CLAY MINERALOGY OF PENNSYLVANIAN SEDIMENTS IN SOUTHERN ILLINOIS[1]

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ABSTRACT

Controversy over the origin of clay minerals in ancient sediments arises because it is difficult to segregate the factors that cause differences in clay mineral composition. A plan of sampling based on four contrasts was used to evaluate some of these factors. Contrasts studied were: (1) permeability contrasts (sandstone vs. shales); (2) environmental contrasts (cyclic sedimentation); (3) weathering contrasts (outcrop vs. core); (4) source area contrasts (orthoquartzite facies vs. subgraywacke facies).

The resultant data indicate that clay minerals are both allogenic and authigenic. Allogenic clay minerals are the rule when inheritance from the source area dominates either postdepositional or environmental effect; authigenic clay minerals are found where the environment dominates. Rapid sedimentation favors a dominance of allogenic clay minerals, and major depositional environmental effects are required to produce appreciable change. Some of the factors that influence clay mineral composition include source area contribution, the depositional environment, postdepositional effects after burial, permeability, and postdepositional weathering effects.

INTRODUCTION

The disagreement among clay mineralogists concerning the origin of clay minerals in ancient sedimentary rocks arises from the difficulty of evaluating those factors that control clay mineral composition. The contrasting opinions of Millot (1949) and Rivière (1951) regarding the effects of environment and inheritance on clay mineral composition are widely known. Any solution to the controversy must be concerned with both the isolation and evaluation of the factors that cause clay mineral change. The present study attempts such a solution for Pennsylvanian sediments in a restricted area, and is concerned principally with factors of source area composition (inheritance), depositional environment, and postdepositional history.

Along the southern edge of the Eastern Interior coal basin abundant outcrop and subsurface sections make possible a detailed sampling of a vertical profile of Pennsylvanian sediments (Fig. 1). The purpose of this paper is to report the results of an integrated stratigraphic, petrologic, and clay mineral study of some 1800 feet of Pennsylvanian sediments in both outcrop and subsurface.

A previous paper (Glass, Potter, and Siever, 1956) on the clay minerals from outcrop samples of basal Pennsylvanian orthoquartzitic sandstones and their associated clays and shales showed that the sandstones contain relatively

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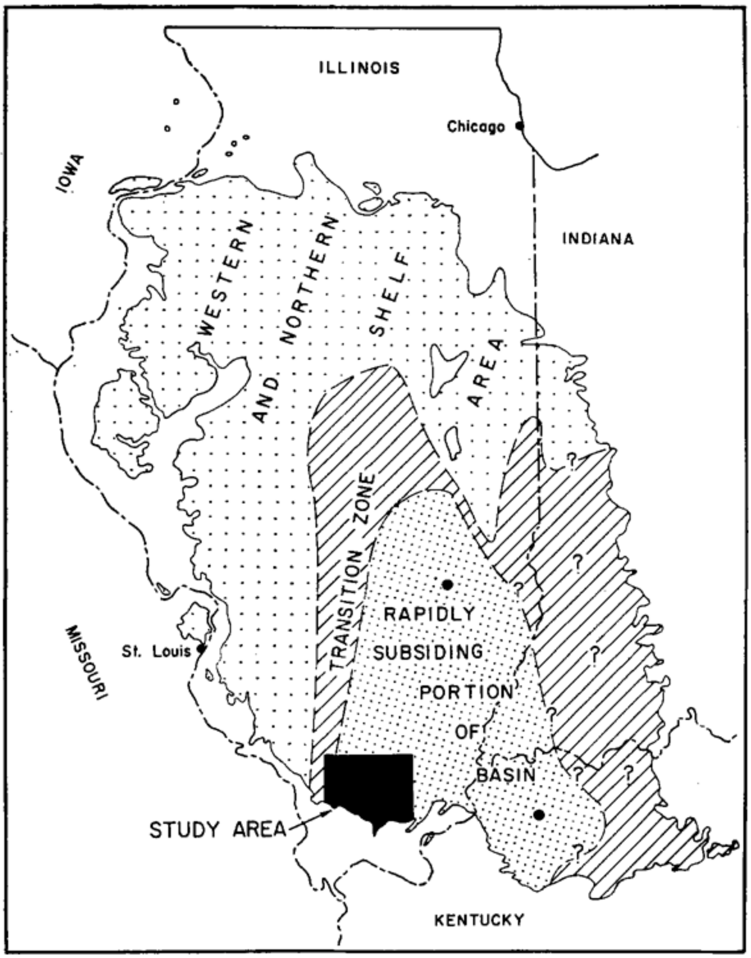

FIGURE 1. —— Index map of the Eastern Interior coal basin showing area studied.

much more kaolinite and less illite than their associated and intimately interbedded shales (Fig. 2). Contrasting postdepositional histories, induced by contrasting permeabilities rather than by either contrasting source area contributions or depositional environments, were considered the cause of the difference. The sampling design used in that study permitted evaluation of sediments with contrasting permeabilities where the factors of source area contribution and exposure in outcrop were identical. In the present paper the clay minerals from outcrop orthoquartzitic sandstones and their associated shales are compared to their subsurface equivalents as well as to outcrop and subsurface samples of younger Pennsylvanian subgraywacke sandstones and their

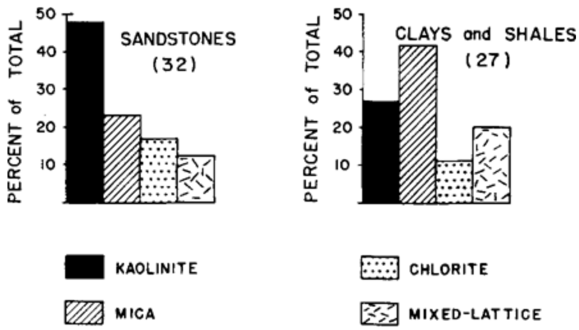

FIGURE 2. — Histograms showing contrasting average clay mineral composition of basal Pennsylvanian outcrop sandstones and of clays and shales.

associated shales. The resultant sampling permitted an evaluation of sediments with contrasting permeabilities where the factors of source area contribution and exposure are different. Incidental to this objective the possible effect of environmental contrasts above and below coal beds of Pennsylvanian cyclical sedimentation was evaluated.

GEOLOGIC SETTING

The Pennsylvanian sediments of the Eastern Interior coal basin are predominantly clastics. The generalized stratigraphic sequence is shown in Figure 3. Petrologically the sandstones of the basal Caseyville group are orthoquartzites (Siever and Potter, 1956, p. 325). With passage of time source area erosion contributed progressively more immature detritus to the coal basin so that above the New Burnside coals subgraywacke rather than orthoquartzitic sandstones accumulated.

The lithologic proportions of the orthoquartzitic and subgraywacke sandstones are distinct. The orthoquartzitic facies is dominantly sandstone and shale. The subgraywacke facies is dominantly shale, sandstone is minor, and coal, black fissile shales, and limestones are present. Although marine fossils rarely can be found in the orthoquartzitic facies, they are common in the subgraywacke facies. In contrast to the lithologic units of the orthoquartzite facies, many of the lithologic units of the subgraywacke facies are traceable over wide areas.

Source area contributions to the two petrographic facies vary. The subgraywacke sandstones have more feldspar, mica, rock fragments, biotite, and chlorite than the orthoquartzites. Although zircon, tourmaline, and rutile are the dominant nonopaque heavy minerals of both facies, the subgraywacke facies also contains garnet and apatite. The most abundant sedimentary structures for both facies are those typical of shallow-water sediments—cross-bedding and ripple marks.

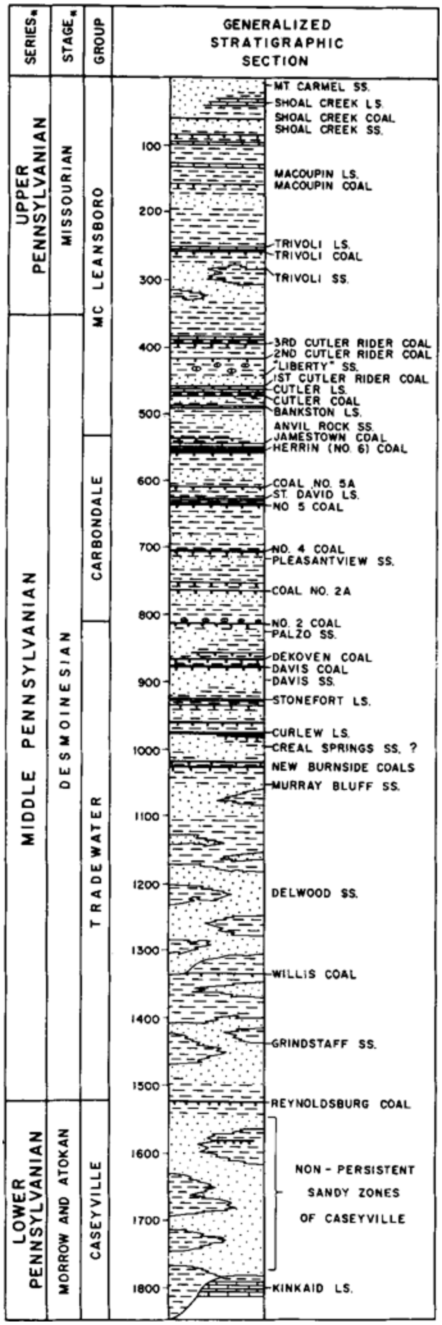

FIGURE 3. — Generalized stratigraphic section. Series and stage taken from Moore and Thompson (1949).

Analytical Procedure

Approximately 160 clay mineral determinations of the clays, shales, and sandstones were made. X-ray analyses of oriented aggregates of the <2-micron fraction were made both before and after ethylene glycol treatment. The abundance of kaolinite, illite, chloritic clay minerals, and mixed-lattice assemblages was determined with a precision of 1 part in 20 when possible. The results were tabulated as averages and expressed as parts in 10 (Table 1). The table evaluates contrasting source area contribution (subgraywacke vs. orthoquartzite), contrasting permeabilities (shale vs. sandstone), contrasting exposure to meteoric agents (outcrop vs. core), and contrasting depositional environments (shales above and below coal beds).

TABLE 1. — AVERAGE CLAY MINERAL COMPOSITIONS CONTRASTING PETROGRAPHIC FACIES, EXPOSURE, AND ENVIRONMENT (PARTS IN TEN)

	Subgraywacke					Orthoquartzite				
	Kaolinite	Illite	Mixed Lattice	Chlorite	Number	Kaolinite	Illite	Mixed Lattice	Chlorite	Number
Outcrop										
Sandstone	4.7	2.9	0.6	1.8	9	5.0	2.5	1.5	1.0	18
Shale in Sandstone	4.0	3.3	2.7	?	5	3.6	3.8	2.2	0.4	16
Shale	1.7	4.8	1.5	2.0	8	1.8	4.6	2.4	1.2	11
Core										
Sandstone	3.5	3.8	0.8	1.9	9	3.4	3.4	2.6	0.6	7
Shale in Sandstone	2.2	4.2	1.5	2.1	3	1.0	5.7	1.8	1.5	3
Shale	1.5	4.6	1.5	2.4	38	1.1	6.1	1.4	1.4	17

RESULTS AND DISCUSSION

Permeability Contrasts (Sandstones vs. Shales)

The differences in clay mineral composition between outcrop sandstones and shales (Table 1) show that both the subgraywacke and the orthoquartzite sandstones contain relatively more kaolinite than do the shales. Clay mineral data as well as thin-section evidence (Glass, Potter, and Siever, 1956, p. 752) suggest that some of the kaolinite is not detrital in origin. Presumably controlled by circulation of meteoric waters, kaolinite formed in the sandstones after exposure. This process may follow a pedological evolution. The same contrast, however, is observed to a lesser degree for core samples. This indicates 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.

The increased relative kaolinite content of the sandstone implies that post-depositional formation of kaolinite occurred; otherwise compositions should remain similar for both sandstones and shales. Growth of the kaolinite crystals in buried sandstone interstices required the presence of solutions of such composition that crystallization from supersaturated solutions eventually occurred. Several factors may have been responsible for such crystallization. It may have been favored by an original acid depositional environment or by postdepositional intrastratal solution. In part this intrastratal solution may have been related to circulation of ground water during periods of low base level. In any case, formation of kaolinite in sand grain interstices need not necessarily cease upon burial, but could proceed more or less continuously during later geologic history whenever the necessary conditions prevail. The high compressibility of the buried muds minimizes the effects of solution in muds after burial.

Exposure in outcrop under renewed influence of percolating meteoric waters causes even greater permeability contrasts as reflected in increased amounts of kaolinite. Exposure augments the process of clay mineral formation and represents another stage in the postdepositional history of the sediment. For permeable sediments we must consider not only source area contributions and possible depositional environment, but also the postdepositional history—changes after burial and changes upon exposure. The effects of permeability may extend also to silty and sandy shales. Therefore, because they are the least permeable, the best estimates of clay mineral composition at the time of deposition are obtained from shales.

Although kaolinite formation was observed in all Pennsylvanian sandstones sampled in this study, it must not be concluded that every sandstone will show similar results. These data pertain only to Pennsylvanian sandstones in the Eastern Interior basin. Although many sandstones in other regions of similar and different geologic ages show the development of authigenic kaolinite, a large number of sandstones of various geologic ages do not contain authigenic kaolinite. Evidently the conditions necessary for kaolinite formation were not present in those sandstones.

Environmental Contrasts

If the composition of the source area contribution is to be obtained from shales, the possible effects of a depositional environment must be isolated. The concept of environmental contrasts in Pennsylvanian cyclic sedimentation is not new (see Weller, 1930). In general, sedimentation from the sandstone upward to the coal bed has been considered as nonmarine, and sedimentation above the coal considered as marine. For the subgraywacke facies with its cyclical sedimentation, comparisons are made easily between shales above and below coal beds where environmental contrasts are most likely to occur. For the orthoquartzite facies where cyclic sedimentation is generally absent, these distinctions cannot be made. For the subgraywacke facies in Table 1, the group designated as shale in sandstone includes shale units beneath coal beds associated with sandstones. The group designated as shale for this facies includes shales distinctly above coal beds and not generally associated with sandstone units. For the orthoquartzite facies, the shale in sandstone group includes thin shale units in massive sandstone bodies, and the shale group includes the thicker shale units.

If weathering effects are ignored for the present and attention focused on core samples, it can be seen (Table 1) that for the subgraywacke facies the shale in sandstone group below coal beds averages slightly higher in kaolinite and less in chlorite than the shale group above coal beds. For the orthoquartzite facies, no essential differences in shale compositions are noted. Because the difference in the subgraywacke facies may not seem significant and the number of samples for the shale in sandstone group too small, detailed data are presented for cyclic sediments in cores to show that these differences are real and consistent.

Trivoli Cycle.—The stratigraphic succession and clay mineral composition for the isolated Trivoli cycle are shown in Figure 4. Above the coal occur black shales, limestone, and dark shales succeeded by gray shale that becomes sandier towards the top of the section. Beneath the coal are the underclay, gray shales, sandstones, and sandstone-shale interlaminations. The base of the section shows the uppermost shale of the underlying cycle.

Sediments from the basal sandstone to the coal (inclusive) are richer in kaolinite than those sediments above the coal. Higher relative amounts of kaolinite were observed in the sandstones. The uppermost sandy shales are slightly richer in kaolinite than the marine shales immediately above the coal. The only obvious mineralogical difference is in kaolinite content. Higher amounts of kaolinite were observed where shales are sandier, or beneath the coal bed where the shales are generally associated with more permeable sediments. With regard to environmental contrast, the so-called nonmarine section is richer in kaolinite than the known marine section.

Cutler Cycles.—Where the stratigraphic succession of cyclic sedimentation becomes more complex, as shown by the Cutler cycles in Figure 5, differences in clay mineral composition are more outstanding. Under depositional conditions that include five coal beds, the differences above and below coal beds may be observed in greater detail than in the isolated Trivoli cycle.

Above the Third Cutler Rider coal the gray shales show consistent composition, kaolinite content decreasing slightly as the coal bed is approached. Chlorite content remains high and no significant variation is noted for mixed-lattice materials. Below the Third Cutler Rider coal kaolinite content increases suddenly and remains fairly constant until the underlying Second Cutler Rider coal is approached, where it again decreases. Accompanying the increase in kaolinite immediately below the Third Cutler Rider coal, the amount of mixed-lattice materials increases sharply, with proportionate decrease in illite and chlorite. This is a common feature of many underclays and the effect is soon lost with distance from the coal bed, chlorite and mixed-lattice materials increasing to more usual proportions. It appears that the acid environment of the coal swamp may have altered the sediments upon which it rested, alteration proceeding in the direction of formation of mixed-lattice materials, and possibly kaolinite, at the expense of illite and chlorite. The underclay represents

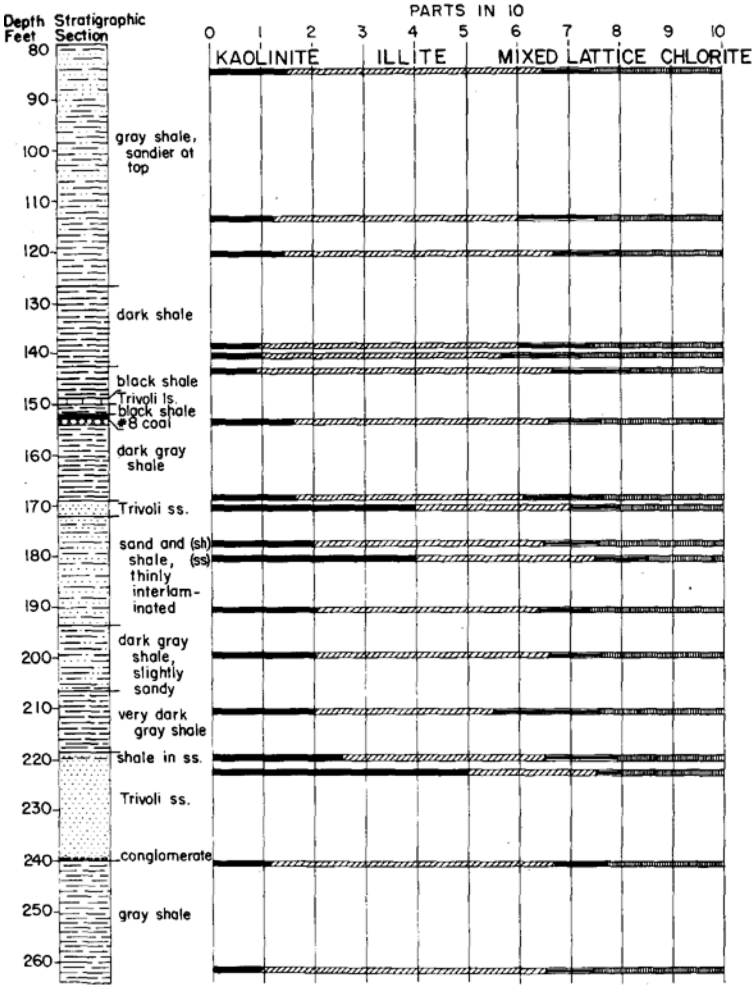

FIGURE 4.—Stratigraphic section and clay mineral analyses for the Trivoli cycle; Madison Coal Co. no. 25, NE¼ NE¼, Sec. 12, T. 8 S., R. 3 E., Williamson Co., Illinois.

the altered host sediments in contact with a coal swamp, and the acid reservoir of the swamp could have effectively altered sediments even after they were buried. The compositional changes in the underclay are similar to those encountered in soil profiles and represent degradations in the solid state. In coal swamps, the changes are caused by the depositional and postdepositional contact effects of the swamp on underlying sediments.

Immediately beneath the Second Cutler Rider coal the effect of the coal swamp is more striking. Kaolinite composition increases sharply, remains high in the permeable sediments, and then decreases as the underlying coal

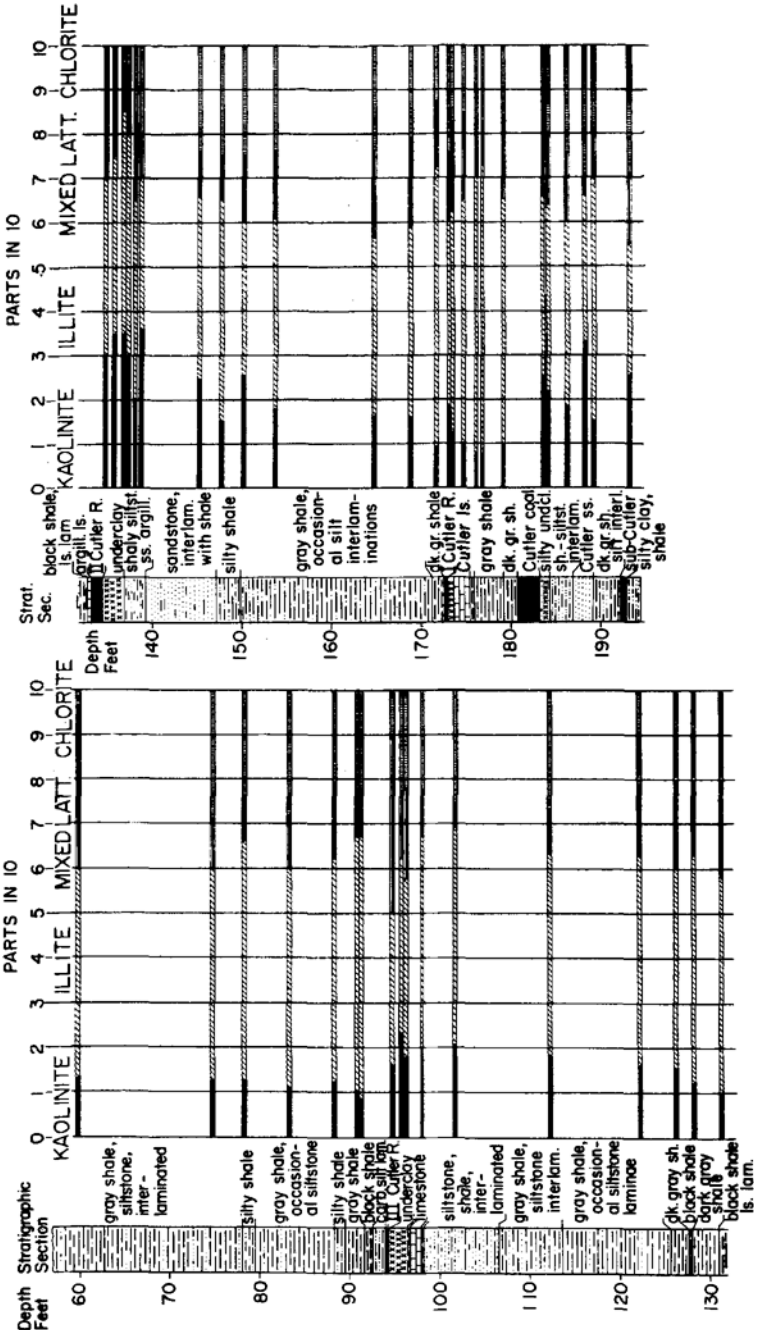

FIGURE 5. — Stratigraphic section and clay mineral analyses for the Cutler cycles; SE¼, Sec. 27, T 8 S., R. 3 E., Williamson Co., Illinois.

beds are approached. Chlorite has been eliminated completely and amount of mixed-lattice materials is high. As the effect of the swamp is reduced with distance, the typical pattern of increasing chlorite and decreasing mixed-lattice materials occurs. This sequence is identical with that observed for the Third Cutler Rider coal except that the intensity of alteration is greater. The factors that affected the degree of alteration are not known.

The First Cutler Rider coal represents a minor interruption in the marine sequence above the Cutler coal. Here the First Cutler Rider coal overlies the marine limestone above the Cutler coal. The effect of the coal is seen as a slight increase in kaolinite in the underclay, the sediments underlying the coal returning to more average marine proportions at shallow depth. In this sequence the effects of the coal bed are limited.

Beneath the Cutler coal kaolinite content again increases, higher relative amounts being observed in the Cutler sandstone. The effects of the coal swamp are not as striking as in the case of the Second Cutler Rider coal. It appears that factors other than thickness of the coal bed are responsible for the degree of alteration. The underclay of the sub-Cutler coal shows increased kaolinite only.

The differences in shale compositions above and below the coal beds cannot be attributed to cyclic changes in source area composition or to weathering. It seems more likely that these differences may best be explained by contrasting depositional environments. The unit of sedimentation from the basal sandstone to the coal bed may have been deposited in a fluviatile or fluviolacustrine environment of "acid aggressive waters" (Millot, 1949) which culminated in the deposition of organic matter that formed the coal. However, two compositional variations are noted for sediments under coal beds. The underclay in contact with the coal is higher in mixed-lattice materials and lower in illite and chlorite than the shales, and the sandstones are higher in kaolinite than the shales. It would appear that these differences represent postdepositional changes, the former caused by proximity to the coal swamp and the latter induced by permeability. Thus the possible effects of the depositional environment need not cease upon burial; the effects of the swamp, and of intrastratal and meteoric solutions in the more permeable members, could continue to work effectively after deposition. For marine environments the effect of the coal swamp would be minor. Source area contributions would remain virtually unaffected except for possible regrading of illite and chlorite. Degradations induced by source area weathering and transport tend to be recovered in marine basins.

In the orthoquartzite facies where cyclic sedimentation is not apparent, no marked compositional differences are observed for core samples in Table 1 between shale (thick units) and shale in sandstone (thin units) except for the suggestion of a slight increase in mixed-lattice materials in thin units. Other core data not included in this study substantiate this observation. Although postdepositional effects seem indicated by the higher kaolinite content of the sandstones, the shales show no changes and probably reflect source area composition.

Thus for both the subgraywacke-facies marine shales and the orthoquartzite-facies fluvio-lacustrine shales there is an illite-kaolinite-chlorite complex of clay minerals. The association probably always will be one of the more difficult to interpret in terms of environment. If the effect of the depositional environment is slight, the same clay mineral composition may be characteristic of a range of both near-shore marine and nonmarine environments. Where the effect of the environment or environmental contrast is great, as for the coal-sandstone hemicycle, differences may occur in shale compositions.

Because of the possible environmental and postdepositional effects on the composition of shale below coal beds, the best evaluation of original source area contribution probably would come from the marine sequence above the coal bed. In noncyclic sedimentation this distinction is not necessary, and shale compositions should be representative of source area contributions. Therefore, interpretations may be erroneous if the possible effects of the depositional environment and postdepositional changes are not eliminated.

Weathering Contrasts (Outcrops vs. Core)

The effects of exposure of permeable sandstones to meteoric waters have been discussed. Other than the increase in kaolinite there is a change in chlorite structures; in core sandstones chlorite is dominant but in outcrop sandstones vermiculite and mixed vermiculite-chlorite are dominant. Only in rare instances is chlorite destroyed in outcrop sandstones.

Four shale groups have been discussed:

Subgraywacke facies: (1) below coal beds (shale in sandstone).

Subgraywacke facies: (2) above coal beds (shale).

Orthoquartzite facies: (3) thin shale units in sandstone (shale in sandstone).

Orthoquartzite facies: (4) thick shale units in sandstone (shale).

In the subgraywacke facies the composition of outcrop shales above and below coal beds shows greater contrasts than do their core equivalents (Table 1). The increased contrast is caused by the additional alteration in outcrop of the shales below coal beds (shale in sandstone). The outcrop shales above coal beds (shale) show no significant differences from their core equivalents. That is, circulation of meteoric waters has caused alteration of shales below coal beds but has not substantially affected those above coal beds.

The direction of alteration is similar to that observed in soils—increased mixed-lattice materials and kaolinite, reduction of illite, and destruction of chlorite. The controlling factor in such an alteration process seems to be the association of shales with permeable sediments below coal beds. Where the association and influence of permeable sediments is lacking, as for the outcrop marine shales (above coal beds), little variation in composition occurs between core and outcrop. The data in Table 1 emphasize the control that permeable sediments exert on clay mineral composition in outcrop. It is interesting that comparable changes are not found in outcrop sandstones. Other than the increase in kaolinite and alteration of chlorite to vermiculite, outcrop sandstones generally show little effect of destruction. Evidently the alteration process for the two lithologies is quite distinct and selective.

For the orthoquartzite facies where large bodies of permeable sandstone are prevalent and could exert an influence on any shale, the thin outcrop shale units (shale in sandstone) show a much greater compositional contrast to their core equivalents than do the thick outcrop shales (shale). Thus we must consider not only association with permeable sediments but also the thickness of the shale unit. For these reasons the degree of alteration of shales for this facies may be highly variable, but it should be kept in mind that thin shale units in permeable outcrop sandstones are more susceptible to alteration than thick units.

For the four shale groups considered, only one of them—subgraywacke-facies shales above coal beds—shows no essential compositional differences between core and outcrop. All others are associated with sand bodies and may show differences from their core equivalents. For orthoquartzite outcrop samples extreme variations in composition are encountered from intensely altered shales to those that show little variation in composition from their core equivalents. Hence in outcrop there may exist a selectivity of alteration controlled by factors other than permeability or thickness. Mineralogical changes that occur in soils may also occur in ancient sedimentary rocks.

Stonefort Cycle.—The Stonefort Cycle (Fig. 6) shows the effects of weathering on cyclic sedimentation. The cycle is only 26 feet thick from the base of the upper sandstone to the base of the lower sandstone. The Davis sandstone at the top of the section represents the basal unit of the overlying cycle and the lowermost shale may be included in the underlying cycle. Between the two sandstones the section shows a fairly typical range of lithologies.

When the additional effects of weathering are imposed on a cyclic section, mineralogical contrasts reach their highest development. The upper Davis sandstone shows high development of kaolinite and contains vermiculite-chlorite. However, a small clay lens within the large sand body shows a selective alteration evidently controlled by permeability. Chlorite has been destroyed completely and kaolinite has increased in proportion over that found in the sandstone.

The dark shales beneath the Davis sandstone are low in kaolinite and are similar in composition to their core equivalents. However, the shale in contact with the Davis sandstone shows increased amounts of mixed-lattice materials and a decrease in illite and chlorite. Downward from the contact, illite and chlorite increase and mixed-lattice materials decrease. This sequence is similar to that observed for the effects of the coal swamp on underlying sediments. It appears that in this case the high permeability of the overlying sandstone may have permitted circulating meteoric waters to alter the contact shales but to a lesser degree than they altered the clay lens in the sandstone. Alteration has progressed to intermediate stages and has not reached the kaolinite stage. Away from the contact the effects are soon lost and more typical compositions occur.

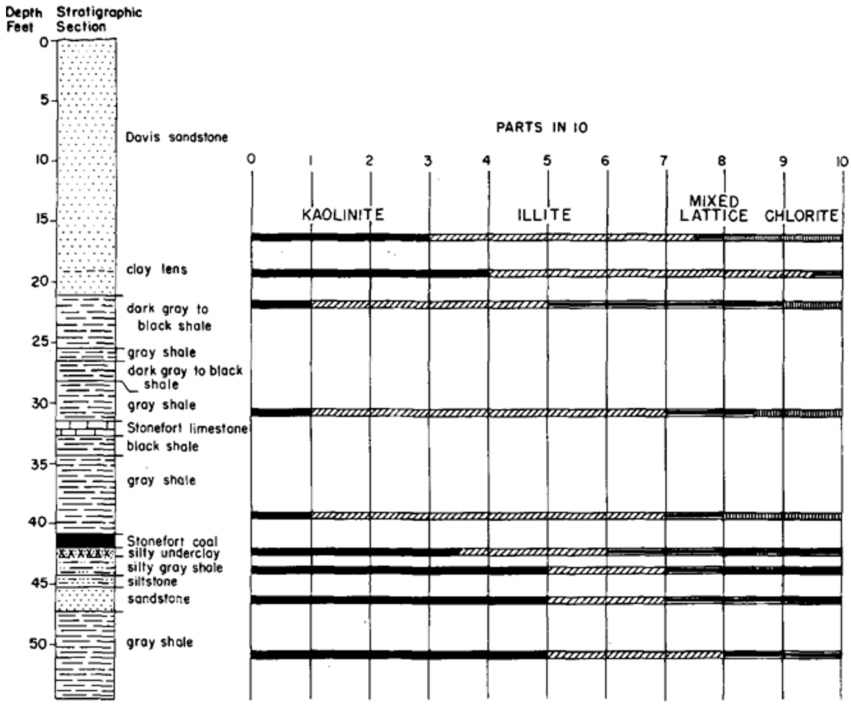

FIGURE 6. — Stratigraphic section and clay mineral analyses for the Stonefort cycle; NE¼ NW¼ NE¼, Sec. 30, T. 10 S., R. 4 E., Saline Co., Illinois.

Beneath the coal bed, alteration has been excessive. Kaolinite comprises about half the clay mineral composition, chlorite has been eliminated, and content of mixed-lattice materials is high. Here again the association with permeable sediments has accelerated clay mineral alteration. The basal shale member also has been altered. If this shale actually is included in the underlying cycle, the effects of overlying permeable sediments and intense drainage conditions at the base of the outcrop may have contributed to an effective alteration of the shale.

It seems unlikely that such drastic mineral contrasts in a small depositional thickness of sediments could be explained by changes in source area composition. More feasible is the concept that clay particles from a homogeneous source area underwent continual change during the depositional and postdepositional history of the sediment. This history for cyclic sediments includes not only the possible effects of the environment of deposition and postdepositional changes induced by permeability and proximity to the coal swamp, but also subsequent alteration in outcrop.

The clay mineral compositions of outcrop shales are not the best indicators of original source area composition as they may have undergone alteration since deposition and exposure. It is thus obvious that the most reliable data must come from core shales. In noncyclic sedimentation almost any shale composition is typical, but for cyclic sediments containing coal beds only the shales above coal beds should be used. The groups listed in Table 1 as core shales therefore will be used for evaluation of source area contrasts.

Source Area Contrasts (Orthoquartzite vs. Subgraywacke)

Averages for core shale compositions (Table 1) for the two facies are consistent. Subgraywacke shales are higher in chlorite and somewhat higher in kaolinite than the orthoquartzite shales. The latter are significantly higher in illite. As it is known that their respective sandstones show differences in maturity (source area contribution), and that the effects of diagenesis for these shales are probably minimized, the difference in composition must be a reflection of the different source area contribution. The subgraywacke shales contain a larger proportion of *known* marine sediments than do the orthoquartzite facies, and any diagenetic change towards illite formation in a marine environment should show increase in illite and decrease in kaolinite. However, the results indicate a higher illite and lower kaolinite composition for sediments of more probable nonmarine origin. The compositional differences, therefore, are not in the direction of illite formation by diagenesis. Differences in source area composition alone can account for the change.

If the uppermost Mississippian Chester shales (Kinkaid) are compared with the Pennsylvanian the following differences are noted (parts in ten):

		Kaolinite	*Illite*	*Mixed Lattice*	*Chlorite*
Pennsylvanian					
Subgraywacke facies	(38)	1½	4½	1½	2½
Orthoquartzite facies	(17)	1	6	1½	1½
Mississippian					
Chester (Kincaid)	(12)	–	7	1½	1½

Chester sandstones show even more mature characteristics than do the Pennsylvanian orthoquartzite facies. These sediments thus show a correlation between clay mineral composition and maturity of the associated sandstones. That is, illite decreases and kaolinite and chlorite increase where they are associated with less mature sandstones.

SUMMARY

Clay mineral compositions of Pennsylvanian sediments in the Eastern Interior basin show variability controlled by the factors of source area composition, environment, permeability, and exposure. The clay mineral composition of a sediment reflects not only the original contribution from the source area, but also changes that may have been induced by the depositional environment, postdepositional changes after burial, and postdepositional changes after exposure in outcrop. Permeability is an important influence in postdepositional changes.

Clay minerals are both allogenic and authigenic. Allogenic clay minerals are found when inheritance is dominant over either postdepositional or environmental effects; authigenic clay minerals are found when the environment is dominant. Rapid sedimentation favors a dominance of allogenic clay minerals, and major depositional environmental effects are required to produce appreciable change.

The illite-kaolinite-chlorite association of clay minerals, where the effect of the depositional environment is slight, may show the same clay mineral composition for a range of both near-shore marine and nonmarine environments.

I believe that the basic philosophy of this study is more important than any of the foregoing specific conclusions. When clay mineral studies are closely integrated with other features of a sedimentary sequence, such as lithology, sedimentary structures, sedimentary petrology, and paleontology, it is possible to isolate some of the variables that affect clay mineral composition. Such integrated studies of ancient sediments will permit us to evaluate not only the factors of source area and depositional environment, but also those of postdepositional diagenesis. Integrated studies of ancient sediments thus may contribute as much or more to the geologic interpretation of clay minerals as the study of clay minerals in modern sediments.

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