POSTDIAGENETIC CLAY MINERAL ENVIRONMENTAL RELATIONSHIPS IN THE GULF COAST EOCENE[1]

by

J. F. Burst, Jr.
Shell Development Company, Houston, Texas

ABSTRACT

An extensive survey of clay mineral relationships in the subsurface Wilcox formation (Eocene) has shown progressive diagenetic conversions with depth. Montmorillonite, a common constituent of Wilcox outcrop material, becomes less evident below 3000 ft and is not normally found in an unmixed state below the 9000–10,000 ft overburden level. At depths between 3000 and 14,000 ft, montmorillonite lattices are commonly interpersed with illite components, the frequency of which increases with depth to a virtual elimination of montmorillonite swelling characteristics below 14,000 ft.

Chlorite is present at all stratigraphic levels including surface exposures. It appears to be a more dominant constituent at depth; however, observed increases in basal intensities in samples that had been more deeply buried may result from more perfect crystal development rather than quantitative differences.

The diagenetic conversion of montmorillonite to illite and possibly to chlorite has resulted in a distribution of the last two minerals that is related to estimated depositional environments as reconstructed from micro-paleontological criteria in at least one well in southern Louisiana. It is inferred, therefore, that different chemical characteristics in the ancient Wilcox seas are responsible for the distribution coincidence even though the mineral groups defining the distribution were not necessarily indigenous to the ancient Wilcox sea.

Correlations between clay minerals and environment are not particularly noted in the investigation of analogous environmental situations in Recent sediments, and it is thus concluded that the environment indicators which appear as minerals in lithified sediments such as the Wilcox are present in freshly deposited sediments in the form of submineralic chemical constituents such as absorbed ions, molecular groups or subcrystalline lattice configurations which are not detected by the ordinary clay mineral identification procedures. The change to mineralic form is aided by the natural "bombing" resulting from normal increases in temperature and pressure due to burial. The process is apparently a continuum through the entire subsurface residence of the sediment and the results are seemingly in accordance with phase equilibria.

PART I.—EFFECT OF BURIAL

Geological workers have generally recognized the progressive lithification of materials found in successively older beds. In terms of clay mineralogy this lithification has usually been found to coincide with a progressive loss of swelling characteristics. This loss has been implied specifically by the dominance of swelling clay material in Recent and late Tertiary sediments

---

[1] Publication No. 155, Shell Development Company, Exploration and Production Research Division, Houston, Texas.

and of mixed-layer materials in the Paleozoic sediments in contrast to the virtual absence of swelling clays in still older sediments and in metamorphic rocks.

Geologic age, however, does not seem to be the controlling feature in the reduction of clay swelling capacity. A survey of the swelling parameter as a function of age reveals instances of well-lithified argillaceous beds considerably younger than certain other beds, the clays from which swell readily in ordinary laboratory testing. Also revealed are varying degrees of swelling ability in sediments of the same age which presumably were composed of uniform material at the time of deposition. This paper shows that anomalies of this type may be related to differences in burial depth and geothermal gradient.

Recently Yoder and Eugster (1955) have suggested that the transformation in the three-layer silicate lattice as a function of time, pressure and temperature is more fundamental than a simple loss of swelling properties. From their investigations, it is possible to deduce that progressive metamorphism ensues in a sediment, from the time the particular mineral components are originally deposited in a basin, through the period of increasing overburden pressure and temperature, to a point of physical and chemical rearrangement that is described, in the hand specimen, as metamorphism. Concomitant with a morphological change could be structural transformations through the 1Md–1M–2M polymorphic mica sequence which would progress as a function of pressure and temperature.

In analysis of clay-size material, particularly that from the commonly heterogeneous field sample, detection and classification of these polymorphic mica types is often difficult. The much more easily evaluated characteristic, which can also vary with prolonged pressure and temperature treatment, is the ability of certain clay mineral structures to expand and collapse in reaction to various routine laboratory tests ; e.g. thermal variations, ethylene glycol saturation. It is this characteristic, therefore, together with an apparent chlorite development, that serves in this study as criterion for postdepositional diagenesis.

Variables other than time, pressure and temperature contribute to the adjustment of lattice parameters in the natural subsurface "bombing" that a clay material undergoes during the passage of geologic time. For instance, the degree of crystal development within the clay structure at the time of original deposition seems to be important in regulating the "montmorillonite–illite" transformation under any given set of conditions. The well-developed expandable lattices that originate in bentonitic volcanics seem to retain their swelling capabilities after greater burial depth and for a greater span of geologic time than do the so-called degraded, three-layer, mica lattices common to most sediments.

Another point to be considered in the "montmorillonite–illite" transition is the specific location of an expanded clay in any particular stratigraphic sequence. In order for an expanded lattice to collapse, a path of egress must be provided for the interlayer water which will be discharged. Presumably, the absence of porosity in a section will retard the escape of this water and limit the progress of diagenesis.

Recognition of these variables within the over-all problem makes a suitable area for field study difficult to find. In order to eliminate as many inequalities as possible, and in order to isolate the effects of pressure and temperature, it is necessary to find a single time unit in which the beds (1) are essentially conformable, (2) originate from the same source, (3) are deposited in approximately the same sedimentary environment, (4) have been subjected to a minimum of tectonism and (5) are spotted with lenticular, porous sand bodies interspersed within a more or less contiguous and homogeneous argillaceous matrix. In addition, material from this stratum must be available along dip at various levels of burial. The Wilcox sediments of the Gulf Coast in southern United States can be sampled so as to satisfy the above conditions and were chosen for detailed study.

The Wilcox outcrop area conforms quite closely to the general outline of the Mississippi embayment of southeastern United States (Fig. 1). The Wilcox group is exposed for some 800 miles along the west side of the embayment area, in a general northeasterly direction from the Mexican border to Cairo, Illinois. On the east side of the embayment area the Wilcox is exposed in an extensive archlike trend bordering the Appalachian plateau and mountains and the Piedmont belt through Tennessee, Mississippi, Alabama, Georgia and South Carolina.

From Fig. 1 it can be seen that the Wilcox dips southward at a low angle from its northernmost exposure to approximately central Louisiana. Farther gulfward, the dip is somewhat steeper.

Lithologically, the Wilcox is composed of interstratified shales, silts, and friable to well-cemented sandstones. Marine beds are common in the exposed sections in Alabama where excellent examples of oyster reefs and glauconite accumulations are also present. The Wilcox exposed west of the Mississippi embayment is almost entirely nonmarine. It is characterized by the common occurrence of lignite and it contains several beds of alluvial kaolinitic materials that are mined in the area as fire clays.

A generalized north-south cross-section (Fisk, 1944) from Cairo, Illinois to the Gulf of Mexico shows (Fig. 2) the steeper dip of the Wilcox gulfward from central Louisiana. Isotime lines that show significant changes in dip slope, such as the Wilcox top in this illustration, are not uncommon in the Gulf Coast. By sampling outcrops and selected intervals in the subsurface Wilcox section, a study can be made on a single group of formations from a point of exposure, through ever-increasing overburden, to a burial depth of approximately 16,000 ft subsea.

The part of the Wilcox chosen for this study is comparable to that shown in Fisk's (1944) cross section from Vicksburg, Mississippi, to Plaquemines, Louisiana. It includes samples from wells drilled in the relatively steeply sloping portion of the Wilcox at burial depths ranging from approximately 17,000 ft to almost 16,000 ft. The geographical locations of the wells from which samples were studied are shown on Fig. 3.

The specific intervals sampled are shown in a composite section of the traverse in Fig. 4. Wells are numbered consecutively from shallow to deep. Samples from the shallower wells, 2, 3 and 4, were obtained from drill cuttings, whereas only cores were used for sampling the deeper wells.

Wilcox sedimentation is judged to have been similar to that in Recent time. It is characterized by a series of deltaic advances and broad inter-deltaic bay and lagoon areas usually separated from the open sea by long ridgelike barrier islands. Detrital sediments were derived primarily from the north and carried into the ancient sea basin by an ancestral Mississippi River drainage system. The clay mineral suite in the suspended load was not thought to vary significantly in character during the Wilcox interval except for seasonal flooding effects. This assumption is based on the role of uniformitarianism and follows the consistency in mineral components found in the suspended material of the present Mississippi River.

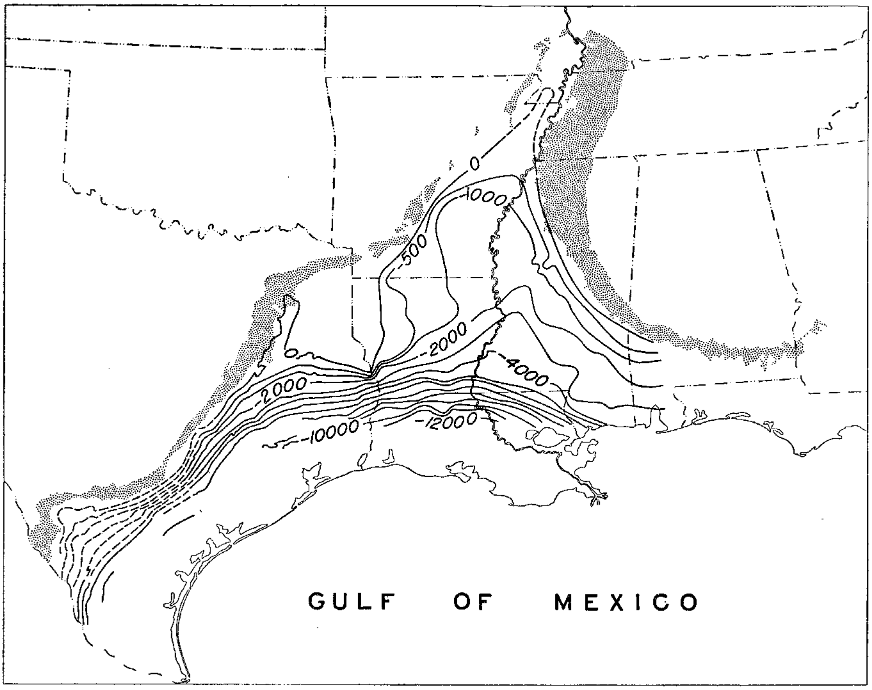

FIGURE 1.—Wilcox exposure trend and structural contours on subsurface Wilcox top.

The suggested diagenesis in the Gulf Coast Wilcox sediments becomes apparent if representative clay mineral analyses of superposed strata within the formation are divided into three groups: (1) shallow sediments higher than 3000 ft depth, (2) intermediate-range sediments between 3000 ft and approximately 10,000 ft, and (3) deeply buried sediments below the 10,000-

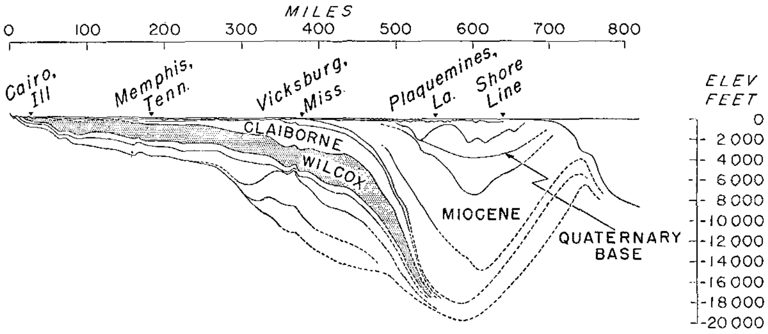

Figure 2.—Cross section of Mississippi Embayment, Tertiary sediments (After Fisk, 1944).

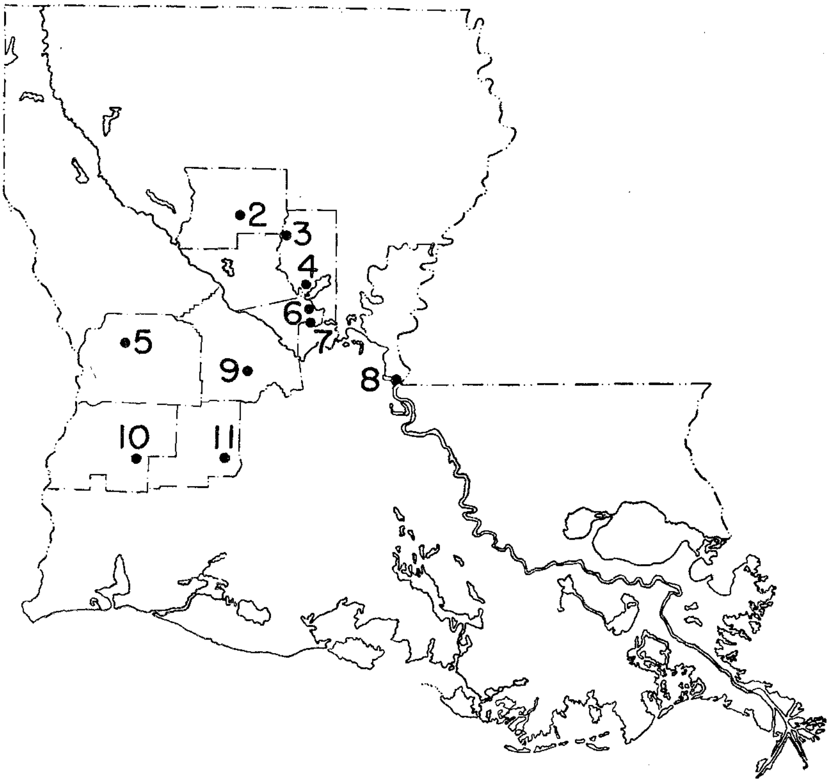

Figure 3.—Location of wells sampled for diagenesis study.

12,000 ft interval. The two major transitions with depth (progressive reduction of swelling capacity and increased chlorite thermal stability) are illustrated in Figs. 5 and 6 through comparison of x-ray diffractograms of minus two micron material, recovered from the three depth ranges cited above.

Swelling capacity was measured (Fig. 5) by treating the clays with ethylene glycol and subsequently heating to 400°C for one-half hour. An increase in the 001 basal lattice dimension to 17 Å (approximately) means that a clay is fully expandable. Normally clay of this type is included in the suspended load of the present-day Mississippi River and in outcrop samples of the Wilcox. The top row of diffractograms in Fig. 5 show that this type of material is also found in the shallow burial zone of the Wilcox.

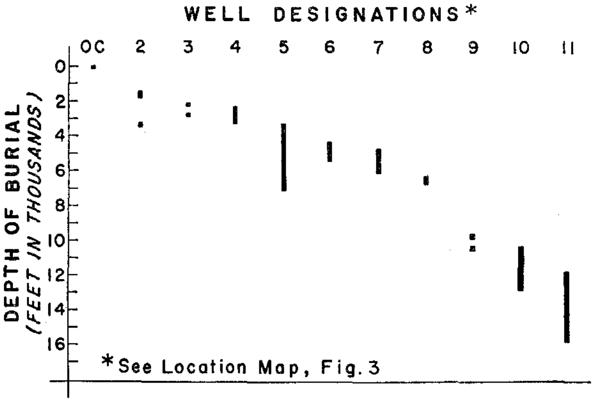

FIGURE 4.—Sample recovery depths in Wilcox sediments, central Louisiana.

In the mid-ranges of burial depth (3000–10,000 ft) progressive reduction in swelling capacity reflects progressive interlayering of the expandable material with units of a nonexpandable clay. The reduced swelling ability is shown in the center patterns of horizontal rows 2 and 3 (Fig. 5) in which the standard glycol treatment has expanded the lattices to only 13.5 and 12.7 Å respectively.

In the extreme burial depth ranges (below 12,000 ft) glycolation produces asymmetry in the primary illite basal reflection by causing a slight swelling on the low-angle side. The glycol treatment was not able to swell any portion of the deeply buried material to the 17 Å spacing.

Variation of the 10 Å illite reflection with depth is of interest (see center column, Fig. 5). From an extremely weak reflection in patterns of upper zone sediments, the 10 Å line increases in relative intensity to become the dominant reflection of patterns representing the deepest zone.

Chlorite is not an exceptional constituent in Wilcox sediments. It is present at all depths and in outcrop samples. Whether or not it increases in amount or in diffraction ability with depth is questionable; however, some differences which arise in x-ray patterns of heated Wilcox clays can be correlated with depth. One difference is observed in the last (650°C) column in Fig. 6 as a progressive intensity increase in the 14 Å diffraction line.

Certain anomalies are encountered when the mineral data are compared with burial depth on a sample-by-sample basis; however, study of several hundred patterns from various depths indicates that a progressive loss in montmorillonite swelling capacity and a progressive perfection of chlorite crystal development is the rule rather than the exception. The specific reactions in this progressive diagenesis are beneficiations of degraded and fragmental mineral lattices by gradual fixation of potassium and magnesium to form illite and chlorite respectively. A similar process was suggested by Grim in 1951.

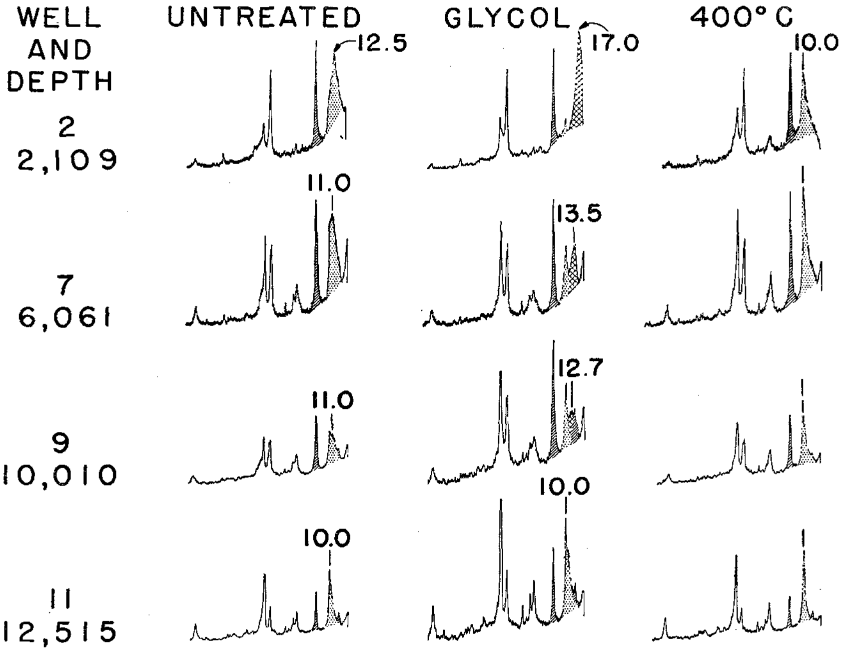

Figure 5.—x-Ray patterns showing progressive loss of expandable material with depth.

According to paleontologic and lithologic interpretations the sediments along this entire Wilcox dip section were deposited from a continuous and uniform source in shallow water close to the shore line. They are interspersed with deeper marine deposits; however, there seems to be no pattern to these marine contributions which would explain a progressive mineral variation through several thousand feet of sediment.

Actually, it does not appear that any important progressive, geologic variations operate in this section other than time, temperature, and overburden pressure. It has been concluded, therefore, that the integrated effect of these three variables is a common contributor to the final mineral character of ancient clay sediments. The effect can be described as "postdepositional diagenetic mineralization" or simply diagenesis. Strakhov (1953) divides the history of sediments into three stages:

> (a) sedimentogenesis, or the formation of the sediment, (b) diagenesis, or the stage of the transformation of the sediment into sedimentary rock, (c) epigenesis, or the stage of alteration of the already constituted rock under tectonically produced changes in the physical and chemical conditions of its existence [excluding metamorphism and weathering].

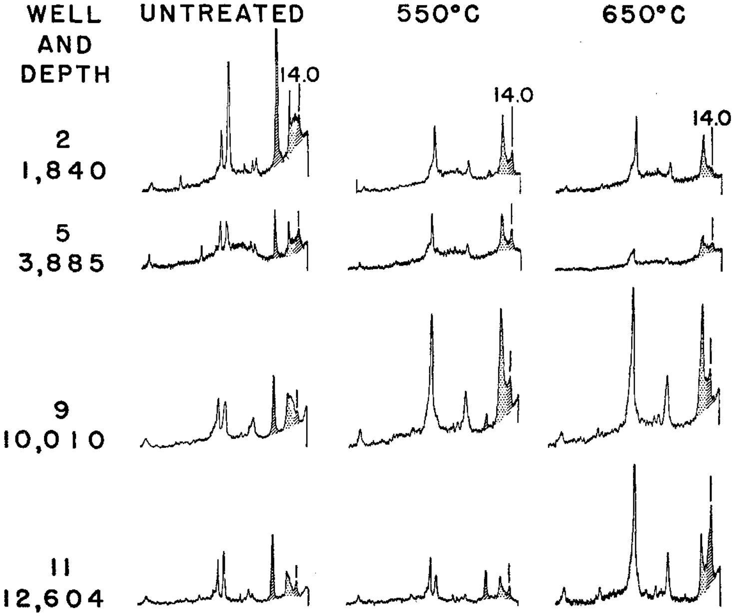

Figure 6.—x-Ray patterns showing changes in chlorite characteristics with depth.

The type of change described above probably overlaps both (b) and (c) in Strakhov's classification. In other discussions such a change has been called "incipient metamorphism." Inasmuch as the process of alteration with time, temperature and pressure seems to be a continuum, it does not conveniently lend itself to division by nomenclature. Therefore, the term "postdepositional diagenetic mineralization" is suggested to define roughly an area of change between the superficial alteration of clays on first contact with depositional waters and the drastic alteration resulting from severe tectonism.

It is further concluded that diagenetic alteration must be considered on the same basis as environmental chemistry and source area petrology as an important contributor to the ultimate mineralogy of a buried sediment.

Proper appreciation of this factor may account for apparent violations of the "uniformitarianism" concept.

PART II.—EFFECT OF SEDIMENTARY ENVIRONMENT

The reconstruction of sedimentary environments in ancient rock sequences is an important application of geologic principles to petroleum exploration. It is often advantageous to "locate" a given sample in a sequence not only with respect to its relative age (vertical position), but also with respect to its relative or, if possible, specific occurrence in the geometry of an ancient depositional basin (transverse position). Several authors (Millot, 1949; Grim, Dietz and Bradley, 1949; Powers, 1954) have inferred from their work in Recent sediments that clay mineral distributional patterns are created in marked parallelism to facies relationships, being influenced by such physical and chemical forces as water depth and temperature, current velocity, and Eh, pH relationships of the depositing medium. Clay mineralogists in the petroleum industry have hoped for many years to reconstruct ancient depositional basin geometry by relating the patterns resulting from Recent mineral distributions to similar situations in the geologic past.

Diagenetic alteration, such as outlined in the first part of this paper, seemingly would eliminate any direct relationship between Recent and ancient mineral distributions: however, in a detailed investigation of approximately 700 ft of core material from well no. 11 (Fig. 4) correlation was established between the relative amounts of illite and chlorite and depositional environments as reconstructed independently from paleoecological data. This well, known as the Richardson and Bass (Shell), Luma Darbonne, No. 1, Allen Parish, Louisiana, is a 16,000 ft wildcat in which the bottom 5000 ft, through the entire Wilcox interval, was continuously cored.

Figures 7, 8 and 9 show x-ray diffraction patterns of the clay fractions (less than 2 microns equivalent spherical diameter) from 48 sampling sites in the interval 12,157–12,795 ft. Attention is directed to the relative intensities of the 7 Å and 10 Å diffractions.

In Fig. 7 are x-ray diffractograms of the materials representing slightly more than 200 ft of subsurface section from 12,157 to 12,383 ft. The labels 10, 7 and *Q* on the patterns designate the diffraction lines that are used here as characteristic of illite, chlorite and quartz, respectively. Kaolinite, which also has a prominent diffraction at 7 Å, is present in many of the sediments, but the intensity of the chlorite 14 Å lines and the deficiency of the kaolinite 2.38 Å reflections indicate that kaolinite contributions are not materially significant. Accordingly the 7 Å line intensity is construed as indicative of chlorite content.

The similarity of the patterns in the first column is evident; however, there is an abrupt change in curve character between the samples from 12,212 and 12,233 ft. The relative intensities of the 7 Å and 10 Å peaks in 12,233, 12,252 and 12,266 are considerably different from comparable peaks in the first column. The trend reverses however, in 12,308 and 12,312 and once again the 10 Å peak is nearly as high as the 7 Å peak. In the samples from 12,325 to 12,383 ft another marked change in curve character is noted in which the 10Å reflections are consistently dominant over the 7Å reflections. As a group, these curves differ from the curves in the first column and from the curves in the second column. The clay materials in the interval covered by the patterns in Fig. 7, therefore, show an obvious tendency for clay minerals to be grouped in characteristic assemblages.

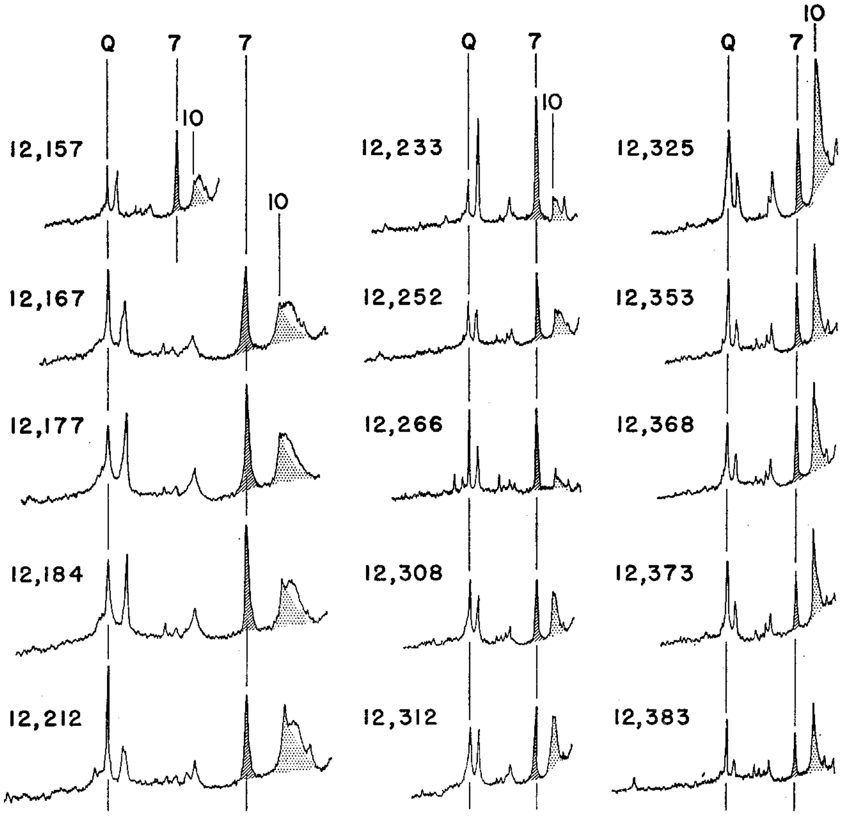

FIGURE 7.—x-Ray patterns from Luma Darbonne no. 1 Well, Allen Parish, Louisiana; depths 12,157–12,383 ft.

The grouping continues down the section (Figs. 8 and 9). In particular, sharp breaks in mineral character can be seen between the 12,434 and 12,437.5 ft samples and between the 12,452 and 12,467 ft samples. These breaks set off an interval of sediments containing predominantly 7 (or 14) Å material from sediments both above and below which contain relatively more 10Å clays. Similar breaks in mineral content are shown in

Fig. 9 below the 12,583 and 12,731 ft levels. The 150 ft interval between these levels contains somewhat less 7 Å material than do the sediments which bracket it both above and below.

Figures 7, 8 and 9 show that the clay mineral suites in deep Wilcox sediments tend to vary systematically with stratigraphic position. In general, this variation is seen as a reversal in the relative intensities of x-ray diffraction peaks representing chlorite and illite.

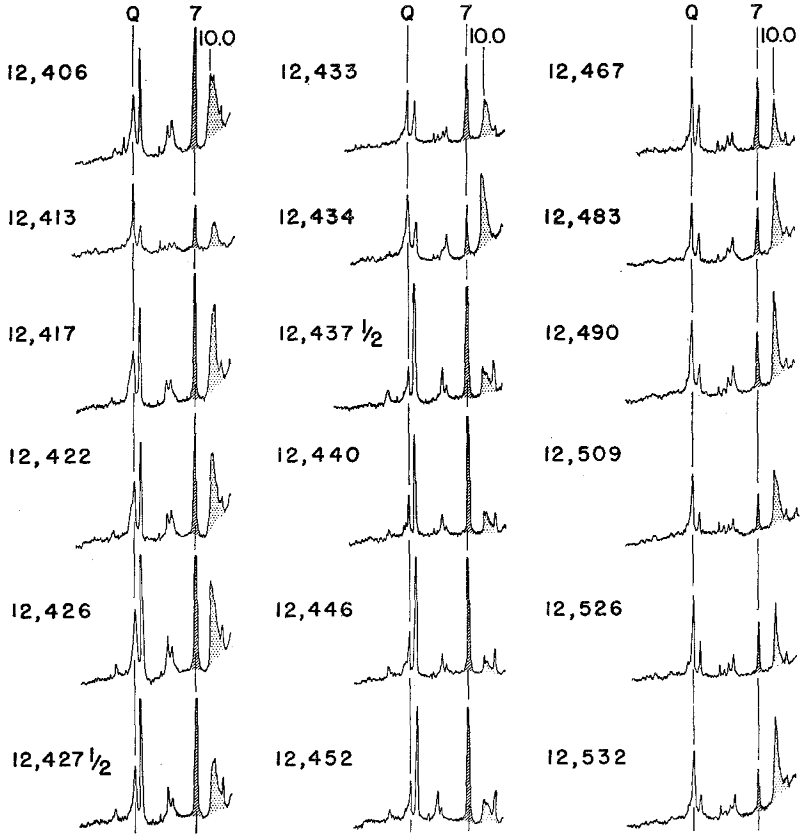

FIGURE 8.—x-Ray patterns from Luma Darbonne no. 1 Well ; depths 12,406–12,532 ft.

To present these data in an easily interpretable form a mineral ratio log has been constructed by plotting the 7–10 Å intensity ratio versus depth (Fig. 10). In this log, deviations to the right represent x-ray patterns of a typical chloritic sediment whereas the points at the left side represent patterns which indicate a considerable illite content.

Extreme deviations seem to be higher than the actual 7–10 Å line intensity ratios in Figs. 7, 8 and 9., The apparent anomaly arose when many of the more intense 7 Å diffraction lines had to be cut off in order to fit them to the presentation.

The mineral ratio log is compared in Fig. 10 with a log of estimated depositional environment as reconstructed from paleontological and lithological interpretations (Rainwater, E. H., personal communication, 1951).

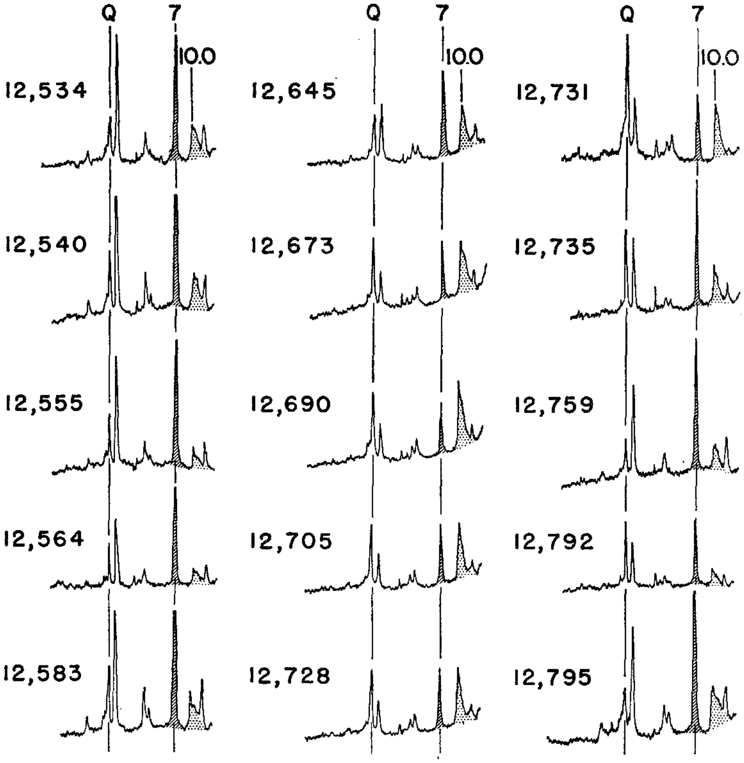

FIGURE 9.—x-Ray patterns from Luma Darbonne Well ; depths 12,534–12,795 ft.

Four environments—deltaic, lagoonal, beach, and shallow nearshore marine —were recognized. Certain relationships between the two logs are quite striking. The most obvious correlations are those between marine beach environments as designated in the log to the left and the sharp projections to the right in the mineral ratio log at 12,970, 12,550–12,600, 12,450, 12,270 and 12,235 ft. A second correlation, not quite so obvious, is observed in the moderate deviations to the right which correspond to environments interpreted as marine at 12,875, 12,730–790, 12,540, 12,405–430, 12,310 and 11,980 ft. No differentiation could be made between lagoonal and deltaic environments on the basis of this clay log.

The general appearance of the mineral ratio log suggests a periodicity or cyclic deposition wherein the amount of 7 Å material rises gradually through the lower portions of the cycle to a maximum at the time of beach deposition and then retreats abruptly through the marine facies to a minimum. Two complete environmental cycles are in evidence between 12,660 and 12,400 ft. Within this section, progressing from bottom to top, are encountered, successively, lagoonal, deltaic, beach, marine, and again, lagoonal, deltaic

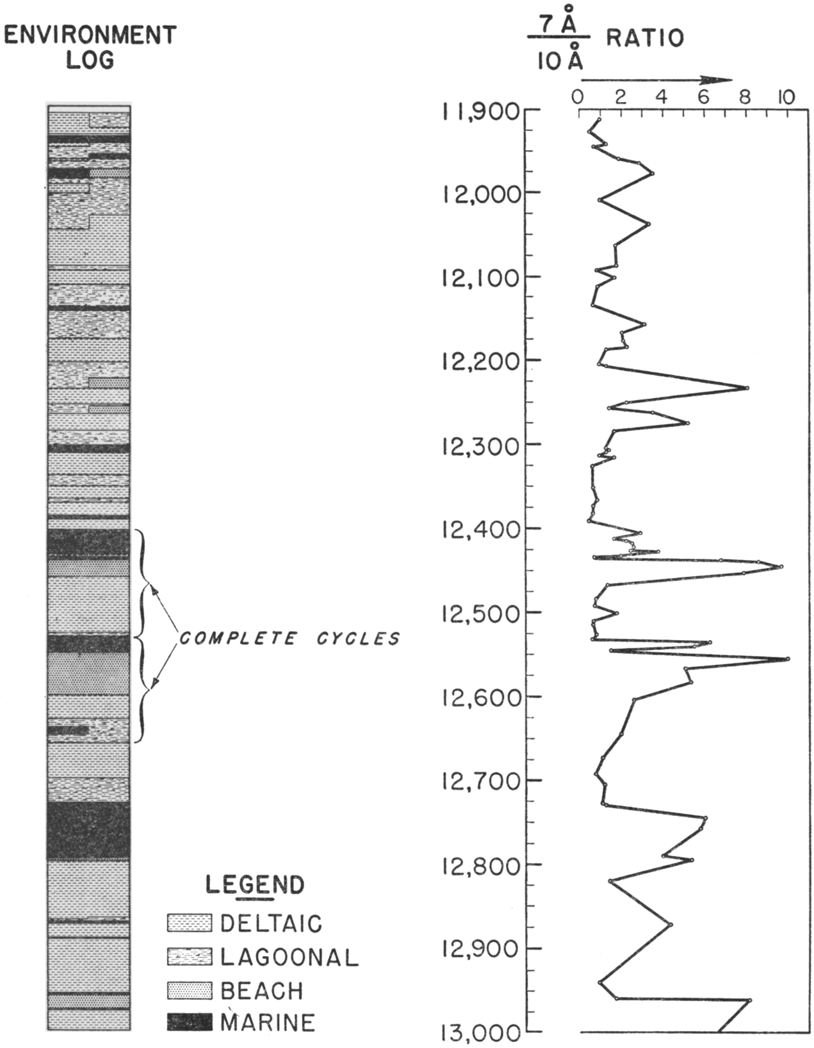

Figure 10.—Environmental–mineral ratio log comparisons, upper Wilcox, Luma Darbonne no. 1 Well.

beach, and marine environments. In both instances the chlorite/illite log conforms to the cyclic depositional character.

The data are construed to mean, therefore, that clay mineral suites in lithified sediments can vary systematically with depositional environment and that the reconstruction of ancient environments through mineral characterization of clay-bearing strata is possible even though the mineral groups defining the environments were not necessarily indigenous to the original sediments.

CONCLUSIONS

Several conclusions may be drawn from the two sets of data presented in this report. First, it has been shown that a mineral diagenesis is evident as Wilcox rocks are buried progressively deeper and lithified. Second, it has been shown that, after lithification and burial, a mineral correlation with prediagenetic variations is still possible. In fact, the correlation with environment is seemingly more easily resolved after diagenesis than before. At least this seems to be true in the light of experiences with Recent sediments such as reported by Milne and Earley (1958). In this light it is further concluded that submineralic chemical constituents, indicative of environment, are present in and on marine clays and are subsequently incorporated as diagnostic lattice constituents by diagenesis. The minerals present in a sediment after diagenesis may not necessarily resemble the materials originally distributed in a basin; but the relative distribution of the diagenetic minerals may well follow the variations in environmental chemistry during original sedimentation owing to the absorption/adsorption of characteristic, submineralic building blocks at that time. The subsequent change of these submineralic components to definitive structures is accomplished through a natural "bombing" which results from normal increases in temperature and pressure due to burial.

ACKNOWLEDGMENTS

The author is indebted to Mr E. H. Rainwater, Shell Oil Company, Technical Services Division, for his generous aid in locating suitable material for research and for the frequent contributions of his knowledge of Gulf Coast sediments to the general theme of the investigation. The author is also indebted to Dr William S. Pike and other members of the Shell Oil Company, New Orleans Area Staff, for their technical and administrative cooperation during the course of this study.

REFERENCES

Fisk, H. N. (1944) Geological investigations of the alluvial valley of the lower Mississippi River : *Mississippi River Commission* Publication, Vicksburg, Mississippi, 78 pp.

Grim, R. E. (1951) The depositional environment of red and green shales : *J. Sed. Pet.*, v. 21, pp. 226–232.

Grim, R. E., Dietz, R. S. and Bradley, W. F. (1949) Clay mineral composition of some sediments from the Pacific Ocean off the California coast and the Gulf of California : *Geol. Soc. Amer. Bull.*, v. 60, pp. 1785–1808.

Millot, Georges (1949) Relations entre la constitution et la genèse des roches sédimentaires argileuses : *Géol. Appliq et Prosp. Min.*, v. 2, Nancy, France, 352 pp.

Milne, I. H. and Earley, J. W. (1958) Effect of source and environment on clay minerals : *Amer. Assoc. Petroleum Geologists, Bull.* 42, pp. 328–338.

Powers, M. C. (1954) Clay diagenesis in the Chesapeake Bay area : in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council, pub. 327, pp. 68–80.

Strakhov, N. V. (1953) Diagenesis of sediments and its significance in sedimentary ore formation : *Izv. Akad. Nauk SSSR Ser. Geol.* no. 5, pp. 12–49.

Yoder, H. S. and Eugster, H. P. (1955) Synthetic and natural muscovites : *Geochim. Cosmochim. Acta*, v. 8, pp. 225–280.