

THE CLAY PETROLOGY OF SEDIMENTS

by

CHARLES E. WEAVER¹
Shell Oil Company, Houston, Texas

ABSTRACT

Studies of the Recent indicate that, at the most, somewhat less than half the clay minerals are altered to any extent in a marine environment. Probably most of this alteration is in the form of cation adsorption or reconstitution of slightly weathered illites and chlorites to their original form. There appears to be little if any evidence that the detrital basic lattice is being altered to a measurable extent in Recent marine sediments. In the near-shore environments there is usually a coincidence of clay mineral suites and environments.

A major change in the clay mineral composition of sedimentary rock occurs within the Mississippian. Illite is the dominant clay mineral of the pre-Upper Mississippian sediments. Post-Lower Mississippian clay suites are more variable in composition; illite becomes less abundant and montmorillonite and kaolinite more abundant. This change is best related to a change in regional tectonics. The clay minerals seem to have no preferred lithologic associations, although owing to epigenetic alterations porous sandstones commonly have different clay mineral suites from those of adjacent shales and carbonate rocks.

In many instances clay mineral facies coincide with environmental facies. As the clay mineral criteria for distinguishing any given type environment are extremely variable, it is thought that segregation of clay mineral suites by sorting is usually more effective than by diagenesis.

Expanded clay minerals appear to be partially contracted by the time they have been buried to 10,000–15,000 ft. It remains to be proved whether this is caused by chemical modification of the basic lattice with burial or if the detrital clay lattice has the inherent ability to contract, without chemical rearrangement, when buried to a sufficient depth.

INTRODUCTION

The literature on the clay minerals in sediments has been reviewed briefly by Grim (1953). Rivière and Visse (1954) reviewed the European literature and arrived at the same general conclusions as the present author. The present report will deal chiefly with the work done since 1953, although some attempt will be made to evaluate the pre-1953 data.

Many of the clay mineral data on sediments obtained before the years 1945 to 1950 are unreliable because experience and methods of identification had not yet been sufficiently advanced. Of the major clay mineral groups little was known of chlorite, mixed-layer clays, and variations in types of illite, montmorillonite and kaolinite. Techniques still are not sensitive enough to identify the many clay species that are present in each major clay mineral group, particularly when the clay minerals occur as mixtures

¹ Publication no. 22, Shell Oil Company, Technical Services Division.

as they usually do in sediments. However, we now have a preliminary picture of the origin and distribution of the major groups of clay minerals and, in instances, some of the species within the groups.

Some misunderstanding among clay mineralogists and clay petrologists has been occasioned by a lack of uniformity in the connotation of some of the terms used to describe the more important processes which affect clay minerals. For this reason a few terms used in this review will be defined. Weaver (1958a, b) suggested that in order best to understand the genesis of clay minerals it is essential that the modifications which affect the basic lattice be distinguished from those which affect the interlayer material. Thus, chemical diagenesis would be restricted to modifications of the basic lattice, and alterations affecting the interlayer material would not be considered as diagenetic processes but as adsorption or exchange. For instance, the process involved when a mica stripped of its potassium regains its potassium is not considered to be diagenesis but potassium adsorption. This terminology has the advantage of indicating something of the magnitude of the alteration which has taken place.

The processes referred to by the words "adsorption" and "diagenesis" should be qualified further as to the time during which the process was acting. Syngenetic alterations occur while the clay is still in contact with sea water, and epigenetic alterations occur later. Epigenesis eventually passes into low-grade metamorphism.

Recently some have tended to call mixed-layer illite-montmorillonite clays illites. The word illite is here applied only to 10Å clays that show no appreciable expansion when treated with ethylene glycol (this implies less than 10 percent interstratified expandable layers). These clays may have a 1M_d, 1M or 2M structure.

RECENT

Fluviatile and Deltaic Muds

Grim's review of the pre-1953 literature indicates illite as the predominant mineral in Recent marine sediments. Montmorillonite is locally abundant and kaolinite is surprisingly common. It should be kept in mind that before Grim, Dietz and Bradley's (1949) paper there appears to have been no mention of chlorite in Recent muds. It seems likely that much of the material identified as kaolinite is chlorite, and that much of the "illite" of the early literature is mixed-layer illite-montmorillonite.

Millot (1953, p. 167) reports that the clays transported by the Oued Sebou, Niger, Durance, Meurthe, Mosel, Rhine and Rhone rivers and deposited in the river valleys, estuaries and deltas "contain a replica of the material in the up-stream basins."

Clay mineral studies of the Mississippi Delta (Milne and Earley, 1958; Grim and Johns, 1954a, 1955) indicate that there is very little difference between the clay composition of the river-suspended sediment load and that of the delta muds. The data of Grim and Johns indicate that between the

river and delta samples there is generally less than 10 percent difference in the amount of any one clay mineral.

The montmorillonitic Guadalupe Delta (Grim and Johns, 1954) and the kaolinitic Orinoco Delta (Dietz, 1941) are both similar in composition to the surrounding soils.

The Chesapeake Bay sediments (Powers, 1958) contain a clay suite (illite, chlorite and kaolinite) similar to that carried by the Susquehanna River (Weaver, 1958b).

Shallow and Deep-sea Muds

Only a relatively minor amount of work has been done on deep-sea clays. Correns (1937, 1939) found that kaolinite is a common constituent of the sediments in the equatorial part of the Atlantic Ocean. He also showed that most of the sediments from the same area contained greater than 50 percent calcium carbonate. As kaolinite presumably is formed only in an acid environment and as the rivers carrying detritus to this area drain tropical lateritic (kaolinitic) soils, there seems little doubt that the Atlantic Ocean kaolinite is land derived and detrital in origin. Dietz (1941) concluded

... the clay mineral distribution on the sea floor is regionally similar to that on land in having a relative abundance of kaolinite and iron oxide in tropical regions and of illite and montmorillonite in temperate and polar regions. This suggests that deep-sea clays are terrestrially derived.

Dietz (1941) was of the opinion that illite is the dominant clay mineral in the deep-sea clays and montmorillonite is normally absent (although he obtained base-exchange capacities of 53 and 47 meq/100 g for two Pacific deep-sea clays; these values are similar to those found for the Gulf of Mexico highly montmorillonitic muds). Recently studies by Murray and Harrison (1956) of clays from the Sigsbee Deep of the Gulf of Mexico and by Powers (1957) and Rivière and Visse (1954), of deep-sea sediments from the Pacific indicate that montmorillonite and mixed-layer illite-montmorillonite are the dominant clays in the samples examined. Earlier Revelle (1944) suggested that beidellite was the dominant clay mineral in the deep Pacific red clays. Analyses of Recent samples from the Peru-Chile trench (Schmalz, 1957) showed systematic clay mineral differences that appear to be related to differences in source area. Chlorite with micas and kaolinite were the dominant clays in the area which contained an abundance of basic minerals—labradorite, amphibole, pyroxene, and basaltic volcanic glass. Chlorite was absent and illite and kaolinite were the dominant clays in the adjoining area where albite and muscovite were dominant minerals (quartz was a dominant mineral in both area). Thus it appears that no general statement can be made concerning the clay mineral content of deep-sea clays. They appear to be largely detrital in origin (aside from those that have formed from volcanic material) and are likely to have just as varied a clay mineral suite as the shallower water muds.

The recent American literature indicates that there is also a good relation between the geographic distribution of the clay mineral suites of Recent

shallow marine muds and source areas. The few examples in which there is a reasonable knowledge of the clays in the marine environment, the rivers, and in the source rocks are listed in Table 1.

TABLE 1.—RELATION BETWEEN CLAY MINERALS IN RECENT MARINE MUDS AND SOURCE MATERIAL

Locality	Dominant Clay Mineral		
	Recent Marine Muds	Clay Detritus Carried by Rivers	Source Material
Eastern Atlantic Coast	Illite ^{1, 2}	Illite ^{1, 3}	Illite ^{1, 3, 10}
Eastern Gulf Coast	Montmorillonite ^{1, 4, 5}	Montmorillonite ^{1, 4, 5}	Montmorillonite ^{5, 6}
Western Gulf Coast	Montmorillonite ⁷	Montmorillonite ⁷	Montmorillonite ^{8, 10}
Southern California Coast	Montmorillonite-Illite-Kaolinite ⁹	Montmorillonite-Illite-Kaolinite ⁹	Montmorillonite-Illite-Kaolinite ¹⁰

¹ Powers (1954, 1957).

² Murray and Sayyab (1955).

³ Weaver (1958b).

⁴ Grim and Johns (1954a, 1955, 1956).

⁵ Milne and Earley (1958).

⁶ Ross, Miser and Stephenson (1929).

⁷ Grim and Johns (1954).

⁸ Kunze (personal communication).

⁹ Grim, Dietz and Bradley (1949).

¹⁰ Weaver.

The dominant clay mineral character of the Recent fluvialite, deltaic, shallow marine, and deep marine sediments is apparently controlled by the detrital clay material derived from the land areas. Although the bulk character of the marine clay suite is determined by the source material, considerable local variation in the composition of the shallow clay mineral suites usually has been attributed to syngenetic alterations of the detrital clay material (Table 2). Recent studies indicate that in general there is an increase in the relative amount of illite or chlorite, or both, and a decrease in the amount of kaolinite seaward (Grim, Dietz and Bradley, 1949; Grim and Johns, 1954; Griffin and Ingram, 1955; Powers, 1954, 1957; Nelson, personal communication). Powers (1954) found no seaward decrease in kaolinite in the Chesapeake Bay area, although Nelson (personal communication) reports finding a decrease in the proportion of kaolinite down the Rappahannock estuary. Grim and Johns (1954a, 1955) report that in the Gulf of Mexico the increase in illite is restricted to the shallow water facies and that further from shore the amount of illite decreases and the amount of montmorillonite increases. Most of the earlier studies attributed these variations to diagenetic effects (which will be discussed later) but in some more recent studies detrital explanations have been presented. Investigations in the Gulf of Paria (Van Andel and Postma, 1954) indicate that illite is the dominant clay mineral.

Kaolinite occurs everywhere in approximately equal abundance and montmorillonite is considerably more abundant in the open Gulf of Paria clays than in the delta platform (deltaic-estuarine facies) clays. Van Andel and Postma suggest that the illite and kaolinite are flocculated early and form relatively large floccules, whereas the size of the montmorillonite particles increases more slowly and therefore they can be transported farther (Whitehouse, 1951, 1952; Whitehouse and Jeffrey, 1955). This trend for montmorillonite to increase preferentially to illite seaward is similar to that occurring in the eastern Gulf of Mexico (Grim and Johns, 1954); however, Grim and Johns found that the Guadalupe deltaic facies were strongly montmorillonitic. The lack of a similar, more montmorillonitic shoreward facies in the Gulf of Paria may be due to the absence of a true delta in this area and to mostly estuarine or prodeltaic near-shore deposition.

Milne and Earley (1958, p. 328) have presented an example that illustrates how variations in shallow marine sediments can be related to source differences.

Montmorillonite, the predominant clay mineral in the Mississippi River and delta sediments, is apparently the stable product of soil development and rock weathering in the drainage basin of the Mississippi River. The sediments of the Mississippi Sound-Mobile Bay area, lying east of the Mississippi Delta and derived ultimately from Appalachian Province, contain considerably more kaolinite. Transition zones between the two sediment types can be differentiated.

Hypothesis Concerning Alteration of Clay Minerals in Marine Environments

Aside from Van Andel and Milne and Earley, most students of the Recent have attempted to explain the clay mineral variations in Recent marine muds in terms of alteration and modification of pre-existing clay minerals. Table 2 contains a list of proposed clay mineral alterations and a summary of the major reasons for inferring such alterations. Unfortunately the observations in Table 2 cannot be considered as proving exclusively any of the alterations suggested. The authors listed have presented detailed arguments in favor of their hypotheses. The present author would like to mention some alternative hypotheses, many of which have not been given sufficient consideration. Most of the data are of such a nature that they can be explained by numerous hypotheses. The observation made by many authors that one type of clay decreases as another increases cannot be considered proof that the one clay is altering to the other. These various segregation tendencies can equally well be explained by such things as preferential flocculation (Whitehouse, 1951, 1952; Whitehouse and Jeffrey, 1955), current sorting, effects of different source areas, floods, periodic variations in composition and concentration of river detritus, and probably numerous factors of which we are not aware. These explanations are quite involved and, as a result, are little understood or studied.

For example, one possible source of variation that has not been investigated adequately is the seasonal variation in the types of detrital clay min-

TABLE 2.—PROPOSED CLAY MINERAL ALTERATIONS

Original Mineral	Alteration Product	Observations
Kaolinite	Destroyed	Decrease in abundance from fluvial to marine muds. ^{1, 2}
Kaolinite	Chlorite	Decrease in kaolinite and the presence or increase of chlorite. ^{1, 3, 4}
Kaolinite	Illite	Same as above.
Illite (stripped)	Montmorillonite	Presence of montmorillonite in deep-sea muds. ⁵
Illite (stripped)	Chlorite	Decrease in stripped illite coincidental with increase in chlorite; increase in thermal stability of chlorite with increased salinity; decrease of Mg in interstitial water with depth in core; greater Mg/K ratio in HCl leachate of clays than in interstitial water; increase in Mg content of HCl residues with increase in salinity. ⁶
Montmorillonite	Chlorite	Presence of mixed-layer chlorite-montmorillonite; increase in chlorite with increase in salinity and with decrease in montmorillonite; decrease in Al ₂ O ₃ /MgO seaward; Na/Mg ratio of interstitial water greater than sea water. ³
Montmorillonite	Illite	Decrease in montmorillonite coincidental with increase in illite and increase in salinity; decrease in Al ₂ O ₃ /K ₂ O seaward; Na/K ratio of interstitial water greater than sea water. ^{1, 3}

¹ Grim, Dietz and Bradley (1949).² Milne and Earley (1958).³ Grim and Johns (1954).⁴ Griffin and Ingram (1955).⁵ Murray and Harrison (1956)⁶ Powers (1954, 1957).

erals carried by the rivers. Under normal conditions the river may carry highly weathered clay derived largely from soil material. This material might be deposited relatively near shore whereas, during periods of flooding, the river would obtain much of its clays from the relatively fresh outcrop material (Weaver, 1958b); this latter material would be transported further out to sea than the material carried during the low-water stage and therefore the muds would show variations in the relative amounts of the different clay minerals and in the stability of various types of clay minerals with increasing distance from the river mouth. Such variations in the composition of the river clay detritus would be most pronounced in regions of relatively large relief but would also be of importance in areas where tributaries of a major river drained a variety of different source areas. A major flood by one of the

tributaries could cause considerable change in the clay suite customarily transported by the main river.

Another situation of this type probably exists in the Texas Gulf Coast area. The outcropping Tertiary and Cretaceous rocks and soils adjacent to the Gulf are dominantly montmorillonitic. Further to the north where the topography is more rugged the outcropping Paleozoic rocks are composed predominantly of illite and chlorite. The suspended clay in the lower part of these rivers at normal and low-water stage is largely montmorillonite (Grim and Johns, 1954; Kunze, personal communication); however, it is possible that a large amount of rain in the Paleozoic outcrop area would afford a clay mineral suite at flood stage that was relatively high in illite and chlorite. This flood clay suite would probably be swept through the deltas and be deposited further from the delta than the low-water clay suite. The average trend would thus be for montmorillonite to decrease and for illite and chlorite to increase seaward. Some mechanism of this type, combined with flocculation and selective sorting, might possibly account for much of the variation found in the shallow marine clay suites. The effects of long-shore currents, which can transport clays and sands hundreds of miles, have not been thoroughly evaluated in most Recent studies.

Most of the chemical data on clay samples confirm the x-ray data indicating a change in mineralogy seaward. The data provide some clues but do not provide exclusive proofs of the processes involved.

Variations in the magnesium and potassium content of Recent marine muds are frequently cited as another line of evidence that one type of clay mineral is altering to another type. Powers (1954, 1957) shows by studies of interstitial water and adsorbed cations that magnesium is adsorbed by the clays preferentially to potassium. These data are used to support the idea that chlorite is forming in marine sediments. In 1934 Kelley and Liebig leached a soil clay and a montmorillonite with sea water for several days and found that magnesium was preferentially adsorbed by the clay minerals in an exchangeable condition. The theoretical Mg/K ratio of sea water is 3.34 and the Mg/K ratio of the cations adsorbed on the clays were 5.6 and 7.0—these latter ratios are quite similar to those reported by Powers (1957). Thus it seems likely that magnesium is preferentially adsorbed between the expanded clay layers. Whether this magnesium eventually forms a brucite sheet and thus a chloritic clay is still speculative. The data presently available indicate that it is present in an easily exchangeable form.

Chemical analysis of the clay fraction also presents data which are commonly difficult to interpret. Grim and Johns (1954) show that the open Gulf clays contain 0.92 percent more MgO than the deltaic clays (3.37 percent as opposed to 2.45 percent); however, the Gulf clays contain 1.98 percent less CaO than the deltaic clays (1.34 percent as opposed to 3.32 percent). Thus from this data the increase in total magnesium could be accounted for merely by the base exchange of magnesium for calcium.

The increase in K₂O content gulfward is 0.85 percent (1.51 percent as opposed to 2.36 percent). Part of this increase can be accounted for by the

adsorption of potassium on the exchange positions of montmorillonite. Kelley and Liebig (1934) found that after leaching montmorillonite with sea water 6.6 percent of the exchange cations were potassium; however, it is more likely that most of this potassium is adsorbed by stripped or degraded illite. Numerous people who have worked with soils (reviewed by Reitemeier, 1951, and Weaver, 1958c) have shown that weathered illites are capable of fixing several percent of potassium between the potassium-deficient illite layers. Samples from the Ouachita Mountains (which supply detritus to the Gulf of Mexico) containing 50–70 percent of weathered illite (glycolate to 16.6Å) contain 1.6–1.9 percent K_2O . When these samples are treated with KOH the expanded illite contracts to 10Å and fixes 1.9–3.3 percent additional K_2O . These samples show this same contraction when soaked in sea water for 20–30 days. Samples of sediment from the northern part of the Brazos River (in the area where it drains through Paleozoic illitic shales) contain an abundance of expanded illite which readily reverts to illite when treated with potassium. Thus there is little doubt that expanded illites (which are being identified as montmorillonite) are carried into the Gulf of Mexico and that after reaching the Gulf, they are quite capable of fixing potassium and contracting to 10Å. These clays are probably present in sufficient abundance to account for much of the increase in K_2O content of the clays seaward.

Powers (1954) illustrated a similar process acting in the Chesapeake Bay area, and Grim, Dietz and Bradley (1949) and Grim and Johns (1954) suggested that such a process might be acting in marine environments; however, the latter authors believed that most of the illite was formed by the fixation of potassium between montmorillonite layers, although Grim, Dietz and Bradley (1949) concluded that “In general very little montmorillonite seems to be lost during marine diagenesis.” Experimental evidence indicates that beidellitic clays (high-aluminum montmorillonite) will fix some potassium and form mixed-layer illite–montmorillonites, but montmorillonite (low aluminum montmorillonite) fixes relatively little potassium (Wear and White, 1951; Weaver, 1958c).

Extrapolation of Recent to Ancient

Another method of evaluating the validity of the theories on syngenetic processes listed in Table 2 is to see what the implications must be concerning the clay mineral composition of ancient sediments.

According to the data in Table 2 all the clay minerals that are altering to chlorite are dioctahedral, aluminum-rich minerals, whereas the chlorite found in ancient sediments is largely trioctahedral and either magnesium- or iron-rich (Weaver, 1958a). (One example of dioctahedral chlorite has been found and will be discussed under ancient sediments.)

Hydrothermal studies by Yoder and Eugster (1955) have shown that the stable low-temperature muscovite or illite is the 1M and 1Md variety and that the stable high-temperature variety is the 2M polymorph or common

muscovite. The fact that all the micaceous glauconites that have been studied are apparently the 1M or 1Md variety would further suggest that this is the stable low-temperature structure, and if illite is forming by syngensis it should be this type. As yet no one has reported on the structure of Recent illites; however, one illite-rich limestone mud sample from the Bahamas was found to be composed predominantly of 2M illite. Except for glauconites, the 1M illites are relatively uncommon and the 2M illites common in ancient sediments (see Ancient).

Most mixed-layer illite-montmorillonites, which are quite common in sediments (Weaver, 1956b), have a 1M or 1Md structure. It is also likely that most of these mixed-layer clays formed from material in which all the layers originally were expanded but then were partially contracted by the fixation of potassium between some of these layers. The questions when and how are yet unanswered. Does this fixation occur when the clays are in contact with sea water or after burial (syngenetic vs. epigenetic)? Is the original expanded material a true montmorillonite? If so, it is necessary not only to fix potassium between the clay layers but to substitute aluminum for silicon in the tetrahedral lattice, as all analyses of mixed-layer illite-montmorillonites indicate a higher aluminum content than is normally found in montmorillonite. Or is the original starting material actually beidellitic in composition (high aluminum), thus making it necessary only to fix potassium between the layers and not to modify the basic lattice? The two processes are fundamentally different, and before we understand diagenesis it is necessary to determine if one or both are operative. Most discussions of Recent diagenesis describe only interlayer adsorption and do not suggest any modification of the basic lattice. If these inferred alterations from one clay type to another are brought about only by interlayer adsorption, then in many instances there should be a big difference in composition between the clays so formed and those found in ancient sediments.

In summary it seems rather certain that in the Recent the bulk of the clay minerals in marine sediments are detrital in origin and retain most of their detrital characteristics; however, stripped illites and probably stripped chlorites are being reconstituted by potassium and magnesium adsorption and beidellitic clays are likely adsorbing some potassium and forming mixed-layer illite-montmorillonite. Illite and chlorite may be forming on the sea floor by alteration of other clay minerals but this has by no means been proved.

The above discussion admittedly is not conclusive but is intended to evaluate the data at hand to see if the generally accepted conclusions are firmly based. It is obvious that in most instances where any sizable alteration is suggested (as in Table 2), numerous other hypotheses could be advanced to interpret the data.

Relative Abundance of Detrital and Syngenetic Clay Minerals

From the available data some attempt can be made to evaluate the relative volumetric importance of these various processes. Powers (1957) says that in

the Chesapeake Bay "... the detrital fraction (illite plus kaolinite) slightly outweighs the diagenetic fraction." (The diagenetic fraction here refers to chlorite formed by the precipitation of magnesium between the layers of detrital stripped illite and thus in the present terminology would be considered adsorption and not diagenesis.)

In the Rockport area Grim and Johns (1954) indicate that there is a 21 percent increase in illite and a 17 percent increase in chlorite in passing from the deltaic clays to the open Gulf clays. In the Mississippi Delta area Grim and Johns (1954a, 1955, 1956) report an approximately 20 percent maximum increase in total illite, chlorite and kaolinite in passing from the deltaic clays to the open Gulf clays (farther out into the Gulf this increase becomes less and the clay suite is similar to that in the delta). If the variations reported by these authors are all assumed to be due to syngenetic processes, which seems unlikely, then it appears that approximately 20-40 percent of the clay suites in these areas is syngenetic in origin.

TABLE 3.—DIFFERENCES IN CHEMICAL COMPOSITION BETWEEN SHOREWARD AND SEAWARD CLAYS

	MgO				K ₂ O				Al ₂ O ₃			Fe ₂ O ₃		
	1	2	3	4	1	2	3	4	2	3	4	2	3	4
Shoreward	2.02	2.45	2.90	3.38	0.84	1.51	2.36	2.52	18.05	22.62	22.31	6.35	8.79	6.70
Seaward	9.04	3.37	4.16	2.11	0.84	2.36	2.51	3.43	19.02	18.14	19.98	7.07	9.89	5.56

		Shoreward	Seaward
1. Chesapeake Bay	Powers (1957)	Salinity 1 part/ thousand	22-25 parts/thou- sand.
2. W. Gulf of Mexico	Grim and Johns (1954)	Delta	Open Gulf.
3. Pacific Ocean	Grim, Dietz and Bradley (1949)	Bay	13 abyssal, slope, and canyon samples.
4. Gulf of California	Grim, Dietz and Bradley (1949)	River	Lower Gulf of Cali- fornia.

Table 3 contains a compilation of some of the chemical data of Recent clay fractions, which indicates the differences in chemical composition between the near shore, more continental clays and the open marine clays. Aside from the 7 percent increase in MgO in Powers' samples, the chemical modifications are relatively small. If in Powers' samples the 7 percent MgO is considered to be present between sheets of stripped illite as a brucite layer, then the seaward samples could have 30-35 percent or more chlorite than the shoreward samples. This is in the range indicated by Powers. The chemical changes in the other areas are much smaller and most of these changes could

be accounted for by cation exchange and reconstitution of relatively small amounts of stripped illites and chlorites. Further, if the chlorite in the Chesapeake Bay is formed by magnesium adsorption then it is evident that the nature of the source material controls to a large extent the amount of chlorite that can be formed in this manner. That is, stripped micas (or stripped chlorite?) are more likely to be altered to chlorite than is montmorillonite, which commonly is the dominant clay in the other areas studied. Thus studies of the Recent indicate that, at the most, somewhat less than half the clay minerals are altered to any extent in a marine environment. As suggested by Grim and Bradley (1955), probably most of this alteration is in the form of cation adsorption or reconstitution of slightly weathered illites and chlorites back to their original form. In some situations different cations than were there originally may be adsorbed (or precipitated) between the detrital clay sheets. This latter process needs more thorough investigation before its significance can be evaluated. In any event there is little if any evidence that the basic detrital lattice is being altered to a measurable extent in Recent marine environments.

ANCIENT

Relation of Clay Minerals to Age

Pre-Upper Mississippian.—Grim (1953) indicated that montmorillonite is generally absent in sediments older than the Mesozoic, and he believed that "metamorphic processes would cause the alteration of montmorillonite to a mica type of mineral. . . ." Grim also suggested that kaolinite is less abundant in pre-Devonian than in post-Devonian sediments. Kaolinite he believed to be altered to mica by a complicated metamorphic process. Grim further concluded that very ancient sediments must be composed largely of the illite and chlorite types of clay minerals.

Analysis of the available data indicates that a major change in the composition of clay mineral suites occurs generally at the middle of the Mississippian. Pre-Upper Mississippian rocks contain relatively simple clay mineral suites, whereas post-Lower Mississippian clay suites are in general more complex and variable in composition. Table 4 summarizes the published pre-Upper Mississippian clay mineral data.

Weaver (1958a, b) and Jonas (1958) report that the older Paleozoic illites that have been examined in detail are the 2M type. All the mixed-layer illite-montmorillonites (which in most instances formed from volcanic ash) appear to have a 1M or 1Md structure. When the illite content of these mixed-layer clays becomes high (ratios of 9 : 1 and 4 : 1), they still have a 1M structure. These clays are frequently mistaken for illite, for such a small amount of montmorillonite is commonly difficult to identify. It may be that in rare instances these mixed-layer clays eventually fix potassium between all their layers and thus form 1M illites. For some reason these mixed-layer illite-montmorillonites seldom lose all their montmorillonitelike layers. It may be that a mixed-layer illite-montmorillonite can not be altered to illite by normal

TABLE 4.—PRE-UPPER MISSISSIPPIAN CLAY DATA

No. of Samples	Age	Location	Clay Mineral	Reference
10	Devonian and Ordovician	Eastern U.S.	Illite dominant, kaolinite, and mixed-layer illite-montmorillonite common	Van Houten (1953).
13	Upper Ordovician	Ditto	Illite dominant, kaolinite minor	Weaver (1953a).
—	L. Silurian and U. Ordovician	„	Illite dominant, kaolinite and chlorite minor	Griffiths, Bates and Shadle (1956).
48	L. Ordovician	„	Illite dominant, chlorite usually minor, mixed-layer illite-montmorillonite and chlorite locally abundant	Weaver (1953b).
—	Silurian	„	Illite dominant, kaolinite locally abundant	Folk (personal communication)
20	L. Mississippian and Devonian	„ „	Illite dominant, chlorite minor to common	Weaver (1958b).
19	L. Mississippian to L. Silurian	„	Illite dominant, chlorite, kaolinite minor	Weaver, Wright and Bates (1952).
—	L. Ordovician	„	Illite dominant, chlorite minor	Folk (1952).
12	L. Mississippian to Ordovician	Illinois	Illite dominant, chlorite and kaolinite minor	Grim, Bradley and White (1957).
100	L. Mississippian	Central U.S.	Illite dominant, chlorite, kaolinite, and mixed-layer illite-montmorillonite minor	Weaver (1958a).
150	L. Mississippian to U. Ordovician black shales	Central U.S. and Canada	Illite and mixed-layer illite-montmorillonite dominant, chlorite and kaolinite minor	Weaver (1958b).
53	L. Ordovician	W. Texas	Illite dominant in 65% of samples, chlorite in 35%. Mixed-layer illite-montmorillonite minor	Jonas (1958).
—	L. Mississippian	Ohio	Illite dominant, chlorite and kaolinite common	Nelson (1955).
7	Devonian	Central U.S. and Canada	Illite dominant	Adams and Weaver (1958).

sedimentary processes (non-biogenic) but that low-grade metamorphism is necessary to make the final conversion. During the process of metamorphism the 1M structure is altered to a 2M structure, and 1M illites, therefore, are rare.

Most of the chlorite and mixed-layer chlorite-vermiculite in the older rocks is trioctahedral; however, several occurrences of dioctahedral chlorite were noted. As reported previously by Weaver (1953b) chlorite is common in the Middle Ordovician K-bentonite beds. Additional analyses of 58 samples from Pennsylvania, Tennessee, Virginia, Alabama and Kentucky, collected by Gilmor Hamill of The Rice Institute, indicated that approximately one-third of the K-bentonites contain chlorite or mixed-layer chlorite-vermiculite (probably weathered chlorite). These chlorites are dioctahedral with a 060 spacing of 1.50Å and a series of 001 intensities similar to those calculated by Brindley and Gillery (1956) for a theoretical chlorite that had a dioctahedral mica layer and a trioctahedral brucite layer. The 003 (4.75Å) reflection for this type of chlorite is much stronger in comparison to the other 001 reflections than is normally found for chlorites in sedimentary rocks. In no other diffraction patterns were intensities of this type noted. It is of interest to note that these dioctahedral chlorites are very low in iron, as are the mixed-layer illite-montmorillonites in the K-bentonite beds.

This then appears to be an example of a syngenetic or authigenic chlorite. The ash presumably altered to a dioctahedral montmorillonitelike mineral. Magnesium was abstracted from the sea water and precipitated as brucite between the layers. This method of forming chlorite (which is the type of chlorite students of the Recent believe is being formed in the Recent muds) must be extremely rare, as little dioctahedral chlorite is found in sediments.

Post-Lower Mississippian.—Throughout most of the United States the clay mineral suites of the post-Lower Mississippian sediments are considerably different from those in the pre-Upper Mississippian. Montmorillonite, mixed-layer illite-montmorillonite, and kaolinite become more abundant in the younger sediments. Because of the relative complexity of the post-Lower Mississippian sediments, only a general summary will be attempted. As the clay minerals in sandstones are frequently altered by postdepositional processes they are excluded from the review.

Data from the Mid-continent region indicate that the major change in clay mineral suites occurs at about the middle of the Mississippian (post-Meramecian). In the Forest City (Robbins and Keller, 1952), Illinois, Arkansas, Ardmore, and Anadarko basins, and Ozark uplift (Weaver, 1958a), mixed-layer illite-montmorillonite or montmorillonite, or both, become abundant and in many instances are the dominant clays in Upper Mississippian rocks. In some areas these clays appear at the beginning of the Meramecian and at others at the beginning of Chesterian. In most areas they are more abundant in the Chesterian. In general they appear in progressively older Mississippian rocks westward. These expanded clays are present in the Upper Mississippian (upper Tesnus) of the Marathon geosynclinal sediments although they were not found in the Ouachita (although volcanic

tuff beds are present) and Appalachian geosynclinal facies. In the Ouachita Mountains the Upper Mississippian (Stanley) illite and chlorite shales interfinger with montmorillonitic basinal shales (Weaver, 1958a). It is thought that the lack of montmorillonite in the Appalachian and Ouachita geosynclinal facies is largely a function of source differences although low-grade metamorphism may be responsible in part. This widespread and relatively abrupt occurrence of montmorillonite and mixed-layer illite-montmorillonite in the Late Mississippian strongly suggests that this was a time of considerable volcanic activity.

The Pennsylvanian sediments generally have a relatively complex clay mineral suite (Murray, 1954; Siever, 1953; Glass, Potter and Siever, 1956; Weaver, 1958a; Glass, 1958; Bates and others, 1957; Potter and Glass, 1958). It is quite common for Pennsylvanian clay mineral suites to contain illite, chlorite, kaolinite and montmorillonite, or mixed-layer illite-montmorillonite, or both. No bentonite beds are reported as such in the Pennsylvanian, and it is likely that much of the montmorillonite and mixed-layer illite-montmorillonite was derived from older Mississippian and Ordovician rocks. This complex clay suite is characteristic of sediments both in epicontinental basins and in geosynclines (Appalachian, Ouachita and Marathon). The post-Pennsylvanian orogenic movements in these older mountain areas seemingly were not sufficiently severe to cause any serious alteration of the Pennsylvanian clay minerals. It is in the Pennsylvanian that small-scale extreme lateral and vertical variations in clay mineral suites first become pronounced. Many of these variations represent environmental differences. Keller (1956) has presented an excellent example of what appears to be a kaolinitic continental facies grading into an illitic marine facies. The pre-Upper Mississippian small-scale or environmental variations are relatively minor, either because of homogenization due to depth of burial and metamorphism, or because of the preferential erosion of the continental and transitional facies (Gilluly, 1949) wherein occur most of the major clay mineral variations.

Relatively little information is available on Permian rocks. The Permian was a period of active volcanism (Eardley, 1951) and "primary" montmorillonite is again relatively abundant. Swineford's (1955) study of the Permian of Kansas showed that illite and chlorite were the dominant clay minerals, although montmorillonite was common in the upper part of the section. Mixed-layer chlorite-vermiculite is abundant in the Upper Permian Yates formation of West Texas (Dodd, Conley and Barnes, 1955; Earley and others, 1956). Kaolinite and illite are the dominant clay minerals in the Permian Phosphoria formation of Montana (Weaver, 1955). Illite, montmorillonite, and mixed-layer illite-montmorillonite all occur as dominant clays in samples from New Mexico (Adams and Weaver, 1958).

Krynine (1950) found kaolinite, and to a lesser extent, illite, to be the dominant clays in the Triassic New Haven arkose of Connecticut. Illite is thought to be the principal clay in the red Triassic of New Jersey and Massachusetts (Van Houten, 1948). Hooks and Ingram (1955) reported that the

Triassic red shales of North Carolina are composed predominantly of illite and montmorillonite. These authors believed the clay minerals were detrital and indicative of the nature of the weathering in the source area.

In the Rocky Mountain region illite appears to be the predominant clay mineral in the Spearfish and Chinle (Van Houten, 1948) and illite with chlorite in the Chugwater red beds.

Baker (1950) believes that the Shinarump and Chinle (Upper Triassic) red beds of southern Utah and northern Arizona are bentonitic (montmorillonitic). Illite and mixed-layer chlorite-vermiculite are reported to be the dominant clay in the Triassic of Germany (Lippmann, 1956). The relative lack of kaolinite in the Triassic and Permian red beds would suggest that if they are representative of a period of tropical, lateritic-type weathering, most of the clay minerals were derived from the mildly weathered C-horizon of the soils as suggested by Hooks and Ingram (1955).

The fluvial and fluviolacustrine Upper Jurassic Morrison sediments of Colorado (Keller, 1953) and the Black Hills (Tank, 1956) commonly contain relatively pure illite and kaolinite clays and mixed illite and kaolinitic clay suites. Montmorillonite is dominant but of less volumetric importance in some sediments. Baker (1950) reports that the Sundance and Morrison formations are bentonitic. Griffiths and others (1954) reported finding illite, kaolinite and chlorite in the Upper Jurassic Salt Wash sediments. The Upper Jurassic shales of Saskatchewan contain abundant montmorillonite but illite and kaolinite are also present (Adams and Weaver, 1958).

Glass (1951) found that kaolinite is the dominant clay in the Upper Cretaceous rocks of New Jersey. Illite is common and chlorite and montmorillonite are present in a few samples.

Volcanoes were active throughout the Gulf Coast during Late Cretaceous time, and Ross, Miser and Stephenson (1929) have reported that montmorillonite is abundant in the Upper Cretaceous of Texas, Oklahoma, Arkansas, Louisiana, Alabama and Mississippi. Kunze, Templin and Page's (1955), and Adams and Weaver's (1958) studies confirm this, although all the other clay minerals, particularly kaolinite, are commonly present in abundance (Simons and Taggart, 1954).

Throughout the Denver Basin of Colorado and Nebraska and the Williston Basin, Saskatchewan (Weaver, 1958b), the Lower Cretaceous Dakota group (continental to shallow marine) has a highly variable composition. In Colorado Waagé (1955) found that kaolinite is generally dominant in the more continental facies and illite in the marine facies. Montmorillonite and mixed-layer illite-montmorillonite and chlorite are also abundant.

Many authors have reported the great abundance of montmorillonite in the Upper Cretaceous in this area and also in Montana, Wyoming, and the Dakotas. But again it is not uncommon to find relatively complex clay suites containing four or five different clay minerals, or suites which are predominantly illite or mixed-layer illite-montmorillonite. Gude (1950) reported that kaolinite is commonly the dominant clay mineral in the Laramie formation near Golden, Colorado.

In summary it appears that montmorillonite is extremely abundant in the Upper Cretaceous. Volcanic material is generally accepted as the source for most of this montmorillonite and it is also apparently the source for much of the Upper Cretaceous kaolinite (Ross, Miser and Stephenson, 1929; Waagé, 1955).

As insufficient data are available on the Tertiary to discuss it in detail, it will be discussed as a unit. The data do suggest that there is relatively little difference in the clay mineral suites of the various Tertiary series. Once volcanism got well started during Upper Cretaceous time it continued to be active during Tertiary time and, as a result, the Tertiary sediments are characterized by their large quantities of montmorillonite and mixed-layer illite-montmorillonite.

In the Eocene marls of New Jersey, Glass (1951) found, in addition to glauconite, abundant montmorillonite and mixed-layer illite-montmorillonite. The Miocene clays are composed largely of kaolinite and illite.

In scattered samples from the Texas Gulf Coast, Simons and Taggart (1954) found that kaolinite was the dominant clay in the Lower Eocene (Queen City, Carrizo, Wilcox) and montmorillonite in the post-Lower Eocene Tertiary. Roberson (1957) also found that kaolinite was the predominant clay with minor amounts of illite, chlorite and montmorillonite in the Lower Eocene of the northeastern Texas Gulf Coast. Burst (1958) found that either illite, montmorillonite or kaolinite could be the dominant mineral in the Eocene Wilcox shales and that chlorite and mixed-layer illite-montmorillonite are usually of secondary importance. The relatively high kaolinite content of the Lower Tertiary may be a reflection of the climatic conditions that produced the commercial kaolinite and bauxite deposits of the southeastern United States. Montmorillonite and mixed-layer illite-montmorillonite are abundant in the lower Eocene Porters Creek shale (Powers, 1957) and in the Oligocene and Miocene (Powers, 1958; Milne and Earley, 1958).

In the nonred Eocene lacustrine sediments of Utah either montmorillonite, illite, mixed-layer illite-montmorillonite, or chlorite can be the dominant clay mineral (Weaver, 1958b).

Van Houten (1948) reported that illite is the principal clay in five red Eocene formations from Wyoming, Colorado and New Mexico. Montmorillonite commonly is present in minor amounts, and kaolinite is dominant in four of 26 samples. These identifications were made by differential thermal analysis. x-Ray analyses of the red shales from two of these formations (Wasatch and De Beque) indicate that in addition to illite and kaolinite, chlorite and mixed-layer illite-montmorillonite are commonly present.

The Eocene, Oligocene, Miocene and Pliocene shales of California seem to be variable in composition (Milne and Earley, 1958; Adams and Weaver, 1958; Quaide, 1956; Weaver, 1958b). Montmorillonite is probably the most abundant clay but mixed-layer illite-montmorillonite is common. Chlorite and mixed-layer chlorite-vermiculite are relatively abundant and may be dominant (both clays are much more abundant in the sandstones than in the shales). Illite and kaolinite are present in varying amounts in many samples

and although both are sometimes dominant, in many samples they are absent.

Mineralogy: As in the pre-Upper Mississippian, all the illites (except glauconite) that were x-rayed by the film method (approximately 50) had a 2M structure. The diffractometer patterns of the other samples suggested that most of them were the 2M variety. It was not possible to obtain many high-illite samples from the California Tertiary. Here it is possible that many of the illites have the 1M structure, presumably inherited from biotite which is abundant in many of the shales and sandstones. All mixed-layer illite-montmorillonites apparently have a 1M structure.

All the chlorites and mixed-layer chlorite-vermiculites examined were the trioctahedral variety. An iron-rich chlorite chamosite-septechlorite is quite common in the California Tertiary. The even orders are 10-20 times as strong as the odd orders and differential thermal analysis suggests a high iron content. In thin section it appears that this material has formed from biotite.

Discussion.—The general distribution of clay minerals through the geologic section is probably first a function of tectonics and the type of source rock. This primary relation is modified by climate, syngensis, preferential segregation, epigenesis, and metamorphism. These various processes operate with varying efficiency throughout geologic time and in many instances are capable of masking the clay suite-source relation.

The first major feature to explain is the relative abundance of illite and the relative scarcity of kaolinite and montmorillonite in the pre-Upper Mississippian sediments. Grim (1953) has suggested that this may be due to the metamorphism of these clay minerals to illite. This explanation may well apply to the truly metamorphic rocks but is probably not applicable to rocks that have suffered only deep burial (less than 25,000 ft) or regional uplift without developing incipient metamorphism. Montmorillonite and kaolinite are abundant in the sharply folded and overthrust Upper Mississippian Springer shales of southern Oklahoma.

Volumetrically more than 50 percent of the pre-Upper Mississippian sediments are composed of carbonate rocks (J. L. Wilson, personal communication). As kaolinite is relatively rare in carbonate rocks in general and is usually most abundant in the near-shore continental sediments, which have been preferentially destroyed by subsequent erosion (Gilluly, 1949), it is not surprising that little kaolinite is found in early Paleozoic sediments. Moderate amounts of kaolinite are present in unmetamorphosed Precambrian Belt shales.

The increase in kaolinite, montmorillonite, and mixed-layer illite-montmorillonite and the added complexity of the clay mineral suites near the end of the Mississippian roughly coincide with a major change in the tectonic pattern of North America and also with an increase in complexity of heavy mineral suites (Pettijohn, 1957; W. W. Rubey, personal communication). In pre-Devonian time, orogenic activity was restricted to long, narrow belts along the borders of the present continent. During Devonian time large

areas in the stable interior of the continent were uplifted, and from Mississippian time on, much detrital material was derived from these areas of epeirogenic uplift (Eardley, 1951). This regional change in orogenic activity could affect the clay mineralogy in three ways: (1) change the source area from one of predominantly metamorphic rocks to one where igneous and older sedimentary rocks were an increasingly important factor; (2) provide many source areas which were much closer to the site of deposition; (3) increase area for fresh water continental deposition. These three factors would tend to increase the kaolinite and montmorillonite content of clay material while reducing the illite and chlorite contribution. The amount of kaolinite would be augmented by the increase in continental land area and by the increase in the amount and preservation of shallow marine near-shore sediments. These large land areas provide fresh water lake-type environments in which volcanic ash could be deposited and altered to montmorillonite (see Diagenesis).

It is also likely that concomitant with the change in the tectonic pattern there was an increase in volcanism. The first major post-Devonian volcanic activity apparently occurred during the Upper Mississippian and may have ushered in the "widespread unrest in early Pennsylvanian" in the south central part of the present continent and other areas (Eardley, 1951). The Pennsylvanian sediments are, in general, mixtures of clays derived from the borderland orogenic belts and of older sediments from the interior epeirogenic uplifts.

The Permian, Triassic and Jurassic were times of excessive volcanism (Eardley, 1951), as is suggested by the common occurrence of montmorillonite throughout this section of rocks. Volcanoes were relatively inactive during Early Cretaceous times but volcanism was apparently rejuvenated with renewed vigor in the Late Cretaceous (preceding Laramide orogeny) and resulted in the deposition of strongly montmorillonitic sediments throughout the United States. Volcanic activity continued unabated throughout the Tertiary. Uplifted igneous and metamorphic rocks continued to supply illite, chlorite and kaolinite to the Tertiary basins but this contribution is probably at least matched by montmorillonite and mixed-layer illite-montmorillonite derived from contemporaneous volcanics and older montmorillonitic sediments.

Relation of Clay Minerals to Lithology

Shales.—The data just presented indicate that illite is the most abundant mineral in shales. Montmorillonite and mixed-layer illite-montmorillonite are next in abundance, followed by chlorite. Kaolinite and mixed-layer chlorite-vermiculite (montmorillonite) are least abundant. There is no apparent relation between the clay mineral suite and the color of shales.

Limestones and Dolomites.—Grim, Lamar and Bradley (1937) reported that illite is the major clay mineral in 35 Paleozoic limestones from Illinois and that small amounts of kaolinite were present in half of them. In Robbins and Keller's (1952) study of 27 limestones from central United States, ranging

in age from Cambrian to Recent, they too found that illite is the most common clay mineral and that it occurs, usually predominantly, in all but two samples. Kaolinite is present, normally in minor amounts, in about one-fourth of the samples, and montmorillonite is dominant in two samples. In a study of 15 Triassic, Jurassic and Cretaceous limestones (greater than 40 percent calcium carbonate) Millot (1949) also found that illite is the dominant clay although kaolinite may be present in amounts up to 50 percent. Millot (1949) suggested that the calcium and kaolinite content of sediments are related inversely; however, a plot of Millot's data indicates no marked relationship and, aside from a few highly kaolinitic lacustrine samples, the distribution is random. Attapulgite and kaolinite are predominant in many of the Eocene limestones of North Africa (Rivière and Visse, 1954). Talc is abundant in some of the Recent limestones along the coast of Florida.

Jonas (1958) reported that 50 out of 53 samples of Lower Ordovician Ellenburger carbonate rocks of West Texas contained both illite and chlorite (chlorite is as abundant or more abundant than illite in 35 percent of the samples). Mixed-layer illite-montmorillonite is commonly present but in minor amounts. The illite was reported to be the 2M type and therefore was considered to be detrital in origin. Potter and Glass (1958) found that illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite all occur in abundance in the thin Upper Pennsylvanian limestones from Illinois but that illite is generally dominant. They reported that "some of the limestones are similar in clay mineralogy to the typical subgraywacke shales and others differ markedly."

In some instances where the clays in interfingering limestones and shales differ it was found that the limestones were calcarenites and essentially more clastic than the surrounding shales (Weaver, 1958a). In such situations the clay minerals bear no direct relationship to an alkaline, carbonate depositional environment.

Weaver (1958b) concluded :

On the basis of several thousand analyses it is apparent that illite is the predominant clay mineral in limestones and dolomites; however, all of the other major clay minerals are commonly found, and are frequently predominant, through thousands of feet of limestones. Illite is the predominant clay mineral in all sediments and is not noticeably more abundant in limestones than in shales. For example, the Paleozoic limestones are predominantly illitic but no more so than the Paleozoic shales. In most cases where shales and limestones are interbedded, they contain the same type of clay minerals. Yoder and Eugster's (1955) studies on the synthesis of illite and the writer's study on naturally occurring illites indicate that there are low-temperature and high-temperature illite polymorphs. As most of the illites in limestones (and shales) are the high-temperature polymorphs, it is unlikely that they were formed by marine diagenesis and more likely that they are detrital and were derived from muscovite or illite in the source area. In the Recent the eastern Florida lime muds are illitic as are the Atlantic Coast clay muds, and the western Florida lime muds are montmorillonitic, as are the Gulf of Mexico clay muds.

Clay Minerals in Sandstones Versus Clay Minerals in Shales.—In many instances there is significant difference between the clay minerals in sand-

stones and those in adjacent shales. Glass (1958) recently has presented an excellent example from some Pennsylvanian cyclothems of Illinois which illustrates such differences. He found that kaolinite was more abundant in the sandstones than in the shales and quite convincingly showed that

... kaolinite crystals form in sand bodies prior to exposure and that exposure in outcrop augments the process. Permeability, therefore, must be considered as a factor in clay mineral formation not only in outcrop but also in subsurface.

Smithson and Brown (1954, 1957) reported that dickite is common in many Carboniferous and Middle Jurassic sandstones of England. It is associated with highly altered heavy mineral assemblages and partially dissolved feldspars. Smithson and Brown (1954, p. 185) believed that the feldspar altered to dickite owing to "... changes which took place after deposition and appear to be dependent upon depth of burial." Fothergill (1955) reported that kaolinite was more abundant in the Oligocene La Pascua sandstones of Venezuela than in the surrounding shales and believed that the kaolinite was formed by the alteration of feldspars on the sea floor. Griffiths, Bates and Shadle (1956, p. 1) report "Small patches of kaolinite of about the same size as the detrital quartz grains occur in many quartzites and presumably represent in situ decomposition of feldspar fragments." Potter and Glass (1958) found more kaolinite in subsurface Pennsylvanian sandstones than in the surrounding shales and concluded that the increase in kaolinite was due to postdepositional alteration.

At what stage the kaolinite formation occurred is not yet clear. It is apparently caused by acid intrastratal solutions. In continental sandstones these acid solutions would be available and could begin leaching the permeable sandstones immediately after deposition. In deltaic and marine sandstones acid solutions are not so readily available, but it is possible that the CO₂ produced by bacterial activity in the muds would escape into surrounding bodies of sand and produce the neutral to slightly acid condition which favors the formation of kaolinite. In other instances it is likely that the leaching is done by meteoric waters that have migrated from the sandstone outcrops.

Burst's (1958) data on the Wilcox indicate that chlorite is more abundant in the deltaic, lagoonal and marine sandstones than in the adjacent shales, with the marine rocks having the greatest difference.

Quaide (1956) reported that chlorite is relatively more abundant in some California Pliocene arkosic sandstones than in the adjacent shales. He believed much of the chlorite is secondary. Milne and Earley (1958) found that some upper Miocene sands from California contain considerably more chlorite-like material than the enclosing shales. They believed the chlorite material was formed by solutions expelled from the surrounding shales. The writer has found that concentrations of chlorite in Tertiary marine sands are a common phenomenon.

Secondary illite has been found in sandstones (Krynine, 1940; Weaver, 1955; R. L. Folk, personal communication) but it is apparently less common than kaolinite and chlorite.

In many instances it appears that the clean, more quartzose sandstones are more apt to contain secondary kaolinite. The clay mineral suite in most argillaceous, graywacke and arkose sandstones is similar to that in the adjacent shale. This presumably reflects permeability differences.

Petrographers are generally agreed that there is some relation between type of clay mineral suite and type of sandstone (Krynine, 1948; Pettijohn, 1957; Griffiths, Bates and Shadle, 1956); i.e. orthoquartzites—illite and kaolinite; graywackes—illite and chlorite; arkose—kaolinite and montmorillonite. Although these relations in general exist, there are many exceptions and it is not clear how numerous are the exceptions. Orthoquartzites may contain kaolinite but the clay suite is often composed entirely of illite or mixed-layer illite—montmorillonite (9 : 1–4 : 1) or both. Also, as was discussed before, much of the kaolinite in orthoquartzites has a postdepositional origin and thus does not reflect the character of the source material. Graywackes eroded from older metamorphosed geosynclinal rocks generally contain an illite and chlorite clay mineral suite, but the younger graywackes (post-Mississippian) have relatively complex clay mineral suites. Illite, chlorite, mixed-layer illite—montmorillonite, montmorillonite and kaolinite commonly are all present and in many instances montmorillonite and mixed-layer illite—montmorillonite are predominant, i.e. Atoka (Pennsylvanian) and Miocene of the Gulf Coast. The clay content of only a few arkosic sandstones has been determined in detail but if the relative lack of kaolinite in Permian, Jurassic, and Triassic red shales is any indication, then kaolinite is probably relatively rare as a detrital constituent of arkoses. Nearly any of the other clay mineral types can occur as the dominant clay mineral in these red shales. Hooks and Ingram (1955), in their study of Triassic arkosic rocks of North Carolina, concluded that

Arkosic sediments, in general, can have almost any type of clay mineral in the clay fraction, depending on the nature of the source rock, the climate and topography of the source area, and the chemical environment of the depositional site.

The fact that arkosic sandstones by definition contain much feldspar would suggest that they would generally contain little detrital kaolinite. Arkosic sands are a reflection of a “retardation of the weathering processes in the source region” (Pettijohn, 1957). Where the weathering of feldspars is retarded, the clay formed is usually illite and not kaolinite. Although some “granite wash” sandstones in California contain kaolinite, many of them also contain either montmorillonite, illite, or mixed-layer illite—montmorillonite as the major clay constituent.

Shale Classification.—Glass (1958) showed that in some Lower Pennsylvanian and Upper Mississippian shales from Illinois the subgraywacke shales (shales associated with subgraywacke sandstones) tend to have a higher chlorite and kaolinite content than the orthoquartzite shales, which are higher in illite. A similar trend can be seen in the Ouachita facies shales (Weaver, 1958a)—the Stanley graywacke shales contain illite and abundant chlorite; the Atoka subgraywacke shales contain illite, illite—montmoril-

lonite, some kaolinite, and less chlorite than the Stanley; the Jackfork protoquartzite shales are similar to the Atoka but contain less chlorite and kaolinite and more illite. Bokman (1953) believes the Stanley had primarily a crystalline source area, and Weaver's (1958a) data indicate that the Atoka source area probably contained more metamorphic rocks than the Jackfork source area. In central Pennsylvania the subgraywacke Reedsville, Oswego, and Juniata shales contain more chlorite than the highly illitic shales in the overlying Tuscarora orthoquartzite. The Oswego and Juniata sediments were derived from a predominantly metamorphic source and the lower Tuscarora from a predominantly sedimentary source (Folk, personal communication).

Potter and Glass (1958) found that the Illinois Pennsylvanian shales are predominantly illitic but that shales associated with the Middle and Upper Pennsylvanian subgraywackes are more chloritic than the Lower Pennsylvanian orthoquartzite shales. The subgraywacke section contains a larger proportion of marine sediments than the orthoquartzite section; however, the source area for the subgraywackes contained metamorphic rocks which were absent in the orthoquartzite source.

These data indicate that, in a general sense, subgraywacke shales commonly contain more chlorite than the associated illite-rich orthoquartzite shales and that this difference is primarily due to source differences. However, as Folk (1956) has pointed out, subgraywackes and orthoquartzites can occur in close proximity and be derived from the same source area. In such a situation the shale differences as well as the sandstone differences are due to differing degrees of sorting in the depositional environment.

The composition of Paleozoic and Mesozoic arkosic shales appears to be extremely variable.

Kaolinite is generally considered to be, claywise, the stable end-product of weathering, yet there is no striking concentration of kaolinite in the shales associated with the mature orthoquartzite-carbonate facies. This would imply either that the tectonic and climatic conditions which favor the development of mature sandstone and chemical rocks do not favor the development of the end-product clay mineral (kaolinite) or that weathering has passed beyond the kaolinite stage, and colloidal or gel material is formed and transported to the sea where it recombines to form the stable marine clay (illite). If the latter explanation is correct, one would expect to find considerable bauxite and laterite associated with the orthoquartzite-limestone sediments. It seems more likely to the author that the former concept is more generally applicable and that the degradational end-product is seldom developed on a large scale under pre-orogenic conditions.

Although some generalizations can be made, there is not always a direct and obvious relation between the clay mineral composition of shales and the mineral composition of associated sandstones. Clays derived from a given source rock are more closely related to climate, drainage, and topography than they are to the composition of the source rock—at least more so than are the sand-size minerals. Further, clays are more readily segregated in

the depositional environments than are sand-size minerals; and lastly, clays probably are more susceptible to postdepositional diagenesis than sandstones. Thus, we would expect only a very vague or complex relation to exist between shale composition and sandstone composition. With more work the relation may become apparent, but it is suggested that it may be inappropriate to separate shale types into the sandstone classification. It is likely that a more complex classification is needed, perhaps one that is genetically related to weathering conditions rather than composition of source material and to depositional environment rather than maturity.

Relation of Clay Minerals to Depositional Environments

Millot (1949, 1953) seems to have been the first to make a detailed attempt to relate clay minerals to environments of deposition. He found kaolinite to be dominant in fluvio-lacustrine deposits where acid leaching was active. In all other environments except basic lakes (which contained montmorillonite) illite was reported to be the major clay present (Millot, 1953). Numerous studies since then have indicated that relation exists in many instances. Murray (1954) showed that in some Pennsylvania cyclothem from Illinois illite was always dominant but that chlorite and kaolinite decreased in going from nonmarine to brackish to marine shales. Glass (1958) found that in some Pennsylvanian sediments kaolinite was slightly more abundant in the nonmarine than in the marine shales. Keller's (1956) study of the Pennsylvanian Cheltenham formation of Missouri indicated that in passing from a nonmarine to marine environment the clay suites changed from a diaspore, boehmite, well-crystallized kaolinite suite to a good to moderately crystallized kaolinite suite to an illite and moderately crystallized kaolinite suite to a largely illitic suite. Degens, Williams and Keith (1957) found that in 70 Pennsylvanian samples the illite-to-kaolinite ratio was statistically higher in marine and brackish-water shales than in fresh-water shales. Burst (1958) reports the reverse of this trend in some Gulf Coast Eocene shale where he found that the chlorite and kaolinite to illite ratio ($7\text{\AA}/10\text{\AA}$) increases (1.1 vs. 1.3) in passing from a deltaic to a marine environment. The contrast is more marked in the sandstones than in the shales. Illite is most abundant in the deltaic sandstones and chlorite in the beach sandstones.

Weaver (1958a) reported that organic-rich marine black shales are composed almost entirely of illite or mixed-layer illite-montmorillonite, or both, and few contain kaolinite.

Keller (1953) found that either illite, montmorillonite or kaolinite could occur as the dominant clay mineral in the nonmarine Morrison shales. Simons and Taggart (1954) found in the marine Gulf Coast Tertiary shales that either illite, montmorillonite or kaolinite could predominate. Lemcke, von Engelhardt and Fuchthaven (1953), in a study of molasse sediments, showed that the clay mineral suites bore no significant relation to the environment of deposition. Rivière (1953) reported that the marine graptolitic clays of the Sahara are almost pure kaolinite. Rivière and Visse (1954) have examined

marine sediments in which illite, montmorillonite, kaolinite and palygorskite are predominant. In the Pennsylvanian Paradox calcareous shales of the Paradox Basin Merrell, Jones and Sand (1957) found the following progressive change from near shore into the basin: montmorillonite with illite, chlorite and illite with montmorillonite, and chlorite and illite.

Weaver (1958a), in reviewing his data from many parts of the geologic section, said that he could find no particular clay mineral that was restricted to a particular environment; that illite, montmorillonite, and mixed-layer illite-montmorillonite could occur in abundance, commonly as the only clay mineral present, in sediments deposited in any of the major marine and non-marine environments; that kaolinite can be found in abundance in sediments of all environments but is most likely to be dominant in a fluvial environment; and that chlorite, although commonly present, is seldom if ever a dominant clay mineral in shales and limestones.

These authors, in most instances, do suggest that clay mineral suites or types are related to environments of deposition but that there are no consistent relations between a specific environment and a specific clay suite. How clay mineral suites reflect the nature of their environment of deposition is not yet clear. A variety of explanations are found in the literature, many of which conflict to some extent. Possibilities to be considered are that clays suffer chemical alteration or are grown from gels in a manner controlled by depositional environment or, alternatively, that the clays are largely detrital and assemblages are segregated into various environments because of variations in rates of deposition, topographic expression, currents, salinities, sediment concentrations, seasonal variations, biological activity, etc. Most investigators have concluded that both detrital and diagenetic processes are operative and that the problem is to decide which process is the more effective; some (Rivière and Visse, 1954; Weaver, 1958a, b) have indicated that they believe clay suites can be segregated into various environments by physical and chemical processes which do not modify the clay minerals themselves. A discussion of the relative effectiveness of these two processes has been given in the foregoing review of Recent sediments.

Data from ancient rocks admit of only the very broadest generalities—abundant kaolinite is normally indicative of a nonmarine environment, and abundant chlorite, illite, montmorillonite, mixed-layer illite-montmorillonite, and chlorite-vermiculite can be found in sediments deposited in any environment—and yet it appears that in many formations minor differences in clay suites are closely related to environments. This suggests that chemical alteration in the depositional environment is not the dominant factor in determining the composition of the clay mineral suite.

Detrital clay minerals can be used to identify environments, but first the effects of source and tectonic framework must be identified and evaluated. The depositional environment controls the specific type of clay mineral suite only in that in a general fashion the type of source material and the type of sedimentation are controlled by the degree and type of tectonic activity (Krynine, 1951; Folk, 1956). Environmental interpretation without the use

of other data is complicated by many factors in addition to those mentioned. For example, even if the source areas are identical the composition of the various clay mineral suites deposited on a stable shelf and in a geosyncline would likely be quite different. If there are 10 major types of source complexes and 3 major depositional frameworks, there would be 30 different clay mineral suites which could be deposited in similar geographic environments. Much more work needs to be done before modal relationships can be established.

Diagenesis (Epigenesis)

Syngensis (alterations that occur when the mineral is still in contact with sea water) already has been discussed. Epigenesis is alteration that occurs when the mineral no longer has contact with the sea water; it includes alterations due to age and depth of burial. Epigenetic alteration in porous and permeable sandstones has been reviewed. Glass (1958) found that degradational alteration may also occur postdepositionally in shales. In underclays in contact with coals he found more mixed-layer clay and less illite and chlorite than the shales not near the coal and concluded that the difference was caused by postdepositional leaching by coal swamp water.

The two major observations that suggest the importance of epigenesis in shales are the striking mineralogic difference between pre-Upper Mississippian and post-Lower Mississippian clay mineral suites and the disappearance of montmorillonite with depth in younger sediments.

Quaide (1956) indicated that in the Pliocene of California there is in general a decrease of montmorillonite and increase of illite with depth. Burst (1958) and Powers (1958) report that in the Gulf Coast Tertiary montmorillonite is absent below the 9000–12,000 ft. level. All three authors believe that montmorillonite is altering to mixed-layer illite–montmorillonite and illite as a function of depth of burial. Burst reports that he found virtually no swelling layers below 14,000 ft. This trend is evident in the Gulf Coast Miocene where the montmorillonite, when glycolated, gives a fairly sharp 17Å peak down to 7000 ft, then a 16–17Å peak down to 9000 ft. From 9000 to 11,000–12,000 ft. the peak ranges from 14–17Å (mixed-layer illite–montmorillonite range 7:3–0:10); below this depth (down to at least 17,000 ft.) the glycolated peak extends from 12Å to 14.5Å (7:3–3:2). Thus, the amount of illite complexed with the montmorillonite increases with depth; however, most of the transitions are fairly abrupt and in most instances there is a good relation between these clay mineral facies and environments (the illite content of the mixed-layer clay increases with increasing water depth). The possibility that this decrease in montmorillonite and increase in illite, chlorite, and mixed-layer illite–montmorillonite with depth is due to differences in source area cannot be eliminated. Grim (1936) and Todd and Folk (1957) by heavy mineral studies showed that in the Eocene the Appalachian Mountains, which are rich in illite and chlorite,

supplied a large part of the detritus to the Gulf Coast geosyncline. Thus it is possible that the montmorillonite was derived locally from contemporaneous volcanics and montmorillonitic Cretaceous sediments, and the illite and chlorite were derived from the Appalachians, being carried westward by longshore currents.

A similar relation apparently exists in the Upper Mississippian Springer shales of southern Oklahoma (Weaver, 1958a). Most of the shale samples that will glycolate to 17Å are shallower than 10,000–11,000 ft. The deeper Springer shales (down to 22,000 ft) are mixed-layer illite–montmorillonites (7:3). Both in the Gulf Coast Miocene and Mid-Continent upper Chester the “crystallinity” of chlorite, in some instances, increases with depth. (When the shallower samples are heated at 500–550°C the chlorite and mixed-layer chlorite–vermiculite range from 13.6 to 10Å; at deeper depths heating will produce a relatively sharp and discrete 13.6–13.8Å peak.) But here again this trend can be related to environment as well as depth. The montmorillonitic samples are from the flanks of the basin and the mixed-layer shales from the middle of the basin. Thus, in these examples, it is suggested that clay mineral changes may equally well be related to environment (depth of water) and depth of burial.

In the California Cretaceous good montmorillonitic shales occur at least as deep as 11,500 ft. In Permian limestone of west Texas excellent (glycolated sample shows sharp 17Å x-ray peak) montmorillonite is found at least as deep as 10,500 ft. and in the Cretaceous limestones of Florida as deep as 13,000 and possibly 15,000 ft.; however, it might be expected that the relatively isolated clay minerals in limestones would be less susceptible to post-depositional alteration than those in shales.

The increased “crystallinity” of chlorite with depth may be largely a reflection of differences in depositional environment. Powers (1954, 1957) and Nelson (personal communication) indicate that in Recent sediments (Chesapeake Bay) the thermal stability of chlorite increases with increasing salinity. Both factors may be operative.

There is good likelihood that below a depth of approximately 10,000 ft. montmorillonite gives way to a mixed-layer illite–montmorillonite with the proportion of illite increasing with depth. Around 15,000 to 17,000 ft. the mixed-layer illite–montmorillonite ratio is approximately 7:3. Samples that are believed to have been at one time buried to approximately 25,000 ft. have mixed-layer ratios of 9:1–4:1. It may be that deeper burial would cause the complete disappearance of montmorillonite layers. This process may, in part, account for the lack of montmorillonite in the older Paleozoic sediments. The great predominance of mixed-layer illite–montmorillonite with a 7:3 ratio in sediments could be interpreted as implying that few sediments are buried more deeply than 20,000 ft.

Many mineralogists have suggested that montmorillonite fixes potassium and is converted to illite; geochemists call upon this process to account for the deficiency of potassium in sea water. However, there has been little detailed speculation as to how this is accomplished. Powers (1958) has

suggested that below the "equivalence level" the

Mg^{2+} (and iron) may move into the octahedral layer of the lattice and replace Al^{3+} which moves into the tetrahedral layer expelling Si^{4+} . The former sites of Mg^{2+} (and iron) would be replaced by K^+ .

Illite would be the result.

The trouble is that there is little, if any, information on the composition of normal sedimentary montmorillonite and mixed-layer illite-montmorillonite. Most analyses of montmorillonite are of commercial grade, relatively pure deposits and are probably not typical. Many analyses of soil montmorillonites (Ross and Hendricks, 1945; Gorbunov, 1956) indicate that these montmorillonites are frequently beidellitic (have a high aluminum content). The composition of the basic lattice of beidellite is quite similar to that of mixed-layer illite-montmorillonite. Table 5 lists the average composition of some illite, mixed-layer illite-montmorillonites, montmorillonites and beidellites. If illite and mixed-layer illite-montmorillonite are forming from montmorillonite, then, in addition to potassium, aluminum is also necessary and some mechanism such as that suggested by Powers (1958) is necessary. However, if most of the expanded clays carried into a marine environment are beidellitic then it is only necessary to add potassium and possibly heat and pressure to form mixed-layer illite-montmorillonite. When a sample of shallow Springer montmorillonite (beidellite?) was saturated with potassium and subjected to a confining pressure of 40,000 psi for 5 days a mixed-layer illite-montmorillonite similar to that at greater depths was formed.

TABLE 5.—AVERAGE STRUCTURAL FORMULAS

¹ Montmorillonite (5)	
-0.33	-0.06
(Al _{1.48} Fe _{0.16} Mg _{0.38})	(Si _{3.94} Al _{0.06}) O ₁₀ (OH) ₂
² Beidellite (2)	
-0.24	-0.47
(Al _{1.37} Fe ³⁺ _{0.50} Fe ²⁺ _{0.02} Mg _{0.22})	(Si _{3.53} Al _{0.47}) O ₁₀ (OH) ₂
³ Mixed-layer illite-montmorillonite (1 : 2-4 : 1) (5)	
-0.36	-0.39
(Al _{1.60} Fe ³⁺ _{0.07} Fe ²⁺ _{0.02} Mg _{0.34})	(Si _{3.60} Al _{0.39}) O ₁₀ (OH) ₂
¹ Illite (5)	
-0.25	-0.55
(Al _{1.44} Fe _{0.35} Mg _{0.22})	(Si _{3.45} Al _{0.55}) O ₁₀ (OH) ₂

¹ Foster (1954).

² Ross and Hendricks (1945), Putnam Clay, Missouri; Java soil.

³ Weaver (1953a), Byström (1956), Grim and Rowland (1942).

The average structural formulas in Table 5 indicate that the composition of the octahedral layers is similar for montmorillonite, beidellite, mixed-layer illite-montmorillonite and illite. The most significant difference is in the tetrahedral layers. As previously mentioned, beidellite in marine sediments is probably scarce as such because whenever sufficient potassium is

available a portion of the layers will contract to 10\AA and a mixed-layer illite-montmorillonite is formed.

Ross and Hendricks (1945) suggested that montmorillonite-type clay minerals form in the absence of appreciable potassium and therefore are most likely to be formed in *fresh water* bodies or by ground water rather than by marine waters, although some montmorillonite is apparently formed under marine conditions. This, in addition to the fact that illite is considered to be the stable marine clay, would suggest that volcanic ash altering in a marine environment would tend to attain a composition more like an illite, beidellite, or mixed-layer illite-montmorillonite than montmorillonite. It is likely that in a marine environment, in the presence of potassium, the ash would in many instances (as in Ordovician K-bentonites) go directly to a mixed-layer clay rather than beidellite.

The idea that ash altering in sea water tends to develop an illite-like lattice is further substantiated by the work of Byström (1956). In her study of the Swedish Ordovician K-bentonites she found that the thicker beds contained a mixed-layer illite-montmorillonite with approximately 1:2 ratio, 2.7 percent K_2O , and 0.21 percent Al in the tetrahedral layer; in the thinner beds the mixed-layer clay had a ratio of approximately 2.3:2, 5 percent K_2O , and 0.32 Al in the tetrahedral layer. Weaver (1953b) described similar mixed-layer clays (from very thin beds) which had a ratio of approximately 4:1, 6.5 percent K_2O , and 0.50 Al in the tetrahedral layer. This would suggest that the ash with the better accessibility to the sea water (which would favor a decrease in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio and the adsorption of potassium and magnesium) would form the most illite-like clay.

Several samples of Recent and Tertiary montmorillonitic muds and shales were leached with LiCl, dried at $250\text{--}300^\circ\text{C}$, and glycolated. The swelling capacity of these samples was only slightly affected and, according to the work of Greene-Kelly (1955), they would be classed as beidellites.

Thus, much of the mixed-layer illite-montmorillonite in sediments may have been derived from volcanic material deposited in the sea. Also, beidellite formed in the soils ("Beidellite with a high content of ferric iron is probably the predominant soil clay mineral of the montmorillonite group," Ross and Hendricks, 1945) is transported to the sea, where it adsorbs potassium and, under the influence of moderate pressures and temperatures, contracts and reorients to form a mixed-layer illite-montmorillonite.

The ultimate ratio of the mixed-layer clay is probably determined by the composition of the basic lattice. In some instances it appears that there is sufficient total charge and tetrahedral charge for the beidellite minerals to form an illite (all layers contracted to 10\AA). The presence of 1M glauconite, biotite, and mixed-layer illite-montmorillonite in deeply buried Ordovician and Cambrian sediments suggests that mere burial will not transform a 1M to a 2M illite. Low-grade metamorphism or shearing-type forces seemingly are necessary to complete this transformation.

In addition to what already has been said here about diagenesis, it is of interest to review briefly some of the recent Russian literature (Strakhov,

1953 ; Belous, 1952 ; Teodorovich, 1954 ; Zaporozhtseva, 1954 ; some of these papers have been reviewed by Chilingar, 1955, 1956). Although there is some disagreement among the Russian authors, in general they report that glauconite forms in a mildly oxidizing environment, lepto-chlorite (frequently reported as intergrown with hematite) in a mildly oxidizing to neutral environment, and chamosite in mildly reducing environment (frequently associated with siderite and ankerite). The pH is considered to be neutral to weakly alkaline. Most of the clay mineral identification seemingly was done with the petrographic microscope and chemical analysis. The general trend of the iron silicate minerals is apparently based on variations in the ferric to ferrous ratio. The more ferrous clays are presumed to be chamosite and the more ferric to be lepto-chlorite or glauconite. Most of the field observations seem to be based on studies of sedimentary iron ore deposits and zones of iron-rich oolites and glauconite. The mode of origin and relation to oxidation-reduction potential is significant but it is questionable whether authigenic chamosite and lepto-chlorite form a significant or detectable fraction of normal sedimentary shales and limestones ; however, lepto-chlorite (high iron chlorite) and chamosite (high iron kaolin) are relatively common in sandstones, where they appear in most cases to be secondary.

CONCLUSIONS

Studies of Recent marine muds suggest to the author that the clay minerals are primarily detrital in origin and reflect the composition of the source area. However, after reaching the marine environment, many of the degraded clays are reconstituted by adsorbing cations between the layers. Whether there is any more vigorous alteration of the detrital clays in a marine environment has not been clearly demonstrated. In the near-shore environments there is, in many instances, a relation between clay mineral suites and environments. It is not yet obvious whether this relation is caused by physical and chemical sorting or by chemical alterations of the detrital clays.

The clay mineral suites become increasingly complex in the younger sediments ; in some areas this trend can be related to a change in regional tectonics. The clay minerals appear to have no preferred lithologic associations, although owing to epigenetic alterations porous sandstones commonly have different clay mineral suites than adjacent shales and carbonate rocks.

In many instances clay mineral facies coincide with environmental facies. As the clay mineral criteria for distinguishing any given type environment are extremely variable, it is thought that segregation of clay mineral suites by sorting is usually more effective than by diagenesis.

Expanded clay minerals appear to be partly contracted by the time they have been buried to 10,000-15,000 ft. It remains to be proved whether this is caused by chemical modification of the basic lattice with burial or if the detrital clay lattice has the inherent ability to contract, without chemical rearrangement, when buried to a sufficient depth.

The following statement by Keller (1953) is still apt :

The extent to which clay minerals and argillaceous rocks can be used as indicators of the environments occurring in the geologic past depends largely, however, upon the ability of the observer to make a judicious interpretation of the mineral evidence before him.

BIBLIOGRAPHY

- Adams, J. A. S., and Weaver, C. E. (1958) Thorium-to-uranium ratios as indicators of sedimentary processes : Example of concept of geochemical facies : *Amer. Assoc. Petroleum Geol. Bull.*, v. 42, pp. 387-430.
- Baker, C. L. (1950) Role of bentonite in Great Plains and Rockies : *Amer. Assoc. Petroleum Geol. Bull.*, v. 34, pp. 1897-1909.
- Bates, T. F., and others (1957) An investigation of the mineralogy, petrology and paleobotany of uranium-bearing shales and lignites : Annual Progress Report, Pennsylvania State Univ., Project No. E-32.
- Belous, N. Kh. (1952) Conditions of formation of iron ores during sedimentation : *Trud. Gorn.—Geol. Inst. Zapad. Sibir. Filial. Akad. Nauk SSSR* no. 12.
- Bokman, J. (1953) Lithology and petrology of the Stanley and Jackfork formations : *J. Geol.*, v. 61, pp. 152-170.
- Brindley, G. W., and Gillery, F. H. (1956) x-Ray identification of chlorite species : *Amer. Min.*, v. 41, pp. 169-186.
- Burst, J. F., Jr. (1958) Postdiagenetic clay mineral-environmental relationships in the Gulf Coast Eocene : These Proceedings.
- Byström, A. M. (1956) *Mineralogy of the Ordovician bentonite beds at Kinnekulle, Sweden* : Sveriges Geologiska Undersökning Arsbok 48, N : O 5, pp. 1-62.
- Chilingar, G. V. (1955) Review of Soviet literature on petroleum source-rocks : *Amer. Assoc. Petroleum Geol., Bull.*, v. 39, pp. 764-768.
- Chilingar, G. V. (1956) Joint occurrence of glauconite and chlorite in sedimentary rocks : A review : *Amer. Assoc. Petroleum Geol., Bull.*, v. 40, pp. 394-398.
- Correns, C. W. (1937) *Scientific Results of the German Atlantic Expedition on the Exploration Ship "Meteor," Bd. 3*, pp. 135-295.
- Correns, C. W. (1939) Pelagic sediments of the North Atlantic Ocean ; in Recent marine sediments, a symposium : *S.E.P.M. Special Pub. No. 4*, pp. 373-395.
- Degens, E. T., Williams, E. G., and Keith, M. L. (1957) Environmental studies of Carboniferous sediments, Part I : Geochemical criteria for differentiating marine from fresh-water shales : *Amer. Assoc. Petroleum Geol., Bull.*, v. 41, pp. 2427-2455.
- Dietz, R. S. (1941) Clay minerals in Recent marine sediments : Ph.D. Thesis, Univ. Illinois.
- Dodd, C. G., Conley, F. R., and Barnes, P. M. (1955) Clay minerals in petroleum reservoir sands and water sensitivity effects, in *Clays and Clay Minerals*, Natl. Acad. Sci. — Natl. Res. Council pub. 395, pp. 221-238.
- Eardley, A. J. (1951) *Structural Geology of North America* ; Harper & Brothers, New York, 624 pp.
- Earley, J. W., Brindley, G. W., McVeagh, W. J., and Vanden Heuvel, R. C. (1956) A regularly interstratified montmorillonite-chlorite : *Amer. Min.*, v. 41, pp. 258-267.
- Folk, R. L. (1952) Petrology and petrography of the Lower Ordovician Beekmantown carbonate rocks in the vicinity of State College, Pennsylvania : Ph.D. Thesis, Pennsylvania State College.
- Folk, R. L. (1956) The role of texture and composition in sandstone classification : *J. Sedimentary Petrology*, v. 26, pp. 166-171.
- Foster, M. D. (1954) The relation between "illite," beidellite and montmorillonite : in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 327, pp. 386-397.
- Fothergill, C. A. (1955) The cementation of oil reservoir sands and its origin : *4th World Petroleum Congress, Proc.*, Sec. 1/B, pp. 1-13.

- Gilluly, J. (1949) Distribution of mountain building in geologic time: *Geol. Soc. Amer. Bull.*, v. 60, pp. 561-590.
- Glass, H. D. (1951) Clay mineralogy of the Coastal Plain formations of New Jersey: Ph.D. Thesis, Columbia Univ.
- Glass, H. D. (1958) Clay mineralogy of Pennsylvanian sediments in southern Illinois, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 566, pp. 227-241.
- Glass, H. D., Potter, P. E., and Siever, Raymond (1956) Clay mineralogy of some basal Pennsylvanian sandstones, clays and shales: *Amer. Assoc. Petroleum Geol., Bull.*, v. 40, pp. 750-754.
- Gorbunov, N. I. (1956) Patterns in the distribution of clay minerals in the main soil types of U.S.S.R.: *Pochvovedenie (Moscow)*, no. 2, pp. 75-89.
- Greene-Kelly, R., (1955) Dehydration of the montmorillonite minerals: *Min. Mag.*, v. 30, pp. 604-615.
- Griffin, G. M., and Ingram, R. L. (1955) Clay minerals of the Neuse River Estuary: *J. Sedimentary Petrology*, v. 25, pp. 194-200.
- Griffiths, J. C., Bates, T. F., and Shadle, H. W. (1956) Guide to field trip of Fourth National Clay Conference: Clay minerals in sedimentary rocks, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 456, pp. 1-20.
- Griffiths, J. C., Cochran, J. A., Groff, D. W., and Kahn, J. S. (1954) Petrographical investigations of the Salt Wash sediments: *Atomic Energy Commission Progress Report*, 63 pp.
- Grim, R. E. (1936) The Eocene sediments of Mississippi: *Mississippi State Geol. Survey Bull.*, 30, 240 pp.
- Grim, R. E. (1953) *Clay Mineralogy*; McGraw-Hill Book Company, Inc., 384 pp.
- Grim, R. E., and Bradley, W. F. (1955) Structural implications in diagenesis: Sonderdruck aus der *Geologischen Rundschau*, Band 43, pp. 469-474.
- Grim, R. E., Bradley, W. F., and White, W. A. (1957) Petrology of the Paleozoic shales of Illinois: *Illinois Geol. Survey, Rep. of Investigations* 203, 35 pp.
- 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. 1785-1803.
- 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.
- Grim, R. E., and Johns, W. D. (1954a, 1955, 1956) Studies of nearshore Recent sediments and their environments in the northern Gulf of Mexico: *Amer. Petroleum Inst. Research Project 51, Amer. Petroleum Nos.* XV, pp. 29-32; XVIII, pp. 15-21; XIX, pp. 16-18; and XX, pp. 20-22.
- Grim, R. E., Lamar, J. E., and Bradley, W. F. (1937) The clay minerals in Illinois limestones and dolomites: *J. Geol.*, v. 45, pp. 829-843.
- Grim, R. E., and Rowland, R. A. (1942) Differential thermal analyses of clay minerals and other hydrous materials: *Amer. Min.*, v. 27, pp. 746-761, 801-818.
- Gude, A. J. (1950) Clay minerals of Laramie formation, Golden, Colorado, identified by x-ray diffraction: *Amer. Assoc. Petroleum Geol. Bull.*, v. 34, pp. 1699-1717.
- Hooks, W. G., and Ingram, R. L. (1955) The clay minerals and the iron oxide minerals of the Triassic "red beds" of the Durham Basin, North Carolina: *Amer. J. Sci.*, v. 253, pp. 19-25.
- Jonas, E. C. (1958) Clay-size minerals in Ellenburger rocks: *Texas Bureau Econ. Geol. Pub.*, In press.
- Keller, W. D. (1953) Clay minerals in the type section of the Morrison formation: *J. Sedimentary Petrology*, v. 23, pp. 93-105.
- Keller, W. D. (1956) Clay minerals as influenced by environments of their formation: *Amer. Assoc. Petroleum Geol. Bull.*, v. 40, pp. 2689-2710.
- Kelley, W. P., and Liebig, G. F., Jr. (1934) Base exchange in relation to composition of clay with special reference to effect of sea water: *Amer. Assoc. Petroleum Geol., Bull.*, v. 18, pp. 358-367.

- Krynine, P. D. (1940) Petrology and genesis of the Third Bradford sand : *Pennsylvania State Univ. Mineral. Ind. Exp. Station, Bull.* 29, 134 pp.
- Krynine, P. D. (1948) The megascopic study and field classification of sedimentary rocks : *J. Geol.*, v. 56, pp. 130-165.
- Krynine, P. D. (1950) Petrology, stratigraphy, and origin of the Triassic sedimentary rocks of Connecticut : *Conn. Geol. and Nat. History Survey Bull.* 73, 247 pp.
- Krynine, P. D. (1951) A critique of geotectonic elements : *Amer. Geophys. Union Trans.*, v. 32, pp. 743-748.
- Kunze, G. W., Templin, E. H., and Page, J. B. (1955) The clay mineral composition of representative soils from five geological regions of Texas : in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 395, pp. 373-383.
- Lencke, K., von Engelhardt, Wolk, and Fuchthaven, Hans (1953) Geologische und Sedimentpetrographische Untersuchungen im Westteil der ungfalteten Molasse des suddeutschen Alpenvorlandes : *Beihefte Geol. Jahrb.*, v. 11, pp. 56-57.
- Lippmann, Friedrich (1956) Clay minerals from the Röt member of the Triassic near Göttingen, Germany : *J. Sedimentary Petrology*, v. 26, pp. 125-139.
- Merrell, H. W., Jones, D. J.; and Sand, L. B. (1957) Sedimentation features in Paradox shales, southeastern Utah (Abstract) : *Geol. Soc. Amer. Bull.*, v. 68, p 1766.
- Millot, Georges (1949) Relations entre la constitution et la genèse des roches sédimentaires argileuses : *Géol. Appl. et Prospection Minière*, v. 2, *l'Univ. de Nancy*, 352 pp.
- Millot, Georges (1953) Héritage et néoformation dans la sédimentation argileuse : *C. R., Congr. Géol. Intern.*, 19th Session, 1952, Algiers, fascicule 18, pp. 163-17.
- Milne, I. H., and Earley, J. W. (1958) Effect of source and environment on clay minerals : *Amer. Assoc. Petroleum Geol., Bull.*, v. 42, pp. 328-338.
- Murray, H. H. (1954) Genesis of clay minerals in some Pennsylvanian shales of Indiana and Illinois : in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 327, pp. 47-67.
- Murray, H. H., and Harrison, J. L. (1956) Clay mineral composition of Recent sediments from Sigsbee deep : *J. Sedimentary Petrology*, v. 26, pp. 363-368.
- Murray, H. H., and Sayyab, A. S. (1955) Clay mineral studies of some Recent marine sediments off the North Carolina coast, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 395, pp. 430-441.
- Nelson, B. W. (1955) Mineralogy of the Bedford formation and related rocks in northern Ohio : Ph.D. Thesis, Univ. Illinois.
- Pettijohn, F. J. (1957) *Sedimentary Rocks* ; Harper & Brothers, New York, 718 pp.
- Potter, P. E., and Glass, H. D. (1958) Petrology and sedimentation of the Pennsylvanian sediments in southern Illinois : A vertical profile : *Illinois Geol. Survey, Rept. of Investigations* 204, 60 pp.
- 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.
- Powers, M. C. (1957) Adjustment of land derived clays to the marine environment : *J. Sedimentary Petrology*, v. 27, pp. 355-372.
- Powers, M. C. (1958) Adjustment of clays to chemical change and the concept of the equivalence level : *These Proceedings*.
- Quaide, W. L. (1956) Petrography and clay mineralogy of Pliocene sedimentary rocks from the Ventura Basin, California : Ph.D. Thesis, Univ. Calif.
- Reitemeier, R. F. (1951) The chemistry of soil potassium : in *Advances in Agronomy*, Academic Press, v. 3, pp. 113-159.
- Revelle, R. R. (1944) *Marine bottom samples collected in the Pacific Ocean by the "Carnegie" on its seventh cruise* ² Carnegie Inst. of Wash., pub. 556, 182 pp.
- Rivière, André (1953) Sur l'origine des argiles sédimentaires : *Congr. Géol. Intern., Algiers, Comptes Rendu*, 19th Session, fascicule 18, pp. 177-180.
- Rivière, André, and Visse, L. (1954) Origin of the minerals in marine sediments : *Société géologique de France*, v. 4, pp. 467-473.

- Robbins, Carl, and Keller, W. D. (1952) Clay and other non-carbonate minerals in some limestones : *J. Sedimentary Petrology*, v. 22, pp. 146–152.
- Roberson, H. E. (1957) Petrology of the Carrizo and Recklow formations, Leon County, Texas : M.A. Thesis, Univ. of Texas.
- Ross, C. S., and Hendricks, S. B. (1945) Minerals of the montmorillonite group, their origin and relation to soils and clays : U.S. Geol. Survey Prof. Paper 205-B, pp. 23–79.
- Ross, C. S., Miser, H. D., and Stephenson, L. W. (1929) Water-laid volcanic rocks of early Upper Cretaceous age in southwestern Arkansas, southeastern Oklahoma, and northeastern Texas : U.S. Geol. Survey Prof. Paper 154-F, pp. 175–202.
- Schmalz, R. F. (1957) Quantitative x-ray modal analysis of sediments from the Peru-Chile Trench (Abstract) : *Geol. Soc. Amer. Bull.*, v. 68, p. 1793.
- Siever, Raymond (1953) Petrology and sedimentation of upper Chester sandstones : *J. Sedimentary Petrology*, v. 23, pp. 207–219.
- Simons, L. H., and Taggart, M. S., Jr. (1954) Clay mineral content of Gulf Coast outcrop samples, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 327, pp. 104–110.
- Smithson, Frank, and Brown, George (1954) The petrography of dickitic sandstones in North Wales and Northern England : *Geol. Mag.*, v. 91, pp. 177–188.
- Smithson, Frank, and Brown, George (1957) Dickite from sandstones in northern England and North Wales : *Min. Mag.*, v. 31, pp. 381–391.
- Strakhov, N. M. (1953) Diagenesis of sediments and its significance in sedimentary ore formation : *Izvest. Akad. Nauk SSSR Ser. Geol.*, no. 5, pp. 12–49.
- Swineford, Ada (1955) Petrography of upper Permian rocks in south-central Kansas : *Kansas Geol. Survey Bull.* 111, 179 pp.
- Tank, R. W. (1956) Clay mineralogy of Morrison formation, Black Hills area, Wyoming, and South Dakota : *Amer. Assoc. Petroleum Geol., Bull.*, v. 40, pp. 871–878.
- Teodorovich, G. I. (1954) A contribution on the study of petroleum source beds : *Biulleten Moscovskogo Obschestva Ispytatelei Prirody*, v. 29, pp. 59–66.
- Todd, T. W., and Folk, R. L. (1957) Basal Claiborne of Texas, record of Appalachian tectonism during Eocene : *Amer. Assoc. Petroleum Geol., Bull.*, v. 41, pp. 2545–2566.
- Van Andel, Tj., and Postma, H. (1954) Recent sediments of the Gulf of Paria : *Verhandelingen Der Koninklijke Nederlandse Akademie Van Wetenschapper, Afd. Natuurkunde Eerste Reeks, Bull.* 20, no. 5, 245 pp.
- Van Houten, F. B. (1948) Origin of red-banded early Cenozoic deposits in Rocky Mountain region : *Amer. Assoc. Petroleum Geol., Bull.*, v. 32, pp. 2083–2136.
- Van Houten, F. B. (1953) Clay minerals in sedimentary rocks and derived soils : *Amer. J. Sci.*, v. 251, pp. 61–82.
- Waagé, K. M. (1955) Dakota group in northern Front Range foothills, Colorado : U.S. Geol. Survey Prof. Paper 274-B, pp. 15–51.
- Wear, J. I., and White, J. L. (1951) Potassium fixation in clay minerals as related to crystal structure : *Soil Sci.*, v. 77, pp. 1–14.
- Weaver, C. E. (1953a) A lath-shaped non-expanded dioctahedral 2 : 1 clay mineral : *Amer. Min.*, v. 38, pp. 279–289.
- Weaver, C. E. (1953b) Mineralogy and petrology of some Ordovician K-bentonites and related limestones : *Geol. Soc. Amer. Bull.*, v. 64, pp. 921–943.
- Weaver, C. E. (1955) Mineralogy and petrology of the rocks near the Quadrant-Phosphoria boundary in southwest Montana : *J. Sedimentary Petrology*, v. 25, pp. 163–193.
- Weaver, C. E. (1956) The distribution and identification of mixed-layer clays in sedimentary rocks : *Amer. Min.*, v. 41, pp. 202–221.
- Weaver, C. E. (1958a) Geologic interpretation of argillaceous sediments : *Amer. Assoc. Petroleum Geol. Bull.*, v. 42, pp. 254–309.
- Weaver, C. E. (1958b) A discussion on the origin of clay minerals in sedimentary rocks, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 566, pp. 159–173.
- Weaver, C. E. (1958c) The effects and geologic significance of potassium “fixation” by expandable clay minerals derived from muscovite, biotite, chlorite, and volcanic material : *Amer. Min.*, In press.

- Weaver, C. E., Wright, H. D., and Bates, T. F. (1952) An investigation of the mineralogy and petrography of uranium-bearing shales: A.E.C. Progress Report, Contract No. At(30-1)-102, Pennsylvania State Univ., 39 pp.
- Whitehouse, U. G. (1951, 1952) Progress reports for the Amer. Petroleum Inst., Project 51, Texas A. & M. College, Oceanographic Dept.
- Whitehouse, U. G., and Jeffrey, L. M. (1955) Peptization resistance of selected samples of kaolinitic, montmorillonitic, and illitic clay materials, in *Clays and Clay Minerals*, Natl. Acad. Sci.—Natl. Res. Council pub. 395, pp. 260-281.
- Yoder, H. S., and Eugster, H. P. (1955) Synthetic and natural muscovites: *Geochim. et Cosmochim. Acta*, v. 8, pp. 225-280.
- Zaporozhtseva, A. S. (1954) About joint occurrence of glauconite and chamosite in rocks: *Dokl. Akad. Nauk SSSR*, Tom 97, pp. 903-905.