POSSIBLE USES OF CLAY MINERALS IN THE SEARCH FOR OIL

by

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ABSTRACT

Most of our general knowledge concerning the distribution and geologic significance of clay minerals is summarized in twelve statements. Some examples and numerous suggestions are given to show the use of clay minerals in interpreting and understanding such problems as tectonics, source, age, boundaries, facies, environments, zonation, correlation, and metamorphism; a relation between the relative abundance of expanded clays and the occurrence of hydrocarbons is suggested.

It is believed that expanded clays retain their pore water to greater depths of burial than do other clays, and that it is this water which transports much of the hydrocarbon. It is shown that whereas time has little effect on the contraction of expanded clays, it does affect the expulsion of pore water from shales.

INTRODUCTION

How can clay minerals be used to prospect for oil? Clay minerals can be used in interpreting and understanding such problems as tectonics, source, age, boundaries, facies, environments, zonation, correlation, and metamorphism. More specifically, concerning oil exploration, clays possibly can be used to delineate areas of sandstone concentration, locate as to direction and distance certain sandstone bodies, and determine porosity and permeability trends in both sandstones and carbonate rocks. An understanding of the effects of burial on clay minerals, among other things, should afford considerable information on the migration of fluids.

GENERALITIES

Most of our general knowledge concerning the distribution and geologic significance of clay minerals is summarized below:

1. We now have a fairly good idea of the clay mineral composition and the magnitude of clay mineral variations in most of the important formations in the United States and Canada. We have a reasonable idea as to the geologic significance of most of these mineralogic variations.

2. The pre-Middle Mississippian clay suites are less complex than those in the younger sediments, and thus can provide less information.

3. In many of the Cretaceous formations (and others) where environments of deposition change abruptly, it is possible to find extreme variations in the

composition of clay suites over an interval of a few feet; whereas in some of the Paleozoic geosynclinal sediments there may be a nearly constant clay suite throughout 5000 ft of section.

4. Although source controls the type of clay minerals that will be delivered to the basin of deposition, local environmental conditions (both physical and chemical) will determine the ultimate distribution of the clay minerals. Thus, both source and environmental information can be obtained though it is frequently difficult to make specific assignments on the basis of clay mineralogy alone.

5. Montmorillonitic clays are modified (tend to become more illitic) by deep burial. Although this is an added complication, once it is recognized due allowance can be made.

6. The types of clay suites and the variations in the clay suites of limestones are similar to those in shales. The same type of information can be obtained from the clays in limestones as can be obtained from those in shales.

7. The clay minerals in sandstones are more apt to have been altered after deposition than the clays in other rocks. This alteration (both degradation and aggradation) can take place immediately after deposition or at any time after burial. Although it is not understood, there seems to be a relation between the alteration of these clays and the development of secondary cements.

8. With clay mineral data alone, it is difficult to identify an individual environment; but when several environments are present, it is often possible to assign them a sequential order ranging from more continental to more marine. If sufficient control is available so that the clay mineral distribution pattern can be established, reasonable environmental identification often can be made.

9. At the present time it is usually necessary to determine the environmental significance of the clay suites by first examining samples from known environments. Once clay–environmental criteria are established for a given area the clay data can be used independently to provide environmental information in the vicinity of the control area.

10. Clays can best be used for environmental determinations where (*a*) sediments are younger than Middle Mississippian (the number of clay mineral types decreases with increasing age), (*b*) environmental contrasts are large (continental versus marine as opposed to inner neritic versus middle neritic—although in some instances the latter distinction can be made), and (*c*) deposition is relatively slow and the clay suites have more opportunity to come to equilibrium with their depositional environment (although the clays are related to environments in both geosynclinal and epicontinental facies, the relation is usually much stronger and more obvious in epicontinental sediments).

11. Variations in clay mineral composition can be used for approximate "time correlation" (in both shale and limestone sequences) where: (*a*) bentonite beds are present; (*b*) unconformities are observed; (*c*) there is a change in source material due to orogenic movement, new source area, changing climatic conditions (weathering) in the source area, or uncovering of new strata by erosion.

12. In thick shale and limestone sequences, relatively minor clay mineral differences can be correlated for considerable distances (10 to 50 miles) along the depositional strike.

Thus, numerous generalities and rules have been established. Although some of these rules are still tentative, at least we are no longer working completely in the dark.

EXAMPLES

From a study of samples spaced at intervals of 500 to 2000 ft in the Paleozoic of Oklahoma (Weaver, 1958) it was possible to obtain general geologic information such as the type and location of source areas, tectonic activity, and formation identification, and to identify major clay mineral facies. Although these data were of considerable interest and of some value to exploration personnel, it was not the type of information that stimulated much demand for clay investigations. More recently it was found that when closely spaced samples are studied in detail, minor clay mineral differences (5–10 percent) can be used to make fairly detailed correlations. These clay mineral profile logs have the potential of being of considerable value for correlation, on both local and regional scales.

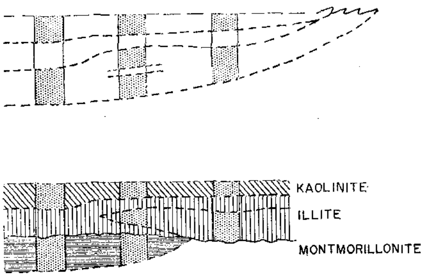


Figure 1.—Schematic cross section showing electric log correlations (upper diagram) and clay mineral correlations (lower diagram).

There are several examples of wells that have bottomed in shales which on the basis of derived properties (color, luster, etc.) have been misidentified and placed 4000 to 5000 ft out of stratigraphic position. In many of these cases the correct identification can be established by careful clay mineral analysis.

Weaver (1958) used clays to unravel a complex sandstone correlation problem in the Springer. Similar use of clays in helping to unravel complex sandstone correlations is shown by an example from the Cretaceous (Fig. 1). The upper diagram shows the correlations based on electric log and binocular-microscope study. The lower diagram shows the correlations based on clay mineral data. Subsequent drilling in search of the truncated edge of the lower sandstone indicated that the interpretation based on clay mineral data was most likely to be correct.

ENVIRONMENTS

Environmental interpretation by clay minerals can be made in three ways: (1) Establish the environmental significance of clay mineral suites by studying known environments. Once these relations are established, the clay suites alone can be used in the same general depositional units for environmental identification. (2) Establish clay mineral trends in a given sedimentary unit, i.e. if a given unit grades from kaolinite to a mixture of kaolinite and illite to a relatively pure illite facies, it normally is safe to conclude that the depositional environments range from " more continental-like " toward " more marine-like." (3) Establish the horizontal and vertical distribution pattern of the various clay suites. These patterns may assume the shape of a delta or river channel, or indicate the presence of a barrier. Examples of the relation of clay minerals to environments have been reviewed by Weaver (1959) and many additional examples are in oil company files.

Lagoonal sediments commonly have clay suites distinct from those of open marine sediments. The ability to determine whether one is shoreward or seaward from a sandstone body is useful, although ultimately it may be possible through clay mineralogy to determine how far shoreward or seaward of a sandstone body a given well is located.

It is believed that with sufficiently detailed work it will be possible to use clays to show trends and variations within the various faunal environments. This will enable one to pinpoint sandstone bodies.

Recent studies indicate relatively little variation between inner, middle, and outer neritic and bathyal clay suites (minor differences do exist in these environments in Gulf Coast Tertiary shales); however, in the strand-line, near-shore area, which is of most interest to the oil exploration geologist, there are frequently major and relatively abrupt changes in clay mineral composition. For example, Grim and Johns (1954) have shown that in the Rockport area the Guadalupe delta contains approximately 70 percent montmorillonite and the bay sediments contain only 30–50 percent montmorillonite.

The Mississippi River carries a clay suite that is composed predominantly of montmorillonite and lesser amounts of illite and kaolinite. Eastward from the Mississippi River, the rivers derive their sediments from the southern

Appalachians and carry a clay suite composed predominantly of kaolinite (Milne and Earley, 1958). It seems probable that the bays and lagoons in the eastern portion of the Gulf of Mexico have a relatively high kaolinite content. Since the Mississippi carries much more sediment to the Gulf of Mexico than do the eastern rivers, it might be expected that the sediments on the seaward side of the sandstone barriers, separating the lagoons from the open sea, would have a relatively high montmorillonite content.

The carbonate muds east of the Florida reef complex are composed largely of illite, chlorite and talc. West of these reefs the muds contain a montmorillonite–vermiculite complex. Such a situation might be expected to exist in ancient sediments wherein an abrupt change in clay suite in a carbonate sediment might suggest the presence of a barrier.

The depositional environment of organic-rich black shales is sometimes difficult to deduce; however, clay analyses indicate that continental organic-rich black shales normally contain abundant kaolinite, lagoonal and brackish water black shales commonly contain both kaolinite and illite and/or mixed-layer illite–montmorillonite, and marine blanket-type black shales are composed almost entirely of illite or mixed-layer illite–montmorillonite, or both.

The clay mineral variations in carbonate rocks are apparently as prevalent as those in shales and it is likely that much the same type of information can be obtained from them.

Commonly the clays in sands are identical or at least similar to those in the enclosing shales. In many instances sandstones have a drastically different clay suite than the surrounding shales. Kaolinite, chlorite, and illite are the most common clays that appear to be abnormally concentrated in sands. The kaolinite can be formed by acid leaching either before or after deposition, and it usually is found in continental and near-shore sands. Chlorite that is poorly crystallized and apparently authigenic in origin is common in many thin marine sands. The distribution of the chlorite and associated cements suggests that much of the alteration occurred after deposition and is due to the flushing of water from the surrounding shale into the sands. Milne and Earley (1958) have noted the conversion of montmorillonite to chlorite in Miocene sands of the Los Angeles basin. The concentration of much of the illite (commonly fine mica) in sands is due to winnowing.

The limited intrinsic geologic information in the clay minerals themselves is no serious handicap. Environmental studies are best made by investigating the whole basin and analyzing hundreds, or thousands, of samples. By measurement of the many mineralogical and chemical variations, a wide variety of clay mineral suites can be identified and their pattern of distribution determined. Then, in most cases the geologic significance of these patterns can be determined in part from our knowledge of the clay minerals, but to a larger extent by integrating these patterns with the data obtained from paleontological, petrological, and stratigraphic studies. As a background of information accumulates, generalities become apparent and more interpretations can be made from the clay mineral data without the need to lean so heavily on other data.

If the clay minerals are predominantly detrital in origin, they may still be used for environmental interpretation. The clay minerals vary in size and chemical activity. Thus when a suite of clays is brought in contact with a series of environments which have different rates of deposition, topographic expression, currents, salinities, biological activity, and redox potentials a sorting and segregation of the clay minerals can occur that may have little or nothing to do with authigenesis or syngenesis.

BOUNDARIES AND ZONATION

Boundary adjustments based on clay mineral differences are common. For example, in Oklahoma the Atoka–Morrow boundary and the Morrow–Springer boundary are based to a large extent on differences in sandstone types. These are convenient boundaries because they usually can be picked on the electric log and normally are placed at the base of a sandstone. In both these instances, the change in clay mineral composition occurs within the shales rather than the sands and may be 50 to 200 ft beneath the first appearance of the " distinctive basal sands."

Merrill and Winar (1958) have given an example of use of clay minerals to separate the Middle and Upper members of the Molas formation of southwestern Colorado.

Gude (1950) subdivided the Laramie formation at Fort Collins, Colorado, into three stratigraphic intervals based on differences in clay mineral suites. Keller (1953) divided the type section of the Morrison into six zones on the basis of clay mineral variations.

In most instances clay mineral changes coincide with formation boundaries based on other criteria. However, in many instances the clay mineral changes allow one to place the boundary more precisely, particularly in the subsurface where only rotary cuttings are available for examination.

REGIONAL TRENDS

There are several relatively thick clay mineral zones which are regional (1000 to 2000 miles) in extent (Flawn and others, 1960) and appear to be approximate time-equivalent units.

A zone of mixed-layer chlorite–montmorillonite occurs in the upper and lower Ordovician and can be traced from the western portion of the southern Appalachians to the Franklin Mountains of extreme west Texas. The mixed-layer chlorite–montmorillonite zone extends from slightly above the top of the Cambrian to slightly below the base of the Chazyan (Arbuckle–Knox–Ellenburger).

During Middle Ordovician time (Black River) periodic volcanism resulted in the formation of at least 14 separate ash falls in the eastern United States.

The volcanic material was altered and preserved as the mixed-layer illite–montmorillonite (7 : 3). These K-bentonite beds have been traced as far west as Minnesota and as far south as Alabama. Discrete ash beds do not appear to have been preserved in the Oklahoma and Texas sediments; however, abnormally abundant mixed-layer illite–montmorillonite exists in the Simpson of Oklahoma and the Woods Hollow and Fort Pena formations of the Marathon area.

A montmorillonite (or mixed-layer illite–montmorillonite) zone of regional extent in upper Mississippian–lower Pennsylvanian rocks can be traced through the eastern and central United States and at least as far west as Nevada. In some of these formations, the montmorillonite is not abundant, but it is more abundant than in the overlying and underlying formations.

The clay zone underlying this montmorillonite zone is composed predominantly of illite, perhaps averaging as high as 90 percent in most foreland formations. The clay suite overlying the montmorillonite zone is, in nearly all areas, a complex suite containing illite (approximately 50 percent) mixed-layer illite–montmorillonite, chlorite and kaolinite. The mineralogic change between these two zones is believed to be due to a major change in the tectonic evolution of the North American continent (Weaver, 1959).

METAMORPHISM

Flawn and others (1960) have shown that x-ray diffractometer patterns, in areas of low-grade metamorphism, can be used to measure the degree of metamorphism of shales.

In the Ouachita Mountains of Oklahoma and the buried Ouachita structural belt of east and south Texas, the presence or absence of kaolinite can be used to locate the boundary between the foreland facies and the geosynclinal Ouachita facies (Fig. 2). By measuring the thickness of the 10Å illite x-ray diffractometer peak (Fig. 3) it is possible to determine the relative degree of metamorphism within the metamorphosed geosynclinal facies (Fig. 2). Table 1 lists the various degrees of metamorphism as established by microscopic study of the sands (Flawn and others, 1960) and the average sharpness ratio values (measure of the relative width of the 10Å x-ray peak) of the shales in these various metamorphic groups.

Table 1.—Degree of Metamorphism of Sands and Sharpness Ratio of Illite 10Å Peak

Metamorphism of Sands	Sharpness Ratio, Illite 10Å Peak
Low grade metamorphism	12.1
Weak to very weak metamorphism	6.3
Incipient to weak metamorphism	4.5
Incipient metamorphism	2.3
Unmetamorphosed Stanley	2.3
Unmetamorphosed Atoka	1.8

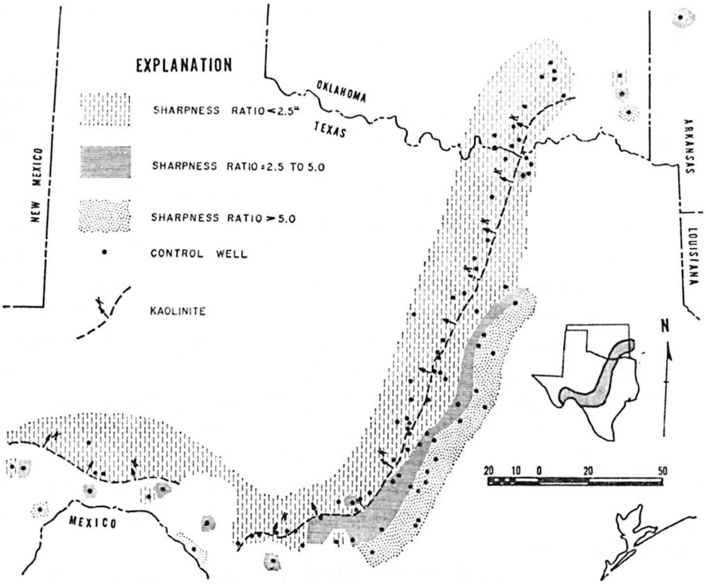


Figure 2.—Map showing boundary between foreland type and Ouachita type sediments as determined by presence or absence of kaolinite. Sharpness ratio is an x-ray measure of the degree of metamorphism. The larger the value, the greater the degree of metamorphism.

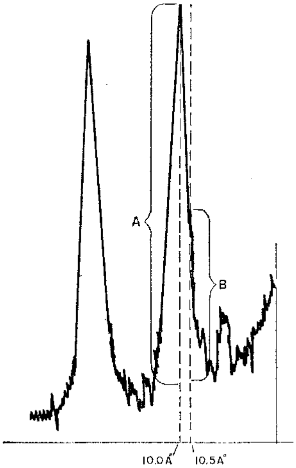


Figure 3.—Portion of x-ray diffractometer pattern showing method of measuring relative sharpness (or narrowness) of the 10 Å illite peak. Sharpness ratio = A/B.

RELATION OF MONTMORILLONITE TO HYDROCARBONS

x-Ray diffractometer patterns of more than 20,000 samples from most of the major basins of the United States suggest that there may possibly be some statistical relation between hydrocarbon reservoirs and expandable clay minerals.

More oil occurs in the Tertiary than in rocks of any other age and the Tertiary sediments contain more montmorillonite and mixed-layer illite–montmorillonite than rocks of any other age. Most of the Cretaceous producing intervals that have been examined contain abundant expanded clay. In the Illinois Basin, the most prolific producing formation is the Chester (Swann and Bell, 1958) and the Chester clay suite contains a higher percentage of expanded clays than any other formation in the basin. The Permian formations are the most prolific producers in the Permian Basin of west Texas (Galley, 1958). The Permian rocks contain more expanded clay than the other sediments in the basin.

In Oklahoma, the Springer, lower Morrow and Simpson formations are prolific producers and contain more expanded clay minerals than the other formations in this area.

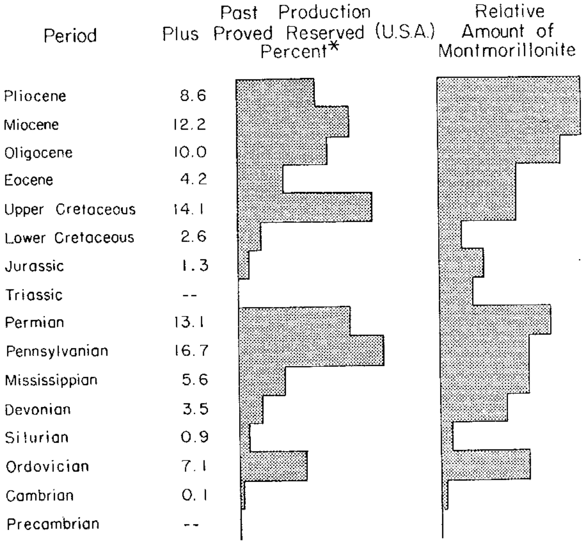
There is little production from the Black Warrior Basin of Mississippi and Alabama and there is also very little expanded clay in these sediments. Most of the production that has been found is from Chester sands. These sands and the enclosing shales contain a larger amount of expanded clay than is found anywhere else in the basin's stratigraphic section.

Obviously, many more data are needed before this relation can be verified.

Figure 4 lists, in percentages, the past production plus proved reserves for various geologic periods. Also included is a rough estimate of the relative amount of expanded clay in the sediments of each period.

In a general way, there is a coincidence between montmorillonite content and amount of oil. The relation is actually better than indicated. For example, the Jurassic sediments have a fair montmorillonite content, but the total volume of marine sediments is relatively small. The amount of expanded clay estimated for the Mississippian and Ordovician is high for the periods as a whole, but most of the Mississippian oil is from Chester age sediments and these sediments contain the great bulk of expanded clay in the Mississippian. In the Ordovician, most of the production is from the middle Ordovician which contains the bulk of the Ordovician expanded clays.

Montmorillonite not only holds more pore water (factor of 10) than the nonexpanded clays (kaolinite, chlorite, and illite), but also a greater pressure is required to squeeze this pore water from between the clay particles (Mielenz and King, 1955). Water is presumably necessary to move hydrocarbons from shales to sands. There are considerable arguments as to whether hydrocarbons are formed at shallow depths or relatively great depths. Assuming that considerable depth of burial is necessary before any appreciable amounts of hydrocarbons are formed, it may be that in muds devoid of expanded, water-bearing clays most of the pore water escapes after only shallow burial and before most of the hydrocarbons are formed. This may explain why formations such as the Chattanooga shale and the Green River shale, which contain little expanded clay, are oil shales—by the time the oil was formed not enough water was left to remove the oil from the shale. On the other hand, greater overburden pressure is required to remove pore water from montmorillonite muds (in the Miocene montmorillonite muds from as deep as 7000 ft are still pliable) and sufficient water presumably would be available to flush out hydrocarbons that were formed at depths of burial exceeding several thousand feet.



*Adapted from Hopkins, 1950.

FIGURE 4.—Relation of oil production to age and relative montmorillonite content.

The expulsion of fluids from muds is influenced by several factors, among which the more important are type of clay, amount of overburden, clay diagenesis, and time. In order to evaluate the relative effectiveness of these factors, clay mineral data, density data, and velocity data were obtained for three thick shale sections which had a similar clay mineral suite but different ages—Plio–Upper Miocene of the Texas Gulf Coast, Oligocene and Eocene of the Texas Gulf Coast, and the Upper Mississippian Springer shale of Oklahoma.

All three of these sections in the areas studied have a similar clay mineral suite and a similar diagenetic change with depth. The clay content of these shales ranges from 60 to 80 percent; the carbonate content is normally less than 5 percent. The clay suite is composed predominantly (50 to 90 percent) of expanded clays. These clays range from completely expanded montmorillonite at shallow depths through successively increasing ratios of mixed-layer illite–montmorillonite with depth. The total amount of expanded clay remains approximately constant with depth. There may be a slight increase (5 percent) in discrete illite at the greater depths, but this is difficult to determine.

A plot of the mixed-layer illite–montmorillonite ratio versus depth shows almost similar curves for the three sections, which range in age from 10,000,000 to 250,000,000 years. When treated with ethylene glycol and x-rayed, the expanded clay gives a fairly sharp 17 Å peak down to 8000–9000 ft. At this depth, the percentage of nonexpanded (illite) layers intermixed with the montmorillonite layers gradually begins to increase and is detected in the x-ray pattern by the forming of a broad peak ranging from 14 to 17 Å with the 14 Å portion increasing with depth. The collapse of expanded layers may start as shallow as 5000 ft, but the percentage is small and not easily detectable by x-ray analysis. Somewhere between 11,000 and 13,000 ft, the increase in nonexpanded layers is shown on the x-ray patterns of glycolated samples by a shift of the broad 14–17 Å peak to one ranging from approximately 12 to 14.5 Å. This 12–14 Å peak gradually gives place to a distinct 13 Å peak (mixed-layer illite–montmorillonite ratio 7 : 3) at a depth of from 12,000 to 14,000 ft. Between the depths of 14,000 and 22,000 ft there is no further peak shift, only an increase in the relative sharpness of the 13 Å peak.

It is of interest to note that the expanded layers at great depth apparently have a 14–15 Å thickness rather than 12 Å as one might expect. This may indicate the formation of incipient brucite layers or it may mean that the expanded layers imbibe only one layer of ethylene glycol rather than two.

Figure 5 contains a plot showing the shift of the 10–17 Å x-ray peak of the glycolated clay with depth. As it is difficult to show the change in shape of this peak, the ratios of the 10 to the 17 Å, 14–17 Å, 12–14 Å, and 13 Å peak are also plotted. As the discrete illite content and the expanded clay content remain relatively constant with depth, the increase in the ratio of the 10 Å peak to the expanded-clay peak with depth is an approximate measure of the gradual shift of the 17 Å peak towards 10 Å as more and more expanded layers are contracted.

Thus it appears that in the diagenesis of montmorillonite the influence of time is of little significance; however, time does appear to be an important factor in determining the density of shales. Though the Plio–Miocene and the Springer shales have a similar clay composition and a similar rate of conversion of expanded clay to nonexpanded clay with depth, the velocity values and density values are quite different (Fig. 5). This suggests that the expulsion of the pore water is not related to the collapse of montmorillonite as one might expect, and further that the contraction of the expanded layers (diagenesis of montmorillonite to illite) has little effect on the overall bulk density of the shale. For example, a shale that is composed of 60 percent clay of which 70 percent is montmorillonite would lose approximately 5 percent by volume, between 100 and 20,000 ft, by contraction of the montmorillonite. These results were confirmed in general by some relatively crude measurements. Samples of shale from the Plio–Miocene section were dried at 100°C and weighed and then dried at 300°C and reweighed. The weight loss should give the approximate amount of interlayer water present. The difference in percent water lost between samples from 3000 to 5000 ft and those from 15,000 to 16,000 ft averaged slightly less than 1 percent by weight or approximately 2 percent by volume.

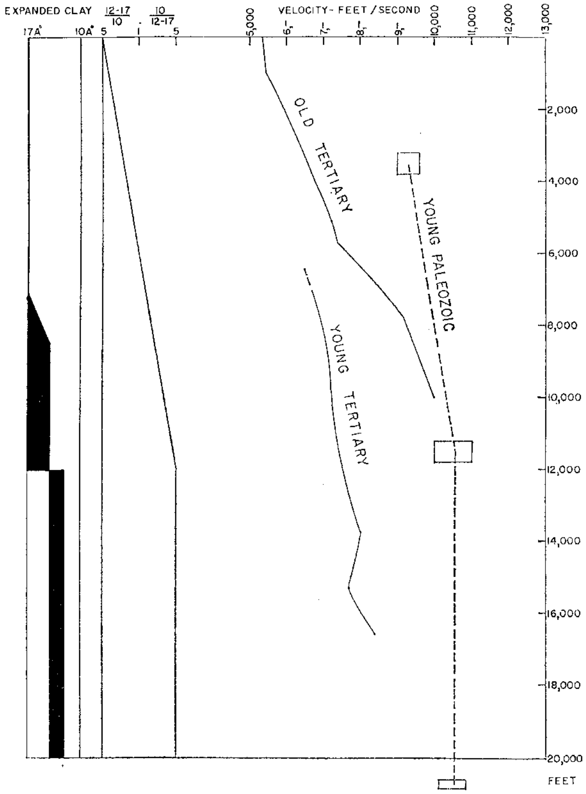


Figure 5.—Graph showing relations of montmorillonite contraction and velocity of shales to depth.

Though volumetrically this change may be minor, it may be quite important if it is the mechanism that involves moving hydrocarbons from between the expanded clay layers (if that is where they are formed) to the pores.

It appears that where factors of composition and overburden pressure are relatively constant, time is an important factor in the migration of water from shales. Thus one is led to conclude that in older sediments hydrocarbons, if present, would be flushed from the shales at shallower depths of burial than in younger sediments. In general, production data tend to confirm this trend.

Much of the above is obviously guess work, but it is equally obvious that few reliable data are available. A relatively minor amount of data could answer a great many questions concerning compaction and migration, and these answers should be of considerable value in exploration for concentrations of hydrocarbons.

Using the limited data available, an attempt is made in Table 2 to relate the density of pore water content of shales to the three variables that appear significantly to influence the water content of shales.

TABLE 2.—RELATION OF CLAY COMPOSITION TO DEPTH OF BURIAL, AGE, AND DENSITY

Clay Composition	Depth of Burial	Age	Density
Non-expanded[1]	Deep[3]	Old[5]	2.65
Non-expanded[1]	Deep[3]	Young[6]	2.5
Expanded[2]	Deep[3]	Old[5]	2.4
Non-expanded[1]	Shallow[4]	Old[5]	2.3
Expanded[2]	Shallow[4]	Old[5]	2.2
Expanded[2]	Deep[3]	Young[6]	2.2
Non-expanded[1]	Shallow[4]	Young[6]	—
Expanded[2]	Shallow[4]	Young[6]	2.0

[1] Illite, kaolinite, chlorite.
[2] Montmorillonite and mixed-layer illite–montmorillonite.
[3] Approximately 10,000 ft.
[4] Approximately 2000 ft.
[5] Paleozoic.
[6] Tertiary.

SUMMARY

The clay minerals in sediments can be identified routinely by x-ray analysis; the distribution of clay minerals is systematic and can be related to some type of geologic phenomenon. Sometimes it is difficult to determine the reason for the distribution solely from the mineralogy, but when the clay petrology is integrated with other available geologic data the cause usually becomes apparent. As more experience is acquired, the interpretative value of clays continues to increase and the intrinsic information in the clay minerals becomes more apparent.

Work to date has indicated that the clay minerals can provide useful information on nearly any type of geologic problem. The types of information and the methods of study vary with the situation. A large number of widely scattered samples from thick formations can be used to decipher the geologic history of a basin, or foot-by-foot sampling of relatively thin formations can provide a detailed environmental interpretation. In some instances, reservoir beds and adjacent sediments contain distinctive clay mineral suites. Our present experience suggests that ultimately clay minerals will be of considerable value in locating stratigraphic traps.

Clay mineral information should be integrated with other geologic information and the geologic problem should be thoroughly understood if the clay data are to be used effectively.

REFERENCES

Flawn, P. T., Goldstein, A., King, P. B. and Weaver, C. E. (1960) The Ouachita system: *Pub. Texas Bureau of Economic Geology,* in press.

Galley, J. E. (1958) Oil and geology of the Permian Basin of Texas and New Mexico in *Habitat of Oil, Amer. Assoc. Petrol. Geol.,* pp. 395–446.

Grim, R. E. and Johns, W. D. (1954) Clay mineral investigation of sediments in the northern Gulf of Mexico: in *Clays and Clay Minerals,* Natl. Acad. Sci.—Natl. Res. Council, pub. 327, pp. 81–103.

Gude, A. J. (1950) Clay minerals of Laramie formation, Golden, Colorado, identified by x-ray diffraction: *Bull. Amer. Assoc. Petrol. Geol.,* v. 34, pp. 1699–1717.

Hopkins, G. R. (1950) A projection of oil discovery . . . 1948–1965: *J. Petrol. Tech.,* p. 7.

Keller, W. D. (1953) Clay minerals in the type section of the Morrison formation: *J. Sed. Petrology,* v. 23, pp. 93–105.

Merrill, W. M. and Winar, R. M. (1958) Molas and associated formations in San Juan basin–Needle Mountains area, southwestern Colorado: *Bull. Amer. Assoc. Petrol. Geol.,* v. 42, pp. 2107–2132.

Mielenz, R. C. and King, M. E. (1955) Physical-chemical properties and engineering performances of clays: in *Clays and Clay Technology,* Calif. Div. of Mines, bull. 169, pp. 196–254.

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

Swann, D. H. and Bell, A. H. (1958) Habitat of oil in the Illinois Basin: in *Habitat of Oil, Bull. Amer. Assoc. Petrol. Geol.,* pp. 447–472.

Weaver, C. E. (1958) Geologic interpretation of argillaceous sediments: *Bull. Amer. Assoc. Petrol. Geol.,* v. 42, pp. 254–309.

Weaver, C. E. (1959) The clay petrology of sediments: in *Clays and Clay Minerals* (6th Conf.), Pergamon Press, New York, pp. 154–187.