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CLAY MINERALOGY IN RELATION TO DELTAIC SEDIMENTATION PATTERNS OF DESMOINESIAN CYCLOTHEMS IN IOWA–MISSOURI

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Abstract—Almost four decades of study of Desmoinesian strata of Middle Pennsylvanian age in south-central Iowa and north-central Missouri have provided the stratigraphic control required to test the variation of clay mineralogy vertically and laterally within various paralic clay and shale facies. Local and regional variations in clay mineralogy within Desmoinesian strata are generally predictable and are in agreement with current knowledge of deltaic deposition. A principal environmental variation within a deltaic system is the change from normal marine salinities in deltaic marine environments to brackish- and fresh-water conditions in the marshy delta plains, in upper interdistributary bays, and within flanking interdeltaic embayments. Changes from marine to nonmarine facies coincide with a decrease in illite, and an increase in kaolin, mixed-layer clays, and in the percentage of expansible layers in the mixed-layer clay. The principal clay detritus entering the area was illite, which underwent various degrees of alteration in different aqueous and subaerial environments within deltaic and interdeltaic areas. Clay-mineral composition alone does not provide unique environmental answers. The distribution of clay-mineral suites within these systems, however, both supports the deltaic–interdeltaic depositional model and can be understood within the context of this framework.

INTRODUCTION

Depositional environments in which Pennsylvanian cyclic sequences were deposited have long intrigued stratigraphers and sedimentologists. Early workers developed nomenclature and classification systems for describing and correlating these widespread deposits. The environmental studies of these sequences have included many techniques and approaches. Among these are regional facies mapping, geometry and sedimentary structures of sandstone facies, and paleoecologic and petrologic analyses of clay and shale facies. By using information from modern depositional systems, further advances have been made toward understanding the formation of coal-bearing paralic rocks.

The mineralogy of shale and clay facies is important in developing a complete paleoenvironmental picture of coal-bearing, cyclic rocks. Fine-grained clastics are volumetrically the most abundant component within most coal-bearing sequences. When considered with other sedimentary data and stratigraphic relationships, the mineralogy of fine-grained clastics provides important additional documentation of the nature of ancient sedimentary environments.

* Deceased.

Almost four decades of study of Desmoinesian strata (Middle Pennsylvanian) in south-central Iowa and north-central Missouri have provided the stratigraphic control required to test the variation of clay mineralogy vertically and laterally within various paralic clay and shale facies. The data are presented here and conclusions are developed within the framework of a deltaic–interdeltaic depositional model.

REGIONAL DEPOSITIONAL SETTING

Throughout the Midcontinent region, the Pennsylvanian System consists of marine and nonmarine strata that alternate repeatedly and in a cyclic manner. Beginning about 1960, workers started to interpret the genesis of various members of the Carboniferous cyclothem in light of the growing volume of research on modern depositional environments and facies. Numerous Carboniferous rock types similar to those defined in western Illinois by Weller (1930) have been interpreted elsewhere to represent deposition in specific deltaic environments (Wanless, 1964, 1969; Wanless and others, 1963, 1969, 1970; D. Moore, 1959; Brown, 1969).

The development of the ideal delta sequence of deposition includes, upward, (1) progradation, (2) aggradation, (3) subsidence and destruction, and (4) marine transgression. Coincident with these deltaic phases are equally important contemporaneous depositional episodes within flanking embayments (Figure 1). Figure 2 shows the relationship between the traditional cyclothemic sequence and deltaic–interdeltaic sequences. Where traditional cyclothems were presumed to begin with a real or inferred unconformity at the base of the sandstone unit, delta cycles begin with deposition of the prodelta facies, which commonly overlies nondeltaic marine sediments (limestones or marine shales). Interdeltaic cycles begin with sparsely fossiliferous, commonly intertidal mudstones and siltstones, laterally equivalent to adjacent prodelta sources. Significant erosion within a cycle occurs chiefly at the base of channels (Laury, 1968): most sandstones (delta-front sheets) are gradational with underlying prodelta siltstones and shales.

Not all Carboniferous cyclic deposits are the same, and the ideal vertical sequence is rarely complete. On extensive shelf areas, such as Kansas, limestones within cyclothems are common. The Midcontinent region stretching southwestward to North Texas is typified by varying amounts of limestones. Nearer to source areas of clastic sediments or to major river systems, such as in Illinois, Iowa, southern Oklahoma, and North Texas, limestones may be thin and less significant. Regional tectonics, source areas, and major drainage systems, therefore, had much to do with the regional character of Pennsylvanian cyclic sequences. Locally, however, it was the specific nature of the delta system with its myriad processes and shifting, short-lived environments that ultimately determined the precise vertical sequence in each area and at each specific locality.

STRATIGRAPHIC FRAMEWORK AND LOCAL DEPOSITIONAL SETTING

Stratigraphic control for this investigation (Figures 3, 4) is based on work by many early geologists. Principal control was provided by reports and unpublished notes of the late Professor L. M. Cline from studies for the Iowa Geological Survey (1933–1941). Similar sequences in Missouri were studied by Greene

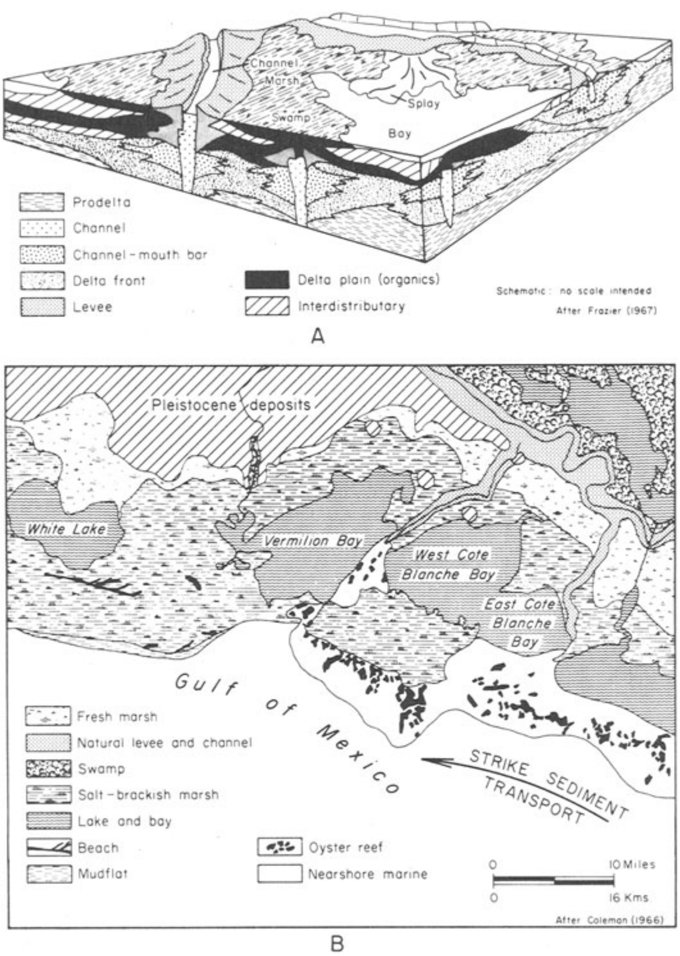

Figure 1. Distribution of Mississippi deltaic–interdeltaic facies. A. Schematic facies relationship within typical Holocene lobe of the Mississippi delta, after Frazier (1967). B. Facies within the southeastern Louisiana delta-flank and interdeltaic embayments, after Coleman (1966).

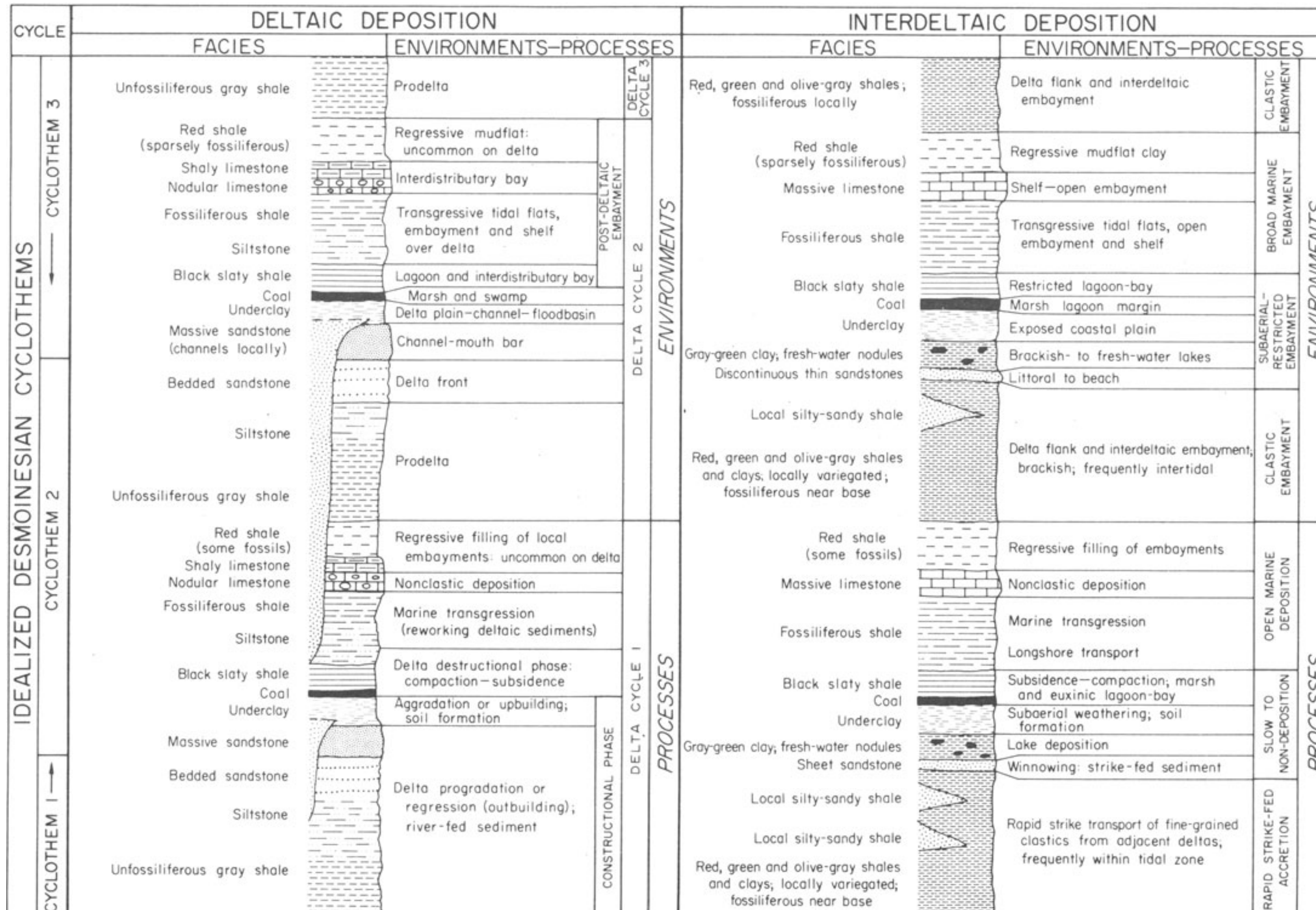

Figure 2. Inferred facies and depositional processes within contemporaneous Desmoinesian deltaic–interdeltaic systems, northern Missouri –southern Iowa.

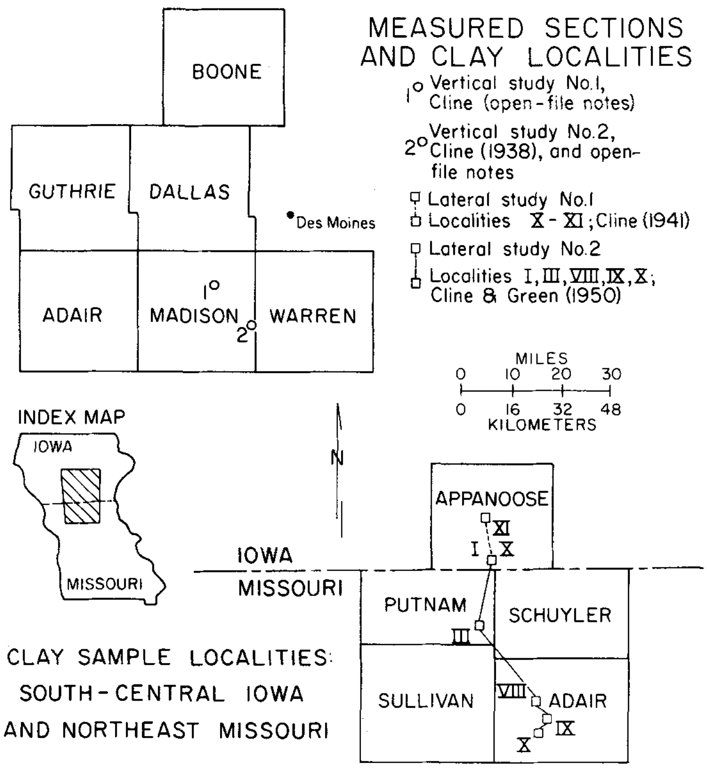

Figure 3. Index map of measured sections and clay-sample locations, southcentral Iowa and northeastern Missouri.

(1914), and in Kansas by R. C. Moore (1936) and Jewett (1941, 1945). Cooperative studies (Weller and others, 1942; R. C. Moore, 1948) involving the Iowa, Missouri, Kansas, and Illinois Geological Surveys resulted in general consensus on regional correlation.

The general depositional nature of Desmoinesian cyclic sequences in southern Iowa and northern Missouri has been interpreted here using criteria and inferred depositional models developed for modern analogues. An idealized composite of the Desmoinesian deltaic sequences in southern Iowa and northern Missouri (Figure 2) illustrates distinctive facies that occur in a more or less predictable sequence.

Fluvial-deltaic deposition occurred mainly in the Illinois basin during Desmoinesian time (Wanless, 1969, Figure 12; Wanless and others, 1969, Figures 9, 10), but minor deltaic systems did build into the nearby Forest City Basin of Iowa and Missouri (Figure 5). A significant period of delta progradation in southern Iowa and northern Missouri resulted in deposition of the Pleasantview Sandstone and associated facies of the Desmoinesian Cherokee Group (Wanless, 1969; Wanless and others, 1969, Figure 10; Laury, 1968, Figure 13). Within the Desmoinesian Marmaton (Appanoose) Group, the fluvial-deltaic Vermillionville Sandstone (locally called Flint Hills in Iowa and Missouri) commonly occurs between the Houx and Higginsville Limestones. Localized fluvial-deltaic sandstones are found between the Myrick Station and Coal City Limestones in west-central Iowa and in north-central Missouri, and thick sandstones occur between the Worland and Cooper Creek Limestones in west-central Iowa (Cline and Greene, 1950; Cline, 1941, and unpublished data; Stookey, unpublished data; R. C. Moore, 1948). Extensive fluvial-deltaic facies are found between the Exline and Hertha Limestones within the overlying Kansas City Group of the Missourian Series in northern Missouri (Figure 6). Generalized stratigraphic cross-sections (Figures 6, 7, 8) show that fluvial-deltaic sandstones occur within each cyclothem somewhere in the southern Iowa–northern Missouri region. Fluvial-deltaic progradation apparently shifted geographically in vertically successive cyclothems, although some multistory sands are recognized, such as in west-central Iowa (Figure 6).

A traverse along the outcrop of any single Desmoinesian cyclothem demonstrates that areas of significant sandstone facies alternate with areas that are composed predominantly of fine-grained, fossiliferous clastics, some coals, and thin limestones. These sequences are interpreted to represent deltaic facies grading laterally into equivalent delta-flank and inter-deltaic-embayment deposits derived from deltaic distributaries (Figure 5).

Limestones commonly transgressed deltaic plains and embayments in Iowa and northern Missouri, since the deltaic deposition, minor in contrast to the Illinois basin, did not prevent the development of shelf limestone environments.

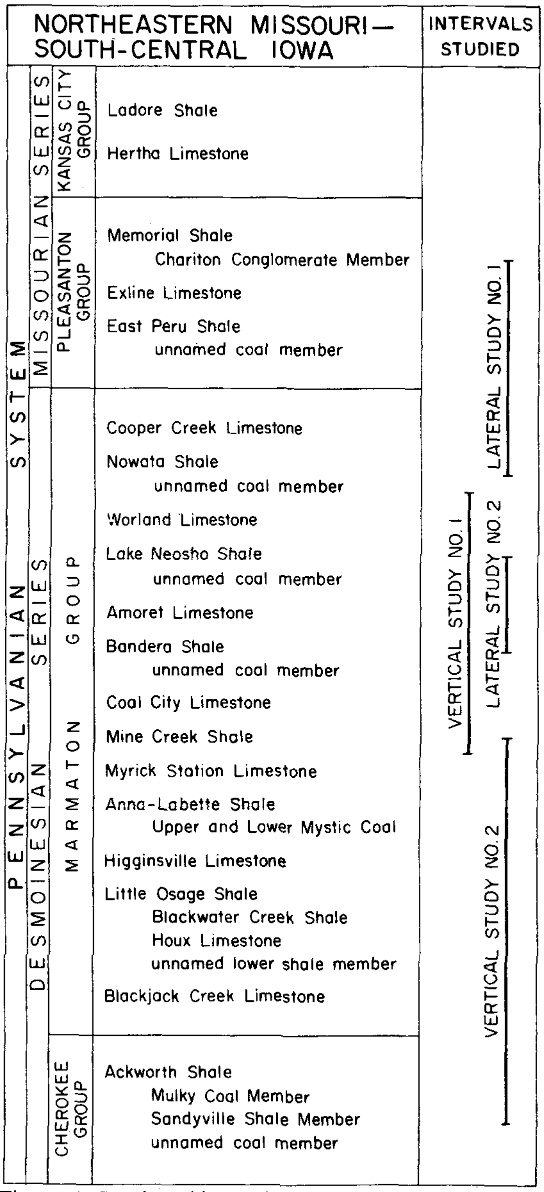

Figure 4. Stratigraphic section, south-central Iowa and northeastern Missouri.

CLAY MINERAL SUITES

Figure 3 shows the location of the measured sections of the cyclothems from which the clay samples were obtained. A simple suite of clay minerals is present within all of the shales and clays studied. Illite and a mixed-layer illite–montmorillonite clay are present in every sample and are the two dominant components. Because the illite could be identified consistently as the high-temperature $2M_1$ muscovite polytype, characteristic of muscovite in igneous and metamorphic rocks, it is considered to be of detrital origin in these rocks. Proof of the detrital nature of the illite in these samples was obtained by K–Ar age determination (Bailey and others, 1962). Kaolinite and dioctahedral vermiculite are present in most, but not all, of the samples. Dioctahedral vermiculite is always a minor component, but kaolinite locally is of importance. No chlorite or discrete montmorillonite were detected in any of the samples. The study includes two vertical sequences and two lateral sequences. Laboratory techniques for preparation and analysis of the clay mineral suites are described in the appendix.

Vertical Study No. 1

Vertical Study No. 1 (Figures 6, 9) includes in ascending order the Amoret cyclothem and the Worland cyclothem. The 35-ft composite section was measured by L. M. Cline (unpublished Madison County stratigraphic sections, pp. 44–51, open-file, Univ. Wisconsin–Madison). The measured section, which extends from below the Coal City Limestone upward to the top of the Worland Limestone, Marmaton Group (Figure 4), was selected because of the highly variable nature of the clay and shale facies, which range from plant-bearing underclays to fossiliferous marine shales. Seventeen samples of shales and clays were analyzed from a vertical sequence through the two incomplete cyclothems. The most significant variations shown by the clay-mineral analyses (Figure 9) are summarized below:

1. There is a marked increase in illite content and

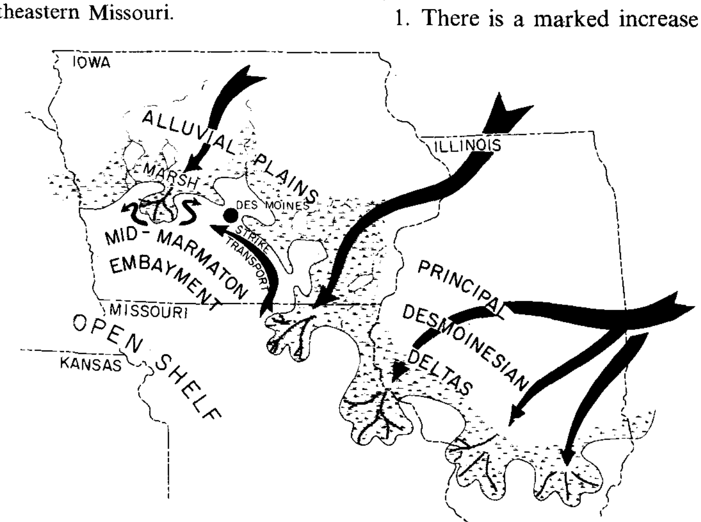

Figure 5. Schematic map of mid-Marmaton (Desmoinesian) depositional systems, northern Missouri–southern Iowa (in part after Wanless, 1964, 1969; Wanless and others, 1970; Laury, 1968).

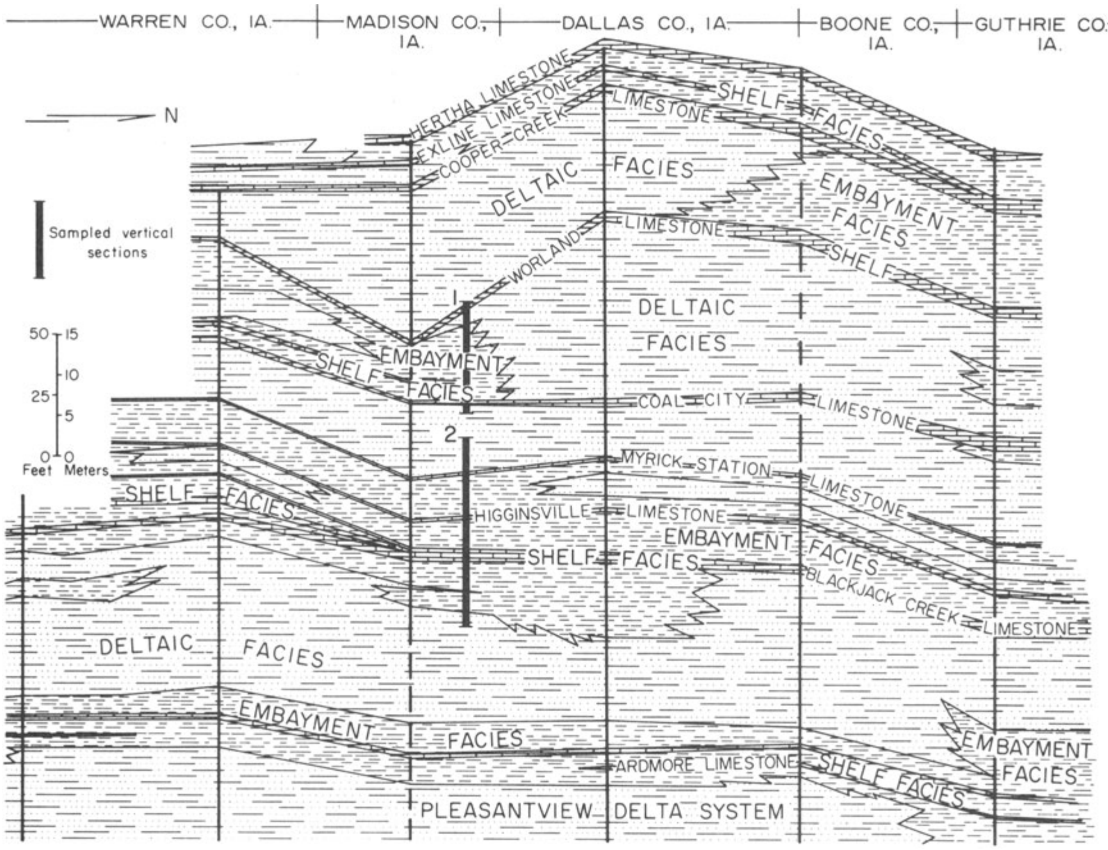

Figure 6. Regional facies relationships, paleostrike section, Marmaton Group, Desmoinesian Series, central Iowa. After Cline and Stookey (unpublished).

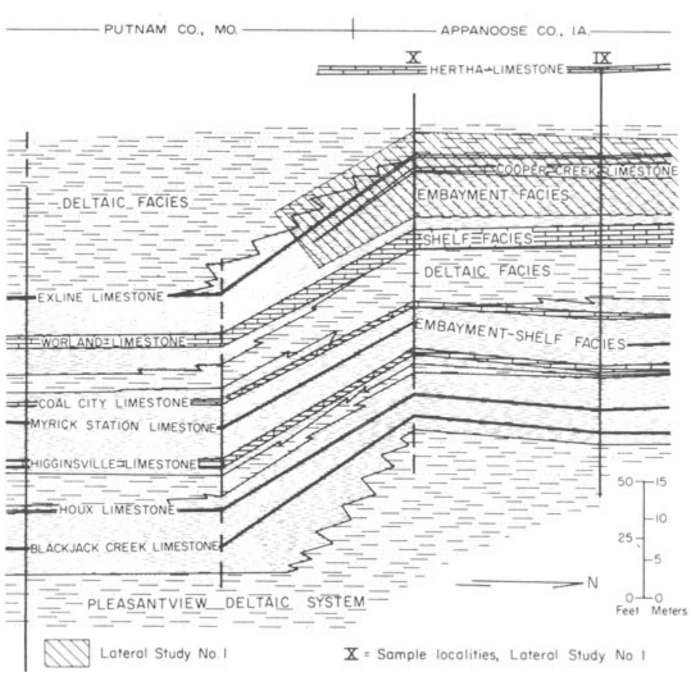

Figure 7. Regional facies relationships, paleostrike section, Marmaton Group, Desmoinesian Series, northern Missouri–southern Iowa. After Cline and Stookey (unpublished).

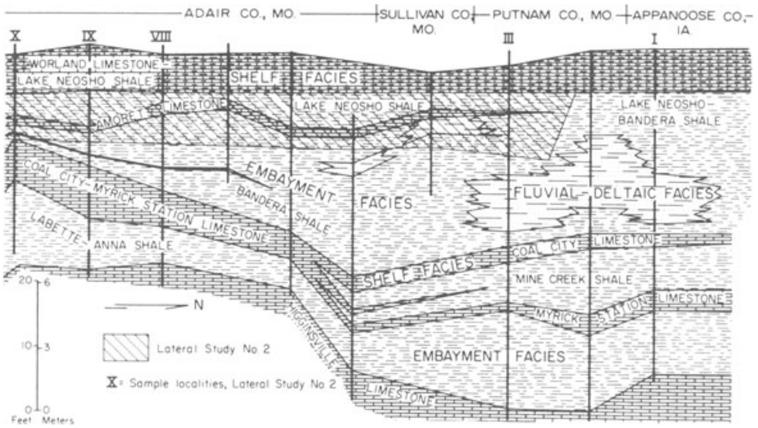

Figure 8. Regional facies relationships, paleostrike section, upper part of the Marmaton Group, Desmoinesian Series, northern Missouri–southern Iowa. After Cline and Greene (1950).

a corresponding decrease in mixed-layer illite–montmorillonite content going from the nonmarine section below the coal to the marine section above the coal. This change is observed in both clay fractions for the Worland cycle, but only in the coarse clay fraction for the Amoret cycle.

2. The percentage of expansible layers within the mixed-layer component decreases in the marine section relative to the nonmarine section.

3. Mixed-layer clay is especially abundant just below and above the coal seams.

4. In the Worland Cyclothem, kaolinite increases in the marine section in both clay fractions, perhaps due to the location of this section in proximity to the shore line.

5. Illite, kaolinite, and dioctahedral vermiculite are more abundant in the coarse clay fraction, and the mixed-layer clay is more abundant in the medium-to-fine clay fraction.

Vertical Study No. 2

Clays for Vertical Study No. 2 are from a vertical sequence through two cyclothems, Blackjack Creek and Myrick Station (Figures 6, 10). The 35-ft section was measured by Cline (1938; and unpublished Madison Co. stratigraphic sections, pp. 150–154, open-file, Univ. Wisconsin–Madison). The section extends from below the Mulky Coal, Cherokee Group, upward to the Myrick Station Limestone, Marmaton Group (Figure 4) and is composed of a variety of fossiliferous and unfossiliferous clay and shale facies, interbedded coals, and marine limestones. Four samples above and below the coals were analyzed for each cycle. The results of the clay mineral analyses (Figure 10) are summarized below:

1. Illite increases within both cycles in proceeding from a fresh-water environment to a marine environment. This change is observed in both clay fractions.

2. In the Blackjack Creek cyclothem, the mixed-layer illite–montmorillonite component decreases as illite increases in the marine section. In the Myrick Station cyclothem, kaolinite and dioctahedral vermiculite decrease as illite becomes more abundant.

3. The number of expansible layers within the mixed-layer component decreases from 30% in the nonmarine section to a minimum of 20% in the marine section.

4. Mixed-layer clay and dioctahedral vermiculite are especially abundant just below the coal in both cyclothems.

5. There is very little kaolinite in the Blackjack Creek cyclothems, but significant amounts in the Myrick Station cyclothem.

Lateral Study No. 1

For Lateral Study No. 1 (Figures 7, 11) clays from the Cooper Creek cyclothem and the overlying Exline cyclothem were collected from two different sections measured by Cline (1941). In central and northern Appanoose County, Iowa (Figure 7), the Cooper Creek Limestone forms a prominent ledge nearly 4 ft thick in places. It is nodular and contains fragmental algae within a finely crystalline matrix. At Locality XI in Appanoose County, Iowa, the Cooper Creek Limestone is the top bed of an incomplete cyclothem (Figure 11), which consists of a thick red and green clay and shale interval, followed by a coal streak, a shale containing abundant calcareous nodules of fusulinids, and the massive limestone on top. It is followed above by another incomplete cyclothem consisting of a plastic underclay, a coal smut, and the massive, fine-grained Exline Limestone. Three samples from clays and shales above and below the Cooper Creek Limestone were analyzed.

The Cooper Creek Limestone thins to the south (Figure 7) near the Iowa–Missouri border. At Locality X in Appanoose County, Iowa, it is recognizable only as admixed nodules of fragmental algae within a green clay. The green clay matrix was sampled at this locality, as well as one clay from the unfossiliferous green and red shale below this zone and a clay and a shale from the Exline cyclothem above. The results

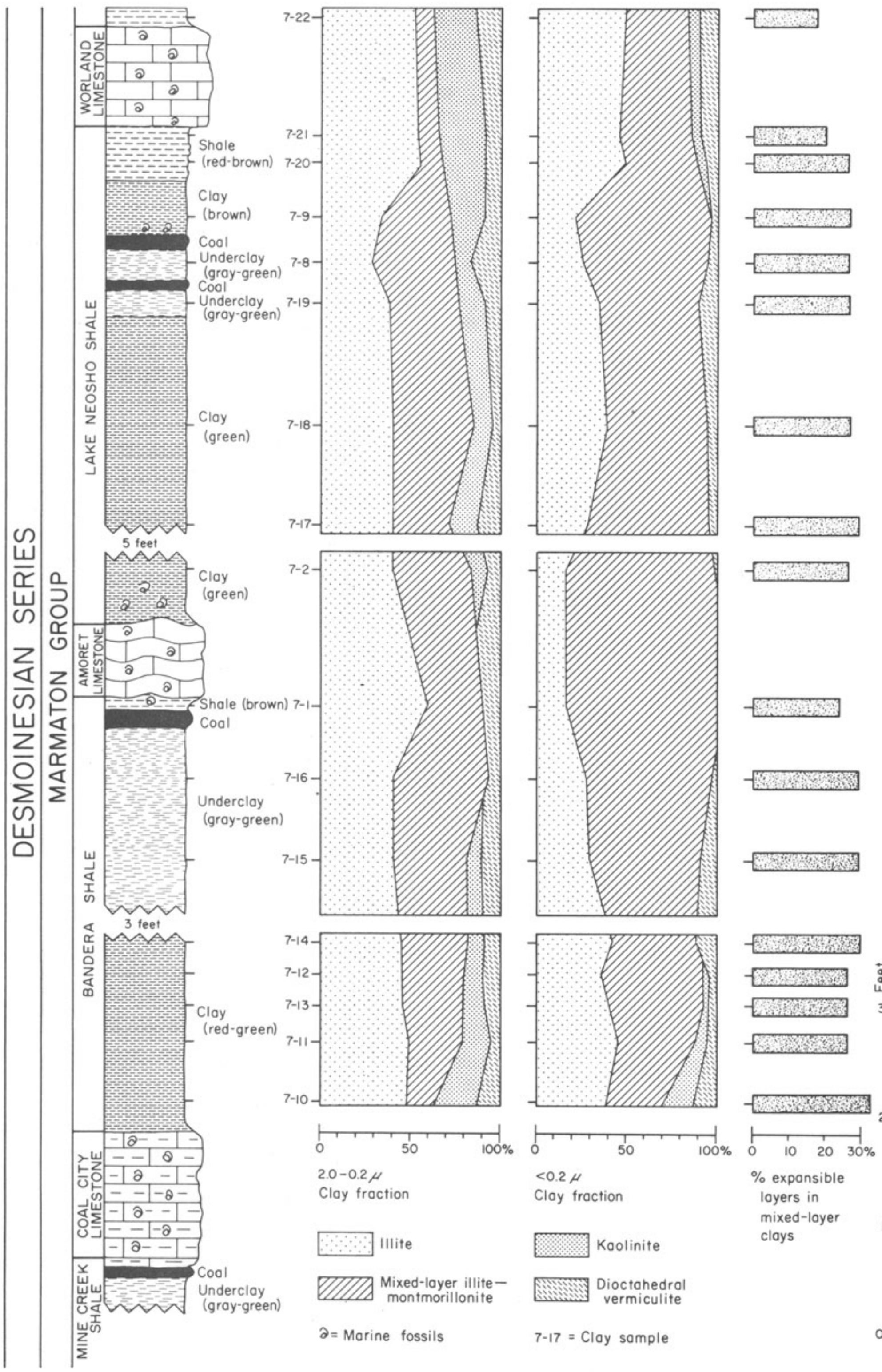

Figure 9. Vertical study no. 1 (Madison County, Iowa) showing stratigraphic sequence and clay-mineral composition.

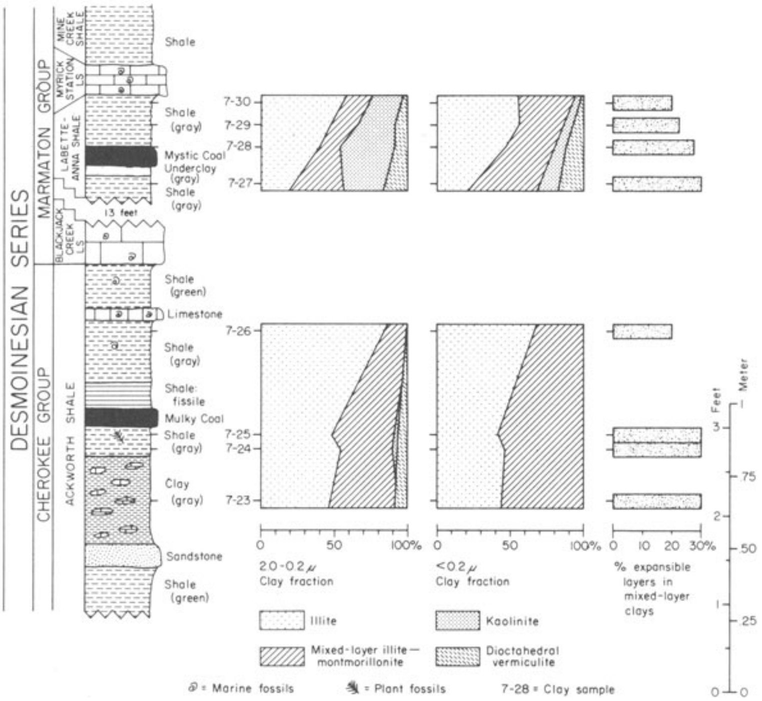

Figure 10. Vertical study no. 2 (Madison County, Iowa) showing stratigraphic sequence and clay-mineral composition.

of the clay-mineral analyses (Figure 11) are listed below:

1. At Locality XI below the massive Cooper Creek Limestone, the clay sample below the coal streak has a low illite and high mixed-layer illite–montmorillonite content. In the shale above the coal, there is a high illite and low mixed-layer clay assemblage. These compositions, therefore, are exactly like those in the nonmarine and marine phases, respectively, of the cyclothems analyzed in the two vertical studies. The underclay below the coal smut associated with the Exline Limestone follows the same pattern, in that it has a low illite and high mixed-layer clay composition.

2. At Locality X, where the Cooper Creek Limestone is wedging out, the green-clay matrix of the algal-limestone nodules contains very little illite and about equal amounts of mixed-layer clay and kaolinite. Nearly identical clay contents are present in the clay below this zone and in the underclay of the Exline cycle above. These clay contents, therefore, are similar to those of the nonmarine phases of the cycles studied previously, but are distinguished by having high kaolinite contents. The shale above the coal in the Exline cycle, however, contains the typical marine clay assemblage.

3. No consistent change was observed along the lateral traverse in the percentage of expansible layers within the mixed-layer component. The observed range was from 25 to 30% expansible layers.

4. Dioctahedral vermiculite is present in most samples, and is especially abundant in the green clay matrix of Locality X.

Lateral Study No. 2

Clay samples within the Amoret Limestone as well as in the overlying Lake Neosho Shale and the underlying Bandera Shale were analyzed from five localities along the northward pinchout of the Amoret Limestone (Cline and Green, 1950). In central Adair County, Missouri, the Amoret is a massive, medium-grained, one-foot-thick limestone. Traversing north through Putnam County, Missouri, to Appanoose County, Iowa, the limestone (Figures 8, 12) first becomes nodular and algal in nature, then develops a clay matrix that gradually increases at the expense of the limestone nodules. In Putnam and Appanoose Counties, the zone of limestone pellets is very thin and appears to merge with the overlying Worland underclay.

The stratigraphic sections and clay-mineral results are illustrated in Figure 12; major results are outlined below:

1. At Localities IX and X in south-central Adair County, the clay minerals present are those of a typical marine assemblage: high illite and low mixed-layer components plus traces of kaolinite and dioctahedral vermiculite.

2. At Locality VIII in central Adair County, the clay matrix of the nodular limestone first appears. It is characterized by slightly less illite, more kaolinite, and more dioctahedral vermiculite. The clay above has more mixed-layer component. These clay assemblages appear transitional between those found typical of marine and nonmarine environments in the vertical studies.

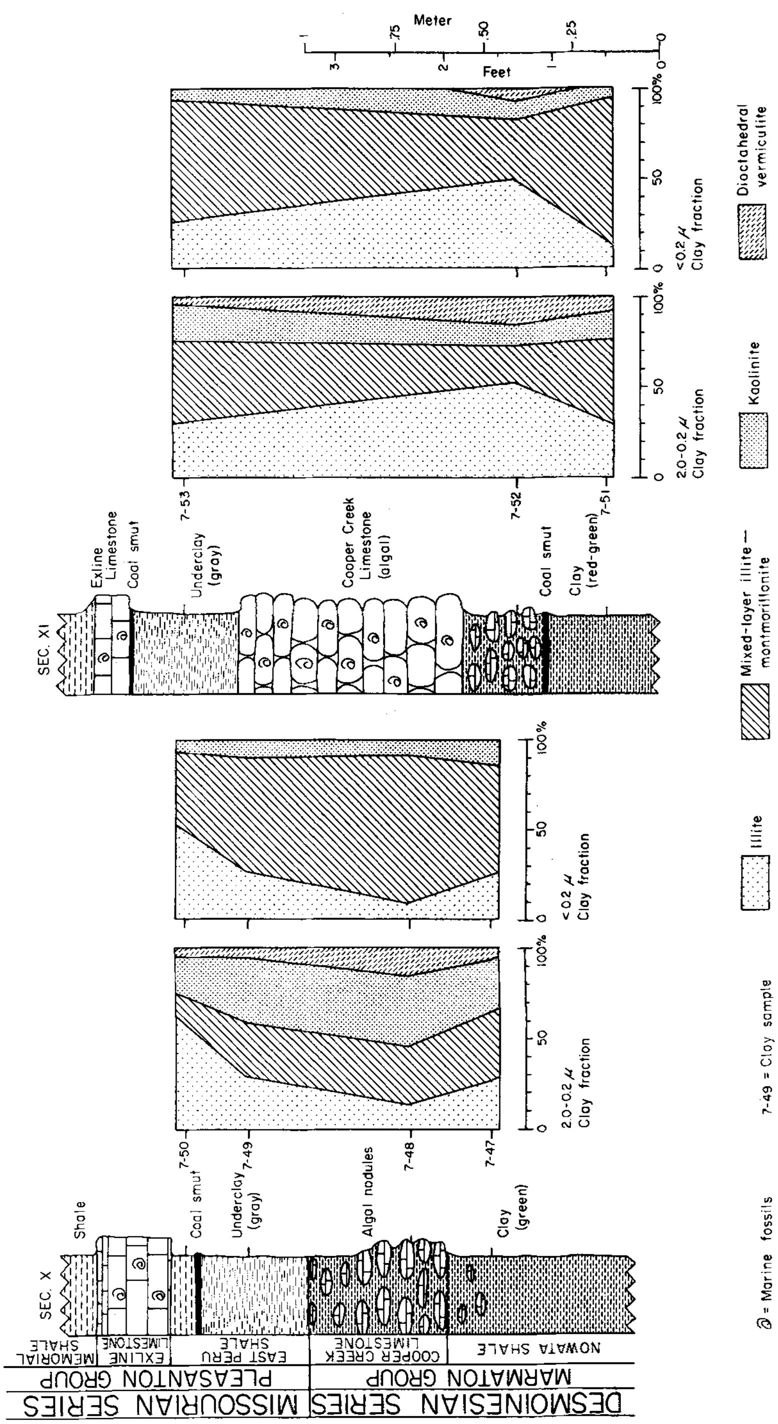

Figure 11. Lateral study no. 1 (Appanoose County, Iowa) showing stratigraphic variations and clay-mineral composition.

3. At Locality III in Putnam County and Locality I in Appanoose County, where the clay matrix has overwhelmed the limestone pellets, the clay-mineral assemblage is typically nonmarine. There is low illite, high mixed-layer clay, abundant kaolinite, and a trace of dioctahedral vermiculite.

4. There is a noticeable increase in the percentage of expansible layers within the mixed layer component along the lateral traverse, from 20–25% at Localities IX and X to 28–30% at Localities I and III.

ENVIRONMENTAL INTERPRETATION

Vertical relationships

The two vertical sequences in Madison County, Iowa, from which samples were analyzed represent principally embayment facies. Vertical Study No. 1 appears to represent a more locally restricted embayment than the broad embayment characterized by vertical Study No. 2.

Vertical Study No. 1 (Figures 6, 9) includes, in ascending order, the Coal City cyclothem, Amoret cyclothem, and Worland cyclothem. The Amoret and Worland section occurs in an inferred embayment marginal to equivalent progradational and channel-fill sandstone; the Coal City section is locally deltaic in nature. The Amoret and Worland bays received some prodelta mud transported from nearby deltas, but little sand entered the embayments (Figure 5). Resulting bay fill underwent soil development or submarsh leaching (underclays) and marsh growth (coals). Following periodic abandonment of sediment supply, continued compaction of the embayment and of subaerially exposed muds resulted in the gradual transgression of thin marine shales and limestones over the embayment clastic facies. Such delta-flank embayments persisted throughout deposition of the Amoret and Worland cyclothems.

Clay mineralogy of the sequence is compatible with an interdeltaic embayment interpretation. Illite content (Figure 9) is generally highest in subtidal marine transgressive facies and moderate to high in subtidal strike-fed, rapidly deposited facies; illite content is normally low within intertidal and subaerial facies. Mixed-layer clays are most abundant immediately above and below coal seams (marsh and subaerial facies); expansible layers decrease from subaerial and marsh facies to marine units. The decrease in kaolin content from nonmarine facies (subaerial, marsh, lake) to marine units (shales) documents the important role played by leaching of clays within the embayment area.

Detrital kaolin apparently entered the basin through nearby delta distributaries. McGowen (1968) has shown that kaolin is concentrated in overbank fluvial facies near point-bar meanderbelt sand bodies, probably as a result of acidic solutions acting on flood-plain clays. Fluvial sand bodies provided conduits by which leaching fluids were removed. Desmoinesian coastal plains composed of extensive meandering river systems are a logical source of kaolin; shifting rivers would have reworked older flood-plain sediments into the dispersal system. Detrital kaolin, therefore, should be an expected component within the fluvially introduced sediment load that was transported through the Marmaton deltas. Vermiculite also was probably part of this detrital kaolin suite. The presence of some kaolin and vermiculite within the embayment facies, especially within the $<0.2\ \mu m$ fraction, however, may have resulted from local *in situ* degrading of other clays to these structures, especially within the subaerial and fresh-water aqueous environments. The increase in expansible layers and the maximum concentration of mixed-layer clays (in the $<0.2\ \mu m$ fraction) in these more severe environments indicate that some structural breakdown probably did occur within the strike-fed illite suite that was deposited within intertidal and various subaerial environments.

Vertical Study No. 2 (Figures 6, 10) includes, in ascending order, the Blackjack Creek, the Higginsville, and the Myrick Station embayment facies; only the Blackjack Creek and Myrick Station cycles were studied. These sequences overlie deltaic facies in the upper part of the Cherokee Group and are overlain by deltaic facies within the Coal City cyclothem. The Blackjack Creek and Myrick Station sequences are inferred embayment facies. The extensive Desmoinesian embayment in northern Missouri and southern Iowa (Figure 6) may have received strike-fed sediment from deltas in the Carbondale Group in the nearby Illinois Basin.

Blackjack Creek and Myrick Station embayment facies are similar to those described for Vertical Study No. 1. Intertidal and subaerial embayment mudstones grade upward into coal (marsh) and, in the Blackjack Creek cycle, into black slaty shale (restricted lagoonal). Marine shales and marine limestones transgressed over the subsiding embayment clastics. Clay mineralogy within Vertical Study No. 2 is generally similar to that described for Vertical Study No. 1. Illite displays a significant increase in going from subaerial and intertidal environments associated with lacustrine (limestone nodules) and marsh (coal) facies upward into transgressive marine shales. With this increase in illite in the Blackjack Creek cycle, a corresponding decrease occurs in the mixed-layer component (and in expansible layers). Such a variation in mixed-layer content is not clear-cut in the Myrick Station cycle, but kaolin and vermiculite display significant reciprocal relationships with illite content. The Myrick Station and Blackjack Creek embayments appear to have been more remote from principal deltaic input than the Amoret and Worland embayments. This suggests, therefore, that the kaolin content within embayments isolated from principal delta sources might best be explained as an alteration product of *in situ* weathering and leaching. There is no evidence of Blackjack Creek fluvial facies within

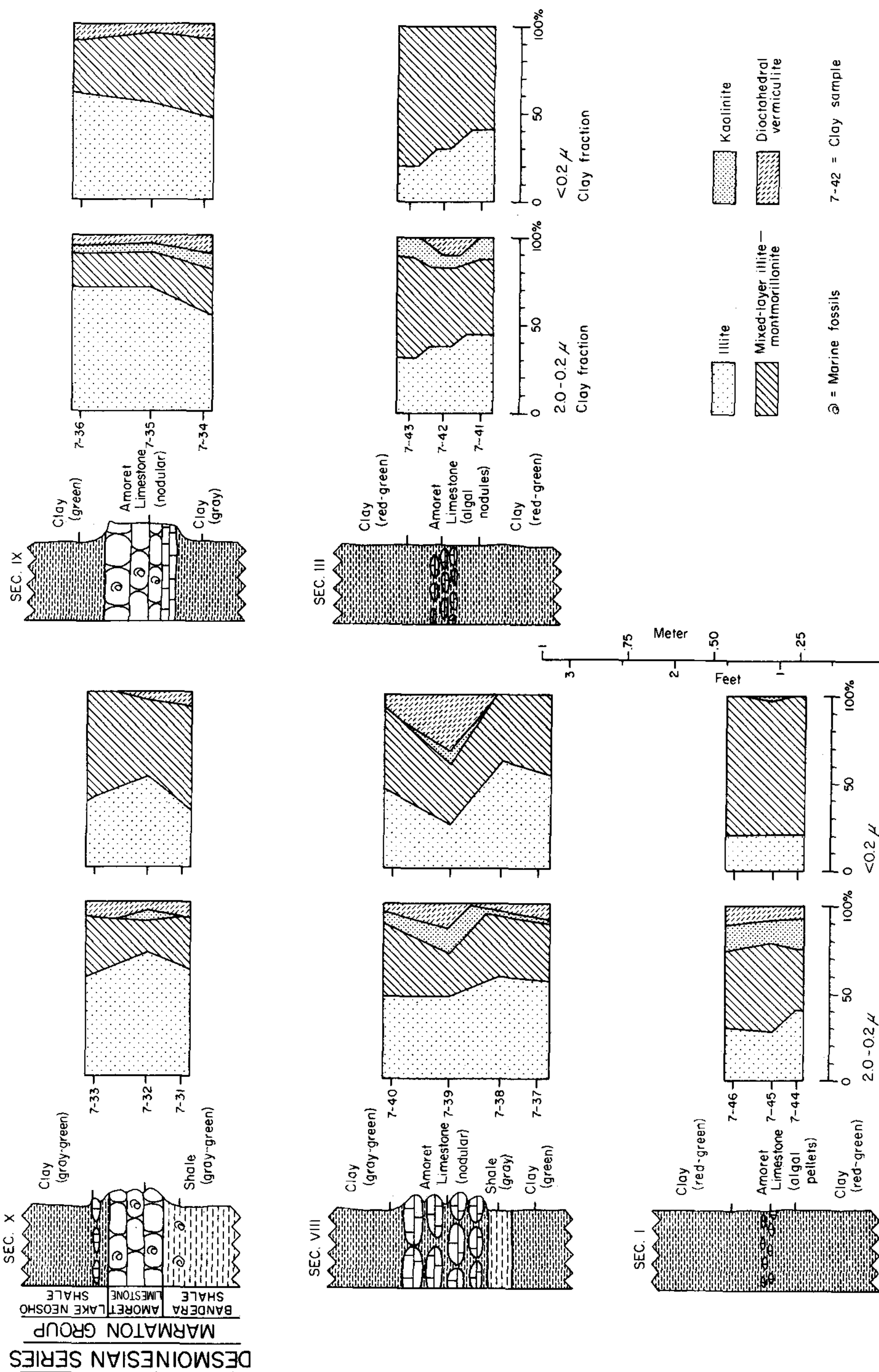

Figure 12. Lateral study no. 2 (Adair County, Missouri-Appanoose County, Iowa) showing stratigraphic variations and clay-mineral composition.

the region, but some Myrick Station fluvial sands occur in Warren County to the south and in Dallas and Boone Counties to the north, suggesting that the Myrick Station coastal plain was occupied at times by some fluvial channels. Kaolinization of overbank mudstones may have occurred in much the same way as described by McGowen (1968).

Lateral relationships

Both Lateral Studies 1 and 2 occur within extensive embayments in southernmost Iowa and north-central Missouri (Figures 7, 8). Both studies involve pinch-out of shelf or open-embayment facies into less marine and/or subaerial environments within extensive interdeltaic-embayment areas. The northwest–southeast-trending outcrop, therefore, approximately coincides with Desmoinesian regional sedimentary strike (or shoreline) in the region. Sediment entered the area through river systems flowing westward and southwestward into the Forest City Basin (Laury, 1968, Figure 13; Wanless and others, 1963, Figure 5). Facies within the two lateral stratigraphic traverses display predictable variations in clay-mineral suites.

In Lateral Study No. 1 (Figures 7, 11), the massive Cooper Creek Limestone (Locality XI, northern Appanoose County, Iowa) overlies a section grading upward from nonmarine to marine sediments. There is a corresponding upward increase in illite and decrease in mixed-layer clays. This vertical sequence typifies embayment fill; i.e. subaerial exposure, subsidence, and marine transgression within interdeltaic bays. In southern Appanoose County (Locality X), the Cooper Creek Limestone pinches out southward into brackish- to fresh-water algal-limestone nodules that separate predominantly nonmarine, intertidal embayment mudstones below from subaerially leached clays (underclay) above. As the Cooper Creek Limestone pinches out, the entire mudstone section, including the matrix of the limestone nodule zone, decreases in illite content and displays a significant increase in kaolin and mixed-layer clays. A "normal" embayment mudstone sequence (Locality XI) that displays an upward non-marine to marine gradation, therefore, changes shoreward (laterally) into a predominantly nonmarine mudstone sequence (Locality X).

In Lateral Study No. 2 (Figures 5, 12), the Amoret Limestone exhibits a similar but northward pinch-out from a massive, open-marine unit in central Adair County, Missouri, to a brackish- to fresh-water nodular limestone overlying a deltaic sequence in Putnam and Appanoose Counties, Iowa. As the Amoret Limestone grades from open marine to nonmarine, the clay mineralogy dramatically changes with this environmental shift: (1) Localities X and IX in southern Adair County, Missouri, exhibit open-marine embayment facies. High illite content, low mixed-layer clays, and a trace of kaolin and vermiculite testify to essentially normal marine salinity with little intertidal or subaerial exposure. (2) Locality VIII in central Adair County, Missouri, exhibits a transitional facies. The matrix of the nodular Amoret Limestone contains less illite, more kaolinite, and more vermiculite, and the overlying clay contains more mixed-layer clays, suggesting a gradually decreasing marine character northward. (3) Localities III and I in Putnam and Appanoose Counties, respectively, occur where the Amoret Limestone has pinched out into limestone pellets. The illite content is low and a suite of kaolinite, mixed-layer clays with a greater percentage of expansible layers, and a trace of vermiculite point to brackish bay, lacustrine, and subaerial environments.

SUMMARY AND CONCLUSIONS

Studies involving vertical sequences of marine and nonmarine facies point to a predictable relationship between inferred Desmoinesian depositional environ-

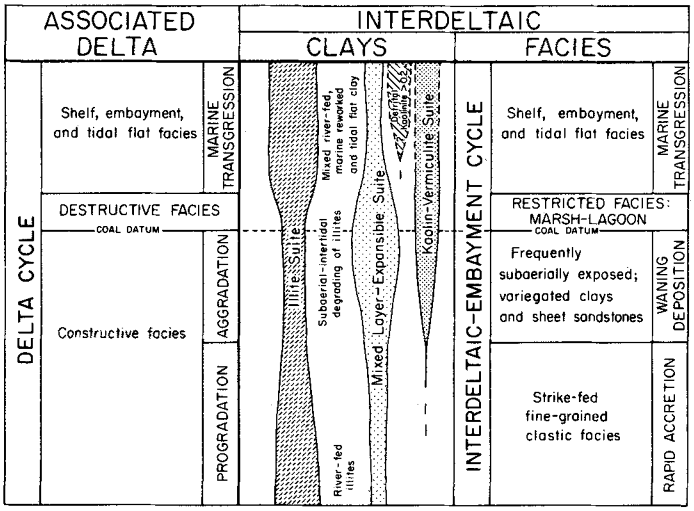

Figure 13. Idealized delta cycle and vertical relationships in clay minerals, Desmoinesian Series, northern Missouri and southern Iowa.

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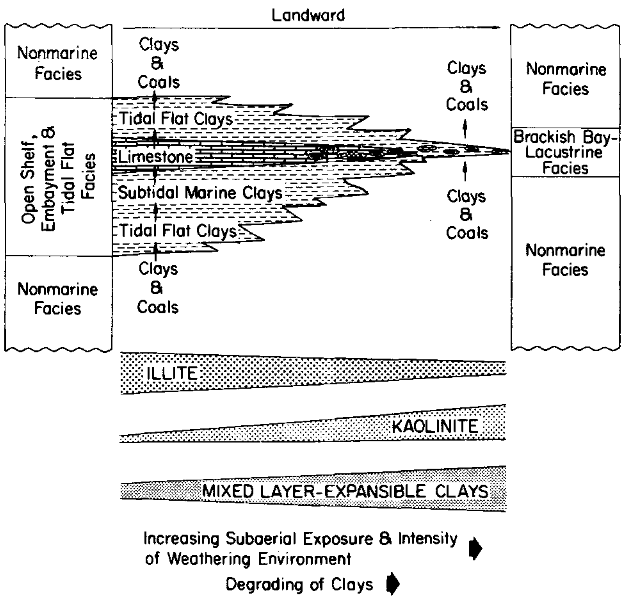

Figure 14. Lateral relationships of clay minerals within a marine-to-nonmarine pinchout, Desmoinesian Series, northern Missouri and southern Iowa.

ments and the general nature of clay-mineral suites within these facies (Figure 13). Vertical studies were located within both local (Vertical Study No. 1) and extensive (Vertical Study No. 2) embayments along a shoreline supplied with sediment by either nearby or distant delta sources, respectively. Progradation of deltas supplied a fresh influx of predominantly illitic clays from distant sources, primarily to the northeast in Canada (Potter and Pryor, 1961). Clays were deposited principally as prodelta mudstones, but considerable suspended sediment and a smaller amount of traction-load was transported alongshore (strike-fed) to adjacent embayments. During repeated exposure on intertidal flats or due to occurrence beneath acidic marsh, illitic clays were degraded rapidly to mixed-layer clays with maximum expansible layers. Locally where fluvial sand-filled channels were present to remove acidic fluids, kaolinite and vermiculite developed. At other times, kaolin-rich deltaic and fluvial plains were eroded, and redeposition of detrital kaolinite ($>0.2\,\mu m$) occurred within the adjacent marine basin. Clay-mineral distribution within the interdeltaic embayments, thus, can be interpreted best in terms of a depositional system in which each of the various cyclic facies is related to contemporaneous delta building and abandonment.

Lateral clay mineral variations also provide documentation that contemporaneous environments within interdeltaic embayments can account for observed differences in clay mineral suites. Lateral changes (Figure 14) from marine to nonmarine mudstones, as proved by limestone pinch-outs, coincide with a predictable decrease in illite and an increase in kaolin, mixed-layer clays, and percentage of expansible layers within the mixed-layer clay.

The use of clay minerals alone to identify various depositional environments is unwarranted, but subtle-to-moderate shifts in percentages within clay-mineral suites, when tied to and calibrated with depositional facies and stratigraphic relationships, point to a very convincing relationship between paleoenvironments and clay-mineral suites. Clay-mineral variations, as well as fossils, sedimentary structural sequences, and other factors, are generally predictable within a depositional model that is compatible with modern facies and processes. Clay mineralogy, therefore, becomes a useful tool for improving the odds of proper interpretation of depositional environments.

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APPENDIX 1

Sample collection and preparation

Previous study by Potter and Glass (1958) has shown that shales and clays, because of their relative impermeability, are least subject of the clastic sediments to post-depositional changes and most apt to retain their original clay mineralogy, either detrital or authigenic. The present mineralogic study has been restricted to shales and clays for this reason. The effects of weathering have been kept to a minimum by removing the outer 2–3 feet of the outcrop surface before sampling. Four-pound samples representative of each stratigraphic unit were collected by means of vertical channel cuts in the case of thick units and by lateral cuts for thinner units.

Clay minerals were separated from each sample and prepared for X-ray analysis according to a modification of methods described by Jackson (1956). The steps involved are: (1) gentle disaggregation, (2) analysis of carbonate content of two aliquots by the method of Patel and Truog (1952), (3) HCl treatment to remove carbonates where necessary, (4) oxidation of organic matter with 30% hydrogen peroxide, (5) digestion, removal of soluble salts and exchangeable bases, and thorough washing with acidized ethanol, (6) dispersal of clay particles by adding 2% Na_2CO_3, boiling, and adding further dilute Na_2CO_3 at a pH of 9.5, (7) separation of coarse clay (2.0–0.2 μm) and medium-to-fine clay ($<0.2\ \mu$m) fractions by centrifuging, and (8) thorough washing of each clay fraction with ethanol and storage in 95% ethanol. Check tests run on several bulk samples indicated no detectable changes in types or relative amounts of clay minerals present as a result of these treatments.

X-ray analysis

The two clay fractions of each sample were analyzed qualitatively by several X-ray methods: (1) randomly oriented powders in 114.6 mm film cameras, CuKα radiation, (2) oriented basal slides in a Norelco diffractometer, CuKα radiation, subjected to several treatments (a) untreated, (b) Mg^{2+} saturated and solvated with glycerol, (c) heated to 200°C for two hours, and (d) heated to 550°C for two hours, and (3) X-ray spectrography. In addition, selected samples containing appreciable percentages of interstratified clays or of dioctahedral vermiculite were X-rayed after treatment with KOH as a test of their ability to fix potassium according to the method of Weaver (1958).

Quantitative X-ray analysis of the clay minerals within each fraction was carried out according to the orienting internal standard method of Mossman and others (1967).

This method eliminates the need for a reproducible degree of orientation from slide to slide. Fithian illite and Murfreesboro kaolinite were used as standards for preparation of the working curves. Separate working curves for different degrees of random interstratification of 10/15.4 Å layers were calculated from the experimental data of Bradley (1945) for the variation of the layer structure factor over the range 25.0–7.4 Å and from the random mixing functions calculated by MacEwan and others (1969) for 5-layer crystallites. The X-ray scattering power for dioctahedral vermiculite relative to the other components was estimated from the experimental data of Bradley (1945).

Quantitative X-ray analysis of clay minerals is particularly difficult because of (1) differential orientation effects, (2) compositional variations, including interstratification within the clay minerals, and (3) variations in crystal perfection. The present study has attempted to compensate for the effects of orientation and interstratification by the method of analysis. In addition, standard clays for the working curves were chosen so that their grain size and degree of perfection would be comparable to those in the sediments under study.

Some idea of the accuracy achieved in this study can be derived from the total clay-mineral content measured for each clay fraction. Ninety per cent of the samples give a total clay-mineral content between 80 and 100%. A total somewhat less than 100% is to be expected because of the presence of small amounts of quartz and amorphous material. For ease in presenting the results, the percentages obtained have been adjusted proportionally to total 100 per cent clay minerals for each clay fraction.

Clay mineral identification

For the purpose of this study, "illite" is used as a term for a 10 Å mica that does not change spacing on heating or solvation. The mica could be identified by means of random powder X-ray films as the $2M_1$ muscovite polytype in all cases where illite is the dominant component of the clay, which is true for most of the coarse clay fractions.

The mixed-layer clay is a dioctahedral mica containing randomly interstratified expansible layers. The positions of the first few basal reflections from the clay in its natural state, after solvation, and after heating, indicate a range from 19 to 32% expansible layers in different samples. The grain size of the interstratified clay is usually smaller than that of the associated illite so that it is most abundant in the medium-to-fine clay fraction ($<0.2\,\mu$m). Because random powder X-ray films do not show any *hkl* reflections with $k \neq 3n$, the interstratified clay is classified as the $1Md$ polytype. Ten samples were tested for K-adsorption by soaking for 15 hr in 1 N KOH, washing, and drying at room temperature. In every case at least three-fourths of the mixed-layer component collapsed to 10.0–10.6 Å. The collapse was most complete and pronounced in the coarse clay fraction. It is concluded that the mixed-layer clay has a high layer charge and is a degraded weathering product of illite. In contrast to the findings of Weaver (1958), the three clays considered to be of marine origin collapsed as readily as the seven samples considered to be nonmarine.

Dioctahedral vermiculite has a 14 Å basal spacing that does not expand on solvation, but collapses to 10 Å on heating. It is slightly more abundant in the coarse clay fraction than in the medium-to-fine clay. The dioctahedral vermiculite, present as a minor component in nine of ten samples soaked in KOH, collapsed to 10.0–10.6 Å as readily as the mixed-layer component. A further test of collapse was made on four additional samples, three of which were associated with marine fossils, by boiling for five hr in a KOH + KCl solution. All four samples collapsed to 10 Å. It is concluded that the dioctahedral vermiculite also is a degraded illite in which most of the interlayer potassium has been removed by weathering.