation is exposed in scattered areas which fringe the south foothills of the Glass Mountains, the best known locality being at Gap Tank, where a nearly complete section is exposed. From this place it extends in scattered outcrops southwestwardly along the Glass Mountains escarpment as far as Wolf Camp. West of the town of Marathon the Gaptank formation is again exposed over an area of about 36 square miles between the main front of the Dugout Creek overthrust on the south and the foot of the Glass Mountains on the north.

In the vicinity of Gap Tank a complete section of the formation shows it to have a thickness of 1,800 feet. The strata are folded into a broad east-west anticline, and beds which are covered on one flank may be found at least partially exposed on the other (Fig. 8). The base of the formation is a limestone 50 feet in thickness, characterized by *Chætetes milleporaceus,* which rests with seeming conformity upon the Haymond. Then follow sandstones and shales, which, from 200 to 800 feet above the base, are interbedded with five layers of coarse conglomerate, containing cobbles of chert and limestone, a large part of which is of the Dimple facies. The conglomerates vary in thickness from 15 to 80 feet, and are in part lenticular. Some of the interbedded sandstones are calcareous, and two horizons, 400 and 700 feet above the base, contain fossils. The upper 800 feet of the formation includes five limestone layers averaging 50 feet in thickness, interbedded with sandy and shaly layers. Fossils have been collected from this member in the vicinity of Wolf Camp, and a few near Gap Tank. It may be convenient to subdivide the Gaptank into two members, calling the upper part characterized by thick limestone beds the upper Gaptank, and the lower 1,000 feet the lower Gaptank, the line of separation being between beds 12 and 13 of the section below.

The following section was measured south of Gap Tank.

Wolfcamp Formation at Top of Section

		Feet
(21)	Fifth limestone. Dense to coarsely crystalline light gray limestone in massive beds	75
(20)	Thin sandstone beds interbedded with soft blue shale	60
(19)	Fourth limestone. Light gray dense limestone in moderately thick beds, becoming brown and thin bedded to the west, where it contains some fossils	40
(18)	Mostly covered; some soft brown sandstone seen	124
(17)	Third limestone. Light gray dense limestone in moderately thick beds, with abundant fossils in cross section	40
(16)	Mostly covered; buff, cross-bedded, medium-grained sandstone in upper part	230
(15)	Second limestone. Light gray massive limestone	55
(14)	Sandstone and shale	124
(13)	First limestone. Light gray finely crystalline limestone in moderately thick beds, containing fusulinas, crinoid stems, and other fossils	40
(12)	Soft buff sandstone, in part calcareous, and some gray limestone near the middle	193
(11)	Fifth conglomerate. Much like those below in general character	15
(10)	Covered on north side of anticline. On south, it consists of brown sandstone with richly fossiliferous calcareous layers. This is the "lower Gaptank" fossil horizon of Udden, Böse, and Beede. There are some thick beds of soft blue shale at the south	140
(9)	Fourth conglomerate. Like those below	15
(8)	Fine-grained buff sandstone forming prominent ledges, cross-bedded in parts	97
(7)	Third conglomerate. Like those below, but of lenticular character	25
(6)	Fine-grained buff sandstone, passing southward into a greater thickness of shale. This contains a nodular ferruginous limestone, with *Pugnax rockymontana*	80–290
(5)	Second conglomerate. Like first, with thin layers of sandy buff limestone	40
(4)	Sandstone and shale	80
(3)	First conglomerate. Composed of coarse cobbles of subangular to rounded fragments of limestone and chert, most of which have the lithology of the Dim-	

	ple. The matrix is a sandy limestone. Thin limestone beds appear to northwest at base having *Chætetes* and *Chonetes mesolobus*	40
(2)	Shales and sandstones	150
(1)	Chætetes limestone. Dark gray, crystalline, containing large masses of *Chætetes milleporaceus*, and also cup corals and brachiopods	50
	Haymond thin-bedded sandstones below.	

West of Marathon the Gaptank formation has been overridden by a great mass of pre-Pennsylvanian strata along the Dugout Creek overthrust fault (Fig. 8). The relation of these earlier rocks, lying with nearly flat overthrust contact upon the Gaptank, is well shown 4 miles S. 15° E. of Lenox, and outliers of the overriding mass resting on Gaptank have been found on the Decie ranch nearly 4 miles from the present main front of the fault. The incompetent Gaptank strata beneath are intensely deformed by minor folds and thrusts, and overturned toward the northwest. Some idea of the complexity of the structure may be obtained at a locality 3.3 miles S. 15° W. of Lenox, where a limestone member is repeated ten times in slightly more than a quarter of a mile by minor folds and thrusts. A clear idea of sequence and thickness of the formation in this region is thus very difficult to obtain.

In this part of the basin the basal bed of the Gaptank with *Chætetes milleporaceus* is a granular and somewhat conglomeratic limestone from 10 to 25 feet in thickness which rests on sandstones that are assigned to the Haymond. There follow some hundreds of feet of alternating sandstones and shales, with a few thin limestone beds. The highest beds are exposed 4.5 miles S. 15° E. of Lenox, where they are overlain with overthrust contact by pre-Pennsylvanian strata, and southeast of the Decie Ranch near milepost 580 on the Southern Pacific Railway. At the first locality are several beds of limestone, one of which is crowded with ammonites of a new fauna. At the second place the strata consist of 5-foot beds of limestone crowded with angular chert pebbles interbedded with sandstone and shale and locally containing fossils. The beds at this latter place are suggestive of the conglomeratic middle portion of the Gaptank at the type locality.

Fossils and correlation.—Fossils occur at various levels in the Gaptank formation west of Marathon and south of Gap Tank, and lists for some of these horizons have already been published.[9] The basal member of the formation is called the *Chætetes* limestone (bed 1 of the section) because of the sporadic occurrence in it of *Chætetes milleporaceus*, a coral restricted in central Texas to the Brownwood shale, at the base of the Canyon and to a much lower zone in the Marble Falls, and in the northern mid-continent region to the Fort Scott and Pawnee limestones in the middle of the Des Moines group, a horizon approximately equivalent in age to the Brownwood. Because of its restricted vertical range in the mid-continent region it is thought to be a good index for correlation; it thus seems probable that the base of the Gaptank is the near equivalent of the base of the Canyon.

The next fossiliferous horizon is in a local limestone layer at the base of the first conglomerate (bed 3), where Schuchert[10] collected, among other fossils, *Chætetes milleporaceus* and *Chonetes mesolobus*. In the shales of bed 6, at two localities about 2 miles south of Gap Tank, is a nodular limestone containing *Pugnax rockymontana*, a typical lower Canyon and Wewoka brachiopod. Micro-fossils identified from this horizon by Harlton are stated by him to be typical Canyon forms.

The most prolific fossil horizon, 700 feet above the base of the formation (bed 10), is best exposed on the south flank of the Gap Tank anticline 2 miles south and southeast of Gap Tank. This is the fossil zone called "lower Gaptank" by Udden and his associates[11] and "upper Gaptank,"

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[9]Böse, Emil, Permo-Carboniferous Ammonoids of the Glass Mountains and Their Stratigraphical Significance, Univ. Texas Bull. 1762, pp. 21–22, 1917. (Identification by J. W. Beede.)

Keyte, I. A., Blanchard, W. G., and Baldwin, H. L., Gaptank-Wolfcamp Problem of the Glass Mountains, Jour. of Paleontology, Vol. I, p. 175, 1927.

Schuchert, Charles, *op. cit.*, pp. 385–388.

[10]*Op. cit.*, p. 386.

[11]Böse, *op. cit.*, p. 21.

by Schuchert.[12] Extensive lists of fossils have been published for this zone, both by the writers mentioned and by Keyte, Blanchard, and Baldwin,[13] but the identifications given in some of these have proved unreliable, a fact suggested by the association in these lists of many Permian species with *Spirifer rockymontanus*, a lower Pennsylvanian fossil. Many of the fossils are long-ranging forms of little importance, but others show a great similarity to the Wewoka fauna. The fauna differs from that of the Wewoka, however, in the presence of *Platyceras* sp., *Tegulifera* sp., *Aulacorhynchus millepunctatus*, *Schistoceras hyatti* (=*smithi*), and *Enteletes* sp.[14] For other forms from this horizon the reader is referred to Schuchert's paper.

Above this level, fossils are uncommon in the Gaptank. In the northwest part of the Marathon Basin, however, 4.5 miles S. 15° W. of Lenox, a prolific fauna of ammonoids was collected from a limestone evidently belonging to the upper Gaptank, species of *Schistoceras*, *Stacheoceras*, and *Pronorites* occurring in great abundance.

The correlation of the Gaptank beds near Wolf Camp is problematical, as they are more than 6 miles from the nearest continuous exposure of Gaptank to the east. Lithologically they are suggestive of the middle or upper Gaptank of the type section. The highest beds contain a great abundance of *Triticites cullomensis*.

From the above facts it is concluded that the Gaptank formation is of Canyon and lower Cisco age. There is no evidence, either stratigraphic or faunal, for a break in the Gaptank sequence. On the contrary, it is separated from the overlying Wolfcamp formation by a physical unconformity whose significance is attested by the appearance above the break of unmistakable Permian ammonites and brachiopods.[14a]

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[12]Schuchert, *op. cit.*, p. 388.

[13]*Op. cit.*, p. 177.

[14]This last named fossil has been identified by various workers as *Enteletes* aff. *waageni*, *E. waageni*, and *E. hemiplicatus*. Actually it belongs to that group of the genus bearing the sinus on the brachial valve, the reverse of the arrangement in all the species with which it has been compared.

[14a]For remarks on Gaptank fusulinids, see p. 142.

POST-GAPTANK OROGENY

It was the conclusion of Udden, Baker, and Bowman,[15] that the major orogeny which disturbed the Pennsylvanian and earlier rocks of the Marathon Basin was of pre-Gaptank age, and that whatever structures the Gaptank possessed were nearly the same as in the Permian above. Subsequent work has shown that the folding is in reality of post-Gaptank and pre-Wolfcamp age, as indicated by two recent papers.[16] It was then that the Caballos Mountains were made.

The unconformity between the Wolfcamp of the Permian and the Gaptank at the top of the Pennsylvanian is best seen 2.5 miles S. 40° W. of Lenox, on the south slope of Dugout Mountain, where fossiliferous upper Wolfcamp with 300 feet of coarse basal conglomerate rests nearly horizontally upon fossiliferous lower Gaptank which is overturned and now dips 35° south. Farther northeast, in the vicinity of Wolf Camp and Gap Tank, the unconformity is less apparent. At Wolf Camp and nearby localities the *Uddenites* bed, assigned by Udden and the writers to the Wolfcamp formation, changes abruptly in thickness from place to place, as though overlapping against a warped and irregularly eroded surface of the beds beneath, but on the whole the Wolfcamp and Gaptank at this locality are about alike in dip and strike.

At Gap Tank the Gaptank formation is overlain by beds correlated with the *Uddenites* zone by the writers, but with apparently equal dip and strike. Toward the south of the tank the folding of the Gaptank increases in complexity and is clearly involved in the orogeny of the rest of the Paleozoic series below.

These northeastern localities doubtless lay at a greater distance from the center of the disturbance, and therefore show more or less of conformability between the Gaptank

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[15]Udden, J. A., Notes on the Geology of Glass Mountains, Univ. Texas Bull. 1753 p. 41, 1917.
Baker, C. L., and Bowman, W. F., *op. cit.*, pp. 107–112.

[16]Schuchert, *op. cit.*, pp. 388–390.
Keyte, Blanchard, and Baldwin, *op. cit.*, pp. 177–178.

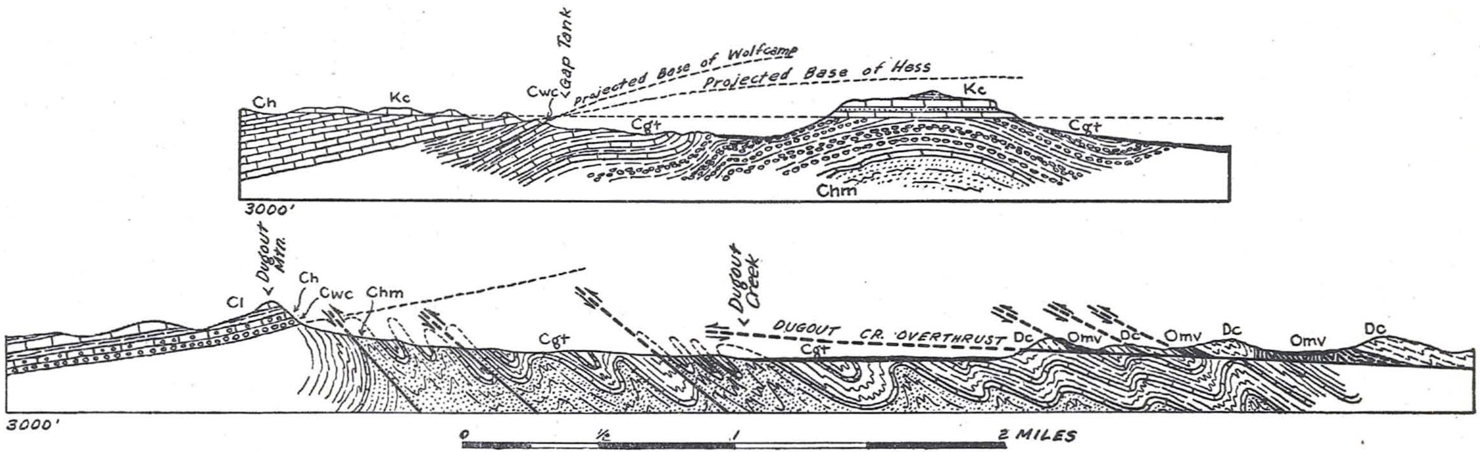

Fig. 8. Structure sections of two areas of Gaptank outcrop. Upper figure: Section extending through Gaptank in an east-southeast direction. Lower figure: Section extending southeast from summit of Dugout Mountain, in the region southwest of Lenox. Omv, Maravillas chert; Dc, Caballos novaculite; Chm, Haymond formation; Cgt, Gaptank formation; CWc, Wolfcamp formation; Ch, Hess formation; Cl, Leonard formation.

and Wolfcamp. The unconformity suggested by the sections of Keyte, Blanchard, and Baldwin,[17] between the *Uddenites* zone and the undoubted Wolfcamp above, is not supported by the field observations of the writers, as shown in the accompanying sections (Pl. III).

The beginnings of the post-Gaptank disturbance are indicated by the extensive conglomerates seen in the middle of the Gaptank, which were in part derived from the erosion of the Dimple formation. The thick, coarse conglomerates of the basal Wolfcamp from Leonard Mountain southwest beyond Lenox, resting on deeply eroded earlier rocks, were deposited shortly after the main disturbance. A later recurrence of orogeny is seen in the extensive angular unconformity and the basal conglomerates at the base of the Hess formation.

PERMIAN

The Permian rocks flank the Marathon Basin on the north and northwest, and form a series of southeast facing cuestas whose escarpment-faces rise sharply above the lowlands of the basin. The system is tilted away from the underlying strongly deformed rocks, so that the twelve-mile width of the range includes the upturned edges of one of the best Permian sections in America. The most striking feature of the stratigraphy of the formations is their great lateral variation in thickness and lithology from northeast to southwest along the range. Some of the changes are clearly the result of unconformities, either by erosion of pre-existing beds or by overlap of the succeeding beds upon an upraised land mass. Other beds vary by rapid changes from one type of deposit to another, and by peculiar changes in thickness, which the different members of the formation appear to share equally. The result of these variations is to make the sections in the eastern and in the western parts of the mountains almost totally unlike.

[17] *Op. cit.*, Pl. XXXI.

The writers have followed Udden's method of studying the formations by means of the measurement of vertical sections and have supplemented this work by tracing out horizons, as far as possible, between the sections. The most important of these sections for the lower part of the series is shown on Plate II, and should be studied along with the text.

WOLFCAMP FORMATION

The Wolfcamp formation is the oldest Permian deposit in the Marathon region, and on paleontological evidence seems to lie very near to the actual base of the Permian. The formation was named by Udden, and its type locality is at a place on the present Taylor Ranch, 12 miles northeast of Marathon, which Böse and Udden called the Wolf Camp. The present investigation has shown that the Wolfcamp is present along almost the whole of the Glass Mountains escarpment, although it is in places mantled by wash, as between Wolf Camp and Leonard Mountain. The position of the Wolfcamp-Gaptank contact in the northeast part of the area is in dispute, and the conclusions of the writers are at variance with those of Keyte, Blanchard, and Baldwin, who have also worked in the area.

At its type locality, the beds placed by us in the Wolfcamp formation have a thickness of 700 feet[18] (Section R, Plate II), and are divisible into three members. The basal member, which can be called the *Uddenites* zone, after its characteristic ammonite fauna, is a shale varying in thickness up to 100 feet. In his section 7 Udden[19] states that the base of the Wolfcamp is at the base of bed 10, or in the middle of the *Uddenites* zone, though on a later page he places the ammonites in the Permian. It would seem that the first statement is either a typographical error, or represents the expression of an earlier idea left unchanged in the final manuscript. Overlying the *Uddenites* zone is a massive gray limestone layer about 50 feet in thickness, which outcrops in prominent

[18]Udden's measurement for these same beds is 529 feet.
[19]*Op. cit.*, pp. 29 and 34.

scarps along the south foot of this part of the Glass Mountains. Keyte, Blanchard, and Baldwin would place these two lower members of the Wolfcamp of our usage in the Gaptank formation.[20] The upper 550 feet of the formation consists largely of green and black shale with thin brown granular limestone layers. This part of the formation contains such characteristic forms as *Lyttonia* and *Schwagerina*, and is unmistakably Permian.

The Wolfcamp formation has been traced toward the northeast by the writers as far as Gap Tank, as shown in Plate III. The *Uddenites* zone and the overlying gray limestone retain much the same character in this direction. The upper Wolfcamp, however, becomes quite sandy and is largely missing due to pre-Hess erosion.

Toward the west, the Wolfcamp is exposed on an uplift 2 miles north of the Hess Ranch, and on the lower slopes of Leonard Mountain. Beyond Leonard Mountain the formation appears in an outcrop which is continuous except where wash-mantled valleys cut gaps in the escarpment. The *Uddenites* zone is found directly above the Tesnus at the east end of Leonard Mountain, but farther west only the upper part of the Wolfcamp is believed to be present. In the region southwest of Leonard Mountain the formation rests upon the Dimple formation, upon pre-Pennsylvanian rocks, and, beyond Lenox, upon highly folded lower Gaptank. The basal beds are conglomerates which near Iron Mountain are 10 feet in thickness, but increase toward Lenox, near which a maximum of 450 feet was measured. These are followed by shale and sandy shale, with thin interbedded limestone layers that are locally fossiliferous. Their thickness is variable on account of the unconformity at the top; 160 feet is found one mile southwest of Iron Mountain. Southwest of Lenox, these upper beds have been removed by erosion along 1.5 miles of outcrop, so that the Hess rests directly upon the basal conglomerate member.

Fossils and correlation.—The *Uddenites* zone, according to Udden's definition, occurs near the base of the Wolfcamp

[20] *Op. cit.*, pp. 175–176.

formation and is significant of Permian time because it contains the ammonoids described by Böse as the Wolfcamp ammonoid fauna. These ammonites do not at all agree with the more primitive assemblage of the lower Cisco, but are more advanced and have already taken on a Permian expression. We agree with Böse that the fauna and especially the genera *Uddenites* and *Daraelites,* show a notable advance over the Cisco fauna; none of the species are identical, and the genus *Daraelites* has nowhere been found below the Permian. This conclusion finds striking support in the association with this fauna of three types of brachiopods, *Enteletes* aff. *suessi.* Schellwien, *Scacchinella* sp., and *Meekella* aff. *irregularis* Schellwien, closely similar to early Permian species of the Carnic Alps. On the other hand, most of the remainder of the fauna is identical with Pennsylvanian forms,[21] a fact on which too much correlation value has been placed by Keyte, Blanchard, and Baldwin. Most of the Cisco brachiopods became extinct towards the close of the Pennsylvanian in the area of central Texas; there the beginning of the Permian is marked by a great expansion of the molluscan fauna, with the absence of fusulinids and ammonoids. In Trans-Pecos Texas, however, the normal marine faunas of the Pennsylvanian continued to live on into the Permian. Therefore, the persistence of Pennsylvanian brachiopods into the Wolfcamp is of little correlation importance, while the appearance of true Permian forms in the *Uddenites* zone is very important.

Limestones about 35 feet above the top of the *Uddenites* zone in the Wolf Camp section are marked by the first appearance of *Schwagerina,* which is generally considered to be an index of the lowest Permian. The genus is abundant in the middle Wolfcamp, but does not range upward into the Hess. The typically Permian brachiopods *Teguli-fera* and *Lyttonia,* along with other Permian genera first appear in the shale above the first *Schwagerina* limestone in a rich and varied fauna.[22]

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[21]For some of these associated forms see Schuchert, *op. cit.,* pp. 391–392.

[22]See Schuchert, *op. cit.,* p. 391. The brachiopod in the Texas Permian heretofore identified as *Richtofenia* is *Tegulifera.*

In the section at Wolf Camp there are no well preserved ammonoids from the upper part of the formation. In the western part of the range, 1.6 miles S. 40° W. of Lenox on the south slope of Dugout Mountain, however, ammonoids occur in some abundance in beds of upper Wolfcamp age. Here are *Stacheoceras* sp., *Pronorites* sp., *Prothallasoceras welleri,* and *Perrinites,* probably *P. cumminsi. Prothallasoceras welleri* was collected by Böse in the lower conglomerate beds of the western Glass Mountains, which at the time he supposed to be in the Hess formation, but which on the basis of our stratigraphic and paleontologic work are believed to be of upper Wolfcamp age. It was because of this placing of the formation that Böse incorrectly said that the Hess is characterized by *Prothallasoceras;* the genus appears to be restricted to the upper Wolfcamp. The presence of *Perrinites cumminsi?* is also very significant, not only in showing that the genus *Perrinites* has a much longer range in the Glass Mountains than heretofore held (and not restricted, as supposed by Böse, to the Leonard), but also in linking the upper Wolfcamp with the upper Wichita, the only other horizon from which *Perrinites cumminsi* has been collected.

Because of the above faunal facts, the *Uddenites* zone, or lower Wolfcamp, is correlated with the lowest Permian, and the upper Wolfcamp with the upper Wichita. Therefore, the Wolfcamp formation is thought to be the equivalent more or less of the Wichita series. In most other respects, however, the faunas of the two formations are quite unlike, largely due to the predominance of the pelecypods and gastropods in the Wichita as opposed to the predominance of brachiopods with many ammonites in the Wolfcamp.[22a]

HESS FORMATION

The Hess formation was named by Udden for the Hess Ranch, where it is well exposed. Because of certain profound changes in lithology and thickness, the formation has not been well understood. The lower half of the beds provisionally referred by Udden to the Leonard formation on

[22a]For remarks on Wolfcamp fusulinids, see p. 143.

Leonard Mountain (Section 4, Bull. 1753) is in reality Hess, and the latter is also represented, as suggested by Udden, in the sections farther west. The formation outcrops in a prominent escarpment between the Hess Ranch and Gap Tank, which rises about 1,000 feet above the Marathon Basin on the south. Toward the west it thins and loses its topographic prominence. The dolomites of the center of the Sierra Madera uplift are also probably Hess, since they underlie conglomerates correlated with the Leonard formation.

The Hess formation is predominantly limestone, and because of distinct differences in the east and west, may be divided into an eastern and a western facies, which intergrade near the Hess Ranch. The eastern facies consists of limestone, abundant in fusulinas, but barren of other fossils except in a few zones. These limestones are mostly thin-bedded, dolomitic, and dark colored, and interfinger eastward in their lower part with vari-colored marls, sandstones, and shales, some of which are red. The eastern facies of the formation has a thin basal conglomerate. In the upper part of the formation north and northeast of Wolf Camp, a cherty fossiliferous horizon has been traced for over 10 miles. The beds above this horizon consist of thick-bedded dolomite which thins from 250 feet in the easternmost section to less than 100 feet northwest of Wolf Camp. Near the Hess Ranch the thin-bedded, dolomitic facies interfingers with massive, light gray, non-dolomitic limestone of the western facies. The two facies are interbedded northeast of the ranch, and farther east, on a mountain 2 miles N. 65° E. of the Hess Ranch, tongues of the western facies are seen to merge into a continuous section of the eastern facies (Section P, Plate II). On Leonard Mountain the rock is entirely light gray, massive, and non-dolomitic, except for a 200-foot wedge of thin-bedded dolomitic limestone at its eastern end, which disappears toward the west (Sections K and L).

The easternmost section measured (Section T), near the Pecos-Brewster County line northwest of the Montgomery

Ranch, has a thickness of 2,100 feet. As shown in Sections S, R, and Q, the Hess thins toward the west, and in Section K, on the Leonard Mountain, it is 700 feet thick, the change in thickness being interpreted as a result of overlap on uplifted pre-existing rocks. Evidence for such an overlap is shown by the tracing of beds in Sections P, O, N, and M. On the escarpment north of the Hess Ranch conglomerates appear progressively higher in the section toward the west (Sections O and P).

The 700 feet of Hess on Leonard Mountain consist of massive, light gray limestone, outcropping in bold cliffs. To the southwest it thins progressively, apparently by overlap on the Wolfcamp, since its upper contact is a continuous ledge, so far as it is possible to trace it. In the region northeast of Lenox it is only 50 feet in thickness. The base of the formation is in all places conglomeratic; on Leonard Mountain, and the mountain west of Iron Mountain, there are thick basal layers of cobble conglomerate in a limestone matrix.

The Hess formation rests upon the Wolfcamp beneath with a well-marked unconformity. The base of the formation along the entire length of its outcrop from the region east of Gap Tank to the foot of the Del Norte Mountains is marked by conglomerate. In many places a perceptible angular divergence between the two formations may be seen, and in others pre-Hess erosion is indicated by the variable thickness of the upper members of the Wolfcamp formation. Moreover, it is the interpretation of the present writers that most of the great thinning of the Hess from east to west is the result of its overlap upon the older rocks. This unconformity without doubt represents a recurrence of movement in the Marathon region of the mountain-making at the close of the Pennsylvanian. It is otherwise difficult to explain its wide extent, when contrasted with the rapid disappearance of any perceptible break at the base of the Wolfcamp formation toward the northeast.

The upper contact is apparently a conformable one with the Leonard. Udden and his associates apparently explained the relations by a great unconformity by which the Hess was removed by erosion in the western part of the mountains. Work by the writers has shown, however, that the Hess thins greatly in this direction, but is present. The contact is well exposed at many places southwest of Leonard Mountain, and northeast of the Word Ranch, and shows no evidence of erosion in either area. The Leonard formation thins eastward from 1,800 feet near Lenox to 300 feet at the Word Ranch. This is interpreted to mean a difference in the amount of synchronous deposition in the east and west. As shown by the sections, not only does the formation thin out as a whole, but there is also a convergence of the various traceable horizons in this same direction (Sections F to K). Moreover, the faunas of the two formations, though similar, are quite distinct. An alternative explanation would be that the upper part of the Hess interfingers westward into the lower part of the Leonard, in which case the faunas would have to change with the lithologic facies. Unfortunately, the Leonard and upper Hess are not exposed for a space of 5 miles northeast of Leonard Mountain, in which distance the Leonard thins from 800 to 250 feet, and the Hess thickens from 700 to 1,600 feet (Sections L and Q). In this critical area conclusive data are thus lacking.

Fossils and correlation.—Excepting *Fusulina* of the *F. elongata* type, fossils are common in the Hess only at certain horizons and localities, most of the formation being unfossiliferous. The most abundant fossils of the eastern facies are from the upper part of the formation. The following species are most important of the Hess fauna:

Enteletes dumblei Girty (first described from the "Hueco").
Rhipidomella n. sp.
Productus ivesi Newberry (uncommon).
Scacchinella aff. *gigantea* Schellwien.
Omphalotrochus sp.

Northwest of Wolf Camp, from beds that are obviously Hess, Böse collected *Perrinites compressus*. He supposed the horizon to be actually Leonard because of the presence of the genus *Perrinites,* which he thought was restricted to that formation, but, as we have seen, this genus occurs also in the Wolfcamp. Since no equivalent form to *P. compressus* has been found from the mid-continent Permian or elsewhere, it is at present of no direct value for purposes of correlation.

In the uppermost Hess, 1.1 miles southwest of the old Word Ranch, there is a fauna quite unlike that above mentioned. It contains ammonoids of similar appearance to those of the basal black limestone of the Guadalupe Point section, but has also a *Perrinites,* possibly identical with *P. vidriensis.* Besides this there occur here in great abundance *Pugnax osagensis* and *Composita mexicana guadalupensis,* which are, according to Girty, the most abundant species in the black limestone at the base of the Guadalupian section. This faunal resemblance suggests equivalence in age. As the beds directly overlying the basal black limestone, i.e., the Delaware Mountain sandstone, are known to be of Word age, it may be that in the section below Guadalupe Point, the Leonard is missing because of the unconformity between the black limestone and the sandstone so clearly seen at Bone Spring and northward,[23] so that beds of Word age rest directly upon those of Hess age.

Nothing in the Hess fauna aids in correlation of the formation with others in central Texas. Since the Wolfcamp and Leonard are correlated on the basis of fossils with the Wichita and the Double Mountain respectively, it would appear very likely that the Hess is at least approximately equivalent to the Clear Fork series. The presence of *Enteletes dumblei* in both "Hueco" and Hess suggests that part of the "Hueco" is of Hess age.

LEONARD FORMATION

The Leonard formation was named by Udden for Leonard Mountain, 9 miles north of Marathon, on whose north slope the formation is well exposed. The lower half of his

[23]Darton, N. H., and Reeside, J. B., Guadalupe Group, Bull. Geol. Soc. Am., Vol. XXXVII, pp. 421–423, 1926.

type section (Section 4) has been found to be Hess, a fact suspected by Udden; the Hess is also present, as predicted by him, in the lower part of his Leonard sections farther west. The Leonard outcrops in a belt extending in a northeasterly direction across the Glass Mountains from the region southwest of Lenox to a point 8 miles S. 25° W. of the summit of Sierra Madera, but for a space of 5 miles northeast of Leonard Mountain the formation is cut out by a faulted uplift and does not outcrop at the surface. The Leonard is also exposed in a semi-circular belt in the Sierra Madera uplift, and in the center of the uplift south of Altuda Mountain, where it is in contact with an igneous plug. The formation thins from west to east across the Glass Mountains, and may be divided into a western and an eastern facies.

The thickest sections of the Leonard were measured 3 miles southwest of Lenox, and south of Sullivan Peak, 4 miles northeast of Lenox (Sections C and F), in both of which it has a thickness of 1,800 feet. The formation thins to the northeast, and is 900 feet thick north of Leonard Mountain. The western facies of the Leonard consists mostly of hard, brown, platy siliceous shale, with which thin layers of limestone are interbedded. The shale approaches a flinty texture in places, and in others is almost a fine-grained quartzite. It has a certain resemblance to the Mowry shale of Wyoming. The limestone beds are cherty, and are granular, crystalline, or dense in texture; some of the denser layers are bituminous, and many of them contain sub-rounded pebbles of chert and limestone. Most of the limestone beds are only a few feet thick, but near Lenox two, and in places three, layers exceed 50 feet in thickness, and outcrop in prominent cuestas. These layers lens out eastward. The upper part of the formation has but few limestone layers and varies from soft shale to conglomeratic sandstone. The shale phase is well exposed at the so-called Clay Slide 2 miles west of Iron Mountain.

The thick limestone layers of the lower Leonard near Lenox form accurate key horizons. In addition, there are two zones characterized by a great abundance of the ammonoid *Perrinites vidriensis*. As shown in the sections (Sections B to K, Plate II), these horizons converge eastward as the formation thins, thus suggesting that the thinning is the result of differences in the amount of synchronous deposition.

Northeast of Leonard Mountain, as stated above, the outcrop of the formation is cut out by a faulted uplift for a distance of 5 miles. When again exposed 2 miles southwest of the Word Ranch, it has its eastern facies. From here northeast, as far as its outcrop extends, the thickness does not exceed 300 feet. Udden[24] believed the lower part to be cut out by faulting, but this is clearly disproved by a wider study of the exposures. The lower part of the formation consists of limestone full of well-rounded chert and quartz pebbles, which passes upward into fossiliferous limestones interbedded with marls and siliceous shales. Toward the east the shales and marls lens out, and the limestones change to dolomite. At the easternmost point at which the formation is exposed its dolomites differ from those of the Hess and Word only in their content of sand and pebbles. This same facies is exposed in the Sierra Madera, where the content of clastic material is inconstant, and passes laterally into featureless dolomite. The conglomeratic phase is well developed in a valley 0.8 mile N. 50° E. of the summit of Sierra Madera.

The most striking feature of the Leonard formation is its great lateral change in thickness. As already shown, evidence favors the interpretation that these great changes are the result of different amounts of synchronous deposition in different places. The thickest sections of the Leonard are farthest to the southwest, and thus nearest to the source of sediments in the uplifted Caballo Mountains, and this was likewise the area of most rapid subsidence. The Word also has its thickest sections in this region, and its greatest amounts of clastic material. If this interpretation is correct, however, it would mean a reversal

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[24]Udden, *op. cit.*, pp. 34 and 46

of conditions from those of the Hess, which is thinnest here, indicating by our interpretation that this was a rising area during Hess time.

The contact between the Leonard and Word, well exposed northeast of the Word Ranch, is also apparently a conformable one, showing no evidence of erosion. West of Leonard Mountain, however, the contact is not continuously exposed over great enough distances to furnish decisive evidence.

Fossils and correlation.—The Leonard formation contains an abundant and varied fauna, but only the most significant forms need to be presented here.

The ammonoid *Perrinites vidriensis* ranges from the lower to the upper part of the formation. In the lower part of the Permian section at Las Delicias, Coahuila, Mexico, the same species occurs, and the Blaine of central Texas has an almost identical one, *Perrinites hilli.*

At certain places in the Leonard, as well as less commonly in the upper Hess, *Productus ivesi* is very abundant; associated with it are at least two other Kaibab species, *P. occidentalis*[25] and *Meekella pyramidalis*. *P. ivesi* and *P. occidentalis*[26] occur also in the San Andres of New Mexico, but none of the three species occurs in the Delaware Mountain or in the Capitan, which are commonly correlated with the San Andres.

Fusulina is not abundant in the Leonard.

It is significant that the Leonard contains faunal elements of both the San Andres and the Blaine, which have been correlated with each other on the basis of sub-surface data.[27] The Leonard appears to have no counterpart in the Guadalupe Point section; as suggested above, it may there have been removed by erosion.

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[25]*P. occidentalis* occurs also rarely in the Word and Capitan, but is most abundant at the lower level. The San Andres species *Marginfera cristobalensis* and *M. manzonica* are common in the Leonard but do not occur at a higher level.

[26]Darton, N. H., Geology of Luna County, New Mexico, U. S. Geol. Surv., Bull. 618, p. 39 (statement by G. H. Girty), 1916.

[27]Gould, C. N., and Willis, Robin, Tentative Correlation of the Permian Formations of the Southern Great Plains, Bull. Geol. Soc. Amer., Vol. XXXVIII, pp. 435–438, 1927.

WORD FORMATION

The Word formation was named by Udden from the Word Ranch.[28] The Word outcrops in a belt extending northeast across the Glass Mountains. It is also widely exposed in the Del Norte Mountains, and is brought to the surface in the Altuda Mountains uplift and the Sierra Madera uplift. An isolated, infaulted wedge of Word is found 1.5 miles N. 50° E. of the Hess Ranch.

Like the Leonard, the Word is characterized by great lateral variations in thickness and lithology. When the thicknesses are plotted (Fig. 9), it is seen that the southernmost sections are the thickest, and that the formation thins toward the north and northeast. On the basis of changes in thicknesses and lithology, it is possible to divide this formation also into an eastern and a western facies, with the transition taking place in the region of Hess Canyon.

In the region between Sullivan Peak and the Del Norte Mountains west of Lenox, the Word beds have a thickness between 1,200 and 1,500 feet (Sections C to F, Plate II). The lower 100 to 400 feet are predominantly cherty limestone, in part dense and bituminous, in part light gray and crystalline. This is followed by beds of siliceous shale, not unlike that found in the Leonard formation, some of which are quite sandy. There are several interbedded, discontinuous layers of limestone, and about 300 feet below the top is a persistent bed of sandstone. Sandstone replaces the siliceous shale in a southward direction along the Del Norte Mountains, where there are 500 feet of sandstone in the upper part of the Word 6.5 miles S. 75° W. of Lenox. As a whole, the formation is marked by an absence of conglomerate, but in the last named region several beds of conglomerate appear with well-rounded pebbles of chert and quartz, which increase in coarseness toward the south as the beds are traced along the front of the mountains. The top of the formation consists of buff sandy dolomite, which grades upward from the sandy and siliceous shale below.

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[28]Incorrectly spelled *Ward* ranch on the Hess Canyon topographic sheet.

The slope-forming outcrops of the Word of this region contrast strongly with the overlying cliff-forming massive dolomites of the Vidrio.

In the more northern sections in this region, in Gilliland Canyon, and on the Altuda Mountain uplift (Sections A, I, and J, Plate II), the formation thins to 700 feet, but retains much the same character. In the region of Road and Hess canyons, the Word is about 1,100 feet in thickness (Sections L, Q, and R), and contains four thick limestone beds. The third limestone from the base extends as far west as Gilliland Canyon, and yields a rich ammonite fauna, described by Böse. The upper limestone bed is quite cherty, and all four are abundantly fossiliferous. East of Hess Canyon the siliceous shale layers lens out, and the limestones change into dolomites; the formation thins in this direction. The base is marked by a thin layer of platy bituminous limestone. The upper limestone member of the Word Ranch is distinct from the Vidrio in being less massive and dolomitic, and in having a great abundance of fossils and chert concretions. Udden, in his type section of the formation at the ranch drew the Word-Vidrio contact at the base of this member. Since the member is replaced to the west by sandy and shaly beds which lie below the natural dividing line at the base of the dolomite cliffs the writers feel justified in accepting the contact drawn by Udden in the western part of the mountains, and in placing this member in the Word formation. At the northeasternmost exposures the formation consists of about 300 feet of cherty dolomite, which locally contains fossils. This facies is also exposed in the Sierra Madera uplift.

As already stated, the Leonard and Word are apparently conformable. Some suggestions of unconformity between the Word and Vidrio are indicated in the correlation of the vertical sections, but on the whole the lateral changes in the formation may most satisfactorily be explained by differences in the amounts of synchronous deposition in different places. The southernmost sections were evidently nearest the source of the sediment, and contain the coarsest clastic materials. This area was likewise apparently the region of greatest subsidence. In the region northeast of the Word Ranch the dolomites of the Word and Vidrio are gradational, and gradational relations are seen in the Del Norte Mountains.

Fossils and correlation.—The Word formation has an abundant and varied fauna, very similar to that of the Delaware Mountain formation, but quite unlike that of the Chupadera. True *Fusulina elongata* first appears in the Word, and in places is very abundant. The most important element of the fauna is, however, its ammonoids, which are found also in the Delaware Mountain and in the upper part of the Permian section at Las Delicias, Coahuila, Mexico. Instead of *Perrinites,* which occurs in each of the lower formations of the Permian, the subfamily Cyclolobinæ is represented by *Waagenoceras,* a more advanced genus. Since in the highest ammonoid horizon of the Double Mountain of central Texas, *Perrinites* rather than *Waagenoceras* occurs, the Word must be represented there by the unfossiliferous beds above the Blaine, if represented at all. Probably most of the Word and the overlying dolomites are younger than any formation of the mid-continent Permian.

VIDRIO, GILLIAM, AND TESSEY FORMATIONS

These three formations constitute a unit of limestone and dolomite at the top of the Permian section in the Glass Mountains, and may most conveniently be described together. They were subdivided by Udden along Gilliland Canyon where the group is divisible into massive dolomite below, thin-bedded dolomite in the middle, and massive dolomite above. Later work has shown that these three divisions are the local phase of the interfingering of different facies. The Vidrio takes its name from the Spanish word for glass, the mountains being known among the Mexicans as the Sierra del Vidrio; the Gilliam is named for Gilliland Canyon;[29] and the Tessey is named for "a post

[29]This name from which the formation name *Gilliam* is derived is pronounced "Gilliand" by the inhabitants of the region. The name is correctly spelled on the Hess Canyon and Altuda topographic sheets. The United States Geological Survey Committee on Geologic Names states that it is inadvisable now to change the name of the formation to conform with the spelling of the type locality.

office now defunct, but once located about 2 miles north from the mouth of Gilliam Canyon,"[30] The Vidrio, Gilliam, and Tessey formations outcrop on the crests and back slope of the Glass Mountains. West of Gilliland Canyon the basal members of the Vidrio form bold cliffs at the top of the main escarpment of the range. The lower part of the group is also exposed on the flanks of the Sierra Madera uplift, in the northern Del Norte Mountains, and on the Altuda Mountain uplift.

This group has an aggregate thickness of about 3,000 feet. The 4,300 feet measured by Böse[31] along Gilliland Canyon is believed to be excessive, due allowance not having been made for faults and other structural complications which are with difficulty determinable in this section. Along Hess Canyon, however, it is possible to overcome these difficulties, and here a section measured by the writers gave a thickness of 900 feet for the Vidrio, 900 feet for the Gilliam, and 1,000 feet for the Tessey.

In the region east of Gilliland Canyon it is practicable to use the tripartite subdivision made by Udden on the basis of bedding. The Vidrio changes eastward from massive to moderately thick-bedded dolomite of dirty gray color, in which many beds are crowded with fusulinas. Except in the extreme northeast, the Gilliam is distinctly thinner bedded than the Vidrio. It is about 500 feet thick along Gilliland Canyon, and consists of dolomite in one-foot to three-foot layers, many of which are crowded with fusulinas. Parts of the formation contain an abundance of badly altered brachiopods and other fossils. Toward the east, beds of brown, moderately coarse-grained sandstone lens in, and the formation thickens to 900 feet. In the section on the east side of Hess Canyon, 40 per cent of the formation is sandstone, which predominates over the dolomite in the upper and lower parts. The sandstones are well exposed from 2 to 6 miles ESE of the Warren Ranch. The upper sandstones are interbedded with red shales which

[30]Udden, *op. cit.*, p. 53.
[31]Udden, *op. cit.*, pp. 21–22

contain a few thin layers of gypsum. The Tessey formation consists of massive or moderately thick-bedded gray and dark gray limestone and dolomite. East of Hess Canyon the Gilliam-Tessey contact is drawn at the top of a persistent sandstone layer. Some of the Tessey dolomites are quite cherty, and locally contain fossils. An exposure in an arroyo 7.5 miles S. 75° W. of the summit of Sierra Madera shows a coarsely brecciated mass of dolomite, sandstone, and gypsum, which passes laterally into undisturbed Tessey strata, doubtless representing a slump into a gypsum bed underground.

On the flanks of Sierra Madera, and in the region a few miles to the southwest, it was not possible to subdivide the group, and the three formations were mapped together.

The Tessey formation passes under recent deposits a short distance west of the mouth of Gilliland Canyon and seems to have no equivalents in the western part of the mountains. About 2 miles west of Gilliland Canyon the Gilliam formation changes over abruptly into massive dolomites and is not traceable toward the west. In the western part of the mountains some layers of fusulina-bearing dolomites and of thin-bedded dolomites are interbedded with more massive strata and are believed to represent a part of the Gilliam. At about the same point where the Gilliam loses its identity, another thin-bedded series appears at a lower level. For this series the senior author recently proposed the term Altuda member,[32] because of its good exposures in the vicinity of Altuda section house. This member contains thin-bedded sandy dolomite and siliceous shale, and reaches a thickness of 400 feet. It is separated from the Word formation below by several hundred feet of massive, cliff-forming dolomites, making up the lower beds of the series. These thin gradually to the west and finally merge with the Altuda member west of Altuda. Overlying the Altuda member is a series of massive dolomites with a maximum thickness of 1,000 feet, which are probably the

[32]"The Bissett formation, a new stratigraphic unit in the Permian of West Texas," Amer. Jour. Sci. (5), Vol. XIV, p. 217, 1927.

equivalents of the upper part of the Vidro and the lower part of the Gilliam in their type locality. The thin-bedded strata of probably Gilliam referred to above lie near the top of the upper massive beds. This member forms the prominent cliffs on Altuda Mountain, and the Altuda member lies on the slopes below it.

The origin of these formations, and of the Capitan limestone farther northwest, which is doubtless their equivalent, has been much discussed. Opinions vary as to whether they are reef deposits, or whether they are of inorganic and chemical origin. At several places in the mountains, in the more massive portions of the group, the writers have observed a peculiar type of cross-bedding, in which the cross beds dip toward the northwest, depart as much as 10 degrees from the normal dip of the strata below, and extend through hundreds of feet of section. Ruedemann suggests that they are analogous to the *"Überguss-schichtung,"* that is, the steep bedding of material "poured over" the outer slopes of reefs, such as are observed in the dolomite reefs of southern Tyrol. Recently Ruedemann[33] has obtained evidence indicating that the Capitan limestone was at least in part of algal reef origin. He writes:

> . . . I found the Capitan limestone on the east side of the [Guadalupe] mountains, north of El Capitan cliff, to be composed, wherever I saw it, of subspherical bodies of calcareous algæ, showing very distinctly fine concentric structure and ranging in size in different beds from small bodies of walnut size to heads half a foot or more in diameter. . . . The brachiopod fauna I saw, with thick-shelled forms, also impressed me as a typical reef fauna.

It is quite certain, however, that neither the Altuda member nor the eastern thin-bedded facies of the group is of reef origin. It is quite possible that the eastern facies may represent lagoon deposits behind the reef, interfingering shoreward with continental red beds and deposits of salt and gypsum.

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[33]Ruedemann, Rudolf, Letter to P. B. King, 1927.

Fossils and correlation.—*Fusulina elongata* is the only abundant fossil of the dolomites. Other fossils are preserved only in certain non-dolomitic beds. In two places in the Vidrio there are beds crowded with *Equamularia guadalupensis*, which, according to Girty,[34] is probably the most abundant species of the Guadalupian brachiopod fauna and is almost restricted to the Capitan. The lithologic character of the Glass Mountains dolomites also points to their equivalency with the Capitan. There is no evidence that formations correlative with the dolomites are present in the mid-continent Permian.

BISSETT FORMATION

The Bissett formation was named by the senior author[35] in a recent paper. Its type locality is Bissett Mountain, 6 miles N.N.E. of Altuda, on whose north slopes the formation is well exposed. The formation outcrops in a belt along the northwest flanks of the Glass Mountains extending from the Southern Pacific on the west to a point 13 miles W.S.W. of Sierra Madera on the east. In this belt its exposures are often widely separated by strips of wash.

The Bissett formation is characterized by conglomerate, the conglomerate members ranging in thickness from 10 to 500 feet. Their fragments are sub-angular to rounded, and are for the most part made up of dolomite derived from the beds immediately beneath, although there are a few of chert, quartz, and quartzite. The matrix is a sandy limestone or sandy marl. In places, particularly in the upper part, the conglomerates are interbedded with red shales, and with thin layers of sandstone and limestone. At a locality 3 miles N. 15° W. of the Warren Ranch, on the west side of Hess Canyon, and 570 feet above the base of the formation, buff shale is interbedded with thin layers of dolomitic limestone which contain ostracods and the casts of pelecypods and gastropods. The ostracods are stated

[34]Girty, G. H., The Guadalupian Fauna, U. S. Geol. Surv., Prof. Paper 58, pp. 367–368, 1908.

[35]King, P. B., The Bissett Formation, a New Stratigraphic Unit in the Permian of West Texas, Amer. Jour. Sci. (5), Vol. XIV, pp. 212–221, 1927.

by Mr. Harlton to belong to the genus *Bairdia* and to be of Permian age. The formation is 720 feet in thickness at this locality; north of the mouth of Gilliland Canyon it is 530 feet; and on Bissett Mountain it is 430 feet. The total thickness is unknown because of the unconformity at its top.

The Bissett formation rests upon the Tessey east of Gilliland Canyon. Near Bissett Mountain it lies upon the upper massive member, which, as already stated, is the probable equivalent of the lower Gilliam and the upper Vidrio. Four miles west of Bissett Mountain only 215 feet of the massive member intervene between the Bissett formation and the Altuda member. This seems to represent an overlap downward across nearly 1,800 feet of strata in a distance of 17 miles. From this evidence, and from the fact that the formation contains fragments clearly derived from the erosion of the earlier rocks, it is concluded that an unconformity separates the Bissett formation from the rocks beneath.

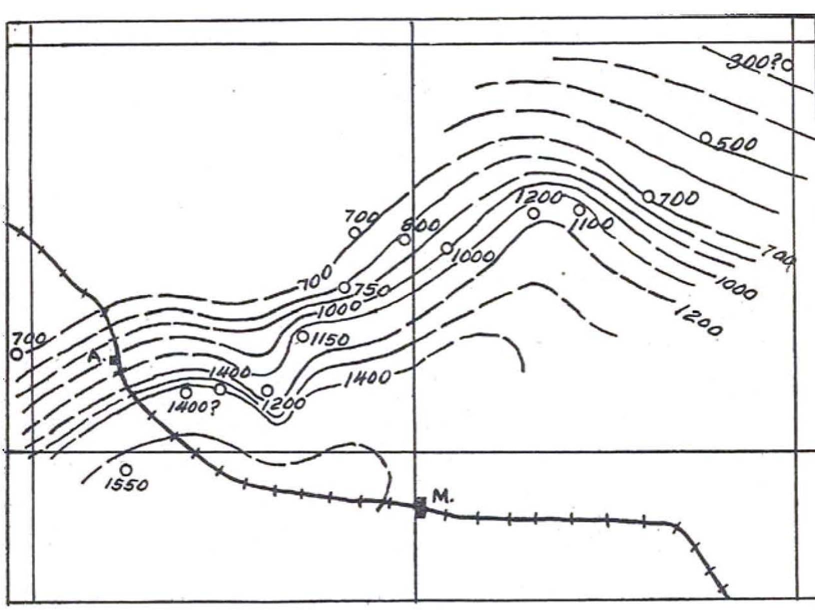

Fig. 9. Map showing variation in thickness of Word formation in the Glass Mountains. Contour interval 100 feet.

The Bissett is likewise separated from the Comanche series above by a well marked unconformity. A divergence in dip between the two may be seen at many of the places where the contact is exposed, and the Comanchean extends across the beveled edges of the formation upon the older rocks of the region.

The age of the Bissett formation is not known. It may be late Permian, Triassic, Jurassic, or early Cretaceous, but the writers are of the opinion that it is of late Permian age.[36]

FUSULINIDS OF THE GAPTANK AND WOLFCAMP FORMATIONS

After this paper was written, Professor Carl O. Dunbar made a preliminary examination of the fusulinids of the Gaptank and has kindly given us the following observations:

The oldest collection is that from the basal limestone conglomerate south of Dugout Mountain. This stone is filled with *Fusulinella meeki* Dunbar and Condra, a form described from the middle Cherokee shales of Missouri. Apparently the same species occurs in the lower part of the Strawn group near Dennis, Parker County, Texas, a horizon considerably lower than the Cherokee shale. It has not been seen in the Canyon group of Central Texas, nor the Marmaton or higher beds of the mid-continental Pennsylvanian, and it was not found above this basal member of the Gaptank formation. It is somewhat surprising to find associated with this *Fusulinella*, south of Dugout Mountain, a new species of *Triticites* of a type rather to be expected at a much higher horizon.

The richly fossiliferous zone between conglomerate beds four and five in the section about Gap Tank is characterized by the very slender species *Triticites irregularis* (Schellwein and Staff) Dunbar and Condra. The same species is widely spread and exceedingly abundant in the Adams Branch limestone of the Canyon Group of Central Texas, a circumstance that agrees well with the other faunal evidence for the Canyon age of this part of the Gaptank. This species of *Triticites* has a rather extended range, however, and in the mid-continental region is common also in the Kansas City formation and recurs even in the Douglas formation.

Specimens from limestone number one at the base of the upper Gaptank in the vicinity of Gap Tank are filled with a small *Triticites* in a silicified condition rather unfavorable for careful identification. Externally, however, they strongly resemble *Triticites moorei* Dunbar and Condra, a species described from the lower Cisco (Wayland

[36]For a discussion of the problem see King, *op. cit.*, pp. 219–221.

member) of Central Texas. This suggests that the Upper Gaptank (beds 13 to 21 of the section) is equivalent to the lower Cisco.

Another collection, from near the top of the Gap Tank beds as represented four miles west of Marathon, includes the species *Triticites secalicus* (Say), which in the mid-continental region ranges from the Lansing into the Shawnee formation.

Two collections from the higher beds referred to the Gaptank at Wolf Camp are comprised of a form referred to *Triticites cullomensis* Dunbar and Condra, which in Kansas and Nebraska is characteristic of the Shawnee formation. There is no evidence here of the presence of beds equivalent to the Wabaunsee stage.

Fusulinids of the Wolfcamp formation, according to Professor Dunbar, justify the following observations:

The *Uddenites* zone is characterized by *Triticites ventricosus* (Meek and Hayden), a species that is non-committal as to the Pennsylvania or Permian age of these beds, since in Kansas it characterizes the uppermost Pennsylvanian (Wabaunsee formation) and extends above the lowest *Schwagerina* beds (Neva limestone), making its final appearance in the Florence flint member of the Chase formation of the Permian.

The first appearance of the genus *Fusulina* is made some distance above the *Uddenites* zone where it is represented by a rather small and slender species of the stock of *Fusulina elongata*. The genus *Schwagerina* is represented first by *S.kansasensis* Beede, which appears shortly above the *Uddenites* zone and which is succeeded near the middle of the Wolfcamp by *S.uddeni* Beede and *S.fusulinoides* Schellwien. The large *Fusulina elongata* Shumard does not occur below the Word formation.

For description of genera and species referred to, see: Dunbar and Condra, Fusulinidae of the Pennsylvanian System in Nebraska, Bulletin II, Second Series, Nebraska Geological Survey, 1927.

ECONOMIC ASPECTS

Several phases of the Glass Mountains stratigraphy have a direct bearing on petroleum problems, and other ones are of general importance. These are summarized below.

Unconformities and orogeny.—There is undoubtedly an unconformity at the base of the Tesnus, which is probably an erosional one. The Tesnus, Dimple, Haymond, and Gaptank appear to be a conformable series throughout. An uplift to the south began in mid-Gaptank time, as is shown by extensive beds of conglomerate, containing angular blocks up to two feet across derived from the Dimple and other earlier rocks. The orogeny of the Marathon region culminated at the close of Gaptank time when the Gaptank and all the older strata were more or less strongly folded, overturned, and overthrust toward the northwest. These are the Caballos Mountains. At the close of Wolfcamp time there was a recurrence of diastrophism, causing the Hess to rest unconformably upon the Wolfcamp. From the Hess to the close of Tessey time there was apparently continuous sedimentation, accompanied by erosion in the uplifted Caballos Mountains to the south, and comparatively rapid sedimentation on the north flank of these mountains. At the close of Tessey time the Glass Mountains Permian was warped and eroded and the Bissett conglomerates laid down unconformably on top of it. At some time during the early Mesozoic the strata were again tilted, and the whole area worn down to a peneplain before the advance of the lower Cretaceous seas.

Sands.—The Tesnus consists in a large part of sandstone, as does the Haymond formation. The Gaptank also contains thick beds of sandstone. Local sandstones occur in the Wolfcamp and Hess, in the former near the uplifted Caballos Mountains, and in the latter in its northeastern portions. The Leonard contains lenses of sandstone toward the west, and its limestones contain much conglomerate. The eastern facies of the Leonard is a sandy dolomite containing lenses of chert pebbles. In the eastern Glass Mountains, and the Sierra Madera uplift, this formation is the only sandy one in the section. The Word contains sandstone beds in its western facies, which increase in thickness and coarseness toward the south. These sandstone beds are absent east of Hess Canyon, and in its eastern facies the Word is a non-sandy dolomite. Sandstone beds are abundant in the eastern exposures of the Gilliam, but are generally absent from the Vidrio and Tessey.

Bituminous layers.—The Dimple limestones are locally quite bituminous. There are some thin bituminous limestones in the Wolfcamp and Leonard. The basal limestone of the Word is very bituminous, and locally exceeds 100 feet in thickness. Black shale is found in the Tesnus, Haymond, and Wolfcamp formations.

Red Beds.—Thin layers of red shale are found in the eastern exposures of the Hess, and thicker ones in the eastern exposures of the Gilliam.

Gypsum.—Thin beds of gypsum are found in the eastern exposures of the Gilliam and Tessey.

PSEUDO-IGNEOUS ROCK AND BAKED SHALE FROM THE BURNING OF LIGNITE, FREESTONE COUNTY, TEXAS

BY JOHN T. LONSDALE AND DAVID J. CRAWFORD

INTRODUCTION

During recent years the Bureau of Economic Geology has received occasional samples from Freestone County, of a peculiar rock that in its external characters resembles vesicular basaltic lava. The specimens submitted had been selected and cleaned of foreign material so that judging from the specimens alone the rock seemed to be of igneous origin. Since the locality is in the midst of Tertiary formations where igneous rocks are not known, a field examination was made, the results of which showed that the igneous-like rock was formed by the burning in place of a bed of lignite with partial fusion and recrystallization of the overlying rocks. The basalt-like rock here called pseudo-igneous rock, was found to constitute only a small part of the rocks affected by the lignite's burning the other materials consisting of burned and baked shale and sooty material residual from the coal. Subsequent to this examination the junior author prepared a detailed map of the occurrence of the material affected by the fire and secured data on local geologic conditions. This work (by the junior author) was done as geologist for the W. A. Reiter interests and the authors wish to thank Mr. Reiter for generously releasing the data for publication. Residents of the neighborhood who assisted during the course of the investigation were W. E. Nanny, Royce Nanny, and D. M. Worth.

The present paper records and describes the occurrence of the psuedo-igneous rock and the baked and burned rocks associated with it. These phenomena are well known in Montana and adjoining lignite areas, where according to

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Rogers[1] such features are actually characteristic of an area of over 200,000 square miles. For information on the burning of lignite beds of Montana and other northwestern states the readers are referred to the papers cited above. The present paper is believed to be the first record of this phenomenon from Texas.

LOCATION

The pseudo-igneous rock and burned shales are found in southern Freestone County, 2 miles east of Donie on the farm of W. E. Nanny and adjoining tracts. The material was traced by disconnected outcrops over an area 2 miles long and one-half mile wide. Figure 10 is a map showing details of the areal distribution of the rock. The outcrops of the material extend in a N.E.-S.W. direction, the northernmost being found on lands of the Clarke estate, the southernmost on the land of B. A. May. The rock described as pseudo-igneous was found at many places in the belt of outcrop as indicated on the map but the area of burned material is much more extensive.

GENERAL GEOLOGY

The rocks of the region belong to the Wilcox formation of the Tertiary ,and include sandstones, gray and black shales and beds of lignite. Occurring with the lignite, especially in horizons immediately above, is a notable amount of silicified wood, showing replacement of trees up to two and one-half feet in diameter. An opening for coal and two bore holes have been made on the farm of W. E. Nanny. Well No. 1 (shown on map, Figure 10) revealed two beds of coal five and twelve feet respectively, with a shale parting. Well No. 2 contained seventeen feet of

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[1]Rogers, G. Sherburne, Baked Shale and Slag Formed by the Burning of Coal Beds, U. S. Geol. Surv., Prof Paper 108, pp. 1–10, 1917.

Allen, J. A., Metamorphism Produced by the Burning of Lignite Beds in Dakota and Montana Territories, Boston, Soc. Nat. Hist. Proc., Vol. XVI, p. 246, 1874.

Bowie, Alexander, The Burning of Coal Beds in Place, Amer. Inst. Min. Eng. Trans., Vol. XLVIII, p. 181, 1915.

Bastin, E. S., Notes on Baked Clays and Natural Slags in Eastern Wyoming, Jour. Geol., Vol. XIII, pp. 408–412, 1905.

coal and the shaft (No. 3 of map) had five and twelve feet beds with the shale parting as in No. 1.

A conspicuous feature of the Wilcox sedimentation of the locality is a massive indurated sandstone bed more or less concretionary that caps most of the low hills. This is shown on the map, and as will be seen, overlies the exposures affected by the burning of the coal. It is probable that the occurrence of this sandstone bed has protected the soft incoherent materials of the burned zone from erosion for where streams have cut through this layer they have eroded deeply removing materials to depths far below that of the burned lignite.

OCCURRENCE AND ORIGIN OF PSEUDO-IGNEOUS ROCK AND BAKED SHALE

The pseudo-igneous rock to a great extent occurs on knolls or just below the tops of hills where weathering has left boulders and fragments of the material imbedded in a grayish to reddish sticky clay soil. In such localities the origin of the rock is not apparent and exposures with large amounts of the material might be mistaken for volcanic plugs. Other exposures are more instructive and show at once the nature of the material. On Buffalo Creek at the point B of the map is found one of the best exposures. Here for some 200 yards along the stream are occasional steep banks, averaging 15 feet high and 25 feet long, separated by areas covered by wash. The burned and baked shale and some pseudo-igneous material are well exposed in these banks. In the exposure farthest downstream the section consists of gray shale in the stream bed overlain by one foot of black carbonaceous shale which in turn is covered by a layer 10 feet thick of baked shale and cinders, included in which are crusts and bunches of the pseudo-igneous rock. The bed of burned material does not exhibit regular stratification, as do the shales below, but shows a mass of shale blocks and cinders jumbled and tumbled together in all possible relations. Near the bottom of this layer there is one fairly continuous stratum of baked shale about four inches thick, broken into blocks a few inches long lying in all positions from horizontal to vertical but all are plainly parts of the same bed. This arrangement has been caused by slumping apparently coincident with the burning of the lignite and this layer probably represents the parting between the two coal beds mentioned previously.

In the exposure farthest upstream the bed of the stream is occupied by a bed of lignite of which four feet is exposed. This lignite is the same as that encountered in the bore holes and shaft only a short distance northeast, since levels of the two are nearly the same and there is no evidence of faulting. The lignite gives place laterally downstream to another exposure of the baked and burned shale. The coal near the contact is sooty and soft, evidently having lost much of its volatile matter. Back a few feet from the contact it is the firm normal lignite of the region. This exposure very plainly records the burning of the coal bed and shows where the fire stopped.

Between the two exposures already mentioned the burned material is in evidence in a number of places, but not so well exposed. The black shale of the downstream exposure can be traced upstream nearly to the lignite where its dip carries it beneath the coal. The zone of material, affected by the burning of the coal bed, exposed in Buffalo Creek, is thicker than that of the coal encountered in the shaft and bore holes. This is due to the fact that the effects of the heat extended some feet above the coal. When the coal was consumed the material above slumped leaving the present confused masses of baked shale and pseudo-igneous rock.

A section made at the point B on Buffalo Creek is given below and is shown graphically on the map.

	Feet	Inches
Soil	3	
Slightly baked and burned sandy shale and clays	6	
Ash and cinders, baked and burned	0	2
Sandstone and clay	2	
Ash and cinders	0	3
Baked shale	2	

Unaffected materials: Clay, shale, and sandstone.

The ash and cinders of the section are thought to represent the actual coal beds. The other materials affected by the heat are the normal sedimentary rocks modified in ways to be described later. Another section from point A of the map one and one-fourth miles northeast of B is given below.

	Feet	Inches
Soil, altered (burned) sandy	1	
Shale and clay	6	3
Ash and cinders	0	5
Altered sandy shale	1	
Ash and cinders	0	2
Baked shale	0	8
Sandy clay	0	2

In this section also the two layers of lignite seem to be recorded in the ash and cinders. There is also the same mass of slumped materials which have been affected by heat.

Keeping the above descriptions in mind, if the map, Figure 10, is again consulted, the nature of the pseudo-igneous rock and the burned and baked shale is reasonably apparent. The central part of the map represents an area of higher land. Lignite beds five and twelve feet thick underlie this area at about thirty-five feet. On the flanks of the higher areas protected by a resistant sandstone ledge are found outcrops of the burned material at essentially the same elevations as the coal. At one or two isolated hills the burned zone completely encircles the hill. The burned material is at one level and the exposures are such as to suggest the outcropping edges of a coal bed. The coal has evidently burned on its outcrop for a distance of over two miles. Where streams have cut through continuity of outcrop of the burned shale is destroyed. It is plain, however, that the exposures were once continuous. That the burning affected only a relatively narrow zone is shown by the bore holes on the Nanny farm where coal was encountered.

An examination of the country in which the materials considered here are found fails to reveal any evidence of igneous activity. The country is rough with numerous

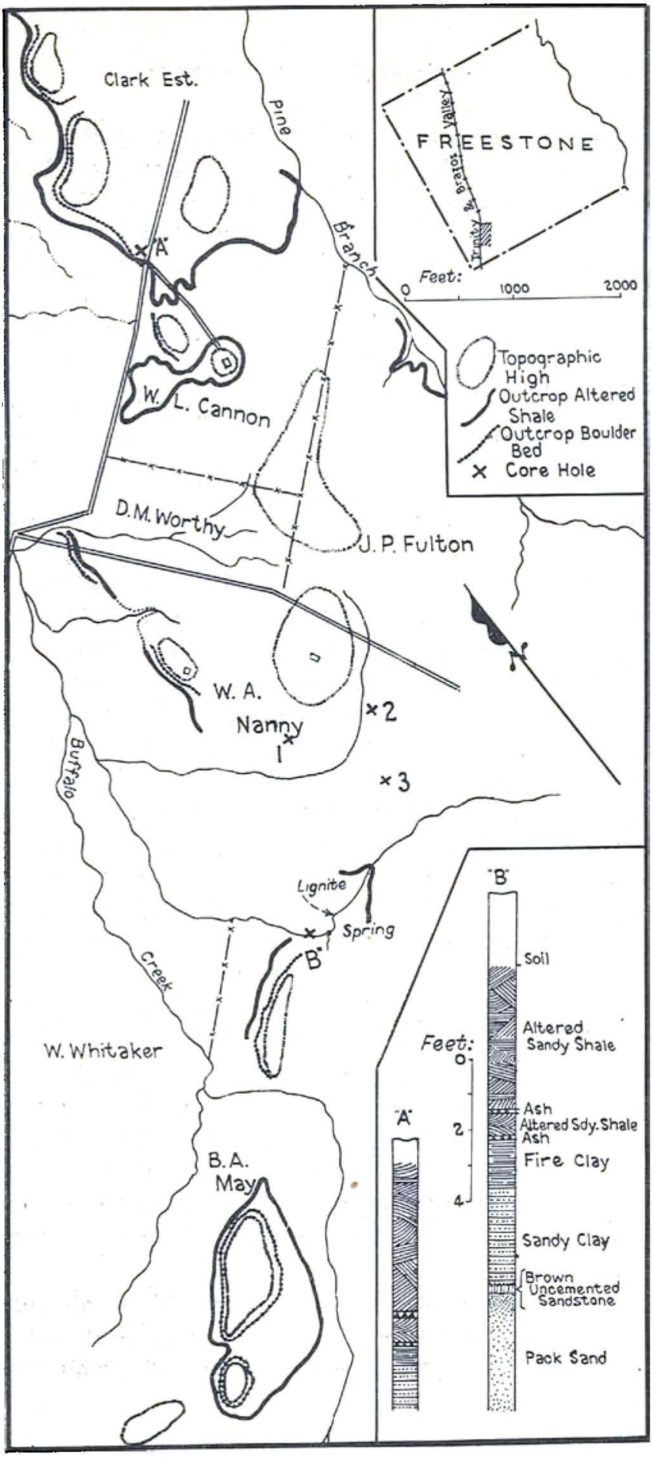

Fig. 10. Map showing geologic details of area in which pseudo-igneous rock and baked shale occur.

gullies and ravines so that any igneous rocks present should be easily found. If low hills capped by isolated outcrops of the burned and fused rock were igneous plugs adjoining ravines would show significant exposures. The fact that the burned shale and baked shale with its fused portions are at one horizon and that this horizon is that of the lignite, and that the actual contact of lignite and burned materials is exposed leaves no doubt as to the origin of the rocks in question.

CAUSE AND TIME OF BURNING

The ignition of coal beds has been explained in a number of ways. Lightning, man and spontaneous combustion are among the favored agencies cited. Rogers[2] has shown that for most occurrences spontaneous combustion is the most likely cause of ignition. Probably this holds for the Freestone County occurrence.

The age of the burning of the coal beds cannot be stated. Judging from the topography of the region the streams have cut their present courses since the fire occurred because outcrops are interrupted by the stream valleys. If the burning occurred since the streams cut through the coal beds ignition in at least seven places must have occurred and this is unlikely. Judging from the amount of erosion, the fire antedated the present era and may have been as early as Pleistocene.

EFFECTS OF BURNING

The formation of the baked shale has been due to the action of heat present during the burning of the lignite beds. The shale blocks left show none of the characters of the shales of the region but are now pink and reddish in color and have been rendered brittle and shell-like. There is present in most exposures also large amounts of incoherent grayish to pinkish material which is of an ashy or cindery nature.

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[2]*Op. cit.*, p. 1

Since the pseudo-igneous rock occurs in the zone of burned materials to only a limited extent it is evident that the rock represents areas in the baking shales where the temperature was sufficiently high to cause fusion. The greatest change due to heat has been above the coal and in the overlying strata. Only the very top of the underlying carbonaceous shale has been affected and the change consists in a gradation from black soft shale to light gray, brittle, harsh material. Above the coal the heat must have been considerable since the present accumulation of burned material slumped from above.

The pseudo-igneous rock constitutes only a small part of the layer of material showing heat effects. It occurs as crusts, stringers and bunches only a few inches in any dimension. These are composed of black vesicular material much of which resembles basalt. In some exposures, as previously indicated, good-sized boulders of the material are present. These, however, are composed of shale along with the pseudo-igneous rock. Judging from the best exposures, highest temperatures were reached above the coal beds in areas controlled by jointing or cracks. It is probable, as pointed out by Rogers, that combustible gases from the coal ignited at some distance above and that here the greatest heat was generated.

In the coal itself combustion was nearly complete. If the ash and cinder layers of the sections represent the coal these may be regarded as true ashes or cinders. They are black sooty materials, very much like the residue from burning of coal in stoves. At the contact of coal and burned material the zone of change was about three feet wide. Evidently ahead of the fire the coal was heated to such an extent that the volatile material was largely driven off leaving a soft more or less earthy residue which graded quickly into normal lignite.

PETROGRAPHY

Several kinds of rock resulting from the burning of the lignite are sufficiently distinct to merit special attention. Among these are slightly baked shale, baked and burned shale, porcelainite-like glass, vesicular basalt-like rock and dense crystalline rock, pseudo-igneous in character. All of these except the burned or baked shales show characters either external or internal, resembling igneous rocks.

The black carbonaceous shale underlying the zone of material affected by the heat grades upward into rock retaining its shaly character but showing cream-gray colors. There is a gradation in this effect and it is evident that the change in color marks the lower limit of effective heat. The change in the shale has been a burning that drove off the carbonaceous material leaving the rock essentially still a shale but slightly harder than the unaltered rock.

Within the heat affected zone, wherever seen, baked and burned shale is the most abundant type of material. This varies in color from gray to brick-red with all shades between. In coherence a variation is also seen since the brick-red material is hard and brittle, but the lighter-colored specimens are softer and less coherent. The changes in this material have been much the same as in the making of brick from clay. The materials with brightest colors are evidently those most affected by the heat and as the higher temperatures were reached the development of ferric oxide occurred, just as in the brick kiln, with characteristic reddish colors. An oxidizing environment must have been present for the formation of the ferric oxide, but this is easily accounted for since the burning was on the outcrop and oxygen would be abundant except in unusual cases. Under the microscope no evidence of fusion or recrystallization of materials of the baked shale is seen.

Fusion of the shales occurred only to a limited extent if the volume of the zone affected by heat is considered. The fusion in some instances was without crystallization of the fused mass, but in others complete crystallization with the formation of igneous rock minerals resulted. That the glassy and crystalline masses considered here were caused by fusion of the shales is evident from a study of the specimens. Plate IV, Figure 1, shows such a specimen. The fusion progressed along joints and spread laterally along bedding planes digesting the shales wherever temperatures sufficiently high were developed.

Glassy material is found usually on the exterior of any fused mass and corresponds fairly closely to porcelainite. In a few instances clear yellowish glass was found, but only as a very thin coating. In some cases the succeeding material (inward) was the porcelainite mentioned above, but in others was dense-black basalt-like rock. Optically the clear glassy material is isotropic with an index of refraction of $1.449 \pm .003$. This is lower than volcanic glasses and corresponds more closely to opal.

The dense-black basalt-like materials (pseudo-igneous rock) show considerable variation in character both megascopically and microscopically. The size of bodies of this sort developed varies from minute threads as shown in Plate IV, Figure 1, to solid masses as much as four inches wide and one foot long. It is usually the case, however, that no mass as large as this is composed entirely of fused material, but includes some undigested shale. The specimen shown in Plate IV, Figure 1, was from a mass some three feet in diameter, which on breaking was found to contain both shale and the black pseudo-igneous rock. It is true also that no larger mass of the material is entirely massive, but is vesicular. Some specimens are exceedingly vesicular while others show only an occasional bubble hole. Figure 2 of Plate IV shows a surface of highly vesicular material. In the hand specimen little difference is seen in the fused black material. Under the microscope, however, there is seen to be a gradation from glassy material through partially crystallized rocks to completely crystalline material.

Plate V may be taken as representative of the partly crystallized rock. The rock megascopically is dark gray and highly vesicular. Figure 2 of Plate IV shows a surface of such material. Under the microscope the rock is seen to be composed of a dense gray glassy groundmass containing innumerable needle-like microlites of feldspar. These are shown in Plate V, Figure 1. A few quartz grains are also present in this type of rock. Certain areas of irregular shape are brownish in color and nearly transparent. These may represent portions of the rock in which crystallization of pyroxene has commenced. Some specimens of the vesicular rock show well developed flow structure comparable to that of certain rhyolites. This is shown in Plate V, Figure 2.

As mentioned above, some portions of the rock are completely crystalline. The darkest, densest specimens are usually of this sort and they approach igneous rocks in their textures and minerals. The greater number of such specimens are holocrystalline and show a texture close to ophitic. Plate VI, Figure 1, is of this type of rock. Plagioclase feldspar, pyroxene and magnetite are the most abundant minerals. Generally speaking, pyroxene is most abundant, magnetite next and plagioclase least, but in some specimens magnetite is very abundant, constituting more than 50 per cent of the rock.

The pyroxene is of two varieties. By far the most abundant is a green slightly pleochroic type corresponding fairly closely to diopside. It is biaxial-positive with an extinction angle of 36° and $\gamma = 1.700 \pm .005$. Associated with it very sparingly is a small amount of gray pyroxene which is biaxial-positive with an extinction angle of 43° and $\gamma = 1.745 \pm .005$. This is thought to correspond to augite and is possibly titaniferous, since a few grains showed violet colors. The pyroxene occupies spaces between feldspars and magnetite and is moulded around them.

The plagioclase feldspar occurs generally in slender laths with euhedral development. Many of these show polysynthetic twinning but some are untwinned or show Carlsbad twinning. The mineral has a mean index of $1{,}580 \pm .005$, an extinction angle of 34° on the (010) section and corresponds to anorthite. In period of crystallization the feldspar was between magnetite and pyroxene. In some specimens the larger plagioclase crystals are filled with dust-like inclusions of magnetite.

The magnetite is present in irregularly-shaped grains which formed early in the recrystallization of the fused rock. Generally speaking, the mineral is irregularly distributed in the rock but in some specimens is present in peculiar parallel structures with pyroxene. These are shown in Plate VI, Figure 2. The formation of magnetite in this rock is of considerable interest. It probably required a reducing environment for its production. This was perhaps furnished by carbon monoxide from the lignite. Probably also the formation of magnetite and the fusion of the rocks with recrystallization took place some distance above the coal in joints or other openings where heat was greater than in the neighborhood of the coal and where oxygen would be in less abundance.

Hematite occurs to a limited extent in many of the specimens. In some cases it has been derived from the oxidation of the magnetite, evidence for this being seen in thin section. In some specimens hematite forms a narrow rim around the vesicular openings of the rock and in a few cases there are spherulites of the mineral.

There are some variations in texture among specimens of the massive crystalline material. One of these consists in a development of much larger crystals of plagioclase than usual. Another is the development of exceedingly large slender crystals of pyroxene with only small amounts of the other minerals present and appearing as a greenish felt-like mass under the microscope. Other specimens include areas of glassy or aphanitic material but these are subordinate. Altogether the specimens examined are igneous-like in their characters, but do not correspond exactly to known types of igneous rocks.

It is impossible to picture exactly the course of crystallization of these pseudo-igneous rocks. While the major conditions have been fusion under conditions of low pressure there may have been added to a limited extent the influence of gases from the heated rocks. Probably such gases would be free to escape and would play little part in the crystallization of the mass. The time required for the fusion and recrystallization of the rock may have been very short. Clinker, from a coal stove, examined during the present investigation, was found to be crystalline and to contain pyroxene and plagioclase. The time involved from charging the stove until the clinker was cold was less than 24 hours.[3]

[3]Observation communicated by E. H. Sellards.

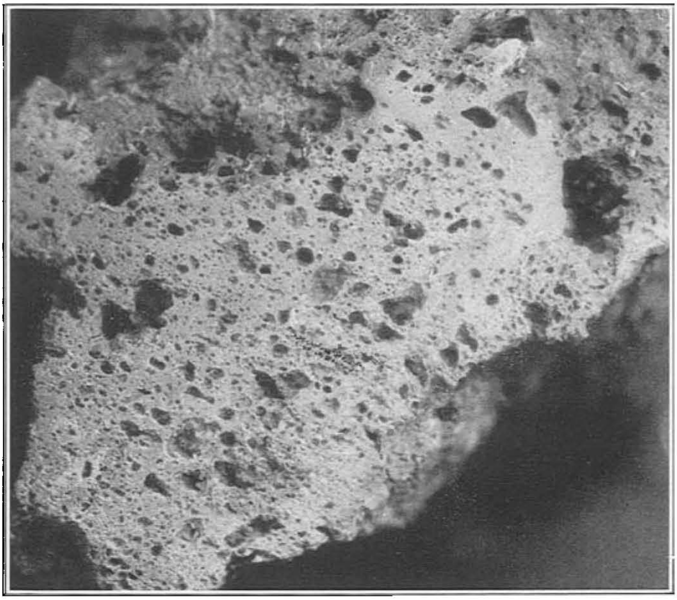


Fig. 1. Photograph of a surface of shale which has undergone burning. The dark gray portions a recrystallized dense crystalline rock resulting from fusion of the shale. The lighter parts are baked but not fused shale. The fusion penetrated along bedding planes and cracks digesting the shale as it advanced.

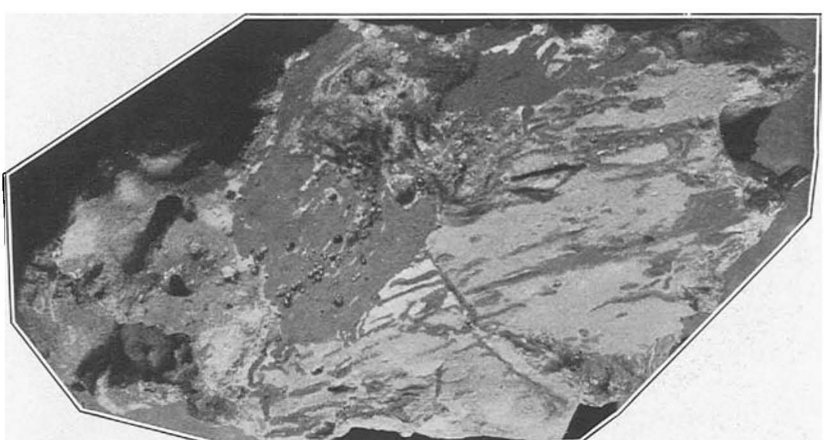


Fig. 2. Photograph of a surface of fused shale showing the highly vesicular character of some of the rock.

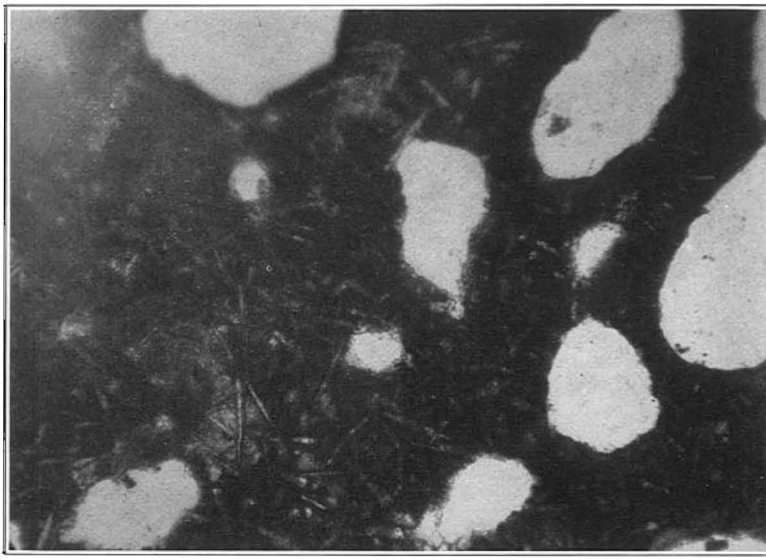


Fig. 1. Photomicrograph of thin section of vesicular fused shale. The groundmass which is dark gray and dense contains numerous microlites of feldspar. $\times$ 46.

Fig. 2. Photomicrograph of fused shale showing flow structure. $\times$ 26.

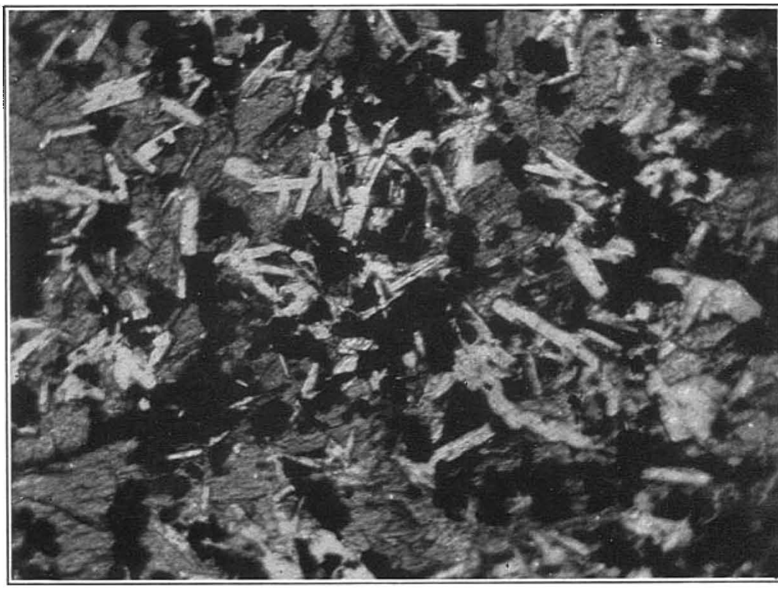


Fig. 1. Photomicrograph of thin section of fused shale. This is from the most dense type and closely simulates basalt. The white laths are Plagioclase feldspar, the dark gray areas are pyroxene and the black magnetite. ×82.

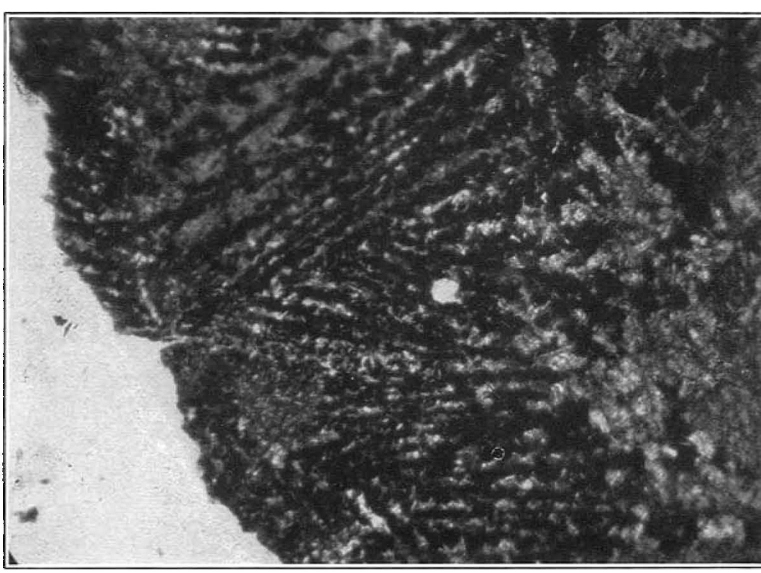


Fig. 2. Photomicrograph showing peculiar intergrowth of magnetite pyroxene and feldspar. The darkest parts are magnetite, the gray feldspar and pyroxene. ×82.

CORE DRILL TESTS FOR POTASH IN MIDLAND COUNTY, TEXAS

BY E. H. SELLARDS AND E. P. SCHOCH

INTRODUCTION

During 1925, 1926 and 1927 two test wells for potash were drilled by the Standard Potash Company on the O. P. Jones ranch in the southwestern part of Midland County, Texas. This locality is within the Great Salt Basin which extends through western Texas, eastern New Mexico, and thence northward into Oklahoma and Kansas, and is near the southern margin of the High Plains region of this basin. The cores obtained from these two wells were made available for study in the field, and selected samples from the cores were brought into the laboratory for closer examination and analysis. The following paper relates to these two wells. The location of the wells is indicated on Figures 11 and 12.

Of the two wells, one was cored by diamond drill from the surface to 2,111 feet, except for short intervals in which the fish tail bit was used. The second well was drilled by rotary, except for occasional coring, to 1,658 feet, below which depth diamond drill was used to 2,617 feet. From the two cores there has been thus obtained a practically complete core section at this locality to a depth of 2,617 feet. This section is supplemented by one or two deep wells drilled in the county by the standard or churn drill method, one of which reached the depth of 4,478 feet.

For the geologic data of the Bulletin, responsibility is assumed by E. H. Sellards and for the chemical data by E. P. Schoch. Sections of the paper not otherwise indicated have been prepared jointly. David McKnight, chemist for the Standard Potash Company, has aided materially

Date of publications, July, 1928.

by records on the cores kept by him as the wells were being drilled.

The search for potash in Texas began as early as 1911. In December of that year Dr. J. A. Udden, then geologist, later Director of the Bureau of Economic Geology of the University of Texas, in company with Mr. W. A. Wrather, visited a well which was being drilled at Spur in Dickens

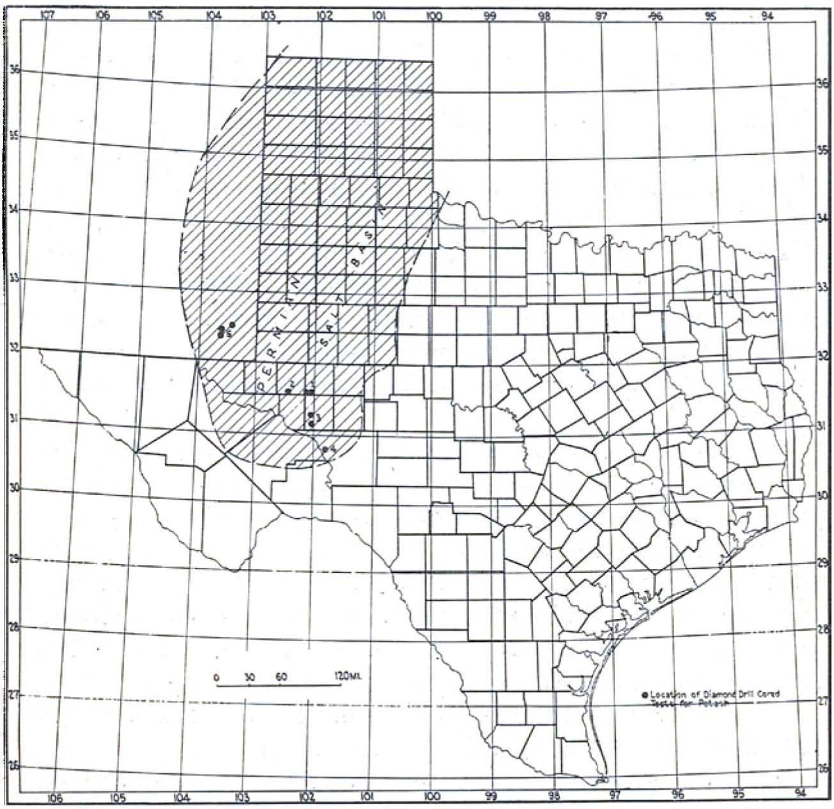


Fig. 11. Location of diamond drill core tests for potash in the Permian Salt Basin of Texas and New Mexico: 1, Midland County; 2, Ector County; 3, Upton County; 4, Crockett County; 5, Lee County. The tests in Midland County were made by the Standard Potash Company (now the American Potash Company); the tests in Ector, Upton, and Crockett Counties have been made by the United States Government under the Potash Act; tests in Lee County have been made by the United States Government, by Snowden-McSweeney interests, and by the Gypsy Oil Company.

County, the well at that time having reached a depth of 2,600 feet. The presence of much anhydrite and salt in this boring, as indicated by the driller's log, prompted the suggestion by Dr. Udden that the water of the well should be analyzed for potash. Later, April, 1912, the water in the well was lowered by pumping to 2,200 feet and a sample taken at that depth. This sample of water was found upon analysis to be unusually high in potash, approximately 5.4 per cent of all solids being potassium chloride. The analysis of this sample of water afforded the first record of the occurrence of potash in the Texas Permian. Some additional samples of water subsequently analyzed from this well and the cuttings and cores obtained from the well were carefully studied, the results of this study being recorded in University of Texas Bulletin 363.[1]

Subsequently well samples were obtained by the Bureau of Economic Geology from several wells in the salt basin of Texas and in 1915 it was possible to report a potash mineral present in three additional wells, as follows: The Borden well in Potter County, the Miller well in Randall County, and the Adrian well in Oldham County. In the winter of 1915–16 the United States Geological Survey began a test boring for potash at Cliffside in Potter County. This boring which reached a total depth of 1,703 feet was discontinued in 1917, no potash having been found.

Under a coöperative arrangement between the Bureau of Economic Geology and the United States Geological Survey rock samples from wells being drilled in the salt basin of West Texas were collected during the years 1918 to 1921. The field representatives in this coöperative work were Mr. O. C. Wheeler, from 1918 to the summer of 1920, and Mr. D. D. Christner, summer 1920 to September, 1921. During Mr. Christner's field work potash minerals were found in the Bryant well in Midland County; the Pitts Oil Company well in Ward County; the Burns well in Dawson County; the Means well in Loving County; the Long or G. A. Jones well in Borden County, and the McDowell well in Glasscock

[1]Udden, J. A., The Deep Boring at Spur, first printing, 1914; second printing, 1926.

County. The potash mineral obtained from these wells was identified in the laboratory of the United States Geological Survey as polyhalite, a hydrated calcium, magnesium potassium sulphate. Analyses of the samples from these drillings were made both by the United States Geological Survey and in the chemical laboratory of the University of Texas. Owing to lack of available funds on the part of the Bureau of Economic Geology the coöperative arrangement with the United States Geological Survey terminated in September, 1921. Similar work, however, has been continued since that time by the United States Geological Survey, Mr. Christner continuing as the Survey representative until November, 1921; since that time the United States Geological Survey representative in the field work has been Mr. H. W. Hoots, and more recently continued to the present time, Mr. W. B. Lang.

The extensive prospecting for oil which is now in progress has resulted in a large number of wells being drilled in recent years in the Texas Permian salt basin in many of which potassium minerals have been detected. However, to determine the thickness of potash bearing strata required, as was early recognized, diamond drill core prospecting. In 1926 the United States Congress passed an act by which there was provided the sum of $500,000, available at the rate of $100,000 per year for prospecting for potash. In the meantime private capital, attracted by the reported occurrence of potash minerals had entered the field and begun exploration for potash by diamond drill coring. In July, 1925, the Standard Potash Company began coring in Midland County, their operations resulting in the two wells here described. Press announcement concerning the first well was made in June, 1926, this being the first definite record based on diamond drill cores showing thickness of potash layers in the Permian salt basin. In 1925 or 1926 the Snowden and McSweeney interest began diamond core prospecting for potash in Lee County, New Mexico. Subsequently the Gypsy Oil Company also inaugurated potash prospecting in New Mexico. Preliminary results obtained under Government appropriation have been announced by the United States Geological Survey on three wells in New Mexico.[2]

PUBLICATIONS

Among the publications relating to potash in the Texas Permian are the following:

Udden, J. A., Potash in the Permian of Texas, American Fertilizer, December, 1912.

——— The Deep Boring at Spur, Univ. Texas Bull. No. 363, October, 1914. Reprinted, 1926.

——— Potash in the Texas Permian, Univ. Texas Bull. No. 17, March, 1915.

——— On the Discovery of Potash in West Texas, Chem. and Metall. Engineering, Vol. 25, pp. 1179–1180, 1921.

White, David, Potash Reserves in West Texas, Mining and Metallurgy, April, 1922.

Hoots, H. W., Geology of a Part of Western Texas and Southeastern New Mexico, U. S. Geol. Surv. Bull. 780B, December, 1925.

Steiger, George, Potash Salts of Western Texas, Chem. and Met. Eng., Jan. 25, Vol. 26, pp. 175–176, 1922.

Mansfield, G. R., The Potash Field in Western Texas, Ind. and Eng. Chemistry, Vol. 15, p. 494, 1923.

Lang, Walter B., Potash Investigations in 1924, U. S. Geol. Surv. Bull. 785–B, 1926.

Sellards, E. H., and Schoch, E. P., Mineable Deposits of Potash Minerals in Midland County, Texas. News edition of Industrial and Engineering Chemistry, Vol. V, No. 21, p. 3, November 10, 1927.

THE GEOLOGIC SECTION IN MIDLAND COUNTY

The formations underlying this part of the High Plains include those of the Cenozoic, Cretaceous, Triassic and Permian. However, at the immediate locality of these wells the Cenozoic sediments have been removed by erosion so that no more than a few feet of soil and residual material overlie the Cretaceous.

CRETACEOUS

The Cretaceous at this locality has a thickness of 200 or 225 feet. Of this interval the uppermost 25 feet or more is

[2]Memoranda for the Press. Issued August 29, 1927 (well No. 1); September 24, 1927 (well No. 2); and February 29, 1928 (well No. 3).

largely a shell breccia in which the genus *Gryphea* predominates. A similar stratum outcrops at the margin of the High Plains to the southwest of these wells, the shell breccia with the overlying Cenozoic forming the rim rock of the escarpment. Underneath the shell breccia is approximately 25 feet of limestone for the most part fine grained, the lower part being more or less sandy. Underneath the limestone are calcareous and non-calcareous sandstones and sands amounting to approximately 150 feet. Surface exposures of the Cretaceous may be seen upon crossing the rim rock on the public road from Odessa to Pecos or from Odessa to McClenny. The Cretaceous of this section is probably of Fredericksburg age.

TRIASSIC

Underneath the Cretaceous are sediments believed to be Triassic in age. These sediments consist of fine silty sand, prevailingly red, although containing inclusions of gray sand. These sediments contain also as a rule mica in small flakes and quite generally sufficient calcium phosphate to be detected by the ammonium molybdate test. No fossils were found in these sediments and their reference to the Triassic is on lithology and resemblance to other Triassic sediments in the state. The Triassic is believed to extend to near 1,342 feet or through an interval of about 1,000 feet.

PERMIAN

The Permian which begins in well No. 1 at 1,342 feet from the surface extends much below the bottom of these wells. The uppermost Permian sediments consist chiefly of red sands and clays. The clays are often mottled and have inclusions of gray clay. The sands are red or dull red and are often moderately well cemented. The sand grains are prevailing small, forming fine-grained sandstones. In the uppermost part of the Permian, approximately the first 100 feet, there is observed only the red sands and clays, there being neither gypsum nor salt present. This interval in well No. 1 extends from 1,342 to 1,465 feet.

With increased depth gypsum veins appear in the cores, the gypsum in these veins being secondarily deposited as satinspar. The interval in which gypsum veins of secondary origin occur in the sandstones in well No. 1 is from 1,465 to 1,728 feet.

The first anhydrite occurring in well No. 1 lies at a depth of 1,748 to 1,754 feet, the corresponding stratum in well No. 2 being at 1,796 to 1,809 feet. The first salt occurring in such quantity as to be the chief constituent of the core is at a somewhat greater depth. In well No. 1 salt crystals and clay were first observed at 1,785 feet and occur generally below this level. In well No. 2 similar salt crystals in shale appear at 1,821 feet. Flame tests, as recorded by Mr. McKnight, indicate the presence of potash in small quantity above these levels. However, potash in the form of polyhalite first appears in appreciable amounts in well No. 2 at 1,929 feet. In well No. 1, owing probably to imperfect core recovery, polyhalite was first obtained in appreciable quantities in the salt at 1,951 feet. Below these depths to 2,617 feet polyhalite is very generally present in varying amounts in association with the salt, and as indicated in the graphic log, in strata of essentially pure polyhalite varying in thickness from a few inches to as much as five feet.

In well No. 2 at the depth of 1,979 to 1,989 or 1,991 feet the core obtained reveals highly soluble potash salts associated with anhydrite. The core through this interval is laminated, a layer chiefly of anhydrite alternating with a layer chiefly of soluble potash minerals. The division of the core into anhydrite and potash mineral layers is not complete as the anhydrite extends somewhat through the potash layers. However, when the soluble minerals are dissolved, the core largely disintegrates. Chemical analyses of the core are given on following pages.

An optical examination of this core was made by Dr. J. T. Lonsdale of the Bureau of Economic Geology, who reports as follows:

An examination of samples from the core from the stratum containing soluble salts showed several minerals. Anhydrite is most abundant and forms a base in which the other minerals occupy interstitial positions with relations suggesting replacement. Carnallite in the piece of core examined is next in abundance and encloses rods and grains of anhydrite. Gypsum was observed in a very few grains enclosed in anhydrite and possibly a hydration product of it. Two biaxial negative minerals were present in small amounts and correspond, possibly, to kainite and vanthoffite. In one grain of carnallite a small area was filled with minute cubes of an isometric mineral, probably halite or possibly sylvite. The core varies considerably in mineralogic nature. Carnallite and anhydrite were fairly constant in amount but the other minerals were present only sparsely and were erratically distributed.

POTASSIUM MINERALS

The principal potassium minerals of the European mines are sylvite, potassium chloride, KCl; carnallite, potassium magnesium chloride, KCl, $MgCl_2$ H_2O; and kainite, potassium chloride and magnesium sulphate, KCl, $MgSO_4$, $3H_2O$. Sylvinite which is largely produced in some of the mines is a mixture of potassium and sodium chlorides, sylvite and halite. Hartsalz is likewise a mixture of minerals consisting of potassium chloride, sodium chloride and magnesium sulphate. From these minerals is obtained the potash produced from the European mines.

Polyhalite, although present in the European deposits, is not there abundant in a pure or unmixed condition and is not mined. In the Texas salt deposits, however, polyhalite is the most abundant potash mineral and occurs, as already indicated, mixed with salt and anhydrite and likewise in strata of the essentially pure mineral. Vanthoffite Na_6, Mg $(SO_4)_4$ referred to as possibly present in the core is a mineral known from the European salt deposits although not occurring in abundance.

CHEMICAL ANALYSES

Analyses have been made in the Bureau of Industrial Chemistry of that part of the core of well No. 2 containing the soluble potash minerals. To obtain the samples for these analyses, the cores were sawed into half cylinders.

Scrapings were then made from the fresh inside surface for a length of twelve inches, thus obtaining at least one-hundred gram portions, which were then ground and mixed to produce homogeneous samples.

The potassium determinations were made by Mr. J. E. Stullken of the Bureau of Industrial Chemistry by means of the perchlorate method, and by Mr. David McKnight, Jr., by the platinic chloride method. The results obtained were essentially the same. Calcium, magnesium and chloride contents were determined by Mr. Stullken by standard titration methods.

The insoluble matter (anhydrite) and the water of crystallization were determined by both Mr. Stullken and Mr. McKnight, and the two results averaged. The insoluble matter was determined by leaching with an adequate amount of water, filtering and heating the residue to remove all water. The leachings were used to determine other constituents of the soluble salts. The water of crystallization was determined by standard methods.

COMPOSITION OF SOLUBLE LAYER

Analysis of sample from depth of 1,981 or 1,983 feet.—In coring through this layer, the driller pulled one barrel of core between 1,975 and 1,985 feet, securing only 6 feet of core,—4 feet above the soluble layer, and 2 feet of potash minerals. A sample was taken from such a portion of the latter as corresponds to a depth of 1,981 feet if the missing 4 feet are assumed to have been lost from the lower end of this barrel,—and at a depth of 1,985 if the missing 4 feet are assumed to be from the uppermost portion of this potash layer. The latter is more likely to be correct because the loss of core was probably due to greater solubility of the material, and in this portion of the barrel there were found some pieces, some as large as 1½ inches in diameter, of a deep red color, which were completely soluble, and which contained "as received" 13.5% K_2O,—that is, much more potash than the remainder of the core.

The center of this core, at 1,981 or 1,985 feet, had the following composition:

	As Received Per Cent	Composition of Anhydrous residue from Aqueous Extract (without Calcium sulphate)
Water of crystallization	9.26	
Portion insoluble in water, anhydrous (practically nothing but $CaSO_4$)	43.60	
Potassium ion	4.06	10.93
or K_2O	(4.88)	(13.17)
Magnesium ion	4.61	12.41
Sodium ion	2.81	7.56
Calcium ion (in extract)	2.98	———
Sulphate ion (in extract)	22.47	41.50
Chloride ion	10.15	27.60
	99.94	100.00

The second column above has been recalculated to express the number of molecules of the simple salts of potassium magnesium, and sodium per 1,000 molecules total of these in the extract:

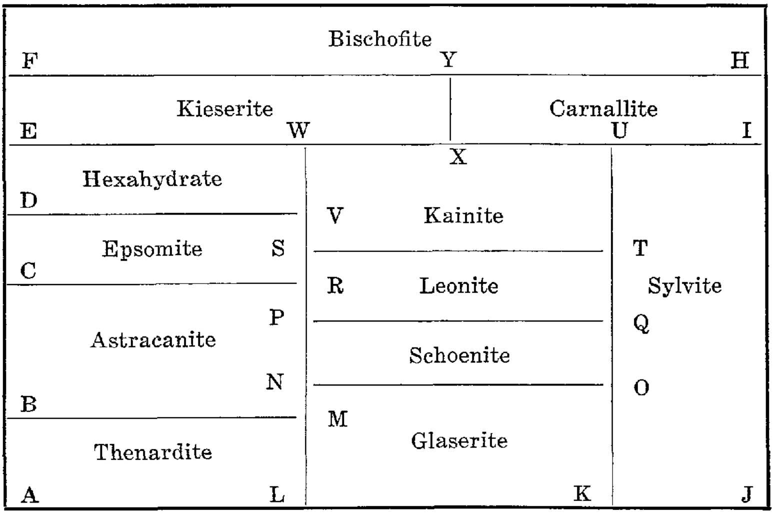
	Molecules
$MgSO_4$	528
Na_2Cl_2	203
K_2Cl_2	172
$MgCl_2$	97
Total	1,000
H_2O	1,700

Since the calcium sulphate is present largely as anhydrite, practically all the water of crystallization in the sample as received belongs to salts of potassium, sodium, and magnesium present, and hence, by calculation, we find that 1,700 molecules of water are present per 1,000 molecules of these salts.

The particular mineralogical combinations of these simple salts of potassium, sodium, and magnesium may now be determined by means of the "paragenesis" diagrams of

Van't Hoff (see Blasdale, Equilibria in Staurated Salt Solutions, page 169). The following diagram presents the mineralogical combinations of these salts which may coexist at 25° C.

25°



The minerals in this diagram have the following composition:

Astracanite	$MgSO_4$, Na_2SO_4, $4H_2O$
Bischofite	$MgCl_2$, $6H_2O$
Carnallite	$MgCl_2$, KCl, $6H_2O$
Epsomite	$MgSO_4$, $7H_2O$
Glaserite	$K_3Na(SO_4)_2$
Hexahydrate	$MgSO_4$, $6H_2O$
Kainite	$MgSO_4$, KCl, $3H_2O$
Kieserite	$MgSO_4$, H_2O
Leonite	$MgSO_4$, K_2SO_4, $4H_2O$
Loeweite	$MgSO_4$, Na_2SO_4, $5/2H_2O$
Schoenite	$MgSO_4$, K_2SO_4, $6H_2O$
Sylvite	KCl
Thenardite	Na_2SO_4

The significance of this diagram is this: Only the substances which are in adjacent squares can remain unchanged when in contact with each other. Hence only three such minerals can be present in contact with each other. These facts were ascertained experimentally by Van't Hoff and his students.

Hence only such three distinct minerals can be present in any portion of this deposit as are shown in contact with each other in this diagram, and their aggregate composition, inclusive of water of crystallization must fit this requirement.

It should be observed in this connection that sodium chloride and calcium sulphate are not to be considered because all the solutions from which these minerals were formed experimentally as well as those in these deposits formed by the evaporation of sea water were also saturated with these two salts, and solid sodium chloride and calcium sulphate were hence neglected from further consideration.

The salts of which the analysis is given above are probably present in the form of the minerals around X and W, because the relative amount of water of crystallization, and the composition of the mixture suffice to give:

	Molecules
Carnallite	87
Kainite	80
Kieserite	357
Hexahydrate	95

Thus it appears that at some points there are the three minerals around X and at others, the three minerals around W.

Analysis of sample from depth 1,987 feet.—The next core barrel pulled extended from 1,985 to 1,991 feet and of this again 2 feet of core were missing.

When the drill was first reinserted to "core" through this length it sank two feet lower than the depth at which it had rested just before where the preceding core terminated. Hence two feet of salts (from 1,985 to 1,987 feet depth) had dissolved while the drill was being removed and replaced. The remaining four feet of core (from 1,987 to 1,991 feet depth) were obtained intact. The top and bottom of this piece (4 feet) of core were analyzed,—with the following results:

The sample from 1,987 feet has the following composition:

	As Received Per Cent	Composition of Anhydrous residue from Aqueous Extract (without $CaSO_4$)
Water of crystallization	9.35	
Insoluble portion	45.23	
Potassium ion	4.08	10.45
or K_2O	(4.92)	(12.54)
Magnesium ion	2.81	7.20
Sodium ion	6.07	15.55
Calcium ion (in extract)	1.88	....
Sulphate ion (in extract)	22.68	46.60
Chloride ion	7.90	20.20
	100.00	100.00

Number of molecules of simple salts of magnesium, potassium, and sodium per 1,000 molecules total of these in the extract:

	Molecules
$MgSO_4$	385
K_2SO_4	175
Na_2SO_4	71
Na_2Cl_2	369
Total	1,000
H_2O	1,740

The 1,740 mols H_2O were obtained by calculation as before: they are the number of mols of water of crystallization in the minerals formed by these salts.

With the aid of Van't Hoff's diagram, we find the mineralogical combinations in which these salts are present to be the following, i.e., those around R and S in the above diagram.

	Molecules
Kainite	81
Leonite	96.5
Astracanite	111.5
Epsomite	96

Analysis of sample from depth 1,990 feet.—The sample from 1,990 feet has the following composition:

	As Received Per Cent	Composition of Anhydrous Extract (without $CaSO_4$)
Water of crystallization	13.49	
Insoluble portion	24.60	
Potassium ion	6.75	13.59
or K_2O	(8.14)	(16.37)
Magnesium ion	6.74	13.56
Sodium ion	1.48	2.98
Calcium ion (in extract)	3.60	....
Sulphate ion (in extract)	33.86	50.81
Chloride ion	9.48	19.06
	100.00	100.00

Number of molecules of simple salts of potassium, magnesium, and sodium per 1,000 molecules total of these in the extract:

	Molecules
$MgSO_4$	660
Na_2Cl_2	81
K_2Cl_2	222
$MgCl_2$	37
Total	1,000
H_2O	1,870

The last is the water of crystallization in the minerals formed by these salts. These numbers of mols, together with the data in Van't Hoff's diagram, lead to the conclusion that these salts are present in the following mineralogical combinations, i.e., those around X and W in the above diagram.

	Molecules
Carnallite	37
Kainite	444
Kieserite	163
Hexahydrate	53

ANALYSIS OF POLYHALITE LAYER FROM WELL NO. 1

Following is the average from thirteen analyses of the polyhalite stratum found in well No. 1 at depth 2075–2080.

	Per Cent
K_2O	15.04
CaO	24.42
SO_3	48.55
H_2O	4.67
NaCl	0.76
MgO	6.56
	100.00

CORRELATIONS BETWEEN WELLS

The two wells as already stated are located between two and one-half and three miles apart, well No. 2 being approximately west of well No. 1. In order to establish a correlation between the two wells the cores were carefully examined and compared through the critical depth of the occurrence of potash to the bottom of well No. 1. In the accompanying sketch, Figure 12, there is given a graph of the wells from the depth of 1,620 to 2,111 in well No. 1 and from 1,658 to 2,211 in well No. 2. It was found that the wells could be readily correlated, particularly by the anhydrite and polyhalite horizons. The recovery of core in well No. 1 was much less complete than in well No. 2, which accounts in part for seeming minor differences in the two wells. (See Fig. 12.)

The dip in the Permian strata is to the west, the corresponding horizons occurring lower in well No. 2 than in well No. 1. The first definite correlation made between the wells is at the first anhydrite horizon. In well No. 1 this stratum lies at the depth 1,748 feet (sea-level datum +1,052).[3] The same stratum is found in well No. 2 at 1,796 feet (sea-level datum +1,008), indicating westward dip of 44 feet in two and one-half miles or 18 feet per mile. The next considerable anhydrite stratum which in well No. 1 is found at 1,779 (+1,021) feet occurs in well No. 2 at 1,837 (+967) feet, the difference between the two wells

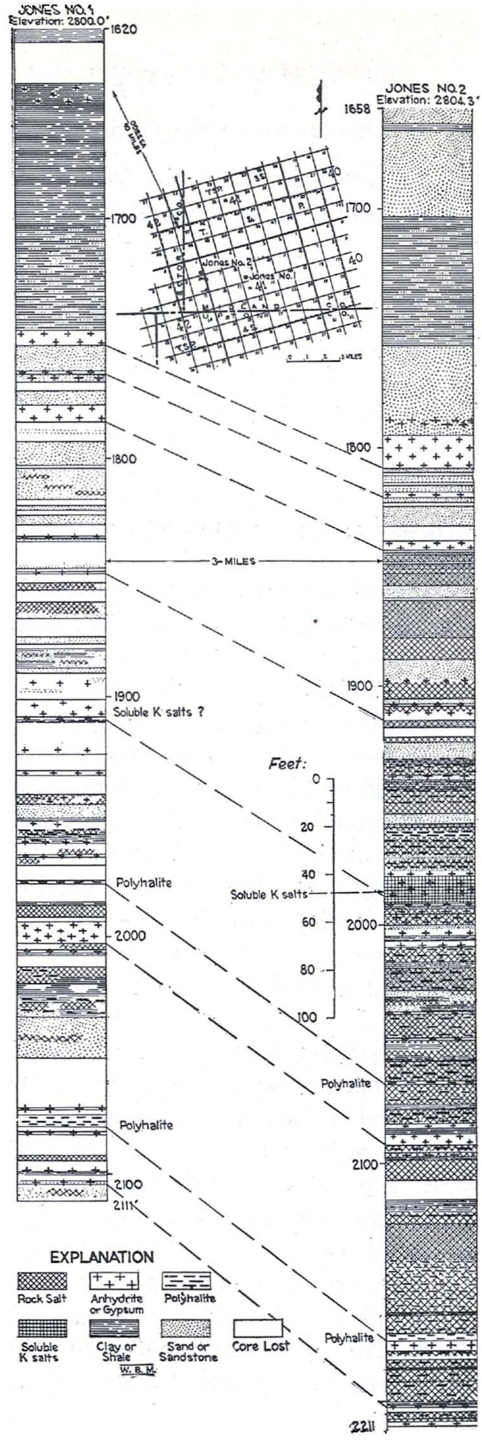


Fig. 12. Correlation between Wells 1 and 2.

at this depth amounting to 54 feet. A thin anhydrite stratum found in well No. 1 at the depth of 1,850 (+950) is correlated with a similar stratum in well No. 2 at 1,810 (+894) or below, the amount of dip at this depth being at least 56 feet, perhaps a little more.[3] At depth 1,908 (+950) in well No. 1 is a thin laminated green clay which correlates with a similar thin clay stratum in well No. 2 at about 1,991 (+813) feet, the interval representing the dip at this depth being about 79 feet. This stratum of clay, as indicated in the graph, lies just under the stratum containing soluble potash salts. The core from the soluble potash horizon in well No. 1 was, with the exception of some pieces of anhydrite, lost in coring owing to the fact that when drilling at this depth the anti-solvent solution was not being used. The use of this solution was begun in well No. 1 at 1,946 feet. However, the occurrence of this layer of soluble potash salts was also revealed by a large increase of potash in the "drill" water.

A thin stratum of polyhalite found in well No. 1 at 1,979 (+821) is found in well No. 2 at 2,067.5 (+737.5) feet, the interval representing the dip being here about 83 feet. A similar rate of dip is indicated in the anhydrite stratum next below which in well No. 1 is found at 1,995½ to about 2,002 feet, and in well No. 2 at 2,087¾–2,093 feet, amount of dip 88 or 89 feet. The deepest horizon in which a definite correlation is made is the polyhalite stratum in well No. 1 at 2,077 (+723) feet and in well No. 2 at 2,172 (+632) feet, the interval representing dip between the two wells being at this depth about 91 feet.

It is thus seen that the Permian strata dip westward and likewise thicken westward. The rate of dip at depth 1,750 feet approximates 18 feet per mile and at depth 2,077 feet approximates 36 feet per mile. The thickening in the strata in two and one-half miles amounts to 47 feet in a stratigraphic interval of 247 feet.

With regard to continuity of strata the anhydrite and potash salts horizons very definitely correlate from one well

[3]The elevation of well No. 1 is not accurately known but is taken at 2,800 feet. Well No. 2 is 4.3 feet higher, or 2,804.3.

to the other, although the recorded thickness for the individual strata is often not the same in the two wells. To some extent this seeming difference in thickness may be due to imperfections in core recovery. It is certain, however, that there are actual differences in thickness of anhydrite strata between the two wells and possibly of the polyhalite strata. The horizons of soluble potash salts as already explained was not recognized in well No. 1 since in the interval in which it should be found there is practically no core recovery other than some pieces of anhydrite from which the potash has been removed by solution.

NOTES ON WELL NO. 1

This well is located on the O. P. Jones ranch in the southwest quarter of Section 9, Block 41, Texas & Pacific Company Survey, in Midland County. The well was begun July, 1925, and completed in April, 1926. Contractor, The Longyear Drilling Company. Total depth, 2,111 feet. Elevation, 2,800. The following notes are largely from a field examination of the core.

	Depth in Feet From	To
Alluvium	0	2
Cretaceous		
Conglomerate of small *Gryphea* shells, the rock material coarsely crystallized	15	20
Shell breccia limestone	21	22.5
Marly limestone rock containing *Pecten* and some other shells; also large calcite crystals	22.5	25
Breccia of small *Gryphea* shells	25	28
Shell breccia including large *Gryphea* at depth of 40 feet	28	40
Fine-grained limestone	40	50
Gray limestone with few organic fragments	51	64
Sandy calcareous rock	64	77
Friable gray non-calcareous sandstone	77	78
No core obtained from this interval, probably friable sands	78	200
Calcareous sandstone rather coarse grained, sand grains well rounded. Fish-tail bit used. Base of Cretaceous sands	200	238
Triassic		
Fish-tail bit used. Largely shales	238	332
Fine silty sand, red with inclusions of gray sand containing much mica. This sample consists of very fine silt	332	338

	Depth in Feet From	To
Sandy non-calcareous micaceous material	338	377
Maroon red sands with minor inclusions of gray sands	377	535
Fine-grained micaceous sandstone and clay	537	577
Prevailingly red sandstones and red clays and silts	577	1068
Red sandstone and clays, calcareous and phosphatic	1068	1108
Red somewhat coarse sands slightly calcareous	1275	1342
Coarse calcareous sands		1342
Permian		
Mottled red sandy clay with gray clay inclusions	1342	1358
Alternating layers of sand and rich red clays	1358	1374
Very sandy clay prevailingly red mottled with gray	1374	1386
Largely red sand with gray calcareous inclusions	1386	1395
Mottled sandy clay, red with gray inclusions	1395	1421
Fine sandstone or clayey sand, red with gray inclusions	1421	1440
Mottled red clay with gray inclusions	1440	1465
Mottled red sandstone with more or less clay. Some gypsum present	1465	1570
Mottled sandstone, gypsum veins, and some clay	1570	1620
Mottled sandstone with some clay and with veins or bands of gypsum	1620	1675
Mottled sandstone, red and gray, red predominating, gray occurring as inclusions in the red	1675	1748
Anhydrite. First or uppermost anhydrite	1748	1754
Mottled red and gray sandstone with some anhydrite	1754	1779
Anhydrite	1779	1785
Red more or less salty sand, including perfectly formed salt crystals of large size, this being the first salt observed in the well. Three inches of anhydrite at 1850 feet	1785	1879
Red sand containing more or less salt	1879	1900
Core largely lost, remnants indicate some anhydrite. This interval believed to contain soluble potash salts and anhydrite. The laminated clay at the base of this interval correlates with similar clay underlying the stratum of soluble potash minerals in well No. 2	1900	1908
Chiefly anhydrite containing in places some salt and clay. Recovery poor	1908	1920
Anhydrite	1920	1922.5
Core not recovered	1022.5	1929
Anhydrite	1929	1931.33

	Depth in Feet From	To
Core not recovered except some pieces of salty clay and anhydrite	1931.33	1941
Imperfect recovery consisting of red salt, and some clay	1941	1945
Puddled material consisting of clay, anhydrite, and salt	1945	1946
Red sands with inclusions of rich red clays	1946	1951
Anhydrite with salt and polyhalite as inclusions and stringers. Upper one-half foot is rich red clay with salt crystals. This core contains the first polyhalite observed in well No. 1 although it occurs in well No. 2 at 1929 feet, which stratigraphically would correspond to about 1865 in this well	1951	1955
Small recovery consisting chiefly of salt with polyhalite as inclusions	1955	1961
Core largely lost except large salt crystals in clay, some anhydrite, and red clay	1961	1971
Recovery of about one and one-half feet including some pure red salt and some polyhalite. This polyhalite stratum at 1979 correlates with stratum in well No. 2 at 2065	1971	1983
Reddish to dark clay	1983	1985
Dark colored salt	1985	1995.5
Dark colored anhydrite	1995.5	1998
Red and drab blue clay and anhydrite	1998	1999.5
About five feet of core consisting of anhydrite with salt crystals	1999.5	2004.5
Core of salt with polyhalite	2004.5	2006
Salt with clay inclusions	2006	2007
Poor recovery consisting of red and drab green sticky clay	2007	2008
Dark colored salt with inclusions and stringers of red clay, and some polyhalite. Recovery about five and one-half feet	2008	2020
Imperfect recovery of dark red clay with some polyhalite and salt	2020	2024
Drab clay with inclusions of salt crystals. Imperfect recovery	2024	2025.75
Drab colored salt with polyhalite stringers	2025.75	2029.75
Core of mixed polyhalite and salt, the salt predominating; some kieserite present	2029.75	2034.75
White well crystallized salt and polyhalite	2034.75	2035

	Depth in Feet From	To
Chiefly red fine-grained sand. The sand grains are uniform and moderately well rounded. Salt crystals in the sand. Imperfect recovery	2035	2051
Imperfect recovery. Corresponds to polyhalite-salt interval in well No. 2 at depth 2145–2160	2061	2077
Polyhalite corresponding to stratum in well No. 2 at about 2176[4]	2077	2082
Anhydrite, polyhalite, and gray clay	2082	2092
Opaque clear salt with slightly reddish tinge and some polyhalite	2092	2094
One foot of core obtained consisting of a few inches of anhydrite sandy clay and a few pieces of rock salt	2094	2103
Anhydrite, friable red sand, and loose sand	2103	2104
Imperfect recovery consisting of pieces of salt and red sandstone	2104	2111

NOTES ON WELL NO. 2

This well which is located on the southeast quarter of the southeast quarter of Section 1, about two and one-half miles west and slightly north of well No. 1, was drilled by rotary to the depth of 1,658 feet and diamond drilled cored from 1,685 to 2,617 feet. The rotary drilling was chiefly by fish-tail bit, although occasional cores were taken as indicated in the descriptions which follow. The well was begun July, 1926, and completed July, 1927. Total depth, 2,617 feet. Elevation, 2,804.3 feet.

The following notes on this well from depth 0 to 1,975 and from 2,192 to 2,617 were made by David McKnight as the well was being drilled. The notes on the core, depth 1,975 to 2,192, are, as were those of well No. 1, based largely on field examination of the cores.

	Depth in Feet From	To
Bailings consisting largely of limestone fragments	1	66
Sample effervesces with hydrochloric acid but major part remains undissolved, the residue being sand	66	100
Mostly yellow sand with small amount of limestone as shown by effervescence in acid	100	150
Coarse gray sand colored by small amount of red mud; some limestone present; good water sand	150	183

[4]The full thickness of five feet for this stratum was not seen by Dr. Sellards because parts had been used for various purposes previous to his examination of the core.—E.P.S.

	Depth in Feet From	To
Red mud, calcareous and slightly micaceous	465	499
Particles of hard red shale and a few particles of gray shale; washing shows mica flakes; some limestone present as indicated by effervescence in acid, but no sand; molybdate solution indicates some phosphate present	690	700
Lumps of red shale and gray sand; some phosphate present	700	710
Lumps of red sand and some gray shale; mica flakes present	730	740
Red and gray shale containing mica flakes and limestones; phosphatic	750	760
Sandy red shale with mica flakes; phosphatic	800	810
Red shale and some gray shale; sandy	820	830
Core of hard red sandy shale, in places containing large amounts of mica. Core obtained by drilling in side of the beds. Ten feet of core obtained; diameter six inches	838	858
Red shale and some gray sand; no mica; trace of phosphate	870	875
Red shale and some gray shale; some sand; calcareous and slightly micaceous; trace of phosphate	880	885
Red and some gray shale; a number of transparent sand grains; some mica; calcareous and phosphatic	895	900
Red and gray shale and sand grains	900	903
Core, the uppermost part of which is puddled clay and sand representing cavings. Below this two feet of hard gray coarse sand, one piece of which contains gravel, followed by one foot of gray sandy shale with layers of red shale; four feet of core obtained	903	914
Red shale and numerous rounded transparent sand grains; phosphatic; no mica	920	925
Red clay and some gray shale somewhat sandy	950	955
Red and some gray shale including some sand, limestone, and mica	980	985
Similar to 980–985, although more sandy and slightly phosphatic	997	1000
Red shale and red sandstone; a few white sand grains and pieces of gray shale and white lime	1017	1020
Core consisting of 2 feet of red and gray sandstone containing mica; 4.5 feet of calcareous		

	Depth in Feet From	To
clay-ball conglomerate; 3 feet of hard, red, sandy shale; 9.5 feet core recovered	1024	1036
Core consisting of 10 inches hard red sandy shale, remainder red and gray sandstone, a part of which is laminated, the laminae lying approximately horizontal; 6 feet recovered	1036	1052
Core consisting of 13 feet of red sand with thin layers of very calcareous red and gray shale containing much mica; 2 feet hard red shale with mica; 4 feet red sand; and 3 feet red shale; 22 feet recovered	1052	1081
Core of hard red shale with much mica; 2 feet recovered	1081	1083
Core consisting of 4 feet of red and some blue shale with much mica, remainder red sandstone and a few thin layers of red and blue shale and calcareous clay-ball conglomerate; 9.5 feet recovered	1083	1094
Core consisting of 6 inches red and gray sand; 2.5 feet red shale with spots of blue shale and much mica; 1 foot clay-ball conglomerate; 4 feet hard red sandy shale with much mica; 8 feet recovered	1094	1102
Core consisting of 9 feet red sand and shale and 1 foot of hard red and blue shale with much mica; 10.5 feet recovered	1102	1117
Core consisting of red and blue shale with little mica; 1 foot of gray sandstone; and 2 feet of pebble conglomerate; 13 feet recovered	1117	1132
Core consisting of 2 feet of conglomerate; 7 feet red shale with much mica; and 1 foot of calcareous sandstone; 10 feet recovered	1132	1156
Core consisting of 1 foot sandstone; 7 feet of hard conglomerate; 1 foot hard sandstone; 9 feet recovered	1156	1170
Rainbow of oil on the sump	1170	1177
Core consisting of 1 foot sand-lime conglomerate, remainder being hard gray sandstone; drilling very hard; 2.75 feet recovered	1177	1181
Core consisting of 4 feet conglomerate, the remainder being hard sandstone and shale; 9 feet recovered. Some pebbles of the conglomerates as large as three-fourths inch diameter	1182	1193

	Depth in Feet From	To
Core consisting of 2 feet sandy shale, the remainder being hard gray sand; 4 feet recovered. This core may be Permian	1193	1202
Core consisting of 2 feet sand-lime mixture, remainder being sandstone in which are included a few lumps of shale; 6 feet recovered	1202	1215
Core of red sandstone including a few lumps of red shale in the upper part; 4 feet recovered	1215	1225
Core of hard red sandstone with some gray spots; 6 feet recovered	1242	1252
Core of hard coarse red sandstone; 2.5 feet recovered	1252	1259
Cuttings consisting of red sandy shale particles	1270	1280
Cuttings of coarse red sandstone	1280	1290
Cuttings of red sand	1290	1298
Cuttings of red shale	1305	1311
Cuttings of sandstone	1311	1314
No recovery	1314	1326
Cuttings of sand grains and shale	1326	1333
Cuttings of sandstone and shale	1333	1363
Cuttings give negative test for potash	1372	1374
No cuttings obtained	1375	1420
Cuttings of red sandstone and shale	1420	1427
No cuttings obtained	1435	1502
Cuttings of red sandstone and shale; phosphatic	1502	1510
No cuttings obtained	1512	1532
Cuttings of red shale and sandstone	1532	1540
Cuttings of gray and red sandstone	1540	1547
No cuttings obtained	1547	1602
Piece of light red pure shale; slightly calcareous; some pieces of gypsum and some phosphate present, but no mica; show of oil and gas	1602	1605
Cuttings of red shale with a little sandstone and some particles of gypsum	1605	1609
Cuttings giving slight test for oil	1609	1614
Red shale with some sandstone and gypsum, faint potassium flame	1614	1616
No cuttings obtained	1616	1635
Cuttings of light red shale with some sandstone and gray shale and gypsum; faint potassium flame, and trace of salt	1636	1638
Show of gas at 1641	1638	1644
Cuttings of red calcareous shale with sandstone and limestone	1645	1646

	Depth in Feet From	To
Cuttings of light red sandstone and calcareous shale	1650	1653
Cuttings of light red shale and sand, trace of salt	1656	1658
Core of hard gray and red sandstone and red shale; a few mica flakes; 2 feet recovered	1658	1660
Core consisting of 1 foot red shale, 5 feet red sand with thin seams of soft red shale; 2 feet of hard red and gray shale; 8 feet recovered. Core contains bands of gypsum	1660	1668
Core of compact red shale with seams of red sandstone and mottled gray shale crystalline gypsum and some mica flakes; 7 feet recovered	1668	1675
Core of hard compact red shale with seams of mottled red and gray shale and thin gypsum bands; 15 feet recovered	1675	1690
Core of very hard sandy red shale with seams of pure red shale and mottled red and gray shale; 11 feet recovered	1690	1701
Hard red shale; 8 feet recovered	1701	1709
Hard red shale with softer seams of sandy red shale; 16 feet recovered	1709	1725
Hard red shale with seams of mottled red and gray shale and sandstone. Drill water at this depth indicates potassium in flame test; 7 feet recovered	1725	1732
Hard red shale with few seams of gray shale and sandstone; 10 feet recovered	1732	1743
Hard red shale with few seams of red sand; 20 feet recovered	1743	1763
Hard red shale; 3 feet of core obtained	1763	1767
Fine red, hard sandstone; 13 feet of core obtained	1767	1780
Hard, red sandstone and shale including 1 foot of anhydrite; 8 feet of core obtained. Potassium indicated in flame test	1780	1788
Seven and one-half feet of core consisting of 2 inches of anhydrite; 4.5 feet of hard, red, sandy shale and at the bottom an additional foot of anhydrite. Potassium indicated in flame test. Gypsum band crossing core diagonally at 1789	1788	1796
Hard, white and gray anhydrite; 12-foot core obtained	1796	1809
Core consisting of 6 inches hard, gray anhydrite; 8.5 feet hard, salty, red shale and 2 feet of hard anhydrite; 10.5 feet recovered	1809	1821

	Depth in Feet From	To
A drilling solution of magnesium chloride, magnesium sulphate, and sodium chloride to retard or prevent the solution of potassium salt was used at 1821 feet and below.		
Core of red shale with some gray shale and inclusions of anhydrite and a few crystals of salt	1821	1825
Core of red shale and anhydrite and some salt; 1 foot recovered	1825	1827
Core of red sandy shale with seams of softer shale and blotches of gray shale and anhydrite; 4.5 feet recovered	1827	1833
Core of red and gray shale and anhydrite; 2.5 feet recovered	1833	1842
Core of which 1 foot is anhydrite and remainder white and pink salt with inclusions of sandy shale; 13 feet recovered	1842	1856
Core of which 3 feet is salt with inclusions of red shale, remainder being red sandy shale with large salt crystals; 6 feet recovered	1856	1862
Core of red sandy shale with many large salt crystals; 9 feet recovered	1862	1873
Core consisting of 8 feet red sandy shale, some large crystals of salt; 8 feet of salt; 1 foot red shale with much salt; 17 feet recovered[5]	1873	1890
Core consisting of 8 feet of red sandy shale with many salt crystals; 7 feet rock salt with some inclusions of red sandy shale; 3 feet red sandy shale with many salt crystals; and 2 feet rock salt with much shale; 20 feet of core recovered	1890	1910
Core consisting of 6 inches salt, 6 inches anhydrite, 1 foot salt, 6 feet salty shale, 1.5 inches pink anhydrite, and 4 feet fine red sand; 12 feet of core recovered	1910	1929
Core consisting of 2 feet fine red sand, 2 feet red and gray salty shale, 6 feet salt with inclusions of anhydrite and some polyhalite, 4 feet sandy red shale with salt crystals, 6 feet salt with inclusions of polyhalite and anhydrite; 20 feet recovered	1929	1950
Core of which 4.5 feet is salt with inclusions of polyhalite and red sand; 6 feet fine red sand with inclusions of salt and polyhalite; and 6.5 feet of salt with inclusions of sand and polyhalite; 17 feet recovered	1950	1967

[5]The description of cores is from the top downwards.

	Depth in Feet From	To
Core consisting of 5.5 feet of salt with inclusions of anhydrite and polyhalite; and 1 foot anhydrite with inclusions of salt and polyhalite; 6.5 feet recovered	1967	1975
Core consisting of 3 feet salt with polyhalite; 1 foot impure anhydrite, the remainder being soluble minerals, carnallite in part, in layers alternating with anhydrite; 6 feet recovered	1975	1985
Core consisting chiefly of soluble minerals, and a few inches of thinly laminated shale with anhydrite; 4 feet recovered	1985	1991
Slight recovery of core, part obtained being salt, polyhalite and clay	1991	1994
Dark colored salt and anhydrite	1994	1996
Anhydrite and dark salt	1996	2001
Two feet of core recovered consisting of anhydrite	2001	2005
Hard red shales	2005	2008
Partial recovery, the recovered portion being chiefly red clays; a 2-inch stratum of anhydrite at 2010	2008	2010
Dark colored salt with polyhalite	2010	2015
Anhydrite with salt	2015	2016
Maroon clays and sand with salt	2016	2018
Dark salt with polyhalite	2018	2028
Mostly sand with salt	2028	2038
Largely salt with polyhalite	2038	2049
Salt with much clay; eight inches of anhydrite at 2048 feet	2049	2058
Dark colored salt with polyhalite	2058	2067.5
Polyhalite	2067.5	2068
Dark colored salt with some polyhalite	2068	2076
Sandy clay	2076	2077.5
Dark colored salt with polyhalite	2077.5	2081.75
Salt and anhydrite	2081.75	2086
Greenish-gray soft shale merging below with anhydrite	2086	2087.75
Anhydrite	2087.75	2093
Clear salt with polyhalite	2093	2095.5
Anhydrite and salt	2095.5	2097.3
Hard greenish-gray sandy clay	2097.3	2098
Dark colored salt	2098	2108
Core not recovered	2108	2115
Salt and some clay and red clay and sand	2115	2119

	Depth in Feet From	To
Dark colored salt with some clays and opaque clear salt with polyhalite; only 1 foot recovered	2119	2126
Core consisting of 6 feet of sand with salt crystals, 3 feet of salt with some clay and polyhalite, 2.5 feet salt and much polyhalite, and 1 foot of dark salt; much polyhalite in the salt at 2143.5–2145 feet and at 2148 feet; 12 feet recovered	2126	2147
Salt with polyhalite. Two-inch stratum of polyhalite at 2150 and at 2162	2147	2162
Core not recovered	2162	2163.25
Red salty clay	2163.25	2164.5
Salt with some polyhalite and clay	2164.5	2171
Salt	2171	2172
Polyhalite	2172	2175.5
Anhydrite	2175.5	2179.5
Salt and polyhalite	2179.5	2181.75
Anhydrite	2181.75	2182.3
Salt	2182.3	2183.6
Clear salt with some polyhalite	2183.6	2185.5
Clay with salt	2185.5	2186.5
Salt with polyhalite	2186.5	2189
Core not recovered	2189	2189.75
Salt and polyhalite	2189.75	2191
Core not recovered	2191	2192
Core consisting of 4 feet salt with polyhalite inclusions, .5 foot of polyhalite with some salt (9% K_2O), 4 feet salt with polyhalite, 1 foot of clay with salt inclusions; 10 feet recovered	2192	2203
Core consisting of 3 feet dark red sandy shale containing thick vertical and diagonal veins of pink salt; 3 feet of salt and polyhalite with inclusions of dark red shale and sand; 2 feet gray anhydrite with salt crystals; 3 feet salt and polyhalite; 4 feet of red sandy clay with salt and some polyhalite; 1 foot of salt and polyhalite; and 1 foot of red sand and salt; 17 feet recovered	2203	2220
Core consisting of 4 feet dark red sandstone including salt and 3 feet red clay with some salt; 7 feet recovered	2220	2227
Core consisting of 3 feet red clay with salt, and 15 feet salt and polyhalite; 18 feet recovered	2227	2245

	Depth in Feet From	To
Core consisting of 6 feet of salt with polyhalite, 1 foot polyhalite with salt (7.8% K_2O), 1 foot anhydrite with salt; 8 feet recovered	2245	2253
Core consisting of 4 feet of salt with polyhalite, 2.5 feet of salt, red and gray sand and shale, some anhydrite, .25 foot plastic clay and 1.25 feet red sand with salt; 8 feet recovered	2253	2261
Core consisting of 7 feet of salt with much clay and sand, 5 feet of salt with polyhalite, 2 feet of salt, anhydrite, clay and polyhalite, 1 foot red clay, 3 feet of salt, clay, anhydrite and polyhalite; 18 feet recovered	2261	2279
Core consisting of 1 foot of anhydrite with polyhalite, 7.5 feet of salt with polyhalite, 6.5 feet of salt clay and anhydrite; 15 feet recovered	2279	2296
Core consisting of 4 feet of salt with polyhalite and 1 foot of red clay with salt; 5 feet recovered	2296	2301
Core of red salty clay	2301	2302
Core consisting of 9 feet of salt and polyhalite, 1.25 feet hard white anhydrite, .25 feet polyhalite; 10.5 feet recovered	2302	2313
Polyhalite	2313	2315
Core consisting of 4.5 feet of salt and polyhalite, 4 inches of polyhalite, and 2 inches of hard gray shale; 5 feet recovered	2315	2321
Core consisting of 3 feet of salt and clay, 2 feet of fine red sand with some salt and 8 feet of salt, sand and anhydrite; 13 feet recovered	2321	2336
Core consisting of 5 feet of salt, sand and anhydrite, 5 feet of salt with some anhydrite and 1 foot of anhydrite; 11 feet recovered	2336	2347
Core consisting of 5 feet of salt, 2 feet salt and polyhalite, 3 feet of salt, clay, anhydrite and polyhalite and 8 feet of salt and polyhalite; 20 feet recovered	2347	2367
Core consisting of 6 feet of salt, 5 feet of salt and polyhalite, 1 foot polyhalite, 7 feet of salt, 1 foot salt and polyhalite; 20 feet recovered	2367	2387
Salt with polyhalite and some clay; 6 feet of core recovered	2387	2401
Core consisting of 6.5 feet of salt with polyhalite and clay, 3.5 feet of salt and polyhalite, 1 foot		

	Depth in Feet From	To
of polyhalite, 5 feet of salt with clay inclusions; 16 feet recovered	2401	2419
Core consisting of 2 feet of salt with polyhalite, 2 feet of anhydrite, 12 feet of salt with polyhalite and 4 feet of red clay with salt; 20 feet recovered	2419	2439
Core consisting of 1 foot of red clay with salt, 6 feet of salt, 1 foot of polyhalite, 12 feet of salt; 20 feet recovered	2439	2459
Core consisting of 2 feet of salt and 14 feet of salt with polyhalite. Thin seam of red clay at 2474; 16 feet recovered	2459	2475
Core consisting of 2 feet of salt with red mud, 1 foot of clear salt, 5 feet of salt with polyhalite, 3 feet of salt with red clay, 2 feet of salt with polyhalite, and 1 foot of red clay with salt; 14 feet recovered	2475	2491
Core consisting of 2 feet of salt with sand, 4 feet of salt with polyhalite, 2 feet of polyhalite with salt and 1 foot of clear salt; 9 feet recovered	2491	2500
Core consisting of 7 feet of salt with polyhalite, 2 feet of salt with red clay, 3 feet of salt with polyhalite, 1 foot of anhydrite and salt and 7 feet of salt; 20 feet recovered	2500	2520
Core consisting of 1 foot of salt, 2 inches polyhalite and 10 inches of anhydrite; 2 feet recovered	2520	2533
Core consisting of thin anhydrite seam at top, 8 feet of impure salt with little polyhalite, 2 feet of clear salt, 3 feet of salt with polyhalite, 6 feet of impure salt; 19 feet recovered	2533	2552
Core consisting of 7.5 feet of anhydrite with polyhalite and 7.5 feet of impure salt; 15 feet recovered	2552	2561
Core consisting of 7.5 feet of impure salt with little polyhalite and 2.5 feet of anhydrite; 10 feet recovered	2561	2575
Core consisting of 1 foot of anhydrite, 3 feet of salt with polyhalite, 4 feet of impure salt with some polyhalite, 4 feet salt with polyhalite, 3 feet of impure salt and 3 feet salt; 18 feet recovered	2575	2593
Core consisting of impure salt with a 4-inch stratum of polyhalite at bottom; 7 feet recovered	2593	2609
Core consisting of impure salt with a little polyhalite; 8 feet recovered	2609	2617

WELL ON THE BRYANT RANCH

A deep well drilled in 1921 on the Bryant ranch about nine miles southwest of Midland, total depth 4,478 feet, affords a record as made by the standard or churn drill through the Permian salt series to the underlying Permian limestones and dolomites. This well is located on Section 9 (northeast corner of section), Block 39, S. T. & P. Survey. The following log is the driller's record preserved under the direction of Frank H. Weaver, drilling superintendent. The description of samples to a depth of 1,670 feet was made in the Bureau of Economic Geology by Miss H. T. Kniker in 1921 from samples submitted by O. C. Wheeler while acting as a joint representative of the United States Geological Survey and the Bureau of Economic Geology. The description of samples from 2,475 to 4,478 was made in the Bureau of Economic Geology by R. T. Short from samples submitted by D. D. Christner. The record of this well is of interest not only as reaching through the salt series but also as the first well in which the occurrence of potash was discovered in Midland County.

Casing record: 20-inch to 172 feet, 15½-inch to 606⅓ feet, 12½-inch to 906 feet, 10-inch to 1,339 feet, 8-inch to 2,680 feet, 6⅝-inch to 3,530 feet.

Driller's Log

	Depth in Feet		
	From	To	Thickness
Yellow sand and clay	0	6	6
Shattered lime	6	12	6
Red and yellow sand, no water	12	80	68
Red sand, small amount of fresh water	80	84	4
Red clay and soft yellow sand, no water	84	133	49
Hard red sand, good supply fresh water	133	139	6
Red shale (red bed series)	139	780	641
Red sand, small amount of fresh water	780	795	15
Red beds	795	815	20
Gray sand, no water	815	835	20
Red beds	835	960	125
Red sand, no water	960	980	20
Red beds ("alkali," fresh water at 990)	980	1040	60
Red sand with streaks of red beds	1040	1136	96
Red beds	1136	1141	5
Gray sand, small amount of fresh water	1141	1196	55
Gray sand, fresh water	1196	1210	14
Red beds	1210	1215	5
Gray sand, no water	1215	1233	18
Red beds	1233	1245	12
Gray sand	1245	1283	38
Red beds	1283	1290	7

	Depth in Feet From	To	Thickness
Gray sand	1290	1295	5
Red beds	1295	1304	9
Gray sand	1304	1350	46
Red beds	1350	1358	8
Gray sand, first salt water	1358	1398	40
Red beds	1398	1665	267
Gray sand, some water	1665	1670	5
Red beds	1670	1740	70
Red rock	1740	1760	20
Salt rock and shells	1760	1925	165
Red and gray shale	1925	1940	15
Blue and gray shale	1940	1961	21
Very hard limestone* and rock salt	1961	1977	16
Salty red and gray shale	1977	2020	43
Light sand, small amount of salt water	2020	2077	57
Red shells, salt and shale	2077	2475	398
Hard gritty limestone (Anhydrite. See sample description)	2475	2484	9
Blue shale	2484	2488	4
Red shells and salt	2488	2500	12
Red salt and gray shale	2500	2670	170
Red and gray shale	2670	2735	65
Gray shale and salt	2735	2745	10
Gritty gray shale	2745	2752	7
Red rock	2752	2764	12
Hard gray rock	2764	2770	6
"Rotten" sand	2770	2810	40
Sand and limestone*	2810	2840	30
Red rock	2840	2855	15
White gritty limestone (Anhydrite. See sample description)	2855	2885	30
Red rock	2885	2920	35
White limestone*	2920	2945	25
Red rock and sandy shells	2945	3028	83
White shelly formation	3028	3225	197
Red sand, salt and mud	3225	3390	165
White sandy limestone*	3390	3405	15
Red rock and salt	3405	3448	43
Gray limestone*	3448	3460	12
Red sandstone	3460	3525	65
Very hard white sand	3525	3600	75
Salt, red and gray limestone* and shells	3600	3705	105

*Probably anhydrite.

		Depth in Feet From	To
Red sand and rock salt	3705	3790	85
White sand	3790	3800	10
Red sand and lime shells	3800	3835	35
Red rock	3835	3845	10
Red sand and lime shells	3845	3930	85
White sand	3930	3950	20
Red sand and salt	3950	3990	40
White sand	3990	4010	20
Red sandy limestone (Anhydrite and sandstone. See sample description)	4010	4060	50
White sand	4060	4075	15
Red rock and salt	4075	4085	10
White sand	4085	4100	15
Red sand and salt	4100	4190	90
Pure crystal white salt	4190	4290	100
Limestone (dolomite)	4290	4320	30
Red sand and salt	4320	4390	70
Gray sand and some salt	4390	4420	30
Gray lime, very hard, increasingly harder and darker	4420	4466	46
Gray sand, hole filled with hydrogen sulphite water	4466	4476	10
Very hard gray lime (Dolomite. See sample description)	4476	4478	2

Description of Samples by H. T. Kniker

	Depth in Feet From	To
Well rounded polished sand, partly reddish and partly clear, mingled with brown clay. Mechanical analysis of sand: coarse sand 17%; medium sand, 26%; fine sand, 45%; very fine sand, 12%. Cenozoic	0	9
Several fragments of concretions of pinkish-white soft limestone containing sand grains. Most of the sand grains are less than one-fourth mm. in size, but some are as large as one mm. Cenozoic	9	29
Brownish-red very slightly calcareous clay containing fine, rounded sand. Most of the sand is clear, but some is red and a few grains are composed of gray chert. Several minute perfect quartz crystals were noted. Mechanical analysis		

	Depth in Feet From	To
of sand: coarse sand, 7%; medium sand, 12%; fine sand, 43%; very fine sand, 38%. Triassic	154	164
Brownish-red clay such as found at 154–164, but containing only a very small amount of sand; some red and white calcareous fragments, probably from concretions	164	490(?)
Brownish-red very slightly calcareous clay; some fine subangular sand, mostly less than one-eighth mm. in size, fragments of reddish calcareous sandstone and some limestone, probably from concretions, and some flakes of mica, mostly muscovite	490	500
Like sample from 490–500. Contains a few well rounded sand grains from one-eighth mm. to one mm. in diameter	500	515
Brownish-red slightly calcareous clay containing some minute sand grains, fragments of red limestone, probably from concretions, some well-rounded sand grains up to one mm. in diameter and a few mica scales	550	
Like samples from 550. A few fragments of gray concretionary limestone are present	610	
Brownish-red very slightly calcareous clay containing brown ferruginous limestone concretions and fragments of concretions; few light gray fragments of limestone, probably from concretions. In washed material a few rounded, polished sand grains and mica scales were noted. In thin section two fragments of brown limestone are seen to be of fine-grained texture and to contain minute grains of sand, about one-fiftieth mm. in diameter. A limestone concretion shows a roughly banded structure, the bands of brown fine-grained calcareous material and finely crystalline limestone being curved	640	
Brownish-red very slightly calcareous clay containing some rounded slightly polished sand grains and some mica. Most of the sand grains are less than one-fourth mm. in diameter. Fairly large clear, green, and brownish mica flakes were noted	670	
Like sample from 670	680	
Brownish-red very slightly calcareous clay containing fragments of light gray calcareous sand-		

	Depth in Feet From	To
stone concretions, a few fragments of fine-grained limestone concretions, clear and green flakes of mica and some rounded sand grains, one-fourth to one mm. in diameter. The sand grains of the concretions are mostly less than one-fourth mm. in diameter	700	
Purplish-red calcareous fine-grained sandstone containing considerable mica, and purplish-brown non-calcareous clay. A crystal of quartz one-half mm. long was noted	875	
Purplish calcareous sandstone containing mica, most of the sand grains being less than one-fourth mm. in diameter	1100	
Red calcareous sandstone composed of sand grains of various sizes, the largest ones being round and measuring two mm. in diameter. Some of the grains show crystalline faces. A few small very fine-grained sandstone concretions are present. Possibly Permian	1300	
Some reddish and some clear quartz sand, a few grains being composed of gray chert. Many of the grains show crystal faces, but some are well rounded	1340	
Brownish-red non-calcareous clay. Washed material consists of clear and reddish round and subangular slightly etched sand grains, even the smallest ones being rounded, a few fragments of red concretionary sandstone and light gray dolomite, and a few crystals of anhydrite. Permian	1540	1750
White and reddish anhydrite and some red clay, light gray and red fairly coarsely crystalline dolomite, and fine round etched sand, some of the grains having crystal faces. Permian	1670	

Description of Samples by R. T. Short

	From	To
Pink and red rock salt, resembling carnallite, and a few fragments of brown shale and anhydrite. The pink salt contains potash	2405	2425
Brown salt and gypsum. In the washed material a very little quartz sand was noted	2475	

	Depth in Feet From	To
White anhydrite and red shale. In the washed material some quartz sand was noted. Numerous small calcareous concretions and many fragments of dark mineral rock, having an adamantine luster and containing many air bubbles were noted, possibly volcanic glass	2477	2482
Dark gray shale with some anhydrite and salt. In the washed material some fragments of fine sandstone and quartz sand were noted	2484	
Clear rock salt with a few pink salt crystals like those from 2405–2425, and some pieces of gray sandy shale and anhydrite. Faint trace of potash	2495	2505
Two pieces of red rock salt, measuring about one-half and one inches square, respectively. Gray shale adheres to both fragments. Strong trace of potash	2550	2560
Massive gypsum and anhydrite, with a few fragments of red shale	2670	2710
Red shale and white anhydrite. In the washed material considerable quartz sand and some small quartz crystals were noted	2855	2880
Red shale, white anhydrite and salt. In the washed material considerable quartz sand was noted. Fragments of fine sandstone, and some small quartz crystals were noted	3100	
White anhydrite and a few fragments of red shale. In the washed material some quartz sand and numerous small quartz crystals were noted	3130	
White anhydrite and a few fragments of red shale. In the washed material fragments of light brown sandstone, a few quartz sand grains and irregular crystals of quartz were noted	3600	3615
Red silty shale and white anhydrite. In the washed material some fragments of sandstone, quartz sand, some of which was very well rounded and some irregular crystals of quartz were noted	3830	3835
Red silty shale and some anhydrite. In the washed material many fragments of fine sandstone and quartz sand, some of which was fairly well rounded, were noted	3835	3840
Red silty shale with some salt. A piece of hard, fine sandstone with siliceous cement and some		

	Depth in Feet From	To
salt was noted. In the washed material some quartz sand was noted, some of which was very well rounded. Some anhydrite and a few irregular crystals of quartz were also present	3840	3870
Red silty shale with a little gray silty shale and anhydrite. In the washed material some quartz sand some of which was very well rounded, fragments of fine sandstone and irregular crystals of quartz were noted	3870	3880
Red silty shale with some salt and a little gray sandstone. In the washed material quartz sand was noted, some of which was well rounded. Anhydrite was also present	3880	3895
Red silty shale and a little light gray sandstone. In the washed material some quartz sand was noted, irregular crystals of quartz were also present	3900	3910
Red and gray, silty, salty shale. One piece of the red shale contains a layer of salt which includes a lentil of anhydrite. In the washed material fragments of fine sandstone, anhydrite and a little quartz sand were noted	3910	3920
Red, silty, salty shale and sand. In the washed material much of the quartz sand was seen to be almost perfectly rounded. Fragments of fine sandstone and a little anhydrite were also present	3930	3940
White anhydrite. In the washed material a very little quartz sand, fragments of fine sandstone, and a few irregular crystals of quartz were noted	3940	3945
Finely ground up, white anhydrite. In the washed material some quartz sand was noted. Fragments of fine sandstone and a few small crystals of quartz were also present	3945	3960
Red sand, with a few fragments of red sandy shale and some salt. In the washed material some of the quartz sand was seen to be well rounded. Anhydrite and some irregular crystals of quartz were also present	3960	3970
Red sand and a few fragments of red silty shale with some salt. In the washed material some of		

	Depth in Feet From	To
the sand was seen to be well rounded. Anhydrite, fragments of fine sandstone and small crystals of quartz were also present	3970	3975
Red sand and some salt. In the washed material some fragments of fine sandstone were noted. Anhydrite and a few irregular crystals of quartz were also noted	3975	3985
Fine red sand with some salt and white anhydrite. In the washed material some fragments of fine sandstone and a few irregular crystals of quartz were noted	3985	4000
White anhydrite with some fragments of red, silty shale, fine gray sandstone and a little salt. In the washed material some fine quartz sand and numerous small quartz crystals were noted	4000	4010
White anhydrite with a few samples of red shale. In the washed material a little fine quartz sand and a few small irregular crystals were noted	4010	4015
Finely ground up, white anhydrite and sand. In the washed material a few small irregular crystals of quartz were noted	4015	4020
Light brown sand and some anhydrite. Some of the sand grains were well rounded. Fragments of fine sandstone and small quartz crystals were also present	4020	4035
Red sand, red silty shale and some salt. In the washed material quartz sand, some of which was well rounded was noted. Anhydrite, fragments of fine sandstone, and irregular crystals of quartz were also present	4035	4065
Light brown sand with some anhydrite and salt. In the washed material some small irregular crystals of quartz were noted	4065	4070
Finely ground up, white anhydrite and some fine, light brown sand. In the washed material some small irregular crystals of quartz were present	4070	4080
Salt and red, silty shale. The salt is coarsely crystalline and mixed with the shale. In the washed material quartz sand was noted. Anhydrite, fragments of fine sandstone and small irregular quartz crystals were also present	4080	4090
Coarsely crystalline salt and finely ground up white anhydrite. In the washed material some		

	Depth in Feet From	To
fine quartz sand and irregular crystals of salt were noted	4090	4120
Red, sandy, salty shale and some sand. In the washed material some of the sand was seen to be well rounded. Fragments of fine sandstone, anhydrite and irregular quartz crystals were noted	4120	4145
Red, sandy, salty shale and a little salt. In the washed material considerable quartz sand was noted. Anhydrite, fragments of fine sandstone, and irregular crystals of quartz were also present	4145	4175
Red shale, white anhydrite and some salt. In the washed material a little quartz sand and numerous small irregular crystals of quartz were noted	4175	4200
White anhydrite, with some small fragments of red shale and a little salt. In the washed material some of the anhydrite was seen to be salmon colored. Numerous small quartz crystals and a little quartz sand were also present	4200	4210
Salt. In the washed material some anhydrite was noted, some of which was salmon colored. Numerous small quartz crystals, a little quartz sand and a very little pyrite were also present	4210	4225
Red silty shale and salt. In the washed material some anhydrite was noted. Fine quartz sand and numerous small crystals of quartz were also present	4225	4290
Gray dolomite, red shale, some salt and a little anhydrite. In the washed material numerous small quartz crystals were noted. In thin section the dolomite was seen to be finely granular. Indistinct laminations were noted in the rock	4290	4300
White anhydrite, gray dolomite, and salt. In the washed material a little quartz sand and numerous small quartz crystals were noted	4300	4305
Finely ground up, anhydrite with some sand and salt. In the washed material numerous small quartz crystals and fragments of fine sandstone, dolomite and a very little pyrite were noted	4305	4375
Red, silty shale, with some salt and a little an-		

	Depth in Feet From	To
hydrite. In the washed material many small quartz crystals and some quartz sand were noted	4375	
Finely ground up anhydrite, sand and salt. In the washed material numerous small quartz crystals were noted	4380	4395
Same as 4380–4395	4395	4400
Gray dolomite with a few fragments of red, silty shale. In the washed material blotches of anhydrite could be seen in the dolomite, having partly replacėd the dolomite. Anhydrite, a few small crystals of quartz and pyrite were also noted. In thin section was seen dolomite of fine texture containing many areas of anhydrite. One fragment contained many fine quartz sand grains	4400	
Salt and anhydrite. In the washed material small irregular quartz crystals were noted	4400	4410
Reddish-brown shale with some anhydrite. In the washed material fragments of fine sandstone, a little fine quartz sand and a few irregular quartz crystals were noted	4415	
Finely ground up, gray dolomite. In the washed material a little anhydrite and a few irregular crystals of quartz were noted	4430	
Like sample from 4430	4440	
Finely ground up anhydrite with some dolomite. In the washed material a little fine quartz sand and a few small quartz crystals were noted	4447	
Gray dolomite. In the washed material some white anhydrite was noted. A little quartz sand, a few small quartz crystals and a little pyrite were noted	4450	
Gray dolomite. In the washed material a very little fine quartz sand, anhydrite and few small quartz crystals were noted. In thin section the dolomite was seen to be granular and to contain small areas of anhydrite which had partly replaced the dolomite. Some fine wavy brown lines were noted in the dolomite which may be bituminous material	4455	
Finely ground up, gray dolomite. In the washed material some white anhydrite and a few quartz sand grains were noted	4458	

	Depth in Feet From	To
Finely ground up, gray dolomite. In the washed material some white anhydrite, a little pyrite, and a few irregular crystals of quartz were noted	4465	
Fine gray sandstone. In the washed material some anhydrite, fragments of red shale and a few small irregular quartz crystals were noted	4475	
Finely ground up dolomite, red, silty, salty shale and a little anhydrite. In the washed material quartz sand was noted. Many small, irregular quartz crystals and a little pyrite were also present	4478	

In this well, as has been noted in the description of the samples, the Cenozoic is present, although the thickness is undetermined. However, from the driller's log it seems probable that the Cenozoic here may extend to 139 feet. Triassic is recognized at 139 feet. In the absence of a complete set of samples, the base of the Triassic cannot be definitely determined. The Triassic, however, extends below 1,100 feet and very possibly to about 1,210 feet, where the last fresh water was obtained. The first salt water encountered in the well, as indicated in the log, is at 1,358 feet, which is within the Permian.

ADDITIONAL DIAMOND DRILL CORE TESTS IN TEXAS

Announcement has been made recently by the Department of the Interior of the results of four diamond drill core tests in Texas made under the Potash Act. (Press bulletin issued by the United States Geological Survey May 28, 1928).

One of these wells, located in the western part of Ector County near Metz, was churn drilled to the top of the salt 930 feet and core drilled thence to a total depth of 2,098 feet. Following is the record on the beds having possible commercial interest as given in the press bulletin.

Bed or Group of Beds	Depth to Top of Bed		Thickness		K_2O in Sample	K_2O in Soluble Salts
	Ft.	In.	Ft.	In.	Per Cent	Per Cent
A	1,280	3	3	7	9.53	15.85
B[1]	1,302	10	3	9	9.32	15.68
C	1,309	5	3	3	10.30	13.31
E	1,635	8	2	0	13.10	19.49
E	1,735	9	2	0	9.55	17.48
F	1,897	0	1	11	11.30	15.72
	1,935	7	3	11	13.50	19.85
G[2]	1,939	6	2	10	.95	.97
	1,942	4	2	8	11.87	17.71

[1]The lower 2 feet of Group B, at a depth of 1,304 feet, contains 11.88 per cent of K_2O in the sample, equivalent to 20.20 per cent in the soluble salts.

[2]Exclusive of the 2 foot 10 inch bed of salt, Group G includes 6 feet 7 inches of polyhalite containing 12.86 per cent of K_2O in the sample, equivalent to 18.98 per cent in the soluble salts.

In a well drilled on the Hughes Roxana Lease, Section 4, William Teer Survey, about 10 miles north of McCamey in the western part of Upton County, the top of the salt was reached by churn drill 440 feet, and the well completed by core drill of 1,230 feet. The following tabulated statements of results on this well is from the press bulletin to which reference has been made.

Bed or Group of Beds	Depth to Top of Bed		Thickness		K_2O in Sample	K_2O in Soluble Salts
	Ft.	In.	Ft.	In.	Per Cent	Per Cent
A[1]	689	7	3	7	9.50	14.73
B	744	0	1	4	12.71	16.87
C	785	3	2	0	9.91	15.64
D	848	0	3	3	11.65	15.06
E[2]	945	6	2	6	7.70	9.95
F	1,109	3	1	5	12.42	20.24
G	1,157	0	1	11	12.04	17.17

[1]Group A contains 4 feet 8 inches of beds, including a 13-inch layer of salt and anhydrite 8 inches above the bottom, which must be discarded.

[2]The upper 1 foot 5 inches of Group E is polyhalite containing 10.78 per cent of K_2O in the sample, equivalent to 14.65 per cent in the soluble salts.

A well was drilled in Crockett County located on the Harris Brothers' ranch in Block HH, nw ¼, Section 16, Gulf, Colorado & Santa Fe Railway Survey, about 25 miles south of Rankin. On this well the churn drill was used to the depth 1,161 feet and the core drill to a total depth of 1,799 feet. In Upton County a well has been drilled on the Burleson-Sun lease, Section 100, 2 miles north of McCamey. In this well the churn drill was used to the top of the salt at 437 feet and the well core drilled to a total depth of 1,501 feet. Both of these wells are reported as giving less promising results than the two wells on which the tabulated data are quoted above.

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