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LITHOLOGIC SUBSURFACE CORRELATION IN THE "BEND SERIES" OF NORTH-CENTRAL TEXAS.

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OBJECT AND METHODS OF THE INVESTIGATION.

This paper presents the results of an attempt to obtain, by a study of well drillings, criteria for correlation, by the character of the beds encountered, of horizons in the "Bend series" of north-central Texas. The result of the work most directly applicable to the needs of the oil-well operator is that of enabling him to know more exactly the position of the producing beds in his well—a result that is of particular value in north-central Texas because certain beds in that region which give no show of oil to the drill may on being "shot" yield considerable oil. To know the part of the stratigraphic section reached by the drill at any stage of the boring also enables the driller to be on the alert for indications of oil at horizons where productive sands are encountered in other wells and to know when the drill has passed all horizons at which the beds are likely to yield oil.

In two wells that lie near each other the succession of beds is so nearly the same that at least some horizons can be correlated from the driller's logs if they are carefully kept. But the character of any bed may gradually change from place to place, so that the farther apart any two wells are the more difficult it becomes to recognize the beds that lie at the same geologic horizon in them. In undertaking this study, however, I started with the assumption that, though the composition of a bed at a certain horizon in any two widely separated localities might be so different that the bed could not be recognized as such, the relation of its composition to the composition of the beds above and below it would show enough similarity to permit its identification. That is to say, it seemed probable that any change in the character of the sediment delivered to one part of an open, continuous basin of deposition would be manifested in all other parts of the basin. Thus, an increase of sand would be recorded all over the basin, in one locality perhaps by an increase in the sandiness of a limestone, in another by the deposition of coarse sandstone in the midst of shale, and in still another merely by a slight increase in the amount or the size of sand in a shale, but everywhere there would be an increase in the proportion of sand; and the same rule would apply to the other constituents.[1] To bring this out it was necessary to represent for each sample obtained from a well the proportions of the three principal ingredients—sand, clay, and lime. Lime as here used includes all the transparent carbonates of the calcite group. No attempt to differentiate the several members of that group was made, though the differentiation of calcite and dolomite, for example, would be valuable. The lower limit for size of grain of material classified as sand is about 0.05 millimeter, but this limit is not definite, depending somewhat on factors other than size. If material as fine as 0.02 millimeter were abundant in a thin section it would be estimated as sand, but beds containing material of that fineness are likely to appear essentially as clay.

The most convenient method of compiling the results obtained seemed to be what I have called the "percentage log," shown in the third and fourth columns on Plate I (in pocket).

[1] Though applied much more roughly, this principle is similar to that used by De Geer in correlating the glacial clays of Sweden. See De Geer, Gerard, A geochronology of the last 12,000 years: Cong. géol. internat., 11e sess., Compt. rend., fasc. 1, p. 241, 1910.

In this log the thickness of rocks represented by the sample is laid off vertically to scale as the vertical coordinate. The width of the column represents 100 units, and the percentage of each of the three constituents in each sample—the lime, clay, and sand—is laid off horizontally across the middle of the space representing the sample.[2]

To obtain these results the samples were examined with a hand lens, which was sometimes supplemented by a binocular microscope. As many types of rock as could be recognized were listed, and the proportion of each was estimated. Fragments of peculiar types and at intervals of the prevailing types were selected to be made into thin sections, which were examined under the compound microscope, and the proportions of sand, clay, and lime in them were estimated. As the work progressed it was found desirable to increase the number of thin sections, even of prevailing types from successive samples, as changes in sandiness might otherwise not be recognized.

The samples examined were obtained from the Seaman well No. 1, in Palo Pinto County, and the Rudd well No. 1, in Comanche County. As those from the Seaman well were the first to be studied the observations on them are somewhat less accurate than those on the Rudd samples.

This method of determining the proportions of the three ingredients is obviously a rather rough one, yet I think it is justified by the results, for it brings out correlations with remarkable detail. It has even certain advantages over the mechanical and chemical analysis employed in the method described by Trager in the paper just cited. Certain changes, especially silicification, which tend to unite the original constituents of the rock so that they can not be separated or which replace them by other substances, interfere, according to the extent to which they are developed, with the correct mechanical or chemical determination of the composition of the rock as it was when deposited, but these changes are not likely to interfere nearly so much with the microscopic recognition of the ingredients, especially of clay and sand. In much chertified beds any routine mechanical or chemical analysis would seem to be almost useless as a means of determining the original composition. On the other hand, the determination of the proportions of the ingredients by the eye may be very inaccurate, especially in an argillaceous rock, as clay may form a dark stain and veil the presence of other constituents. In work on the black limestones that are so abundant in the "Bend series" there is the added difficulty of distinguishing between organic staining matter and clay. The most accurate method of determining the proportions of the constituents sought would undoubtedly be a combination of observation in thin section with chemical and mechanical analyses, but circumstances did not permit me to use the latter methods. The method used, however, probably does bring out relative composition, which is the essential fact in this investigation.

Where distinct fragments of flint could be recognized in the sample their proportion was estimated and represented separately, merely because they could not properly be classed with the other three constituents. It is my belief that flint is produced by the silicification of sediments after their deposition and that for the purpose of the present investigation it should be regarded as replacing lime.

The flint estimated represents only the proportion of its individual particles, not the degree of silicification of the sample. Incipient chertification was recognized in many thin sections made from samples in which no fragments of flint could be found. In general this microscopic chertification is greater in the lower part of the geologic section, increasing downward as the beds carrying distinct flint are approached. It is therefore not surprising that the highest occurrences of fragments of flint should be at different horizons in the two wells—at 2,738 to 2,745 feet in the Rudd well and at 4,090 to 4,100 feet in the Seaman well.

Although the assumption that variations in the proportions of the principal constituents of these beds would be recorded in widely separated parts of the basin in which they were deposited proved, in a general way, to be remarkably well justified, there is one respect in which it requires restriction and interpretation. It might, indeed, have been expected that lime, which is not a true sedimentary constituent but is mostly of organic origin,

[2] This method of representation is described by E. A. Trager in A laboratory method for the examination of well cuttings: Econ. Geology, vol. 15, pp. 170-176, 1920.

would not conform in detail to this assumption. In a general way, of course, more lime accumulated at certain periods than at others, and in the "Bend series" this fact is most obviously indicated by the subdivision of the series into the Smithwick shale and Marble Falls limestone, though it expresses itself also in detail throughout the series. But the accumulation of lime is much more subject to local conditions than that of sand or clay. Furthermore, lime is not related to depth as simply and regularly as sand and shale. Though there used to be a tendency to assume that limestone represented a deposit in deep, clear water, geologists are now beginning to realize that this assumption applies only to certain kinds of limestone and to certain regions. Most of the mollusks, molluscoids, and echinoids whose remains form the largest part of our limestones lived in water shallow enough to give them their needed light and warmth, though not so near the shore and especially not so near the mouths of rivers that they would be injured by the accumulation of sediment. If a generalization must be made concerning the relation of lime of organic origin to depth it would probably be truer to say that on gently sloping offshore sea bottoms limestones are formed between near-shore detrital deposits, which in many areas include clay, and the deep-sea terrigenous clay deposits, which are fairly well represented by the "blue muds" of the *Challenger* expedition. But this generalization also is subject to many modifications to bring it into accord with local conditions. What is essential for the present purpose is to realize that lime is not likely to vary as regularly from well to well as the true sediments, clay and sand, and that on this account logs representing the proportion of lime will require critical interpretation. The ideal correlation would be one based only on the exact proportions of clay and sand.

The results of my determinations, in addition to being summed up in the percentage log, are represented also in columns 2 and 5 of Plate I (in pocket), in terms of definite lithologic types, in what I have called, for convenience of reference, a "synthetic log." In this log the materials found in each sample are, as far as possible, represented by the usual symbols. It was of course necessary to generalize very much in preparing this log. Obviously, moreover, there is no sure way of determining the thickness or relative positions, within the interval represented by the samples, of the different types recognized. Where a boundary between two distinct types lies in the interval represented by a sample and such a boundary has been recorded in the driller's log the position given by the driller's log has therefore usually been accepted. In order to bring out some of the more significant thin beds it has been necessary to exaggerate their probable thickness. Finally in column 1 on Plate I (in pocket), is given the usual graphic form of the driller's log of the Seaman well. No driller's log of the Rudd well was available.

The correlation of the percentage logs was aided greatly by the discovery, made in the course of the work, that the more significant breaks in a stratigraphic series are likely to be marked by the occurrence of autochthonous glauconite, in many instances associated with phosphate, directly above the break or rarely more than a foot or two above it. By autochthonous glauconite I mean glauconite formed in place contemporaneously with the bed in which it occurs. The suggestion that glauconite occurs in this association [3] was the result of observations in San Saba County, Tex. A thin sand that contains nodules of phosphate and is full of glauconite was found not more than a foot or two above the Ellenburger limestone at several places southwest of San Saba. A little west of Richland Springs, at the contact between a sandy formation believed to be the Strawn and a limestone believed to be the equivalent of one of the limestones occurring at Dennis, south of Millsap, in the "Millsap division" as defined by Cummins, a similar very glauconitic sand containing nodules of phosphate was found. To establish the validity of the generalization that glauconite occurs just above stratigraphic breaks it may be stated in advance that each of the samples in the collections of the United States Geological Survey taken from the base of the "Bend series" in three wells that showed this horizon and that were rather evenly spaced over a distance of 120 miles north of the outcrop contained coarse autochthonous glauconite. As will be seen when the synthetic logs are discussed (see Pl. I), glauconite occurs at horizons other than breaks in the stratigraphic succession, but at nearly all these horizons it differs in

[3] Goldman, M. I., Washington Acad. Sci. Jour., vol. 9, p. 502, 1919.

associations and generally in form and character from the glauconite found at the stratigraphic breaks. The latter is usually more abundant, is predominantly coarse (in grains 0.2 to 0.4 millimeter or more, rarely less than 0.15 millimeter in diameter), is less rounded and less regular in shape, is at many stratigraphic breaks fresher, is deeper in color, and is associated with coarse quartz sand, generally somewhat finer than the glauconite, and with very coarse fragments of fossils or with abundant fossils. At some places it fills or penetrates irregularly the skeletons or hollows of the fossil shells. It is commonly accompanied by very abundant sulphide and in many occurrences by fragments or nodules of brown, isotropic phosphate and by a peculiar opaque compact brown substance, supposed to be some form of clay. The glauconite not associated with stratigraphic breaks usually occurs in small, rounded grains, which are scattered through less coarsely fossiliferous limestone or shale and compared with those found at the stratigraphic breaks look as if they were transported and worn forms of them.

The recognition of this association between autochthonous glauconite and stratigraphic breaks is essentially merely an extension and application of the recognition by Cayeux [4] of the connection between beds of phosphate and movements of transgression and regression. In fact, Cayeux begins his paper by calling attention to the association of glauconite and phosphate in the modern deposits of phosphate by which he seeks to explain those of the geologic past.

With such thick beds of glauconite in mind as those, for instance, of the Upper Cretaceous of New Jersey it would appear unreasonable to assert that glauconite occurs only in association with stratigraphic breaks. Apparently the conditions favorable to the formation of glauconite are characteristically associated with periods of maximum emergence or, according to Barrell's definition, with periods of maximum elevation of base-level [5] but are not limited to this association. Cayeux formulates the law for the Paris Basin that "all the deposits [of phosphate of lime] of the Upper Cretaceous originated during periods of great disturbances of the equilibrium of the ocean." I would make the corresponding generalization that in the sections I examined autochthonous glauconite occurs in the "Bend series" only within a few feet above stratigraphic breaks or, where there is no break, only in direct association with maximum elevations of base-level.

It must not be concluded that glauconite is merely a shallow-water deposit coextensive with coarse sand and other near-shore deposits. In the section from the Seaman well I have recognized several stratigraphic breaks that are marked merely by sand, without glauconite. What assumptions may be made, then, as to the special conditions favoring the formation of glauconite? Cayeux, in the paper cited, called attention to the fact that modern accumulations of phosphate associated with glauconite occur in areas of the ocean where great destruction of life has been caused by the meeting of a cold and a warm current. But this is, as Cayeux recognized, too local a phenomenon to account for widespread accumulations of dead organisms and is only one of the disturbances of environment that might result from a movement of base-level. Depth of water and other elements of the environment would also change, and a change in any of them might lead to the destruction of life which would result in the formation of phosphate deposits. But I do not think it should be assumed that a change of environment over a wide area, taking place suddenly, causes a general destruction of life. The essential condition seems to me to be that as a result of the disturbances distinct marine environments come into contact without any physical barrier, and organisms passing from one to another encounter unfavorable conditions and perish in large numbers and during a considerable period of time. From this it can be deduced that glauconite deposits associated with a movement of base-level might not be everywhere entirely contemporaneous, though from what follows it will be evident that the time interval between those formed in different parts of an area as a result of a given movement of base-level is not great.

The association of sulphide with sandy beds in this section admits of two interpretations,

[4] Cayeux, L., Genèse des gisements de phosphates de chaux sédimentaires: Soc. géol. France Bull., 4th ser., vol. 5, pp. 750–753, 1905.

[5] Barrell, Joseph, Rhythms and the measurement of geologic time: Geol. Soc. America Bull., vol. 28, pp. 778, 783, 1917.

one of which has been offered by Waite and Udden,[6] who suggest that the sulphide is due to mineralization after deposition, made possible by the porosity of the sandy beds. Though some of the sulphide I found in the coarse, generally more or less sandy basal beds may have been introduced in this way, I am inclined to believe that most of it is formed syngenetically as a product of the same large amounts of decaying organic matter that probably caused the formation of glauconite. This close relation between glauconite and sulphide has been recognized in modern deposits.[7] The occurrence of sulphide in the glauconitic beds encountered in the two wells here considered appears to be independent of the porosity of the beds. So far as mere impressions can be relied on, the sulphide seems to be as abundant in the dense, argillaceous phases of these beds as in the open, sandy phases. Then, too, it is in several occurrences associated closely with the shells in the beds, filling the tissues of some of them.

On the other hand, I gained the impression that chertification was rather more extensive in some of these coarse basal beds than in beds that lay adjacent to them, a difference which may indicate effects due to circulation, though it may be due merely to the abundance of coarse calcareous fragments in these beds. If due to circulation, this supports the interpretation of Waite and Udden, though it conflicts with their observations. Probably the beds contain both syngenetic and epigenetic sulphide, and though it may be difficult to distinguish these two types a possible means of discrimination may be found in the fact that the sulphide found in material from these wells appears to occur in two forms, one minutely spheroidal, generally gathered into large concretions, the other having sharp crystal faces. These forms may be respectively syngenetic and epigenetic. The problem deserves study, as the differentiation of syngenetic and epigenetic sulphide would help to throw light on the processes of circulation in the rocks.

The classification of the bedding planes that are overlain by glauconite and that mark the boundaries of the units differentiated in this paper or the determination of their significance as compared with other bedding planes must, I believe, be postponed until many more observations on this subject have been made. Every bedding plane represents a break in sedimentation and is related by a series of innumerable intermediate types to universally recognized "disconformities" and finally to unconformities. Barrell's analysis of stratigraphic breaks[8] is very illuminating, but their possible causes seem to me so numerous and their possible relations so complex that, until more detailed study has given better ground for differentiation, I prefer to call the boundaries I have indicated merely stratigraphic breaks, without attempting to define the relative order of magnitude of the time intervals they represent. That they are at least "disconformities" of order B–B in Barrell's system[9] is, I think, unquestionable. In the accompanying plate I have used the wavy line that is generally regarded as symbolizing an unconformity merely because it emphasizes the breaks, without wishing thereby to indicate their significance.

For the same reason that no more specific name has been given to the stratigraphic breaks, the portions of the section separated by the breaks have been called merely stratigraphic units, without an attempt to determine whether they are of the order of members, formations, series, groups, or any other recognized subdivisions. Their variation in lithology and the recognition of most of them so far only underground makes it seem preferable to identify them merely by letters rather than by names.

LOCATION OF WELLS EXAMINED.

In order to give the method adopted for this investigation a thorough test it was desirable that the wells studied should be far apart and that the samples from them should represent a nearly complete section of the "Bend series." In the collections available in the office of the United States Geological Survey these requirements seemed to be fulfilled by samples from two wells of the Roxana Petroleum Corporation—the Seaman No. 1, in Palo Pinto County, and the Rudd No. 1, in northern Comanche County, both of which were drilled into the

[6] Waite, V. V., and Udden, J. A., Observations on the Bend in Bough No. 1 in Brown County: Am. Assoc. Petr. Geologists Bull., vol. 3, p. 338, 1919.

[7] Collet, L. W., Les dépôts marins, especially pp. 168-172, Paris, Octave Doin, 1908.

[8] Barrell, Joseph, op. cit., pp. 776-834.

[9] Idem, fig. 5, p. 79?.

Ellenburger limestone. The location of these wells is shown on the accompanying map (fig. 1). The distance between them is about 45 miles.

The section in the Seaman well is much thicker and much more sandy than the section in the Rudd well. This accords with the belief that the land mass from which the sediments of the "Bend series" were derived lay somewhere to the northeast of the north-central Texas area.[10]

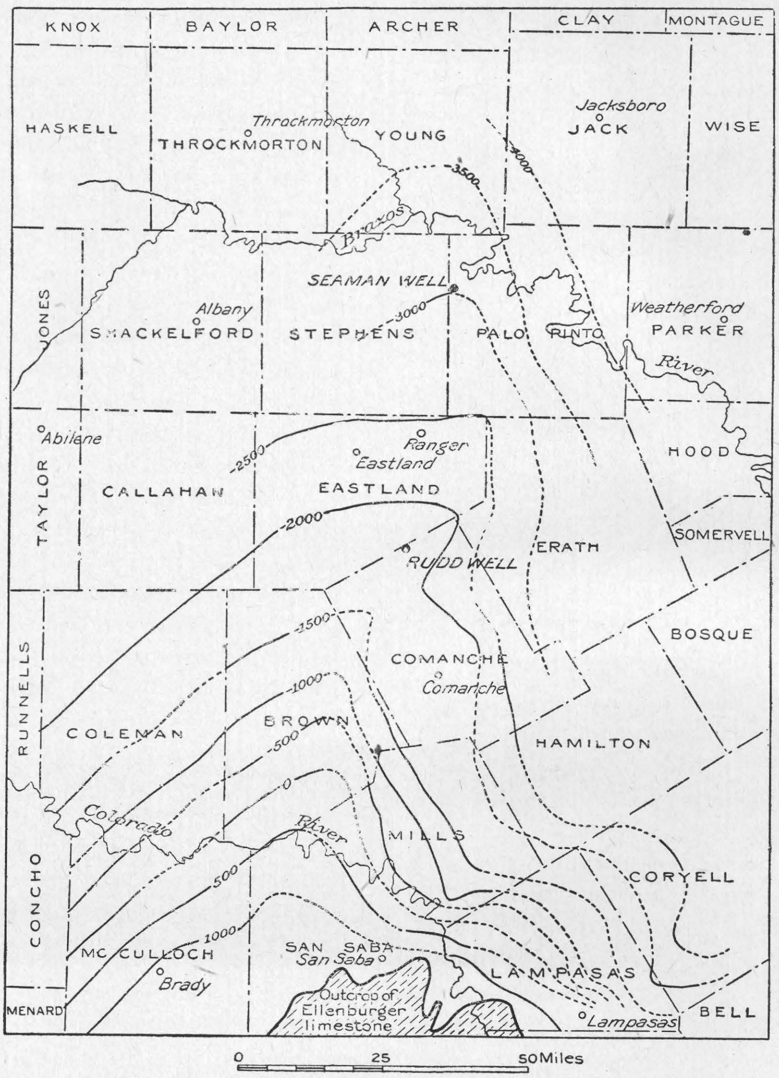

FIGURE 1.—Outline map showing the position of the Seaman and Rudd wells, north-central Texas, and their relation to the "Bend arch." Copied from Texas Univ. Bull. 1849, map facing p. 32, 1918.

[10] The probable position of this land mass was brought out by F. B. Plummer in a paper read before the American Association of Petroleum Geologists at its meeting in Dallas, Tex., in March, 1919, but in the published version of that paper the only reference I find to it is in the discussion by David White (Am. Assoc. Petr. Geologists Bull., vol. 3, p. 149, 1919). It is also discussed in detail and the literature relating to it is fully reviewed in an article by H. D. Miser, on "Llanoria," to be published in the American Journal of Science.

DISCUSSION AND CORRELATION OF THE SEAMAN WELL AND THE RUDD WELL.

INTRODUCTION.

The following discussion will concern itself only with the facts brought out in the graphic logs (Pl. I, in pocket) and with additional facts about the lithology tnat seem important for the correlation but could not be brought out in those logs. For a knowledge of the general character of the beds the reader is referred to the very clear, concise, and well-illustrated paper by Udden and Waite.[11]

[11] Udden, J. A., and Waite, V. V., Microscopic characteristics of the Bend and the Ellenburger limestones, 26 pp., mimeographed and illustrated by photographic prints [Austin, Texas Bur. Econ. Geology and Technology, 1919].

The reader is urged to refer constantly to the graphic logs and to make his own detailed comparison of the units in the two wells, especially as they are represented in the percentage logs. To make such a detailed comparison in this paper, with the constant references to depth that would be necessary, would make the discussion too cumbersome, and as the facts are clearly brought out by the graphic logs it seems superfluous.

There are some differences between the two percentage logs that can not be readily explained. They may be due to defects in the observations, especially to the fact that probably too few thin sections of samples from the Seaman well were examined, or to facts that are not in agreement with the general principle on which the correlation is based. Besides, minor variations that are disclosed in the percentage log of the Seaman well may be concealed in the percentage log of the Rudd well owing to the greater thinness of the equivalent section in the Rudd well, so that of two samples representing any given thickness of beds that from the Rudd well generally represents a greater time interval than that from the Seaman well.

The comparison of the units in the two wells will be based on the correlation I have arrived at without at first proving this correlation in each case. This is a necessary result of the principle that the correlation is based not on direct comparison of the lithologic character of two units but on the relation of that character to the character of formations above and below.

UNIT A.

The examination of the material from the Seaman well was begun with material obtained just below the lowest sample that consisted mainly of yellow sand; of that from the Rudd well with the lowest distinctly sandy sample. The percentage logs bring out clearly the sandy character of unit A, which differentiates it unmistakably from the material that lies below it. In and near the basal samples of this unit from both wells were found certain fragments of white sandstone which differed from others in the same samples partly in being more silicified but especially in that one surface, instead of appearing freshly broken like the rest, was dull, gray stained, smoothed, and slightly pitted, suggesting the surface of a small pebble (half an inch or so in diameter) in a conglomerate. They have been represented in the synthetic log by a conglomerate at the base of unit A.

UNIT B.

In the samples from both wells a difference is immediately noticeable in the character of the shales that directly underlie unit A. They are blacker, less blue-gray than the shales of unit A, much less sandy, more calcareous, and more sulphidic. In shales below unit A sulphides are almost invariably present though in varying abundance.

This unit is too thin in the Rudd well to permit much generalization about its representation in the percentage log, though compared with unit A in that log it is clearly much more calcareous and much less sandy. The much smaller proportion of sand in the Seaman well is also obvious in the percentage log, but the increase of lime is slighter below the contact.

The character of the basal boundary of unit B is very different in the two wells. In the Seaman well it has a feature of special interest brought out in the percentage log—a pronounced, fairly regular increase in sandiness in the upper part of unit C, which reaches a maximum at a depth of 3,045 feet, above which there is a decrease in the amount of sand, also rather regular but more gradual than the increase. The sand appears in sandstones and shales, as represented in a generalized way in the synthetic log. The increase in sandiness of the upper part of unit C may be only apparent, being due to caving of sandy material from unit B in the drill hole, though the large proportion of the sandy material in that part of unit C is very much against this assumption. If the facts are about as represented they may record an ideal boundary between two units. Wherever there is a sharp contact representing a break between two units the sharpness of the contact is due to the fact that the beds representing the time interval between the two units have not been deposited there. Every such break is due to a rise of base-level (the term base-level being used in the sense given to it by Barrell[12]). The true boundary between two formations is the sedimentary surface coinciding

[12] Op. cit., pp. 778, 783.

with the maximum of the oscillation that produced this change of base-level. Some part of the ocean bottom must remain submerged during a rise of base-level, and there the maximum will be recorded in the sedimentary beds. In the Seaman well a surface corresponding to this maximum may be included in the interval represented by the sample from 3,040 to 3,050 feet, in which a maximum of sand would correspond to a maximum of shallowing. For this reason the boundary between units B and C has been placed in the middle of that interval. This boundary is of course not a disconformity and is so represented only for convenience. A name to describe this surface would be useful. The name "akinetic surface" is proposed and defined as the surface in a sedimentary rock which was the outer surface of the lithosphere at some place at the moment an oscillation of base-level at that place passed through its maximum. The word akinetic is derived from the Greek word κινεω, I move, and the privative prefix α. Although the interpretation here given of the boundary between the two formations is a possible interpretation of the observations recorded, it is not inevitable. There may be a considerable time interval, not represented by sediments, between units B and C, and the apparent continuity may be due merely to the reworking of material at the top of unit C into the basal sediments of unit B.

A fact which causes doubt as to the true position of the boundary between units B and C in the Seaman well and points toward its occurrence about the base of the sandstone shown at 3,075 feet is the appearance in the sample from 3,090 to 3,100 feet of shale blacker than any above it and of a type which is distinctly characteristic of unit C. The exact position in this well of the boundary between units B and C within an interval of 30 to 40 feet therefore remains uncertain.

In the Rudd well the boundary is well defined by a typical bed of autochthonous glauconite, with much sulphide, some phosphate nodules, very coarse fossils or fossil fragments, and a little sand.

DIFFERENCE BETWEEN THE SHALES OF UNIT B AND THOSE OF UNIT C.

The prevailing shales of unit B in the Seaman well appear in thin section predominantly finely granular or felty in appearance, passing where coarser into micaceous and sandy shales. They are of an even brown color and full of brown fragments. These fragments usually increase in coarseness with the coarseness of the sediment, and some of the larger ones can be recognized as fragments of plant matter. Sulphides are common and are largely associated with the plant fragments. The lime in these shales, though locally very abundant, is generally disseminated as a fine dust through the mass.

The prevailing shale of unit C as seen in thin section may be described as of the Marble Falls type—that is to say, the matrix instead of being even and granular has more of a flocculent appearance, being amorphous rather than composed of fine mineral matter. The color is usually a blacker brown and, in correspondence with the flocculent character, is less even than in unit B. Organic matter is undoubtedly abundant but does not appear as definite units but rather as a vague, irregular stain, indistinguishable from the argillaceous matter. Sulphides, though present, are therefore not generally as clearly associated with organic elements as in unit B. Whether there is generally more or less sulphide in unit B or unit C could not be determined by the eye, especially on account of the great difference in the amount of this constituent in different fragments. The determination of the part played by organic matter in these shales and of its relation to the amount and possibly to the manner of occurrence of the sulphide is one of the problems which I hope to take up later. The most distinguishing characteristic of shale of the unit C type is the occurrence in it of lime in coarse irregular fragments and grains, many of them clearly fragments of shells. With the increase of the amount and coarseness of the lime and of the fossil fragments or fossils the shale passes by imperceptible gradations into black limestone [13] and then into gray limestone. With these differences in microscopic character between the shales of units B and C in the Seaman well goes a difference in their color to the unaided eye. Those of unit B are generally not quite as black as those of unit C, being more of a blue-black. They also usually effervesce less actively in acid.

[13] See Udden, J. A., and Waite, V. V., Microscopic characteristics of the Bend and the Ellenburger limestones, Texas Bur. Econ. Geology, 1919.

Although these two distinct types of shale are characteristic of units B and C, neither of them is absolutely restricted to its respective unit. Each type is found in smaller amounts in the other unit.

In the Rudd well the microscopic differences between the shales of units B and C are very slight. Sand is not at all abundant in unit B; in the thin sections of many chips there is none. The groundmass of the shales of both units appears equally flocculent. The lime in the shales of unit B is coarsely granular, distinctly not the fine dust that is characteristic of the shale of unit B in the Seaman well. Nevertheless, it is not on the average as coarse as the lime in the directly underlying shales of unit C in the Rudd well, in which a few recognizable coarse fossil fragments are included. Under the hand lens the difference between samples from adjacent parts of the two units is correspondingly slight. These observations on material from the Rudd well are in agreement with the evidence of continuity between the two units in the Seaman well.

DISTINCTION BETWEEN BLACK SHALE AND BLACK LIMESTONE.

From what has been said above of the gradations between black shale and black limestome it follows, as pointed out by many previous workers,[14] that the distinction between black shale and black limestone is more or less arbitrary. In my work I have differentiated them mainly by the appearance of the chips. Angular chips with sharp edges, more or less concave surface, and generally harder appearance I have called limestone. The flatter, more rounded, and more regular chips I have called shale. Where the appearance of the thin section seemed definitely opposed to the classification based on the appearance of the chip I have followed the indications of the thin section. The opinion of the driller, who in addition to seeing the chips knows how the bed drilled, may often be more reliable than an opinion deduced merely from an examination by eye. On the other hand, most drillers appear inclined to generalize the character of a considerable succession of materials. In the synthetic log I have incorporated only my own conclusions, but the facts above set forth should be kept in mind when the synthetic logs are examined and compared with the driller's log.

[14] See Am. Assoc. Petr. Geologists Bull., vol. 3, passim, 1919.

UNITS C AND C′.

In the Seaman well unit C is far from coherent. In the percentage log it appears very irregular. The only generalization that suggests itself is that this unit is distinctly calcareous in the lower part, containing very little sand, but grows sandy toward the top, apparently approaching, more or less by oscillations, the rise of base-level that separates it from unit B. There is more room for considerable difference of opinion about the homogeneity of this unit in the Seaman well than about that of any other unit in the section. If it is to be subdivided, the dividing line would be drawn at 3,320 feet, separating a distinctly sandy and shaly unit above from a succession of black limestones and shales below. To me these two units have not appeared sufficiently distinct, and no glauconite bed was found to indicate a boundary. The correlation with the Rudd well supports this view.

In the Rudd well unit C is very regular and coherent, although it has five sandy zones which may correspond to the five maxima of sand in the Seaman well. If, in accordance with this correlation, the sand between 2,440 and 2,450 feet in the Rudd well corresponds to the sand between 3,440 and 3,450 feet in the Seaman well, the ratio between the part of the section below this sand in the Rudd well compared with the same part of the section in the Seaman well is slightly less than the ratio between the combined units C and C′ in the two wells. Thus:

In the Rudd well 2,445 to 2,525 = 80 feet.
In the Seaman well 3,445 to 3,640 = 195 feet.
The ratio is therefore 80 : 195 = 1 : 2.44.

The combined thickness of units C and C′ is:

In the Rudd well 2,245 to 2,525 = 280 feet.
In the Seaman well 3,045 to 3,640 = 595 feet.
The ratio is therefore 280 : 595 = 1 : 2.12.

This slight difference may be accounted for by the greater sandiness, implying more rapid deposition, in the upper part of unit C in the Seaman well, as noted above.

In the upper part of this unit there is in both wells a sandstone in the midst of shales—in the Seaman well between 3,180 and 3,190 feet and in the Rudd well between 2,290 and 2,300 feet. In both wells it is largely dark gray, medium grained, and more or less calcareous. In the Seaman well there is, in addition, a very little coarse white sandstone. Similar calculations for the distance of this sand from the base of unit C′ show:

In the Rudd well 2,295 to 2,525 = 230 feet.

In the Seaman well 3,185 to 3,640 = 455 feet.

Ratio 230 : 455 = 1 : 1.98.

The ratio of the distances of the sandstone from the top of unit C is as follows:

In the Rudd well 2,245 to 2,295 = 50 feet.

In the Seaman well 3,045 to 3,185 = 140 feet.

Ratio 50: 140 = 1: 2.8.

The much closer agreement of the ratio of distance from the base of unit C′ than the ratio of the distance from the top of unit C with the ratio of the total thickness of the combined units in the two wells may indicate that the upper boundary is placed too high in the Seaman well. If the boundary between 3,070 and 3,080 feet in the Seaman well is chosen, then 3,075 to 3,185 = 110 feet, and the ratio becomes 50 : 110 = 1 : 2.2—that is, the ratio from the top is almost identical with the ratio of the total thicknesses. But in view of the much more sandy deposition in the top of unit C in the Seaman well than in the Rudd well this agreement seems to me as much of an argument against accepting the lower boundary as favorable to it. Moreover, as the upper boundaries of units are supposed to correspond to more pronounced disturbances or interruptions of sedimentation, it is in general to be expected that the ratios of intervals from any bed in the unit to the top of the unit will be less regular than those of intervals from the same bed to the base of the unit.

One of the striking instances of parallelism between the percentage logs of the two wells is the similarity in the relations of unit C′ in both wells. Unfortunately the samples from 2,480 to 2,490 feet, from 2,500 to 2,510 feet, and from 2,522 to 2,546 feet in the Rudd well are missing, but there are enough samples to indicate that the beds in both wells a little above the base of unit C′ record a sudden invasion of a very sandy facies overlying a thin layer of deeper-water sediments and immediately overlain by sediments that were probably laid down in still deeper water. In the Seaman well the base of unit C′ is marked by a very typically developed glauconitic basal bed, more phosphatic than usual, almost exactly similar material marks the base of unit C, and between the two is a sharply defined very sandy layer. In the Rudd well the base of unit C′ is also marked by a glauconite and phosphate layer, and a very sandy black limestone between 2,490 and 2,500 feet appears to represent the sandy layer, but a distinct base for unit C was not located. About 80 per cent of the sample from 2,490 to 2,500 feet is a rather coarsely sandy, coarsely calcareous glauconitic and phosphatic black limestone or shale, but all the fragments examined appeared to have been formed above a basal bed rather than as an actual basal bed. In addition there were considerable traces of coarse quartz sand (1 millimeter or more in diameter). Evidently a basal bed of unit C is present, but from the evidence summarized above it can not be precisely located. The basal beds of units C and C′ in the Seaman well were the only ones not noted in the original examination, probably on account of the black color given to the fragments by the phosphatic material, which seems to veil the glauconite. For this reason and on account of the incomplete record in the Rudd well unit C′ has been treated as essentially a part of unit C.

The respective depth relations of shale and limestone discussed above (p. 3) are probably well illustrated by a comparison of the composition of units C and C′ in the two wells. The Rudd well is in deeper-water deposits, and the large amount of lime in the lower part of unit C in the Seaman well has its equivalent in an exceptionally large amount of almost sand-free clay in the Rudd well. Lime is more abundant in the upper part of unit C in the Rudd well, corresponding to the shallowing indicated by the large amount of sand in the upper part of unit C in the Seaman well, and the shallowing at the base indicated by the sand between 3,610 and 3,630 feet in the Seaman well is represented by sandy black limestone in the midst of shales in the Rudd well.

UNIT D.

Unit D perhaps more clearly than any other unit in the two wells is correlated by the relation of its composition as illustrated in the percentage log to the composition of the units above and below it. In the percentage logs of both wells it stands out as a sharply defined unit, more argillaceous than the units below it and differing distinctly in the proportion of clay from the unit above it. It is in both more sandy and therefore was probably formed in shallower water than most of the lower part of unit C, and thus it affords one of the chief confirmations of the principle assumed above (p. 3) to govern in a general way the relation of clay and lime. In the Seaman well it was deposited nearer shore and is therefore less calcareous than the lower part of unit C. In the Rudd well also it was laid down nearer shore and is therefore more calcareous than the apparently deep-water shales of the lower part of unit C. In the Rudd well unit D is distinguished throughout by the abundance of calcareous spicules, a characteristic of the Marble Falls limestone.[15] In the Seaman well this characteristic was not noted in unit D, which is probably too argillaceous and sandy.

Although this is the highest unit to show abundant spicular limestones and shales it does not represent the highest horizon at which they appear. In the material from the Rudd well they were first noted, though in small amount, in the sample from 2,490 to 2,500 feet, and in that from the Seaman well in the sample from 3,210 to 3,220 feet, but in these higher occurrences they were of a narrower type than those in unit D in the Rudd well.

The base of unit D in the Seaman well is marked by a typically developed glauconite bed with coarse quartz sand, coarse fossil fragments, phosphate grains, and abundant sulphides. In the Rudd well, on the contrary, though the lithologic difference on the two sides of the boundary is sharp, the basal phase of unit D does not appear pronounced. All that was noted was a small amount of sulphidic black limestone or shale, a few coarse quartz grains, and a very few fragments of black shale or limestone with glauconite grains and coarse fossil fragments.

UNITS E, F, AND G.

The rocks between the base of unit D and the top of unit J fall naturally into two groups, which will be treated as such in the following discussion. The higher of these groups consists of units E, F, and G, which together are characterized by abundant lime deposits with minor detrital accumulations.

The most striking fact about this group of units is the great irregularity of the ratios of thickness between the units in the two wells (see graphic logs, Pl. I, in pocket, and table, p. 17) and yet their close similarity in details of lithologic succession, as brought out both in the percentage logs and in the synthetic logs. Another characteristic is the thinness of some of the members and the rather poor definition of some of their boundaries, especially as regards the development of glauconite.

The irregular ratios of thickness of the units may be explained by differences in the amount of erosion in the two localities before the formation of each next higher unit. The greatest departure from the prevailing ratios between corresponding units in the two wells is shown by unit E and may indicate that the unconformity at the top of that unit represents a particularly long time interval. This inference is in harmony with the very characteristic development of the basal glauconite bed of unit D and with the pronounced distinctness of unit D from the underlying units, as shown in the percentage log. Another possible interpretation is difference in the rate of accumulation of the beds in the regions of the two wells. Unit E is mainly limestone and therefore, not being primarily detrital, might have accumulated faster in the deeper water of the region of the Rudd well than the combined detrital and calcareous material in the region of the Seaman well.

The composition of unit E calls for little special discussion. There is close parallelism in the succession of its components in the two wells—at the top a thin layer of purer limestone, then a thin more argillaceous layer, and finally purer limestone nearly to the base. In the Seaman well the first typical spicule limestone or shale was noted in the sample from 3,790 to 3,800 feet.

The first gray limestone in the Seaman well appears at the top of unit F. The strong development of sandy and argillaceous deposition at the base of this unit is brought out in striking parallelism in the two percentage logs. The sample from the base of this unit in the Rudd well contained a small fragment consisting of sand loosely bound by a brown substance, believed to be oil.

Unit G is most striking on account of its great difference in thickness in the two wells, yet its two main lithologic members, the calcareous one in the lower part and the argillaceous one in the upper part, are represented in both

[15] Cf. Udden, J. A., and Waite, V. V., op. cit., pp. 16-19.

wells. In the Seaman well sample from 3,960 to 3,970 feet occurs a peculiar white to light-brown or gray shale with minute brown-black spherules, 0.1 to 0.2 millimeter in diameter. Under the microscope the material is seen to be very finely micaceous or sericitic, with varying amounts of rather coarse sand. The spherules are brown to almost opaque, are weakly birefringent, and have a vaguely radial structure, in some surrounded by a concentric shell of similar substance. At the center of many of them is a small sulphide concretion. They are insoluble in nitric acid, and no test for phosphorus could be obtained after fusing them with sodium carbonate. It is hoped later to determine their nature. Some of the features of the matrix suggest a volcanic origin, but no volcanic glass or unusual numbers of heavy minerals were noted on microscopic inspection. Material of this general type, much of it merely white shale without black spherules, was found distributed through the section in the Seaman well from this uppermost occurrence in the sample from 3,960 to 3,970 feet to fragments in the sample from 4,165 to 4,180 feet—that is, in units G, H, I, and J. This distribution without regard to lithologic facies or apparently to any clear boundary is one of the factors favoring the belief in a volcanic origin. In the Rudd well the only distinct occurrence noted was in unit H between 2,780 and 2,790 feet.

The only show of oil recorded in the driller's log of the Seaman well is in unit G in the interval between 3,960 and 4,010 feet, but the exact depth is not given. The horizon at which it would seem most likely to occur would be that of the coarse glauconitic basal sandstone of unit G, just below 4,010 feet, which, as indicated in the generalized log (column 6, Pl. I) is believed to be the equivalent of the Ranger sand.

UNITS H AND I.

Units H and I are grouped together because they stand out clearly from the units above and below them by being more argillaceous and generally containing more detrital material. In the percentage logs of both wells there is also a clear maximum of clay in unit H. Both units in both wells show two maxima of sand. The lower boundary of unit I is sharply defined in the Rudd well, not only by a well-developed glauconitic bed but also by a sharp and pronounced change, shown in both the percentage log and the synthetic log, from the calcareous material that prevails below it to the more argillaceous material above. In the percentage log of the Seaman well there appears the same sharp increase of shale accompanied by a basal accumulation of sand, but the synthetic log of the Seaman well does not show the sharp lithologic boundary, gray limestones being represented as extending into the lower part of unit I. In the sample from 4,090 to 4,100 feet in the Seaman well, in which the highest gray limestone in unit I appears, traces of very coarse quartz sand with a very few fragments of coarse sandstone like that at 4,072 feet were found, but the scarcity of these fragments and the lack of a definite boundary here in the percentage log make it seem probable that they were derived by caving from beds above. The sample from 4,126 to 4,130 feet in the Seaman well also shows large traces of quartz sand, but no glauconite could be found associated with them. The boundary chosen as the base of unit I is therefore probably the correct one. Probably units H and I together as they appear in the percentage log of the Seaman well record an oscillation, a rise followed by a fall of base-level between units J and G similar to that between units C and B, but the sharp change of facies between units J and I indicates that here the rise of base-level was not continuous from the underlying unit. The upper part of unit I and the lower part of unit H, which were deposited during the period of greatest elevation of base-level, contain several layers with glauconite, sulphide, and sand.

To conform with the boundary between units B and C, the boundary between units H and I in the Seaman well should be taken at 4,045 feet, the approximate position of the akinetic surface, but on account of the greater practical availability of a lithologic boundary and of uncertainty as to the position of the akinetic surface due to the mixed composition of even individual small chips in this part of the section, I have chosen the coarse glauconitic bed shown between 4,068 and 4,072 feet in the synthetic log as the boundary between units H and I. In the sample from 4,060 to 4,070 feet there is about 20 per cent of black calcareous, somewhat glauconitic and very sulphidic sandstone, containing some of the coarsest sand grains noted in any part of the section. But an entirely similar sandstone occurs in smaller amount between 4,040 and 4,050 feet. The lower sandstone was chosen to mark the boundary between units H and I in this well because it is probably the lowest occurrence of such material, because of its greater abundance, and because it seems to be more closely related to the more definite lower boundary of unit H in the deeper-water deposits of the Rudd well. A light-colored sandstone shown just above 2,765 feet in the Rudd well and indicated by mere traces in the sample may be the equivalent of the one between 4,040 and 4,050 feet in the Seaman well.

A peculiarity of the basal sandstone of unit H in the Seaman well is its shattered condition. Delicate veinlets filled partly with calcite and partly with fibrous chert cut through sand grains, through sulphide concretions, and through cement.

In both wells an increase of lime in the upper part of unit H is shown, reaching its maximum just below the base of unit G.

UNIT J.

Unit J falls in both wells into two parts which are very similar but are separated by a pronounced maximum of clay sharply bounded against the upper part. This maximum is accompanied in the Seaman well by a slight sandiness and especially by a peculiar hard, dense black calcareous material containing a little unusually fresh, rather coarse glauconite and a few phosphate spherules—material of the same type as that which marks the base of the unit. In the Rudd well the clay maximum is accompanied by a relatively large amount of coarse sandstone and sand. As the two parts are in general very similar and as vertical limits of the occurrence of the basal type of materials have not been determined and therefore the boundary can not be definitely placed, the two parts have not been separated as distinct units.

A peculiar feature of the lower division is that it is decidedly more sandy in the Rudd well than in the Seaman well. The difference does not seem to be an error of observation, as samples from the upper part of the lower division in the Seaman well were reexamined and no sand or sandstone fragments were found, though in the Rudd well most of the sand represented in the lower division occurs as sand or sandstone easily recognized in the sample. This relation of the lower part of unit J in the two wells is directly contrary to that prevailing in all the units previously discussed and is considered further on page 17.

The base of unit J in both wells is marked by probably the best-developed glauconite bed encountered in the section so far discussed—that is to say, the glauconite is unusually abundant, coarse, fresh looking, and thickly scattered through the thin sections. In the material from the Rudd well some of the glauconite partly replaces or fills calcareous skeletons of organisms. There are an unusually large number of phosphate nodules. Sulphide is abundant. Sand is rather abundant in the material from the Seaman well but scarce in that from the Rudd well and not coarse in either. Shells and fragments of shells occur in both wells but are particularly abundant in the Rudd well. In many of the fragments examined these materials lie in a peculiar dense to opaque brown matrix different from any shales in the section. Many chips of this material in the solid look like limestone. A similar substance forms the body of several chips obtained near the middle of unit J, especially in the Rudd well, and is the matrix of the glauconite noted in the sample from 4,230 to 4,240 feet in the Seaman well. Possibly this is phosphatic material. It requires further study.

A peculiarity of the glauconitic bed in the Seaman well is its occurrence in the sample from 4,300 to 4,310 feet but not in that from 4,310 to 4,320 feet, though the character of the material from the lower interval leaves little doubt that it belongs to unit J and not to unit K. As indicated in the introduction (p. 3), many glauconite layers such as are characteristic of unconformities are not directly at the contact, but here the distance separating them is unusually great. In the Rudd well, on the contrary, the glauconite is evidently very near the contact.

UNITS K AND L.

In the percentage logs units K and L respectively appear very similar in both wells, unit K being calcareous and separated rather sharply from unit L. The beds of both units show several lithologic characteristics that distinguish them from overlying beds.

In the Seaman well unit K consists of limestones of a distinct blue-gray color in the solid, as against the black-gray of the overlying limestones. In thin section the limestone is much purer than most beds of the Marble Falls limestone and rather evenly crystalline, with hardly any traces of fossils, but in nearly all fragments of limestones in overlying units at least traces of fossils are recognizable. The shales of units K and L are also very distinctive, and those of unit L are of the same general character in both wells, but the Seaman well shows no shales in unit K. In the solid they have generally a dull brownish-black appearance; in thin section they have a peculiar reddish-brown rusty color and contain an evenly disseminated meal of more or less fine angular sand grains in a vaguely granular argillaceous matrix. A third characteristic type of material looks in the solid hard and compact like limestone but in thin section is seen to consist almost entirely of coarse rhombs of a colorless carbonate in a dense argillaceous matrix. This material was found in unit K in both wells and in the glauconitic bed shown between 3,042 and 3,048 feet in unit L in the Rudd well. Very probably it is dolomitic. I hope later to study it further. Black shales or limestones with more or less of rhombic carbonate in them are not restricted to unit K. They are rather common in unit J, and isolated occurrences were noted in material from 2,400 to 2,410 feet in the Rudd well and in the upper part of unit D in the same well. But in these higher positions the rhombs are usually smaller and not so closely packed.

As may be seen in the synthetic logs, unit K is separated from unit L in both wells by a bed of very phosphatic limestone in which phosphate spherules and nodules and phosphatized calcareous skeletons, including many echinoid fragments, occur rather closely crowded in a crystalline calcareous matrix. This is a typical phosphatic contact bed in which no glauconite was found. Evidently there are different conditions at stratigraphic breaks which make glauconite predominate at some and phosphate at others. In general, the conditions that prevailed during the deposition of units K and L seem to have been more favorable to the formation of phosphate.

Unit L is composed almost entirely of a very uniform succession of shale of the type described above, which in the Rudd well seems to be rather phosphatic, the phosphate occurring as small brown spherules around 0.2 millimeter in diameter, very slightly different in color in thin section from the shale containing them.

At 3,042 to 3,048 feet in unit L in the Rudd well occurs an exceptionally characteristically developed glauconite and phosphate bed of the contact type. This bed does not, however, appear to separate any distinguishable units. It is probably merely an indication that unit L, like units H and I adjacent to their contact, was formed under conditions approaching those favorable for the formation of accumulations of phosphate and glauconite, so that only a slight shift of base-level was necessary to bring on the favorable conditions. By its associations and in its appearance this bed therefore represents merely a renewal of the conditions that formed the basal bed of this unit. In the Seaman well an equivalent bed may occur in the interval between 4,420 and 4,470 feet not represented by samples.

The well-developed and horizontally extensive glauconite bed that marks the base of the "Bend series," which is here the base of unit L, resting on the Ellenburger (Ordovician) limestone, was mentioned in the introduction. The contact facies is evidently very thin. In the Rudd well only a small amount of coarse sandstone and coarsely glauconitic limestone with some phosphate spherules was found. A peculiarity of the sandstone is that most of the grains were shattered into two to four fragments only slightly displaced and subsequently recemented with what is probably opal. Probably a related phenomenon is the pronounced elongation and straining parallel to the elongation, slight shattering, and penetration of glauconite by sand from the surrounding matrix seen in a fragment of the basal glauconitic shale from 4,490 to 4,510 feet in the Seaman well. Does this indicate movement along this contact plane, perhaps as a result of folding? Shattering, apparently less violent, was noted in the basal sandstone of unit H in the Seaman well. (See above, p. 13.) In the Seaman well the amount of the basal glauconitic material is even less than in the Rudd well, so that is hard to find in the sample. A peculiar feature of the contact zone in the Seaman well is that the bed of shale which carries the coarse glauconite was found only in the sample from 4,490 to 4,510 feet, though the driller places the top of the Ellenburger 9 feet below the base of that interval, and more than half of the sample from

4,510 to 4,519 feet consists of normal shale of the unit L type, apparently free from glauconite with the exception of one fragment, which may well have come from above. The only other trace of glauconite that could be found in that sample was in a minute fragment of crystalline limestone, which was full of it. The basal glauconite bed is not everywhere directly at the contact, but 9 feet is an unusually great distance for the lowest glauconite bed to lie above a contact. Moreover, the sample from 4,490 to 4,510 feet was estimated to contain several per cent of white flint of the Ellenburger type. The relations do not seem entirely normal. In the synthetic log a thin glauconitic limestone deduced from the single fragment found in the sample from 4,510 to 4,519 feet is represented, but this is evidently very hypothetical.

GENERAL CORRELATION WITH THE RECOGNIZED SUBDIVISIONS OF THE "BEND SERIES."

The section in the Rudd well—a sharply defined upper shaly succession from 2,215 to about 2,522 feet (thickness 307 feet), a prevailingly limestone succession from 2,522 to 2,962 feet (thickness 440 feet), and below this to the top of the Ellenburger limestone again prevailingly shale with a little limestone in the upper part—is so similar to the generally recognized section of the "Bend series" and the Rudd well is so much nearer than the Seaman well to the outcrop where the section was originally observed and named that the Rudd section may be taken as establishing the correlation with the type section. In other words, the upper shale, with the probable exception of the part above 2,245 feet, is the Smithwick; the middle limestone is the Marble Falls limestone; and the lower shale is the "Lower Bend" shale. By means of the correlation proposed in this paper these subdivisions can be carried to the Seaman well.

A few of the facts thus brought out require discussion.

Unit A evidently belongs to the Strawn, but unit B is hard to place. If it lies immediately above the Smithwick it should be the equivalent of what has sometimes been called the "Millsap division." As originally described by Cummins[16] the "Millsap" is composed mostly of "blue [sandy?] and black [calcareous?] clays, with an occasional sandstone and limestone and an occasional bed of sandy shale. * * * At Thurber * * * the section * * * was principally bluish clay, or, as the miners call it, slate [calcareous shale?], with a few seams of sandstone and limestone." In a subsequent report[17] Cummins dropped the name "Millsap," and still later[18] he explained that by tracing a coal bed of the Strawn formation to Millsap he had convinced himself that the beds there were part of the Strawn. The "Millsap division" of Plummer[19] Cummins says "is not the same thing" as Cummins's "Millsap division." Plummer defines his "Millsap division" as the "beds between the Smithwick shales and the top of the limestone members outcropping in Parker County," though without defining the precise top of the Smithwick. He describes the "Millsap" as consisting, in its best exposure, at Kickapoo Falls, of thick, massive dark-blue shales with lenticular, unevenly bedded limestones. It is very interesting to note that he says that the basal "Millsap" contains a light-colored quartz sand which is in places separated from the Smithwick by blue marls and thin limy layers. That is to say, as appears in my synthetic and percentage logs of the Seaman well, the maximum development of sand is somewhat above the plane of most pronounced lithologic separation. The same agreement with the results presented in the synthetic log in this paper appears in Plummer's statement[20] that "in places the black shale [of the Smithwick] grades into a sandy blue and yellow-gray layer above." Regarding the fossils Plummer says that "the three lower limestones [of the "Millsap division"] are found to contain a fauna quite different from the overlying Strawn beds," but also that it is the opinion of Dr. R. C. Moore that the fossils "are much younger than the Bend fauna." The extreme disconformity between units A and B and the seemingly slight disconformity if not transition between units B and C as brought out in Plate I would lead to the belief that unit B, which I

[16] Cummins, W. F., Geology of northwestern Texas: Texas Geol. Survey, vol. 2, pp. 372–374, pl. 6, p. 361, 1890.

[17] Cummins, W. F., Notes on the geology of northwest Texas: Texas Geol. Survey Ann. Rept., vol. 4, p. 222, 1892.

[18] Cummins, W. F., Am. Assoc. Petr. Geologists Bull., vol. 3, pp. 146-147, 1919.

[19] Plummer, F. B., Preliminary paper on the stratigraphy of the Pennsylvanian formations of north-central Texas: Am. Assoc. Petr. Geologists Bull., vol. 3, p. 140, 1919.

[20] Idem, p. 139.

take to be about equivalent to Plummer's "Millsap division," should be correlated with the Smithwick rather than with the Strawn.

The presence of a limestone in the lower part of the Smithwick in the Seaman well, instead of the shale in the Rudd well, and of shale below that in the top of the Marble Falls in the Seaman well, instead of the black limestone in the Rudd well, has been discussed above (p. 10) with reference to genesis but requires additional comment with reference to nomenclature. Frank Reeves, who has prepared a report to be published by the United States Geological Survey on part of the Ranger and Eastland oil fields, tells me that in wells in that region a "lime" called the "Smithwick lime" is recognized. It averages about 100 feet in thickness, and its top lies pretty constantly 300 feet above the top of what is there called the "Black lime," taken as the top of the Marble Falls. Between the two lie shales called the "Lower Smithwick shales." In the Seaman well the relation of the limestone between 3,430 and 3,590 feet (thickness 160 feet) in the driller's log or between 3,470 and 3,610 feet (thickness 140 feet) in the synthetic log and the top of a sandy black limestone or calcareous black sandstone at 3,760 feet in both logs (interval in driller's log 170 feet, in synthetic log 150 feet) is so similar to the relation of the "Smithwick lime," allowing for increase in thickness at least of detrital members in the direction in which the Seaman well lies from the Ranger field, that it seems justifiable to assume that the limestone in the lower part of unit C is the "Smithwick lime." Then the "Lower Smithwick shale" is essentially the equivalent of the top of the Marble Falls. Whether paleontology would reveal this relationship is uncertain, as the fauna might be more influenced by environment than by time.

A consideration of thickness ratios in connection with those tabulated on page 17 supports this interpretation. Thus, assuming the Marble Falls in both wells to begin at the top of unit D, we have:

D to J, Rudd 441 feet, Seaman 680 feet, ratio 1: 1.54.

Or, assuming it to begin with the top of unit E in both wells, we have:

E to J, Rudd 344 feet, Seaman 534 feet, ratio 1: 1.55.

Both of these conform to normal ratios. If we assume that unit D in the Seaman well corresponds to the lower part of units C and C′ in the Rudd well—that is to say, that it belongs to the Smithwick—we have:

D to J, Rudd, 441 feet; E to J, Seaman, 534 feet; ratio 1: 1.21,

a very low ratio. Or, if we compare Smithwick thicknesses, we have:

C+C′, Rudd, 275 feet, Seaman, 595 feet, ratio 1: 2.16,

a high ratio; but assigning unit D in the Seaman well to the Smithwick we have:

C+C′, Rudd, 275 feet; C to D, Seaman, 741 feet; ratio 1: 2.7,

which is the highest ratio between corresponding units in the two wells except that for unit G.

The Marble Falls limestone is so well defined a formation, except for the argillaceous unit D at the top and the limestone of unit K below it, that its identification calls for no special discussion. The well-developed basal bed and the numerous lithologic differences which separate it from unit K have been noted above. The inclusion of unit K with unit L as part of the "Lower Bend," of Mississippian age, as against the Pennsylvanian age of the Marble Falls, is absolutely justified by the fossils. P. V. Roundy, of the United States Geological Survey, who is making very fruitful researches in the neglected field of micropaleontology, reports that in the Seaman well the lowest Pennsylvanian fossils he found were in the sample from 4,300 to 4,310 feet—that is, about 10 feet above the base of unit J—and the highest Mississippian fossils in the sample from 4,370 to 4,380 feet—that is, about 50 feet below the top of unit K. In the Rudd well he found unquestionable Pennsylvanian fossils in the sample from 2,920 to 2,930 feet; probable Pennsylvanian fossils in the sample from 2,945 to 2,950 feet, about 12 feet above the contact; questionable Mississippian fossils in the sample from 2,965 to 2,970 feet, about 3 feet below the contact; and definite Mississippian fossils in the sample from 2,975 to 2,985 feet.

RELATIVE THICKNESS OF THE SECTION IN THE TWO WELLS.

The relative thicknesses of the units are presented in the following table:

Relative thicknesses of units A to L in Rudd and Seaman wells.

Unit.	Depth of base (feet).		Thickness (feet).		Ratio (Rudd to Seaman).	Name.		
	Rudd.	Seaman.	Rudd.	Seaman.				
A	2,215	2,665	....	....	....	Strawn formation.		Pennsylvanian.
B	2,247	3,045	32	380	1: 11.87	"Millsap division."		Pennsylvanian.
						..........(?)..........		
C	....	3,610	275	565	1: 2.165	True Smithwick shale.		Pennsylvanian.
C′	2,522+?	3,640		30				Pennsylvanian.
D	2,619	3,786	97	146	1: 1.505	Marble Falls limestone (Rudd 441 feet, Seaman 680 feet.)	"Lower Smithwick shale."	Pennsylvanian.
E	2,690	3,840	71	54	1: 0.761			
F	2,713	3,870	23	30	1: 1.303			
G	2,744	4,015	31	145	1: 4.68			
H	2,805	4,072	61	57	1: 0.935			
I	2,841	4,132	36	60	1: 1.665			
J	2,963	4,320	122	188	1: 1.541			
K	2,985	4,372	22	52	1: 2.365	Rudd 112 feet, Seaman 199 feet.	"Lower Bend" limestone.	Mississippian.
L	3,075	4,519	90	147	1: 1.635		"Lower Bend" shale.	Mississippian.
Total..................			860	1,854	1: 2.155			
Total without "Millsap division."...........			828	1,474	1: 1.78			

There is little to generalize about in this table. The region of the Seaman well, as pointed out on page 6, was nearer than the region of the Rudd well to the old land mass from which the "Bend" sediments were derived; hence the section is much thicker there. In some individual units, however, this relation is reversed. Through units C, D, and E there is a continuous decrease in ratios of thickness with increasing deposition of lime, but this relation to lime deposition does not hold throughout the section.

It is worth special notice that the dominant thickness ratio applies also to the "Lower Bend" in the two wells, a fact which indicates that approximately the same land supplied sediment to this region during the earlier Mississippian deposition. This fact opposes the assumption, which is also otherwise improbable, that unit J derived its sediments from a different source than the overlying members of the Marble Falls. The apparently greater sandiness of parts of unit J in the Rudd well than in the Seaman well may therefore, for lack of a better explanation, be tentatively attributed to local currents.

The presence of the "Lower Bend" limestone in both wells in proportionately nearly equal thickness underlying the big unconformity that separates it from the Marble Falls limestone is very surprising. Doubtless the hardness of the "Lower Bend" limestone tended to preserve it as the surface bed, but even so its occurrence in this way, if general, implies a remarkable planation before the deposition of the Marble Falls. Possibly the position of both wells near the axis of the "Bend arch" (see fig. 1, p. 6) has something to do with this similarity. It would be interesting to determine whether any relation exists between position on the "Bend arch" and the erosion of the "Lower Bend" limestone and shale before the deposition of the lowest Pennsylvanian beds.

COMPARISON OF THE SYNTHETIC LOG OF THE SEAMAN WELL WITH THE DRILLER'S LOG.

Mere hasty inspection reveals at once the wide divergences between the synthetic log and the driller's log, the failure of the driller's log to bring out many essential features, and the error in many identifications. In part these errors and inaccuracies are doubtless due to the special difficulties presented by the section in the Seaman well, particularly to the mixing of ingredients in individual beds and the rapid alternation of beds of different composition.

It will not be worth while to go into a detailed comparison; the reader can make his own on the graphic logs, but a few of the larger similarities and differences will be pointed out. In the driller's log of the Seaman well at least part of the true Smithwick shale might be recognized in the blue shale and slate between 3,150 and 3,430 feet, and the approximate limits of the "Smithwick lime" between 3,430 and 3,590 feet. The approximate limits of the "Black lime" are indicated between 3,760 and 3,870 feet. The similarity of the upper part of unit J to the lower part does not appear. My observations indicate that the only basis for the identification of "sand" between 4,190 and 4,200 feet is a small amount of slightly sandy shale, most of the material being pure black limestone. Apparently the driller mistook flint for sand. The "Lower Bend" shale is well defined, and the distinctive blue-gray color of the "Lower Bend" limestone is brought out by the term "dark-gray lime" applied to the material between 4,370 and 4,420 feet, as against "black-gray" applied to the Marble Falls limestone, though the upper boundary assigned is 20 feet too low. The essential fact I wish to emphasize, however, is that no matter how faithfully a log may represent the dominant lithology of any part of the section penetrated it is not likely to bring out those facts which are needed for establishing an accurate correlation. I believe that an adequate basis for arriving at the stratigraphic results needed in present-day oil geology can be furnished only by a graphic percentage log, which, unlike even the best verbal or graphic log of the usual type, records not merely the dominant rock but shows in quantitative terms the proportions within that rock of the principal constituents, and, to supplement this log, the determination of any characteristics or materials of special significance.

GENERALIZED LOG AND POSITION OF OIL SANDS.

To summarize the results of the study of the Rudd and Seaman wells the generalized log in column 6, Plate I, has been prepared. The thicknesses assigned to different parts of the section are based on average thicknesses in the Ranger field, as reported by different writers.[21] As the Ranger field lies between the two wells the thicknesses used are also for the most part intermediate between those in the two wells. In this log thicknesses of certain beds which I wished to emphasize, especially of glauconite and sandy beds, have been very much exaggerated.

As the most immediate object of this investigation is to supply a framework for determining exactly the stratigraphic position of oil horizons in the "Bend series" in north-central Texas, I have made an attempt to indicate in a general way the possible position in my generalized section of the oil sands recorded by several geologists. The records I have used may be summarized as follows:

Reeves.

[Op. cit. The numbers given to the sands in the generalized log, column 6, Pl. I, in pocket, correspond to the numbers in this list.]

1. "Smithwick lime" (Breckenridge, Caddo, or False Black lime).
2. "Lower Smithwick shale," 80 to 160 feet, above the "Black lime."
3. Top of "Black lime."
4. Second pay, 70 to 130 feet below the top of the "Black lime."
5. McCleskey or Ranger sand, 180 to 220 feet below the top of the "Black lime." Usually directly overlain by gray limestone.
6. Fourth pay, 270 to 300 feet below the top of the "Black lime."
7. Fifth pay, 420 to 460 feet below the top of the "Black lime."

Matteson.

[Op. cit., p. 192.]

(*a*) Smithwick shale; oil and gas from lenticular sands.
(*b*) Contact of Smithwick and Marble Falls.
(*c*) Fincher sand, about 95 feet below the top of the Marble Falls [Marble Falls equals "Black lime"?]. Really a sandy limestone.
(*d*) Gordon sand [=McCleskey or Ranger sand?], 130 to 225 feet below top of the Marble Falls. Overlain by 110 to 160 feet of gray lime.
(*e*) Jones sand, 325 feet below the top of the Marble Falls (Ranger field).
(*f*) Veale sand (Caddo, Stephens County), 640 feet below the top of the Marble Falls.

Hill.

[Hill, R. T., Petroleum in the Texas Bend series; Oil Trade Jour., June, 1918, p. 88.]

I. At Caddo, Stephens County, immediately below the top of the "Black lime."
II. South of Breckenridge, Stephens County, at less than 100 feet in the ["Black"] lime.
III. At Ranger, somewhat over 200 feet in the ["Black"] lime.
IV. At the Morris ranch in Coleman County, in the midst of black shale, over 200 feet below the bottom of the black lime.

[21] Reeves, Frank, unpublished report of the United States Geological Survey on the Ranger and Eastland fields and oral communications. Matteson, W. G., Central Texas oil fields: Am. Assoc. Petr. Geologists Bull., vol. 3, pp. 173-175, 1919. Plummer, F. B., Pennsylvanian formations of north-central Texas: Idem, pp. 139-140.

If the top of the "Black lime" is taken at 520 feet in the generalized log, or a little above the top of unit E, and it is remembered that the Seaman well section is thicker and the Rudd well section thinner than that at Ranger, the basis for the identification of oil horizons that I have suggested in the generalized graphic log can be readily worked out. If my attempted identifications are for the most part nearly right a conclusion bearing on the theory of the origin of oil is suggested. Almost all or all the horizons indicated correspond to the highly glauconitic, phosphatic, sulphidic, coarsely sandy beds of the type that marks the bases of units. That the minerals formed at these horizons are all the product of decaying organic matter, probably mostly animal matter resulting from an unusual destruction of life, seems almost certain. Then the presence of oil in these sands may be due not only to the porosity of the sands but also to the accumulation of organic matter directly in association with them.

Deductive considerations in themselves favor this assumption, for the coarsest sands will naturally be deposited at the bases of units, believed to represent the beginning of transgressions, and the coarsest sands are the ones in which oil is generally assumed to accumulate. But as almost all these basal sands are characterized by minerals believed to be due to unusual amounts of organic matter the relation between the coarseness of the sand and the origin of oil directly in it is inherent. Local factors, such as cementation, may determine the exact position of the oil-bearing bed in a sandy succession of beds, but the fact remains that the presence of the oil and that of the sand are independent effects of the same cause, rather than that the presence of the oil is the effect of the presence of the sand. For that reason it makes little difference whether or not in a sandy series like that in and adjacent to unit H, where the Ranger sand probably occurs, the position of the sand corresponds exactly to one of the beds chosen as the base of a unit or not. It is worth noting that the coarsest sandstone from the Seaman well seen under the microscope occurs at the base of unit H, one of the beds suggested as equivalent to the Ranger sand, and that in the same position in the Rudd well a considerable amount of coarse sand distinguished by a red ferruginous stain was found.

Obviously an attempt to identify oil sands in wells which have not been found to be productive, from general figures and statements as to their positions, is a very speculative and arbitrary proceeding, more likely to express the preconceptions of the author than to form the basis for conclusions. From the synthetic logs of the individual wells it is evident that the wells penetrated numerous thin sandstones that have not been represented in the generalized log and more sand and sandstone than could be represented in the synthetic logs. It has been impossible to indicate in the synthetic logs many sandstones that were neither isolated nor thick, and the driller often fails to record slight amounts of coarse sand or sandstone. On that account the graphic logs can not be taken as conclusive reference data as to the occurrence of possible oil sands. But there are two such sands that can be identified with considerable certainty. One of them is Reeves's No. 3, of which he says that it is at the top of the "Black lime." This is taken to be the same as Matteson's *b*, of which he says that it is at the contact of the Smithwick and Marble Falls (presumably the "Black lime"), and Hill's I, of which he says that it is immediately below the top of the "Black lime." But my logs of the Seaman well show that at the base of unit D calcareous material was deposited, like that at the top of unit E (the major portion of the "Black lime") but more sandy; hence there is good reason for believing that sand No. 3 corresponds with the basal bed of unit D.

The other sand that can be rather definitely identified is the Ranger sand (Reeves's No. 5), of which both Reeves and Matteson say that it is directly overlain by a considerable thickness of gray limestone. The intervals given by Hill, Reeves, and Matteson all agree pretty closely, and as the basal bed of unit G is the only sand found in that part of the section overlain by a considerable thickness of gray limestone, the identification seems fairly trustworthy. The sand at the base of unit H, at 780 feet in the generalized log, is one of the coarsest noticed in the section; and that bed or any of the beds between it and the one at the base of unit G may be the producing bed, but it seems most likely that in the Ranger field the sand at the base of unit G is the main producing sand. As the Ranger sand, according to Reeves, is in places 40 feet thick it may be that locally the entire sandy portion of the section from the base of unit H to the basal bed of unit G, inclusive, constitutes the productive bed.

NATURE OF THE OIL-PRODUCING BEDS.

The lithologic character of the oil-producing beds seems to be one of the interesting subjects of research in the north-central Texas fields. Though I have no precise evidence as to the stratigraphic position of the oil-bearing beds, I have examined seven samples of reported oil "sands" in the collection of the United States Geological Survey. In a general way these samples consisted of sandy black limestone or shales, in some samples coarsely sandy, in some associated with coarse sandstones, but the latter are usually rather tightly cemented with calcite or silica. In thin section none of these materials appeared porous enough to be good reservoirs for oil. A. F. Melcher, physicist, of the United States Geological Survey, who has made determinations of the porosity of samples of similar material from north-central Texas, has reached the same conclusion,[22] and it consequently appears probable to both of us that this material is not the source of the large quantities of oil produced in the region. In view of the fact that in association with one of these samples and with several basal beds in the Seaman and Rudd wells loose grains of coarse sand were found, it seems more probable that there are beds of sand or sandstone so loosely cemented that fragments of them are not recovered in drilling and that these beds yield the oil. This is, however, a question on which those who have studied it more closely and in producing wells are more competent to express an opinion.

TIME REQUIRED FOR THIS METHOD OF WORK.

I found that I could examine the samples at the rate of about two an hour. I had about two thin sections for each sample from the Rudd well and studied these at the rate of about five an hour, but as the materials of the Seaman well were new to me, I studied the thin sections at the rate of about three an hour. Probably the study of the thin sections from a sample would take nearly as much time as the study of the sample. This is an approximate rate for establishing a type section in a new field. In a small area where the section is established the rate of study might for merely practical purposes be much faster. Thin sections can be prepared at the rate of about one and a half an hour. In addition to the petrographer probably two assistants to grind thin sections and to wash, file, and perhaps make certain tests on the samples would be required. I would urge care in washing the samples, as quartz sand, glauconite, and other important ingredients are frequently among the finer parts and are likely to be washed out.

SUMMARY AND CONCLUSIONS.

In this paper I have attempted to show that the relative proportions of sand, clay, and lime as represented in a graphic log called the percentage log serve to differentiate distinct lithologic elements in a stratigraphic section and to help in their correlation between widely separated wells within a single depositional basin. The boundaries of these units are defined in the percentage log either by sharp changes in the proportions of the constituents or by points marking the maximum of an oscillation of base-level. Where the break between two lithologic elements or units is sharp there usually occurs in the sections here described at or near the base of the upper unit a thin isolated bed containing coarse glauconite, associated with abundant calcareous shells or coarse shell fragments, phosphate, very abundant sulphide, and coarse sand. Any of these constituents may be absent or may predominate. Glauconite is, however, the one most likely to predominate, and after that phosphate.

Where the effect of maximum rise of base-level is marked by the greatest proportion of coarse detrital material in a practically uninterrupted depositional sequence the conditions favorable to the formation of the glauconite bed may not occur just at the same time. In that case the horizon of the surface of the lithosphere at that place at the time of greatest elevation of base-level (the akinetic surface), if it can be definitely recognized, should be taken as the boundary.

[22] Oral communication.

Where the percentage composition of the beds above and below the contact of two units is the same, however, it may be necessary to depend on the glauconite bed to mark the boundary.

Directly observable lithologic peculiarities have generally been found useful for separating only the larger, chronologically most widely separated portions of the section, not for differentiating the lesser units.

I wish to emphasize that I do not claim that the methods used here will be applicable everywhere. In regions of deposits formed very near shore, including much sandy material, larger fluctuations may be so confused by local variations of conditions that it may not be possible to disentangle them, though I believe that the method of study by means of the percentage log is always worth trying.

Under these near-shore conditions also glauconite probably does not form, as is indicated by its absence at the base of the Strawn in both wells and at the base of unit B in the nearer-shore Seaman well. On the other hand, as noted above, a typical glauconite layer was found at the base of a sandy formation, probably the Strawn, near Richland Springs, in San Saba County. At least this basal type of formation would be worth looking for in every section until the conditions under which it occurs are better known.

Glauconitic basal beds mark the contact of the Mississippian "Lower Bend" shale with the Ordovician Ellenburger limestone and the contact of the Pennsylvanian Marble Falls limestone with the Mississippian "Lower Bend" limestone. Here they separate units whose distinctness is beyond question. What is then the significance of the units defined by other basal glauconite beds? I think these must be accepted as definite and persistent stratigraphic elements, many of which paleontologic evidence has not yet discriminated. Maybe these elements can not be recognized paleontologically, but that does not invalidate them, if they are persistent and can be recognized lithologically. Probably these units are not all of the same order. The determination of their more exact chronologic and genetic significance in an analysis of sedimentary processes such as that outlined by Barrell [23] must await the accumulation of many more facts. Meanwhile, it must be realized that faunas and sediments are both complicated responses to complicated conditions and are to the investigator merely tools the accuracy of whose product depends on the skill of the hands that use them. Time and environment are two independent factors in the change of faunas. When the time is relatively short and the changes in environment slight the changes in faunas may be slight, though the lithologic change is widespread and distinct. On the other hand similar lithologic facies may be characterized by faunas that can not be differentiated, though the times at which the similar facies were deposited may be rather widely separated. Therefore, the conclusions that appear to be indicated by fossils can not, I believe, offhand and without critical analysis, be taken to supersede those derived from the rocks themselves.

Lithology has an especial advantage in the correlation of well sections, because lithologic material is obtained from the entire well, but fossils, even micro-fossils, are generally found only at intervals. It is therefore always possible to ascertain a good deal about the lithology and consequently not only to recognize units but, where distinct basal beds are present, as here, to place the boundaries of these units with precision within the limits of a single sample.

Some of the problems awaiting solution by the study of the lithology of well drillings have been referred to in the preceding pages. The most fundamental of these problems is the extension and development of correlation by the work of petrologists and micropaleontologists. The method and conclusions presented here need to be checked, refined, and given greater precision. Other microscopic criteria will doubtless be developed, and chemical and physical tests may be expected to furnish additional criteria. One of the criteria I hope to take up next is the mineralogy of the units. The possibility of finding horizon-marking index minerals, especially among the rarer heavy minerals of sedimentary rocks, has been tested by several investigations. The results have not on the whole been very satisfactory. The great variety of minerals present in any sediment and local variation due to currents or independence of drainage areas feeding into a common basin tend to confuse the differences corresponding to differences in age. However, as index min-

[23] Barrell, Joseph, Geol. Soc. America Bull., vol. 28, pp. 776-834, 1917.

erals, if they can be found, afford a much simpler, more direct, and more rapid means of recognizing horizons than the method here presented they are worth looking for.

Except as a means of locating producing beds, however, correlation is for the petroleum geologist merely a preliminary to the solution of his other problems, such as paleogeography, accumulation and migration of oil, and metamorphism—or, as some may prefer to call it, diagenesis and metamorphism—of the rocks as an index to the processes that have affected the oil. The solution of these problems will be advanced not, I believe, by direct observation in a single well but by compilation of similar data from a great number of wells, in the same way that the problems of surface geology are solved by areal mapping. The acquisition of the necessary data is beyond the capacity of a single individual or a single organization. It is therefore to be hoped that the producers of oil will sufficiently realize the importance to their industry of the solution of these problems to enable their geologists to cooperate in investigating them.

Geologists in general should come to regard the study of well drillings as a field worthy of special attention. The information afforded by a continuous sequence of drillings from a single well, from the wells in an extensive field, and from several fields in a larger area has a detail, completeness, and extension which are generally lacking in surface observations. Moreover, once a field is fully drilled an opportunity to acquire records of its subsurface stratigraphy is gone forever. It is therefore to be hoped that every effort will be made to preserve complete series of samples from wells and that central places may be found where these samples can be stored for permanent reference.

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