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Clay-rich Zones in Upper Pennsylvanian (Missourian-Virgilian)
Shelf Limestones, Eastern Kansas

by

Brian T. McNeice

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KANSAS GEOLOGICAL SURVEY
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Brian T. McNeice

B.A., S.U.N.Y. at Geneseo, 1982

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ABSTRACT

Thin clay-rich zones with a complex depositional and diagenetic origin are present in upper or regressive limestones in cyclothems in the Upper Pennsylvanian of eastern Kansas. These clay-rich zones, examined in three typical regressive limestones in northeastern Kansas, are typically 1 to 10 cm thick and separate thicker (typically 10 to 40 cm) wavy limestone beds. Most zones can be traced laterally within a outcrop and some zones were correlated for 70 km. Clay-rich zones are characterized by one or more concentrated to diffuse seams of clay. Seams characteristically contain 10 to 40 weight percent of insoluble residue (predominantly clay), microcrystalline dolomite, and such chemical compaction features such as microstylolites and interpenetrant and truncated fossils. Limestone beds are skeletal wackestones, mottled by burrowing, although burrows do not cut seams. Limestone immediately adjacent to seams differs slightly in composition and texture from the limestone beds, with a decreased percentage of fossil molds, higher clay content, and a muddier texture. Seams lack fossil molds although there is no accompanying decrease in abundance of calcitic fossils.

Development of clay-rich zones was probably initiated by influx of clay from highlands to the south (Ouachita Mountains) or east. The clay was redistributed by burrowing, resulting in a clay content possibly in the range of 10 to 15 weight percent. Clay-rich zones were less lithified than adjacent limestone beds, possibly due to the greater clay content. Mechanical compaction in the zones led to loss

of fossil molds and denser packing of constituents and may have led to chemical compaction, although the degree of lithification at the time of chemical compaction is not clear. Differential mechanical compaction contributed to the wavy shape of the limestone beds. Chemical compaction was the final stage of diagenetic modification in the zones, and was probably controlled by the amount and distribution of clay and possibly the degree of lithification. Irregular chemical compaction, forming several diffuse or concentrated seams in a zone, contributed to the irregular shape of the limestone beds. Chemical compaction may have promoted formation of dolomite associated with the seams; however, the origin of the dolomite is not clear.

TO DON AND JINI

"... they will develop gradually into encrinites, and stalacites, and blatherskites, and one thing and another as the mighty ages creep on and the Archaean and the Cambrian Periods pile their lofty crags in the primordial seas, and at last the first grand stage in the preparation of the world for man stands completed, the oyster is done. An oyster has hardly any more reasoning power than a scientist has; and so it is reasonably certain that this one jumped to the conclusion that the nineteen million years was a preparation for him; but that would be just like an oyster, which is the most conceited animal there is, except man."

Mark Twain

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INTRODUCTION

Thin, clay-rich zones separate wavy limestone beds in the upper or regressive member of Upper Pennsylvanian (upper Missourian through middle Virgilian) cyclothems of northeastern Kansas. Numerous studies have examined the stratigraphy of these units and the lithology of the beds (e.g. Moore 1936; Heckel 1977; Mathews 1978); however the clay-rich zones have received little attention.

The purpose of this study is to determine the origin of clay-rich zones in three upper or regressive limestones, the Plattsmouth, Stoner, and Ervine Creek. Clay-rich zones in the units studied generally consist of one or more seams that have a uniform to patchy distribution of clay or are composed of numerous subparallel microstylolites (Fig. 1). The seams typically contain 10 to 40 weight percent of insoluble matter, predominantly clay; microcrystalline dolomite; and interpenetrant and truncated fossils.

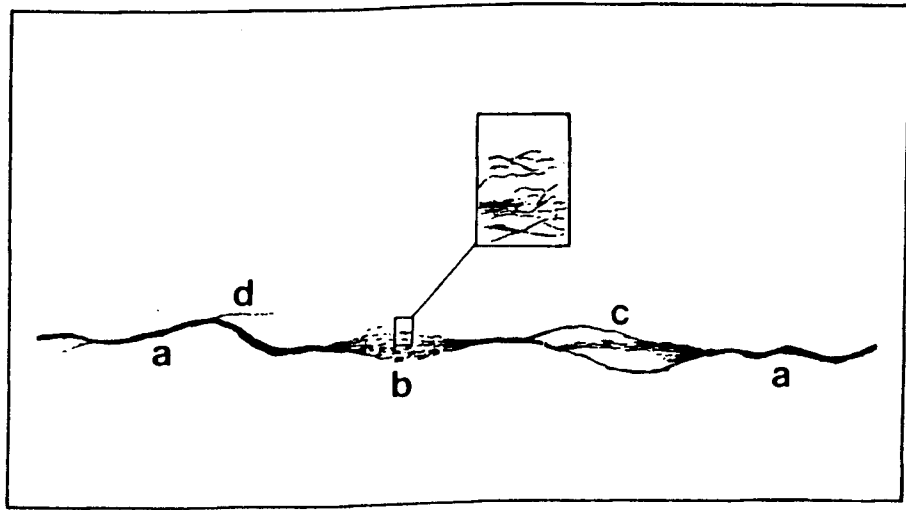
Clay-rich zones probably formed due to small influxes of clay. The clay, which was redistributed by burrowing, probably retarded lithification. Less lithification allowed greater mechanical compaction than in adjacent limestone beds. The greater clay content or poor lithification favored chemical compaction in the zones.

Previous Work

Clay-rich zones have been little studied, and those workers who have examined them have generally suggested different modes of origin. Three general types of clay-rich zones representing three

Figure 1.

Sketch of an idealized clay-rich zone, showing a single concentrated seam (a) that passes laterally into thicker intervals with patchy to wispy accumulations of clay (b) or into thin seams that are concentrated to diffuse (c). Thicker intervals commonly contain lensoidal limestone nodules (c) or small limestone clots (b, expanded view). Small seams diverge from the zone (d). Zone has a maximum thickness of approximately 10 cm.



possibly overlapping origins are recognized in limestones. Zones of origin A (Table 1) are described as thick marls or shale beds separating bioturbated limestone beds. The zones have a uniform distribution of clay and few or no chemical compaction features (Appendix I). Their origin depended on a large influx of terrigenous detritus, predominantly clay, or on a reduction in supply of carbonate sediment; the resultant interval with high clay content is typically modified by differential lithification and mechanical compaction. Such zones are commonly present in shelf limestones and chalks (Table 1).

Zones of origin B (Table 1) have been described as thin, with one or more wispy to continuous seams and abundant microstylolites and interpenetrant grains. The zones separate limestone beds that are bioturbated and planar to wavy in shape. Their origin probably depended on a small influx of clay, modified by burrowing, differential lithification, and mechanical and chemical compaction. Depositional changes other than changes in clay content, such as changes in texture, sedimentation rate, or degree of bioturbation may have been important. Such zones are commonly present in shelf limestones, chalks, and pelagic limestones (Table 1).

Zones of origin C (Table 1) are similar in description to zones described in origin B, with microstylolites and interpenetrant grains. The zones, however, are more closely spaced and discontinuous and may cut across primary bedding. Their origin depends on chemical compaction at sites possibly determined by variations in mode of stress (Appendix I) and possibly by slight

Table 1. Studies of the origin of clay-rich zones. Works are grouped on the basis of origin; origins A-C correspond to three general modes of origin summarized in the text. Barrett (1964) suggested an origin possibly more similar to origin C, and Wilson and Jordan (1983) suggested that chemical compaction may be of minor importance in some zones, similar to origin B. Wanless (1979) also suggested that clay-rich zones formed in intervals containing a high clay content (origin B). *1 indicates the name given to clay-rich zones by workers; *2 and also Kennedy and Garrison (1975); *3 and microstylolite swarms.

ORIGINS	WORKERS	STUDY AREA	LIMESTONE TYPE	ZONE*1
ORIGIN	Hattin (1971)	Kansas and Colorado	Chalk	Shaly chalk beds
A	Wilson & Jordan (1983)	Summary study	Shelf limestone	Clay partings
	Arthur & Fischer (1977)	Italy	Pelagic ls.	Shale interbeds
	Barrett (1964)	New Zealand	Shelf limestone	Residual seams
	Bathurst (1987)	Europe-USA	Shelf limestone	Shaly limestone
ORIGIN	Garrison & Kennedy (1977)*2	England	Chalk	Flaser bedding
	Nelson (1978)	New Zealand	Shelf limestone	Solution seams
B	Oldershaw & Scoffin (1967)	England	Shelf limestone	Shales
	Ricken (1986)	Europe	Pelagic ls.	Marl beds
	Scholle (1977)	Summary study	Chalk	Solution seams
ORIGIN	Logan & Semeniuk (1976)	Australia	Tectonically deformed ls.	Stylolaminite
C	Marshak & Engelder (1985)	New York	Tectonically deformed arg. limestone	Tectonic cleavage
	Wanless (1979)	Arizona and Maryland	Argillaceous ls., some tect. deformed	Clay seams *3

changes in lithology, particularly a high clay content. Such zones are present in argillaceous limestone that was subjected to shear stress or possibly overburden stress (Table 1 and Appendix I).

Origins A and B are similar, differing only in the initial clay content and presence or absence of chemical compaction features. Zones of origins B and C are characterized by similar chemical compaction features; however, zones of origin C are evidently not as closely linked to depositional changes. Because chemical compaction tends to obscure the primary lithology of the zones, the early depositional and diagenetic history of the zones is generally not clear, leading to differing interpretations of origin.

GEOLOGIC SETTING

The Plattsmouth, Stoner, and Ervine Creek limestones (Fig. 2), typical wavy-bedded limestones in the Upper Pennsylvanian of eastern Kansas, were examined to determine the origin of the clay-rich zones. The Plattsmouth Limestone was studied in the most detail, since this unit contains well-defined zones and is exposed in numerous fresh quarries in eastern Kansas.

Pennsylvanian Midcontinent Cyclothem

Limestones and shales in the Pennsylvanian of the Midcontinent occur in repeating, cyclic sequences. Two models have been postulated to explain this cyclic nature. Moore (1936, 1949, 1950) suggested that limestones and shales in the Missourian and Virgilian of eastern Kansas were grouped into shale-limestone couplets, with each couplet a complete transgressive-regressive cycle or cyclothem (A-E, Fig. 3). Cyclothem were grouped into larger repeating cycles or megacyclothem (Fig. 3). In contrast, Heckel and Baesemann (1975) and Heckel (1977) suggested that the basic repeating sequence or cyclothem in the Missourian section of eastern Kansas consisted of five members (Fig. 3). The cyclothem formed as the result of glacial-eustatic transgressions and regressions, although subsidence and local deltaic influxes may have also been important. They also recognized this kind of cyclothem in the Virgilian section of eastern Kansas, although the Virgilian section may contain additional

Figure 2.

Stratigraphic section showing Ervine Creek, Plattsmouth, and Stoner limestones (arrows). Modified from Moore et al. (1951).

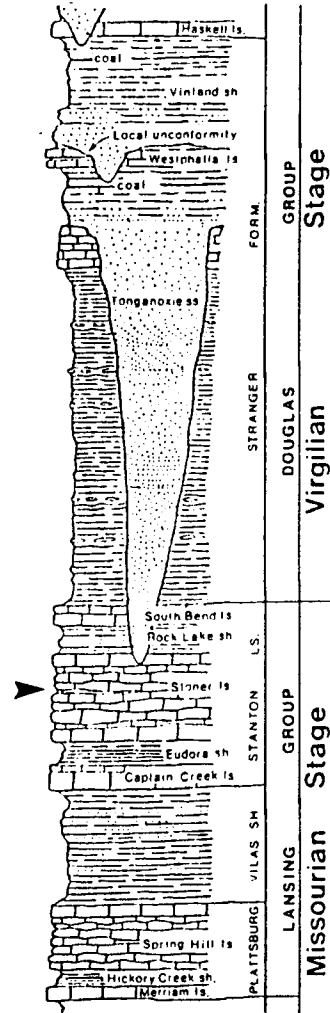
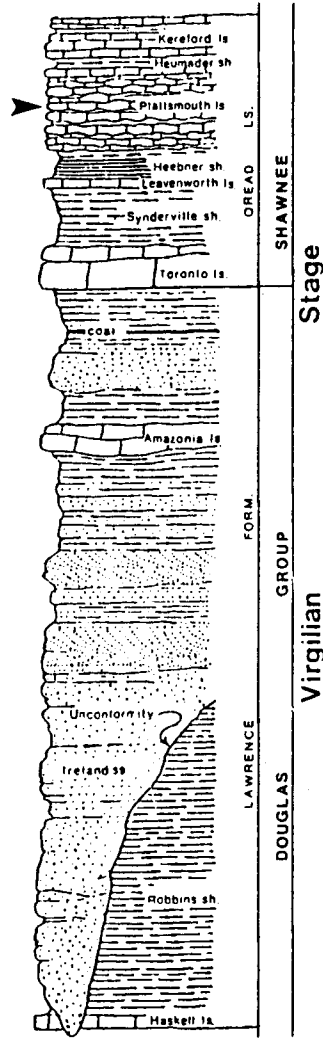
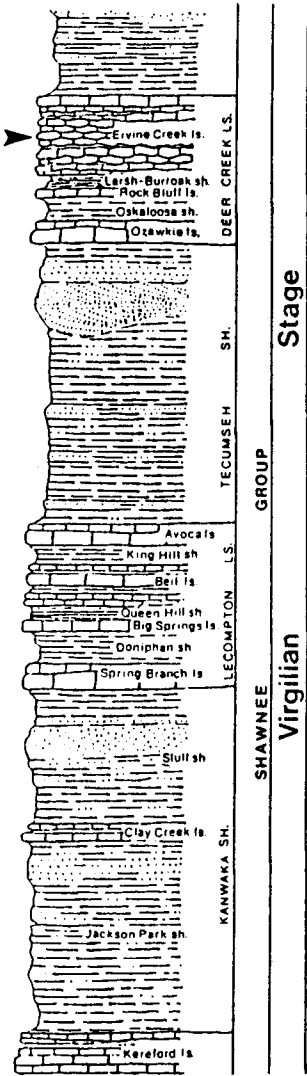
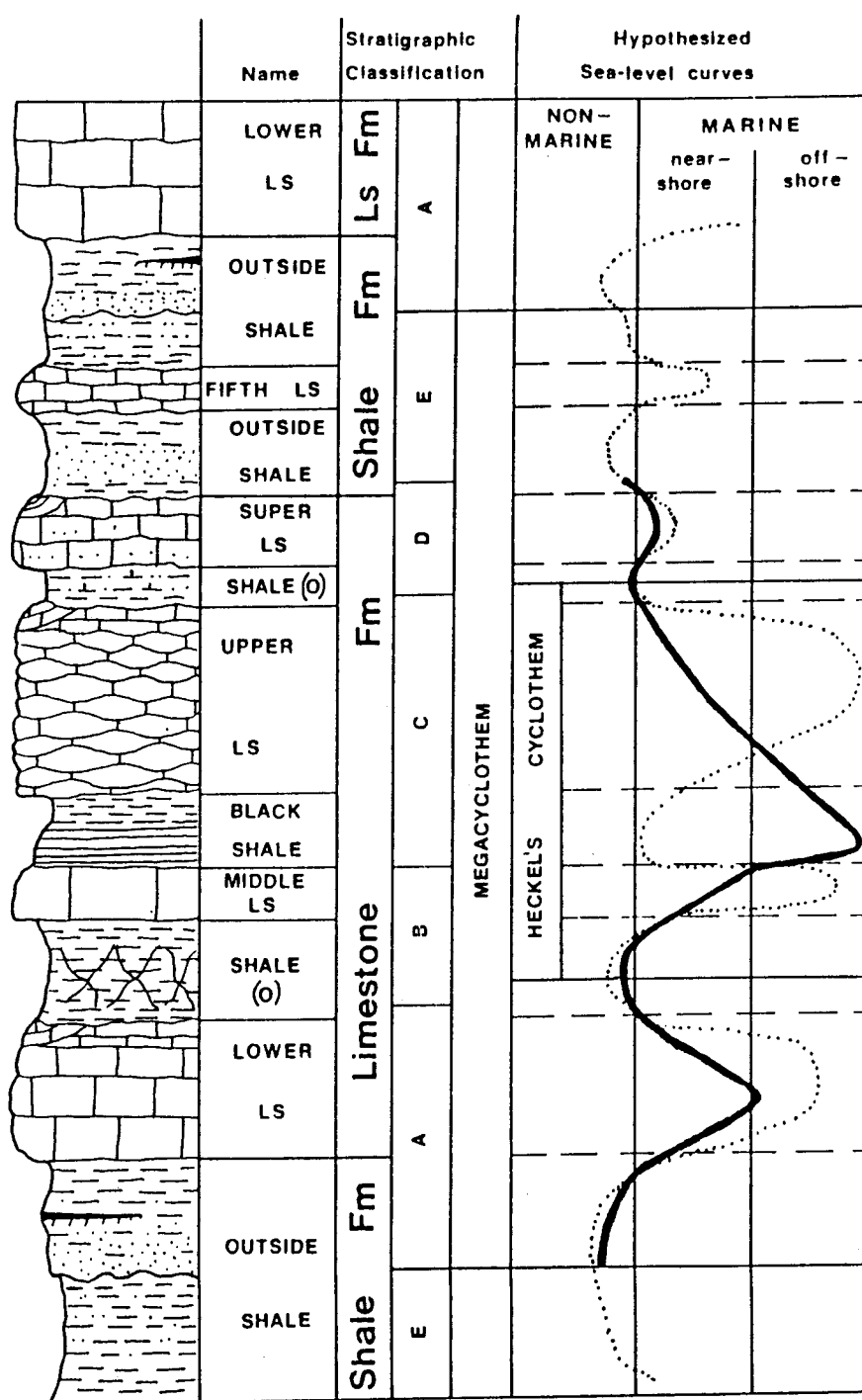


Figure 3.

Ideal Upper Pennsylvanian Shawnee-type megacyclothem (Moore 1936; 1949; 1950), and modified megacyclothem (Heckel and Baesemann 1975; Heckel 1977; Heckel et al. 1979) showing complete development of all members. Megacyclothem consists of five members (A-E), which in general begin with a nonmarine phase in a shale, pass through a marine phase, and end in another nonmarine phase in a shale. Shale (O) signifies a shale with similarities to outside shales. Dashed line depicts sea-level curve of Moore (as derived by Heckel and Baesemann 1975), and solid line depicts sea-level curve of Heckel. Modified from Moore (1936); Moore (1950); Heckel and Baesemann (1975); Mathews (1978); Heckel et al. (1979).

Approximate



limestones (lower, super, and fifth, Fig. 3) that are regarded as incomplete cycles or as fortuitous occurrences (Heckel and Baesemann 1975).

Regressive Limestones

The units examined in this study are characteristic upper, regressive limestones (Fig. 3). Regressive limestones were deposited in a shallow open-marine environment with distant highlands and areas of terrigenous input controlling their lateral extent (Fig. 4) (Moore 1936, 1949; Wanless et al. 1970; Heckel 1977, 1980). These thick (typically 1.5-9.0 m) limestones can be traced along outcrop from Iowa, Missouri, and Nebraska across Kansas into northern Oklahoma (Fig. 4) (Heckel 1980, 1984) and are present in the subsurface in western Kansas and southwestern Nebraska (Watney 1980; Prather 1984). Heckel (1968) recognized that regressive limestones generally show a gradual facies transition along outcrop (Fig. 5), from a northern shoreward facies characterized by shoreline carbonate, into a typically wavy-bedded open-marine facies, and then into a phylloid-algal mound facies that is characteristically thick and massive. The phylloid-algal mound facies changes fairly abruptly into a terrigenous-detrital facies in southern Kansas and northern Oklahoma (Fig. 5). Wavy-bedded portions of regressive limestones are typically skeletal wackestone but commonly grade upward into skeletal packstones or grainstones that may be cross-laminated and are locally oolitic (Fig. 3). Heckel and Baesemann (1975) and Heckel (1977, 1980, 1984) suggested that this change in texture represents a gradual

Figure 4.

Principal tectonic elements of the northern Midcontinent region, showing areas that possibly supplied terrigenous detritus. The Appalachians may have also supplied some terrigenous detritus through a possible inlet to the Illinois basin (Toomey 1969; Heckel 1980). Modified from Toomey (1969), Troell (1969), and Ball (1985).

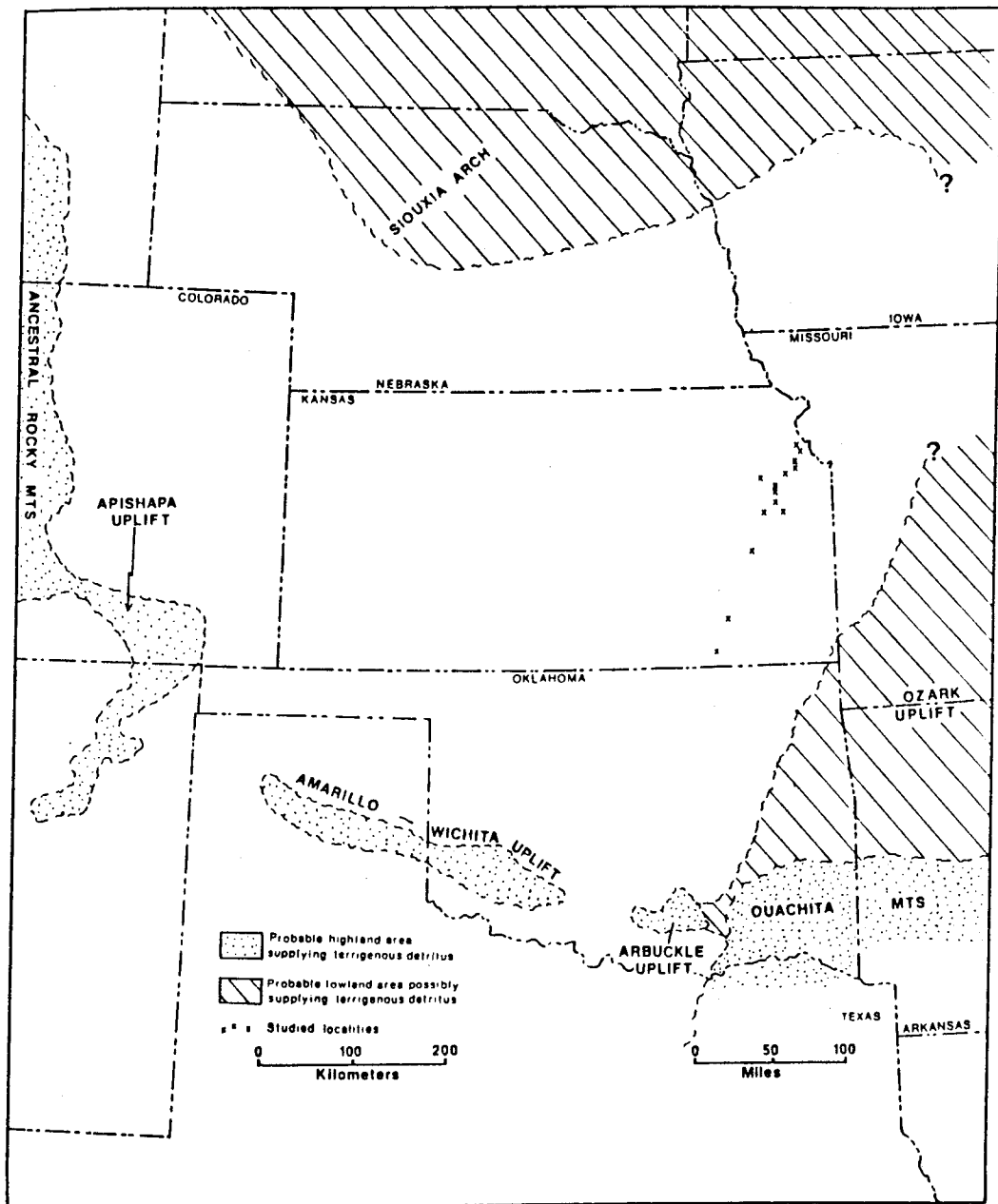


Figure 5.

Pennsylvanian outcrop in eastern Kansas and adjacent region, showing generalized facies belts separated by letters s, m, and t (Heckel 1968; Heckel 1977; Heckel et al. 1979). Stage boundaries are shown by solid lines. Modified from Heckel et al. (1979).

change from a quiet, open-marine environment, below wave base and within the photic zone, to a shallow-marine environment with local shoaling. Fossils present include phylloid algae, brachiopods, bivalves, gastropods, bryozoans, crinoids, and fusulinids; fusulinids are especially abundant in the upper portions of some of the units. According to Heckel (1977, 1980, 1984); Ball (1983); Ball (1985), influxes of terrigenous detritus from prograding deltas in the south or east (Fig. 4) formed the thin clay-rich zones that separate the limestone beds. These influxes may have distributed terrigenous detritus over wide areas, and may have "stifled carbonate sedimentation over several hundred square-mile(s)" (Ball 1983, p. 418).

Diagenesis of Regressive Limestones

According to Heckel (1983) and Railsback (1984), regressive limestones were exposed in varying degree to meteoric water at the end of a regressive cycle, creating characteristic patterns of diagenesis. The wavy-bedded portions of regressive limestones (early-middle regressive calcutites of Heckel 1983) may have passed through the mixing zone or even meteoric-phreatic diagenetic environments, although lower portions of the units may have passed directly into the deeper burial environment without any exposure to meteoric water. Exposure to the mixing zone and meteoric-phreatic environment resulted in the leaching of aragonite grains and precipitation of blocky calcite spar in the voids. The maximum depth of burial of the Missourian and Virgilian sequence in eastern Kansas is estimated to

have been approximately 800 m (K.D. Newell and W.L. Watney, pers. comm., 1986). The estimated maximum paleotemperature was approximately 45° C, assuming a surface temperature of 20° C and present geothermal gradient (Stavnes 1982).

METHODS

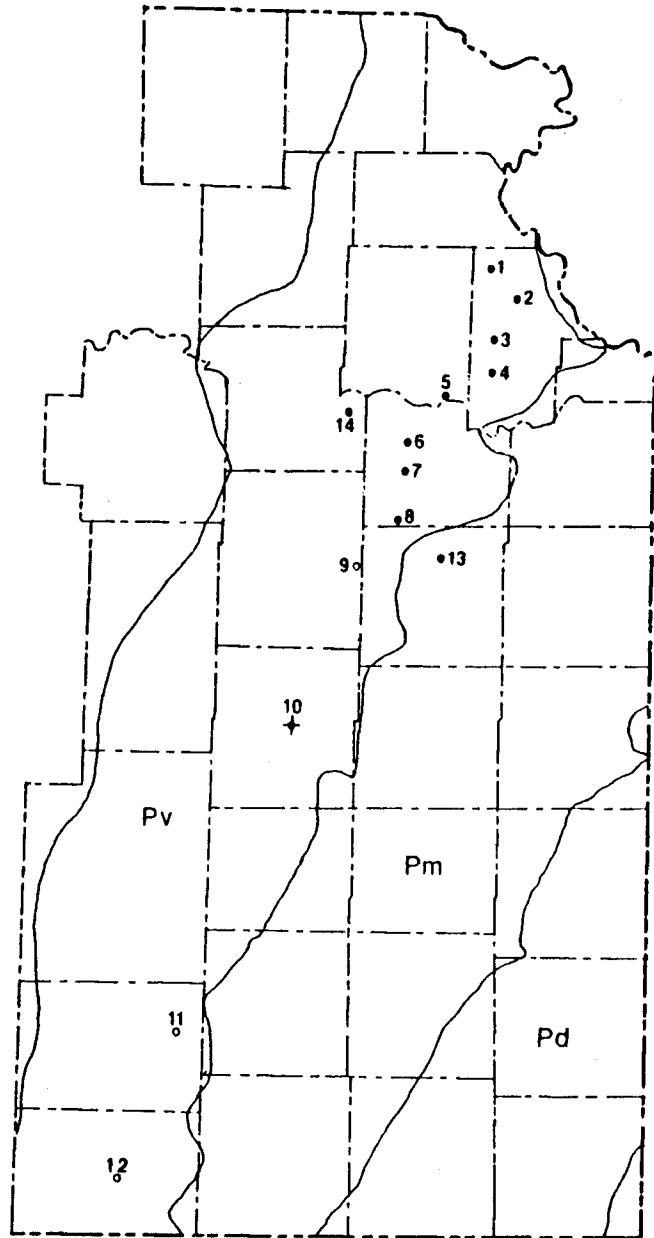
Field Work

Eleven outcrops and one core of the Plattsmouth Limestone (Fig. 6, localities 1 to 12), one outcrop of the Stoner Limestone (Fig. 6, locality 13), and one outcrop of the Ervine Creek Limestone (Fig. 6, locality 14) were examined to document lateral and vertical changes in the form and composition of clay-rich zones and limestone beds. Sections of the Plattsmouth Limestone at localities 2, 3, 5 to 7, and 10 have exposures that are fresher and more complete than exposures at other Plattsmouth localities and were therefore studied in greater detail. The outcrop at locality 5 (Fig. 6) was studied in the most detail, since this active quarry contains laterally extensive and very fresh to slightly weathered exposures. Fresh exposures are necessary for study of the zones, since the zones lose detail after several months of weathering. The core (locality 10) is a comparative section with sections of the Plattsmouth Limestone that are closely grouped in the north of the study area (Fig. 6). The lower three meters or so of the Plattsmouth Limestone were studied in the most detail. This lower portion contains clay-rich zones that are well-defined, easily accessible, and generally less weathered than zones in the upper portion. A detailed sketch of a quarried face of the Plattsmouth Limestone at locality 5 (Fig. 6) records features that do not show up well in photographs. The vertical position of zones in the sketch was determined by measuring from the datum bed, a

Figure 6.

Study area, showing localities examined in the Plattsmouth Limestone (1-12), Stoner Limestone (13), and Ervine Creek Limestone (14). Generalized stage boundaries are shown by solid lines. Sections studied in detail are shown as filled circles. Detailed locations of the sections are given in Appendix II.

le
is
E



Pv VIRGILIAN

Pm MISSOURIAN

Pd DESMOINESIAN

0 KM. 50

Quarry exposures ○ exploratory studies
● detailed studies

Core +

thick, laterally persistent, and easily recognized clay-rich zone used as a datum in a correlation diagram.

Correlation of clay-rich zones in the lower portion of the Plattsmouth Limestone was attempted between localities 1 to 8 (Fig. 6). Correlation between sections was based on the following factors: 1) thickness of zones and limestone beds, 2) measured distance above or below the datum, 3) shape of the zones (one or more seams), and 4) occurrence of chert nodules in some horizons in the limestone. Plattsmouth Limestone locality 9 was not used for correlation due to poor exposure, and correlation was not attempted with Plattsmouth Limestone locality 10 (core) due to the great distance from locality 8. The core section was included in the correlation diagram, however, to emphasize the similar appearance of the zones and to show the continuity of the datum bed.

Petrography

Slabs and 5- by 7.5-cm thin sections were made from samples from representative clay-rich zones and limestone adjacent to the zones from all sections examined in detail (Fig. 6). The thin sections and slabs were examined to determine constituents and diagenetic features. Alizarian red S and potassium ferricyanide stains (Dickson 1965) helped in determining the carbonate composition. Point counts were taken in thin sections from five zones (seams and limestone immediately adjacent to seams) and from adjacent limestone beds in order to compare the numbers and types of fossils in the seams and limestone. To determine abundance of dolomite seven samples of seams

from zones of the Plattsmouth Limestone were analyzed using X-ray diffraction and electron microprobe (Appendix III).

Weight percent of insoluble residue and composition of insoluble residue were determined for samples from seams and adjacent limestone (Appendices IV, V). The composition of insoluble residue was determined by examining the residue visually and by determining the weight percent of organic matter in the insoluble residue (Appendices IV, V). Samples were analyzed to determine 1) if changes in limestone texture are associated with changes in amount of insoluble residue, 2) average percentages of insoluble residue in seams and limestone, and 3) if composition of insoluble residue differs in seams and limestone.

RESULTS

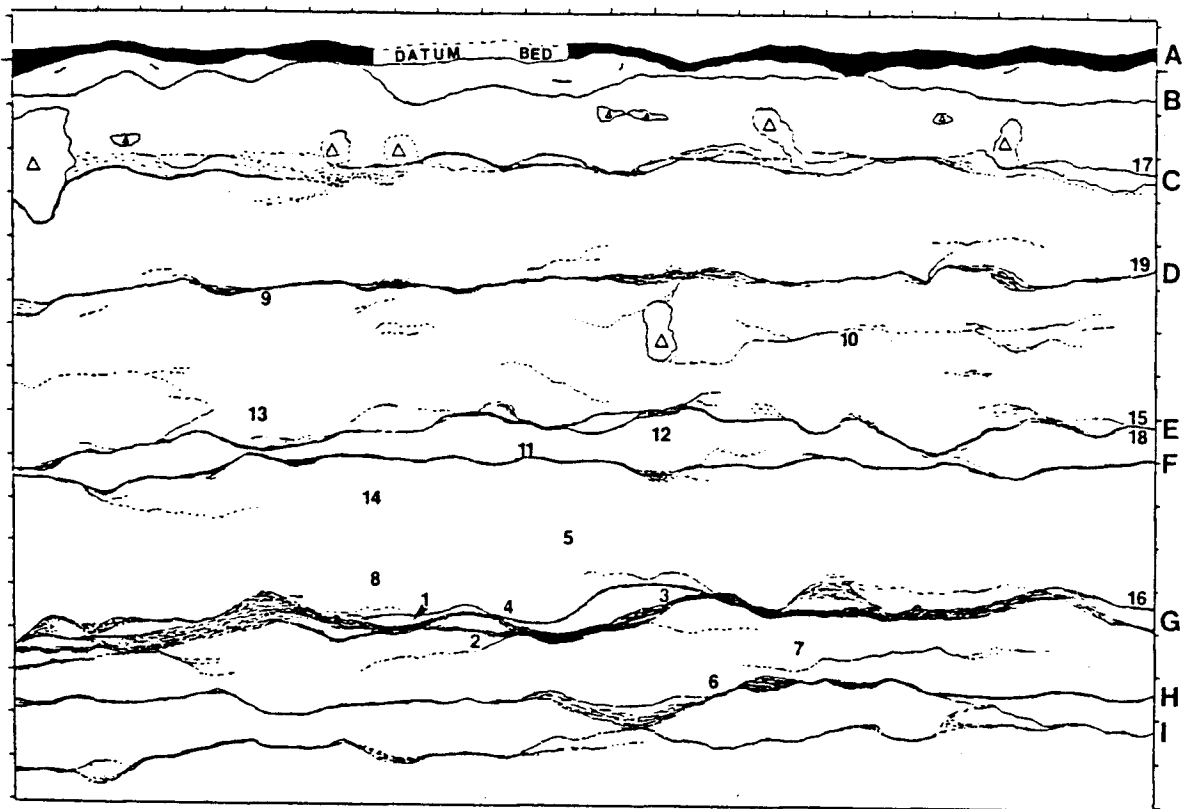
Limestone Beds

Field Work

Limestone beds in the Plattsmouth, Stoner, and Ervine Creek limestones are similar in lithology but differ in thickness and form of the bedding. The limestone beds of the Plattsmouth Limestone are commonly described as wavy, i.e. with an regular lensoidal shape (e.g. Fig. 3); however this bedding shape is not well developed in the sections studied. The beds are typically 10 to 40 cm thick and irregular in shape, ranging from roughly planar to wavy and almost nodular (Figs. 7, 8). Bedding surfaces consist of rounded nodes and antinodes (Fig. 9) with typical relief of 5 to 10 cm. Slickensides are present on some of the steeply dipping nodes. Chert nodules are present in several northern exposures of the Plattsmouth Limestone. These nodules occur in the beds just below the datum bed (Fig. 7) and in the upper portion of the member, and contribute to the irregular shape of some beds (Fig. 7). Beds in the core (locality 10, Plattsmouth Limestone) are similar in lithology and thickness to beds in northern exposures, although there is no chert. Limestone beds in the Stoner Limestone are typically laterally discontinuous and commonly exhibit a lenticular bedding shape (Fig. 10). The limestone beds lack chert and locally contain sutured stylolites with an amplitude of up to 1 cm. The Ervine Creek Limestone is very irregularly bedded (Fig. 11), with limestone beds that commonly

Figure 7.

Sketch of quarry face of the Plattsmouth Limestone at locality 5 showing irregular shape of limestone beds and character of the clay-rich zones (A to I). See Figure 8 for photograph of sketched area. Intervals 1 to 19 correspond to insoluble residue samples in Table 2 (106 to 124). 1 to 14 are limestone samples and 15 to 19 are from seams at a different portion of the outcrop that are placed next to their equivalent seams. Samples were not taken from seams in the sketch area due to their advanced weathering. Each tic mark on the sides of the figure equals 10 cm.



 CONCENTRATED SEAM

 DISCONTINUOUS SEAM

 BURROW FILLED WITH CLAY

 DIFFUSE SEAM

 CHERT

 VERY CONCENTRATED, TOP GRADATIONAL

Figure 8.

Sketch area; bars mark approximate limits of sketch. Datum bed marked by arrow. Locality 5, Plattsmouth Limestone. Hammer for scale.

Figure 9.

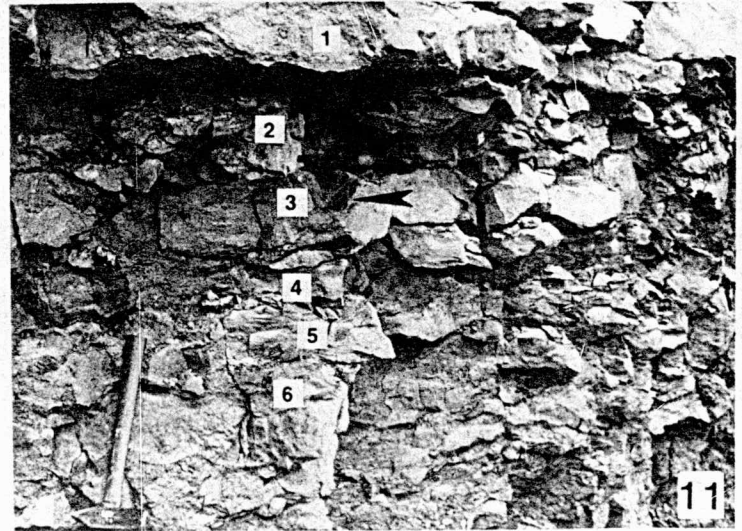
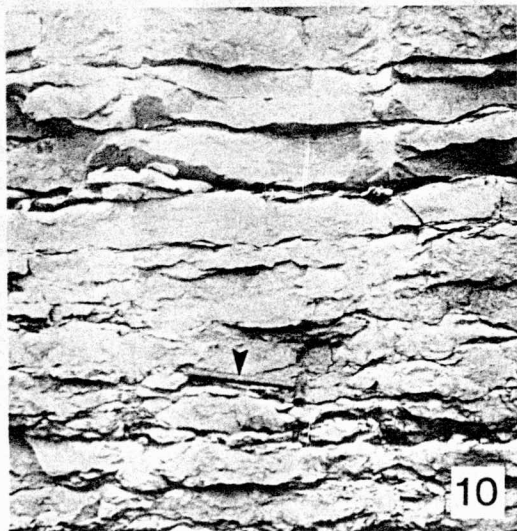
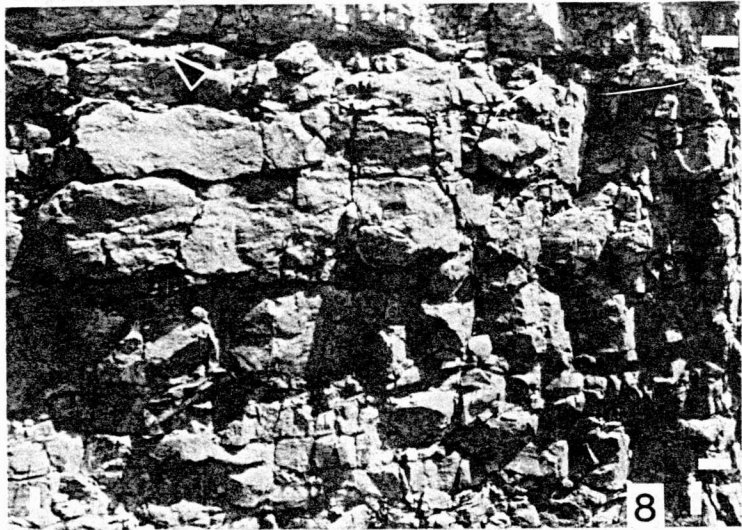
Bedding plane with gently rounded nodes (A) and antinodes. Locality 5, Plattsmouth Limestone. Hammer for scale.

Figure 10.

Weathered exposure of the Stoner Limestone at locality 13 with wavy to roughly planar and lenticular limestone beds. Hammer (arrow) for scale.

Figure 11.

Quarry exposure of the Ervine Creek Limestone, locality 14; 1 to 6 indicate six distinct limestone beds. Note large antinode (arrow).



cannot be with traced with confidence farther than a few meters. Chert nodules are not present.

Bioturbation has apparently destroyed any primary laminations within limestone beds in the three units. Burrows filled with clay are present below the datum bed (Fig. 7) throughout the study area. No clay-filled burrows were observed near any other zones.

Petrography

Texture and composition of the Plattsmouth, Stoner, and Ervine Creek limestones are similar; however, there are slight differences in lithology immediately adjacent to and within some zones (see Contrasts, p. 36). The limestones are typically skeletal wackestone but range from lime mudstone to skeletal packstone. Most limestone beds are mottled, with intervals that are muddy to slightly peloidal grading gradually or abruptly into areas that are less muddy and contain distinct peloids (Fig. 12). Fossils include bryozoans, crinoids, brachiopods, and fusulinids as well as the spar-filled molds of phylloid algae, gastropods, and bivalves. Such originally aragonitic organisms as phylloid algae, gastropods, and bivalves were leached, whereas calcitic organisms are preserved due to a more stable mineralogy. Nonferroan dolomite rhombs 10 to 40 micrometers in size are scattered throughout the limestone but increase in abundance near diffuse seams. Limestone beds contain a mean of 4.5 (SD of 2.0, n of 39) weight percent insoluble matter (Table 2 and Appendix IV).

Figure 12.

Photomicrograph of mottling in limestone bed. Intervals containing distinct peloids and calcite spar (A) are interspersed with intervals that are muddy to densely peloidal (B). Note molds (c). Scale bar equals 1 mm. Sample from locality 7, Plattsmouth Limestone.

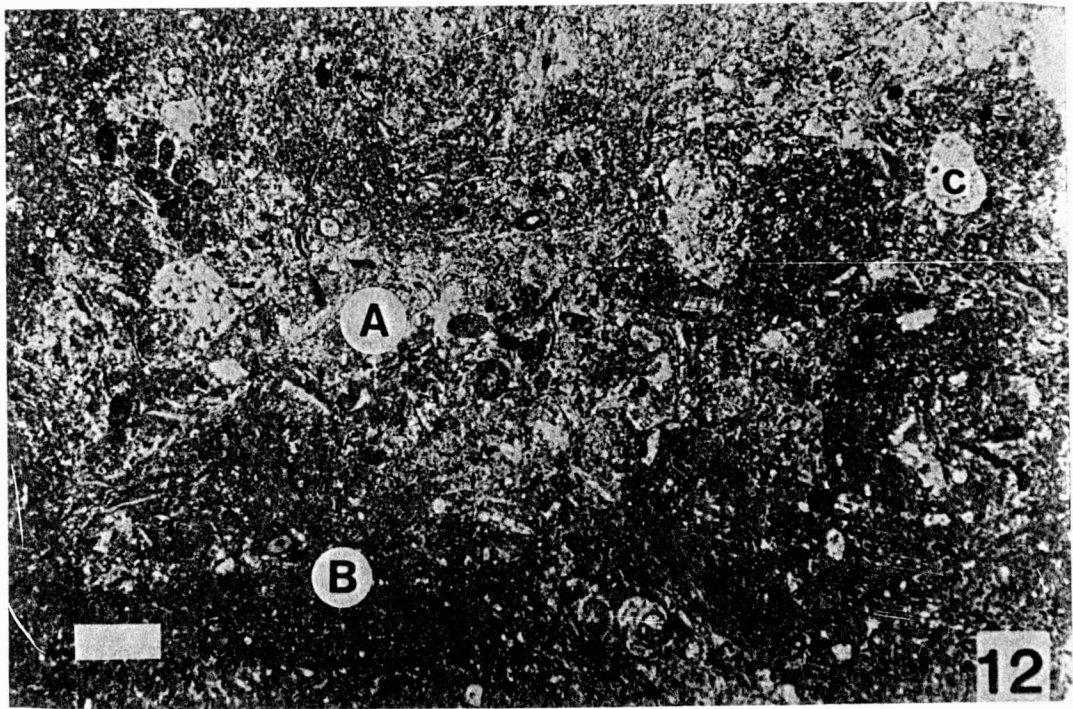


Table 2. Weight percent of insoluble residue and organic matter in seams and limestones. Values of organic matter were determined for the first 96 samples only (Appendix IV). Samples 1 to 88 (Plattsmouth Limestone core, locality 10) correspond to sample numbers in the core (Fig. V-A). 5-1, 5-2, and 5-3 (1 to 19) refer to sampled intervals in the Plattsmouth Limestone, locality 5; 5-2 and 5-3 (1 to 19) are pictured in Figures 30 and 7 respectively. Sampled interval 2-1 is from the Plattsmouth Limestone, locality 2, and sampled intervals 13-1 and 13-2 are from the Stoner Limestone, locality 13; 13-1 pictured in Figure 31. 14-1, 14-2, and 14-3 from the Ervine Creek Limestone, locality 14; 14-3 pictured in Figure 24. "S" denotes a seam sample and "SL" indicates the sample include a portion of a seam. *indicates sample from the datum bed.

SAMPLE	Wt.% Org./ Wt.% Insol.	SAMPLE	Wt.% Org./ Wt.% Insol.
	CORE		CORE
1	6/8.5	45	9/26 (S)
2	7/6.0	46	13/18 (S)
3	7/5.5	47	14/9.5 (SL)
4	7/14 (SL)	48	14/5.0
5	5/21 (S)	49	17/5.5
6	7/12 (SL)	50	16/5.0
7	9/5.5	51	5/90 *
8	8/8 (SL)	52	8/14.0
9	8/10 (SL)	53	9/9.5
10	8/5.0	54	10/6.0
11	10/5.0	55	11/7.0
12	9/5.5	56	9/11.0
13	11/5.5	57	8/29 (S)
14	8/5.5	58	12/5.5
15	9/5.5	59	13/6.0
16	12/5.5	60	10/10 (SL)
17	14/8.0	61	11/6.0
18	12/16 (S)	62	13/2.5
19	11/10 (SL)	63	9/26 (S)
20	13/9.0	64	9/3.0
21	8/5.5	65	8/3.0
22	8/7.0	66	11/1.5
23	8/7.0	67	10/3.0
24	8/16 (S)	68	11/2.0
25	7/16 (S)	69	12/2.5
26	9/8.0	70	7/25 (S)
27	11/8.0	71	10/2.5
28	10/11.0	72	10/2.5
29	7/19 (S)	73	9/3.0
30	7/25 (S)	74	11/8.0
31	9/24 (S)	75	9/23 (S)
32	9/15 (SL)	76	12/4.0
33	9/10.0	77	17/2.5
34	11/8.5	78	11/5.5
35	9/7.5	79	17/14 (SL)
36	8/19 (S)	80	21/2.0
37	10/26 (S)	81	19/2.0
38	8/28 (S)	82	23/2.0
39	7/11 (SL)	83	15/3.5
40	7/3.5	84	8/30 (S)
41	6/3.0	85	11/4.0
42	9/4.0	86	10/4.0
43	8/5.0	87	7/19 (S)
44	8/27 (S)	88	9/5.0

Continued on next page

SAMPLE	Wt.% Org./ Wt.% Insol.	SAMPLE	Wt.% Insol.
	5-1		5-3(1-19)
89	25/21 (S)	122	16 (S)
90	17/7.0	123	42 (S)
91	18/27 (S)	124	34 (S)
	5-2		13-1
92	9/31 (S)	125	3.5
93	8/10.0	126	41 (S)
94	8/11.0	127	4.0
95	9/3.5	128	25 (S)
96	11/3.5	129	5.0
	2-1		130
97	5.0	131	23 (S)
98	4.5	132	3.0
99	4.5	133	2.5
100	4.5	134	2.0
101	4.5	135	2.5
102	4.0	136	4.5
103	5.5		13-2
104	6.0	137	18 (SL)
105	13 (SL)	138	4.0
	5-3(1-19)	139	4.0
106	10.5	140	2.5
107	5.0		14-1
108	8.5	141	4.0
109	5.5	142	4.0
110	3.0	143	4.5
111	4.5	144	14 (S)
112	3.5	145	11 (S)
113	2.5	146	20 (S)
114	3.0		14-2
115	3.0	147	4.0
116	3.0	148	5.5
117	6.0	149	23 (S)
118	3.5		14-3
119	3.5	150	26 (S)
120	28 (S)	151	9.5
121	41 (S)	152	45 (S)

Clay-rich Zones

Field Work

Clay-rich zones in the Plattsmouth Limestone differ in thickness and form both laterally along zones and from zone to zone. Changes in lateral thickness generally occur within a few tens of centimeters, although changes in thickness do not occur in regular, predictable sequence. Thinner portions of zones generally consist of a single seam that typically has a sharp to slightly gradational contact with adjacent limestone and contains a uniform accumulation of clay with scattered fossils (Figs. 7, 13, 14). Thicker portions of the zones consist of either a diffuse seam composed of numerous subparallel microstylolites (Fig. 13) or of several seams that may be concentrated or diffuse (Figs. 7, 14, 15). Diffuse seams commonly have a patchy to wispy appearance (Figs. 7, 14), and some seams die out into the adjacent limestone (Figs. 7, 15). Most zones are a few millimeters to approximately 1 cm thick in single-seam portions, typically expanding to a thickness of 2 to 5 cm in thicker portions. The zones are symmetrical in concentration; i.e., they tend to be equally diffuse or concentrated at upper and lower contacts. Thicker portions of zones commonly contain lensoidal nodules of limestone that are partially to fully enclosed by seams (Figs. 7, 14, 15). Seams that are 5 mm or less thick and that are laterally discontinuous and lack an connection to adjacent zones are present within some limestone beds (Fig. 7). These seams are usually only a few tens of centimeters long, although some can be traced for several

Figure 13.

Zone that changes laterally to the left from a concentrated single seam (at pencil) to a thicker, diffuse seam composed of microstylolites and thin discontinuous seams. Locality 5, Plattsmouth Limestone.

Figure 14.

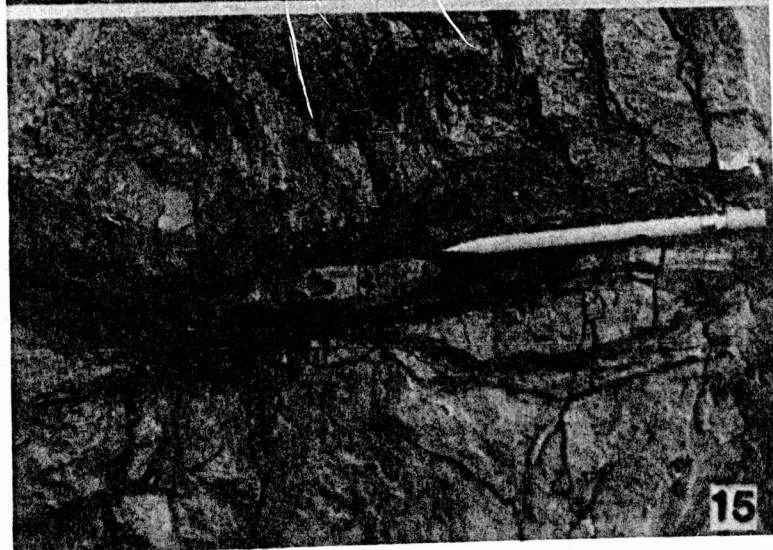
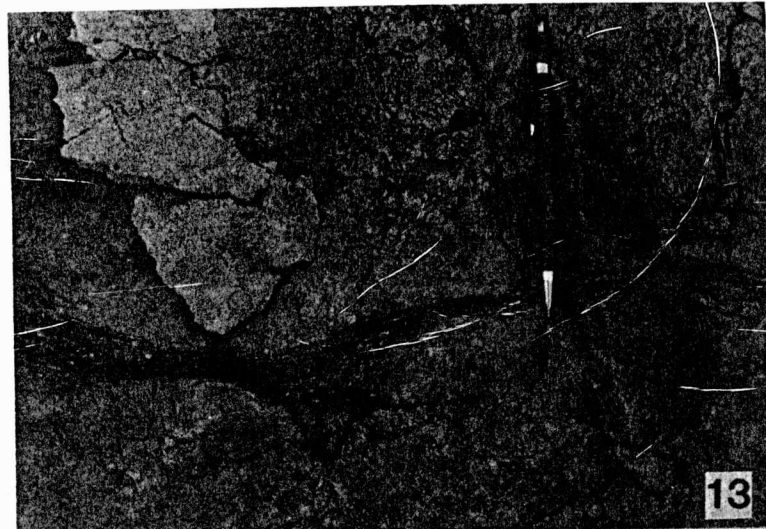
Zone composed of several seams that are fairly concentrated at left and become increasingly diffuse and wispy to the right. Seams enclose lensoidal nodules of limestone. Locality 5, Plattsmouth Limestone.

Figure 15.

Zone containing several lensoidal nodules of limestone that have sharply defined boundaries with seams. Some seams die out into the adjacent limestone (arrow). Locality 5, Plattsmouth Limestone.

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meters. Variations in the form of the zones is not enough to account for the varying relief of adjacent limestone beds; i.e., seams tend to follow changes in the shape of the limestone beds rather than creating these changes in shape by changing thickness laterally.

The datum bed (Fig. 7) is thicker than most zones and consists of single concentrated seam. Although it thickens and thins in an irregular fashion (Fig. 7), it is more planar overall than the other zones. The datum bed and most other zones can easily be traced the length of a single quarry exposure (Fig. 16) and can be correlated for 71 km between localities 1 to 8 (Figs. 17, 18). The datum bed can be traced an additional 60 km to locality 10 (Figs. 6, 18).

Most clay-rich zones exhibit similar thickness and form over the outcrop area, although some zones change character within and between outcrops. For example, zone E (Fig. 18) is locally absent at locality 5, and zone C (Fig. 18) consists of a single seam at most localities but apparently changes to two thin seams at locality 3 (Fig. 18). The datum bed maintains a similar shape throughout the correlation area but is the only zone that increases in thickness. The datum bed is approximately 4 cm thick at locality 1 (Figs. 17, 18), increases to about 10 cm at locality 8, and is approximately 20 cm thick at localities 9 (Fig. 6), and 10 (Figs. 6, 18). The datum bed is not present at localities 11 and 12 (Fig. 6).

Zones in the core of the Plattsmouth Limestone (Fig. 6) are similar in thickness and form to zones in northern localities (Figs. 18, V-A). The zones consist of concentrated or diffuse seams;

Figure 16.

Lateral extent of beds in the lower portion of the Plattsmouth Limestone, below the datum bed (arrow). The exposure is approximately 4.5 m thick; water bottle (A) is approximately 30 cm long. Locality 5.

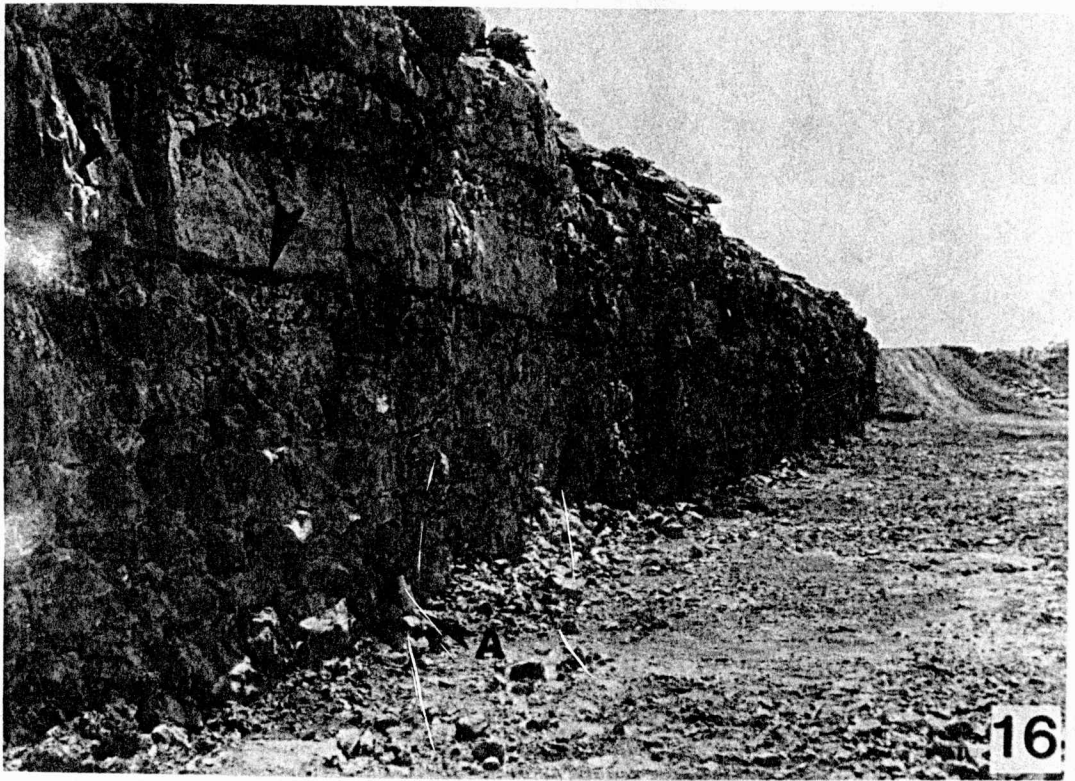
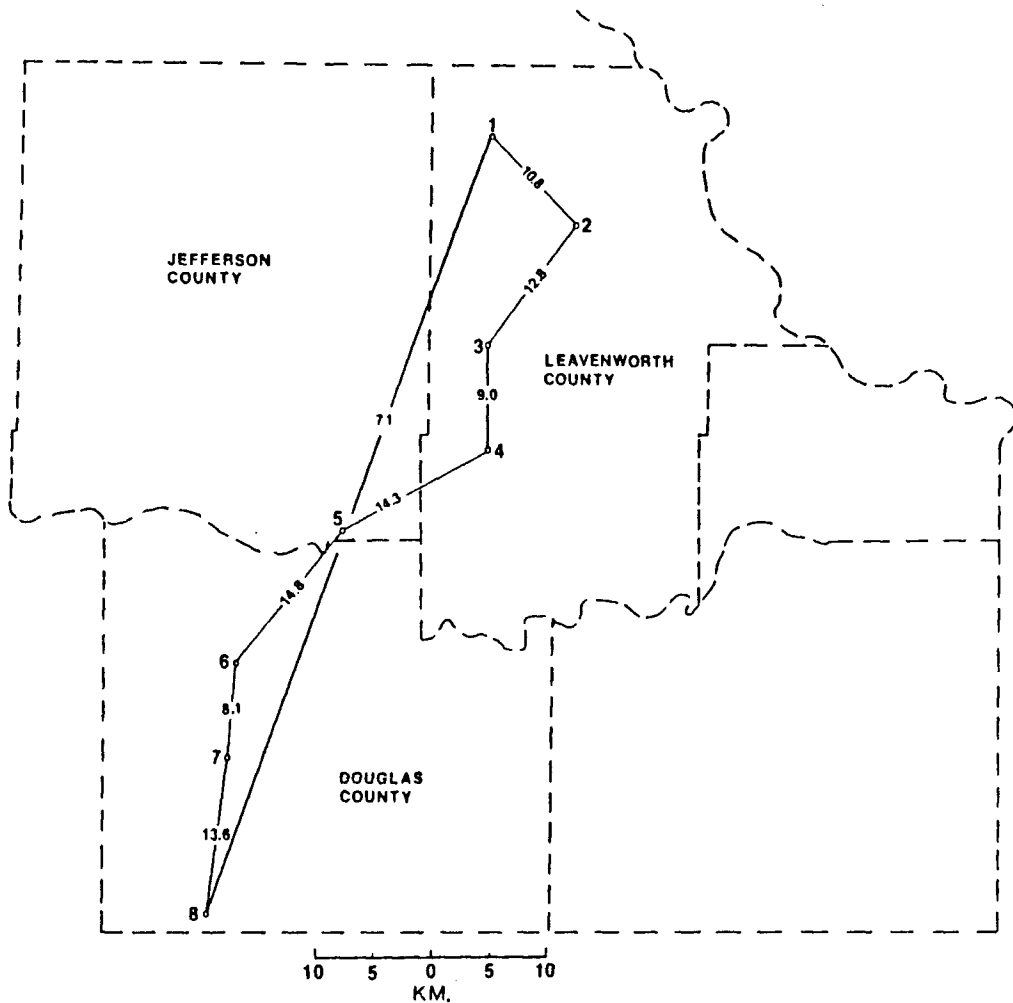


Figure 17.

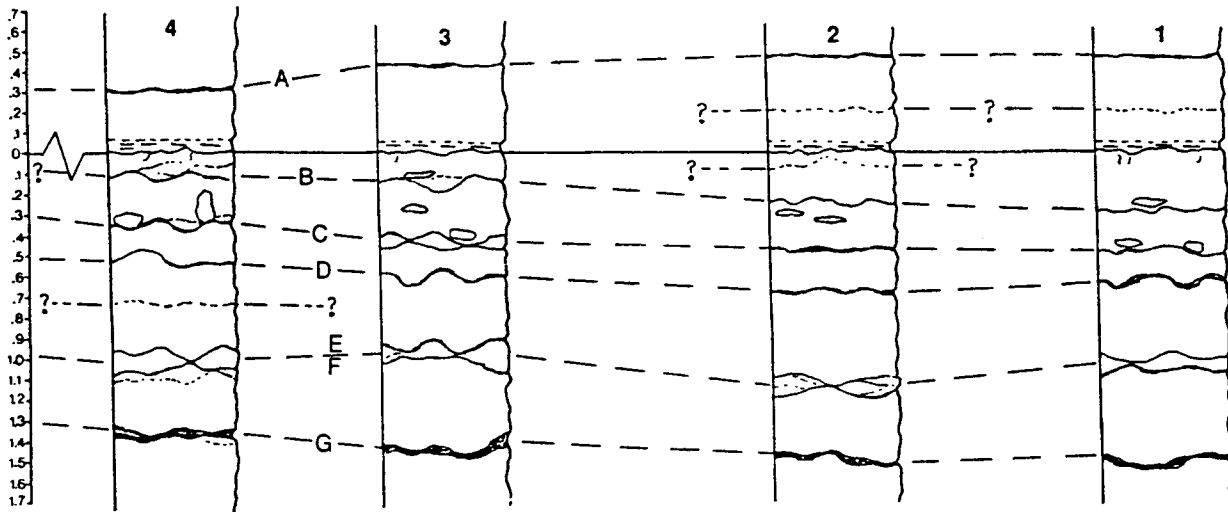
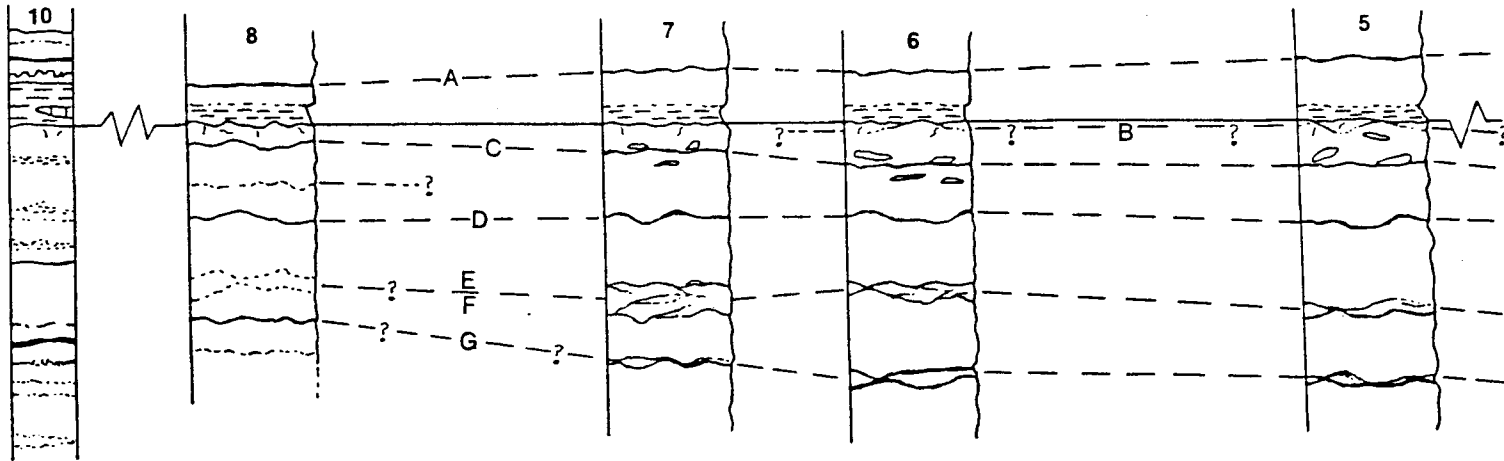
Locations of correlated sections. Numbers next to locations correspond to locality numbers in figure 6. Numbers between localities show distance in kilometers.







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N

Figure 18.

Correlation of clay-rich zones between eight exposures of the Plattsmouth Limestone, localities 1-8 (Fig. 17). The section at Locality 10 (core), approximately 60 km from locality 8 (Fig. 6) is included for comparison of zones and to show lateral continuity of the datum bed. Vertical scale marked in meters.



-  DATUM BED
-  CHERT NODULES
-  BURROWS FILLED WITH CLAY
-  DIFFUSE, DISCONTINUOUS SEAMS

however, diffuse seams contain few distinct microstylolites and are characterized instead by patchy, diffuse accumulations of clay (Fig. 19).

Zones in the Stoner and Ervine Creek limestones, like zones in the Plattsmouth Limestone, exhibit changes in thickness and form both laterally along zones and from zone to zone. Zones in the Stoner Limestone, however, are commonly laterally discontinuous and are more diffuse than zones in the Plattsmouth Limestone, with one or more thin seams (Fig. 20) or a diffuse grouping of microstylolites and thin seams (Fig. 21). Zones in the Ervine Creek Limestone are characterized by abrupt changes in form, generally passing laterally from a single seam to intervals with a patchy, irregular distribution of clay and few distinct microstylolites.

Petrography

Microstylolites are the smallest discrete accumulations of clay in the zones. Microstylolites vary from thin distinct films, approximately 100 micrometers thick (Figs. 22, 23), to diffuse, wispy accumulations of clay that can barely be distinguished (Fig. 24). Microstylolites are planar to undulose and locally sutured; they can be traced laterally only a few millimeters to centimeters before they either diffuse and die out into the limestone or join thicker accumulations of clay (Figs. 22, 23). Microstylolites commonly wrap around and truncate fossils (Figs. 22, 23) and preferentially occur adjacent to fossils in some areas. In thin section they appear as irregular zones containing clay, organic matter, and dolomite (Figs.

Figure 19.

Zone in the Plattsmouth Limestone core composed of patchy, diffuse accumulations of clay. Scale bar marked in centimeters. Locality 10.

Figure 20.

Zone in the Stoner Limestone composed of several distinct seams that converge to the right. Locality 13.

Figure 21.

Zone in the Stoner Limestone composed of microstylolites (A) and a wispy seam (B). Knife for scale. Locality 13.

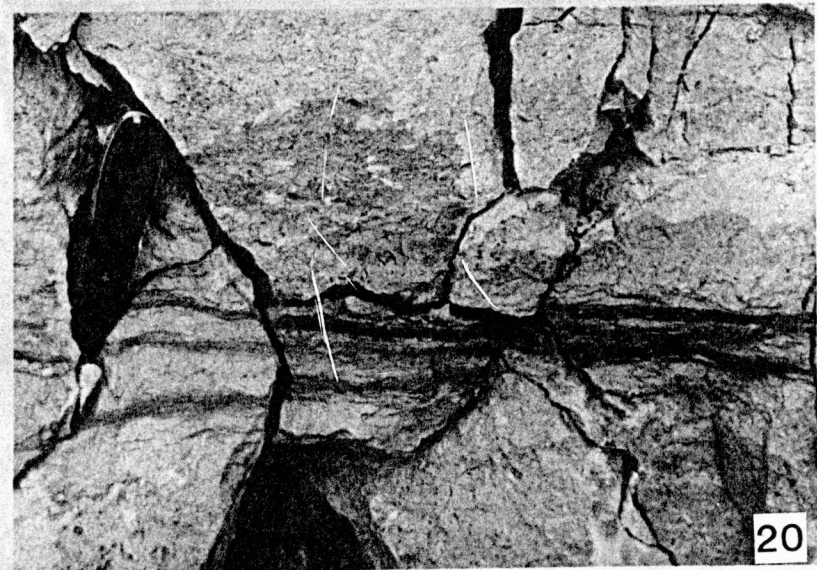
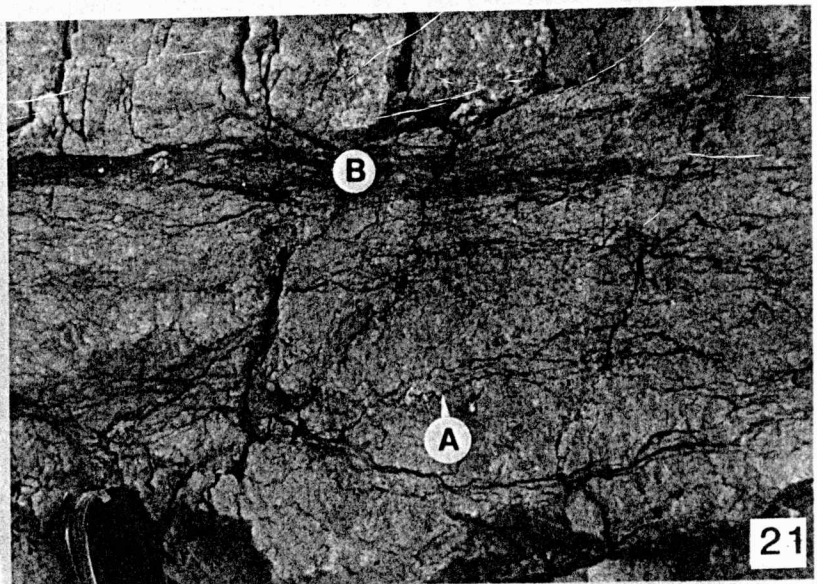


Figure 22.

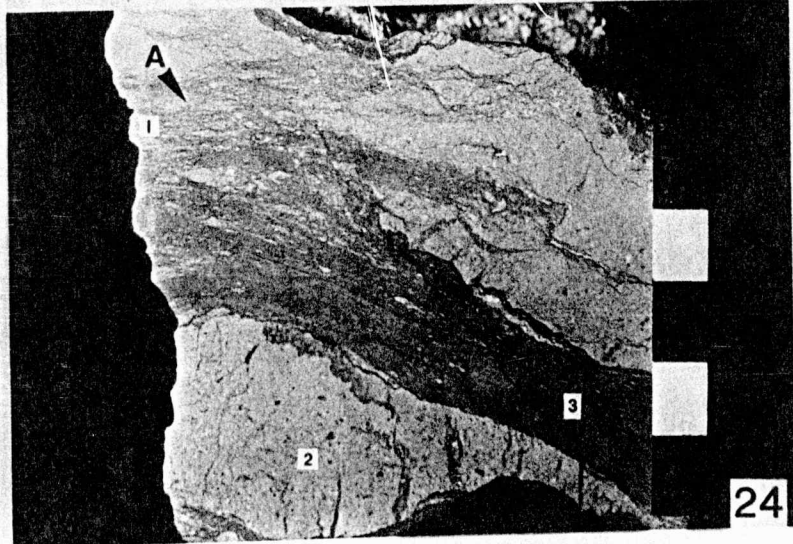
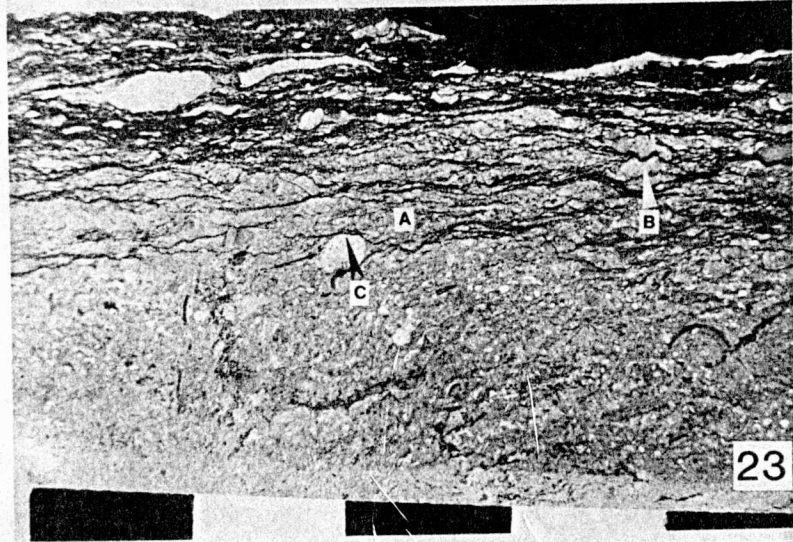
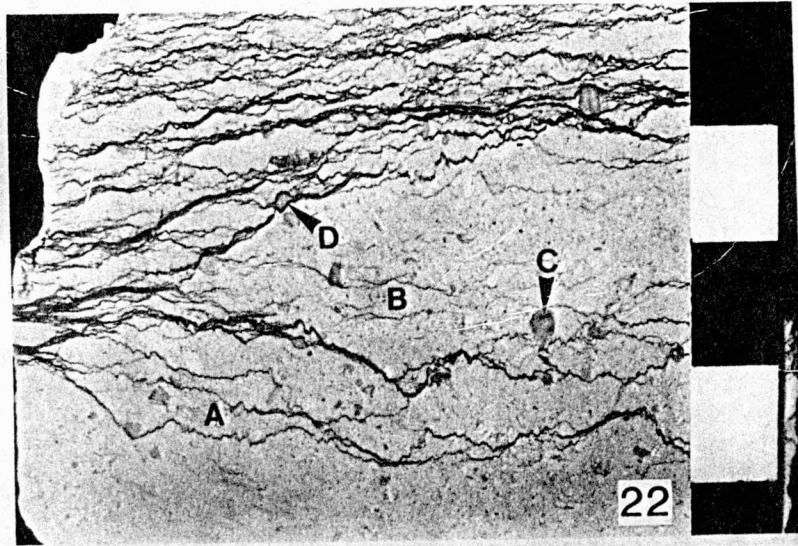
Diffuse zone, with sutured (A) and more undulose (B) microstylolites. Dark spots (C) are crinoid fragments. Microstylolites wrap around some fossils (D). Scale bar marked in centimeters. Sample from locality 13, Stoner Limestone.

Figure 23.

Seam with well-defined microstylolites (black laminae above and below A). Note interpenetrant grains (B). Microstylolites wrap around and truncate some fossil fragments (C). Scale bar marked in centimeters. Sample from locality 5, Plattsmouth Limestone.

Figure 24.

Seam that varies laterally from concentrated to diffuse, with anastomosed, diffuse microstylolites (A). 1 to 3 indicate insoluble residue samples (Table 2, 150 to 152). Scale bar marked in centimeters. Sample from locality 14, Ervine Creek Limestone.



25, 26).

Thick accumulations of clay contain such scattered fossils as crinoids, brachiopods, fusulinids, and bryozoans but no molds of fossils in a matrix of clay, dolomite, organic matter (Figs. 27, 28), and argillaceous lime mud (in diffuse accumulations, Fig. 29). The fossils are commonly crushed, truncated, and interpenetrant (Figs. 27, 29). Crinoids were the most resistant to crushing and dissolution. Dolomite that is associated with the microstylolites and thicker accumulations of clay (Figs. 26, 28) typically ranges in size from 10 to 40 micrometers; the rhombs are largely nonferroan but can have ferroan rims. Ferroan dolomite is locally abundant in intraskeletal porosity. Dissolution of dolomite adjacent to microstylolites was not observed. Results of x-ray analysis (Table 3) show that seams in the Plattsmouth Limestone contain amounts of dolomite that vary from less than 5 percent to more than 30 percent. The dolomite is slightly calcium rich (55 mole percent to 58 mole percent, Table III-A). Seams, excepting the datum bed which contains 90 weight percent insolubles, contain from approximately 10 to 40 weight percent of insolubles, with a mean of 27 (SD of 8, n of 27) weight percent (Table 2 and Appendix IV).

Figure 25.

Photomicrograph of anastomosed microstylolites. Scale bar equals 1 mm. Sample from locality 5, Plattsmouth Limestone.

Figure 26.

Photomicrograph of anastomosed microstylolites (A). Note dolomite (B). Scale bar equals 50 micrometers. Sample from locality 5, Plattsmouth Limestone.

Figure 27.

Photomicrograph of concentrated seam, with broken fossils in a matrix rich in insoluble matter and dolomite (small light points, arrow). Scale bar equals 500 micrometers. Sample from locality 10, Plattsmouth Limestone.

Figure 28.

Photomicrograph of dolomite in a concentrated seam. Scale bar equals 50 micrometers. Sample from locality 5, Plattsmouth Limestone.

Figure 29.

Photomicrograph of diffuse seam, with numerous microstylolites (wispy black laminae, A); limestone (B); and interpenetrant (C) and crushed fossils. Scale bar equals 1 mm. Sample from locality 5, Plattsmouth Limestone.

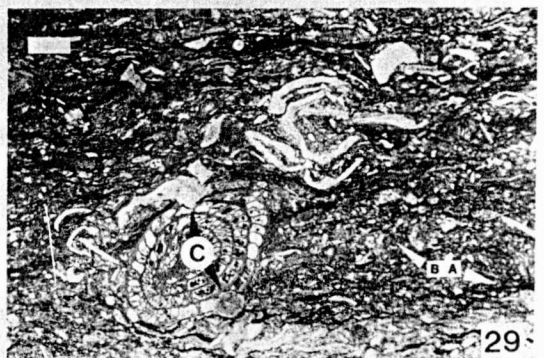
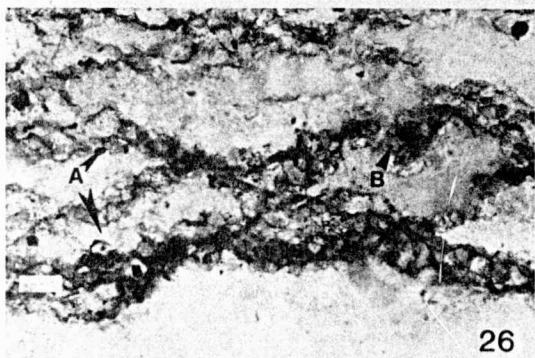
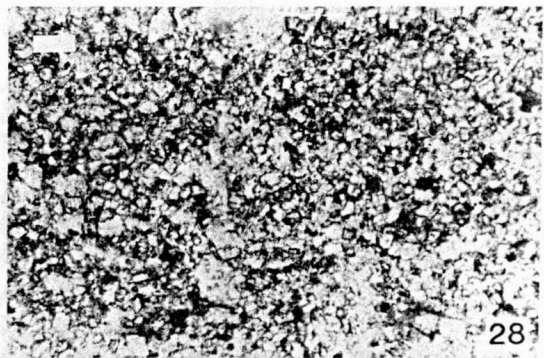
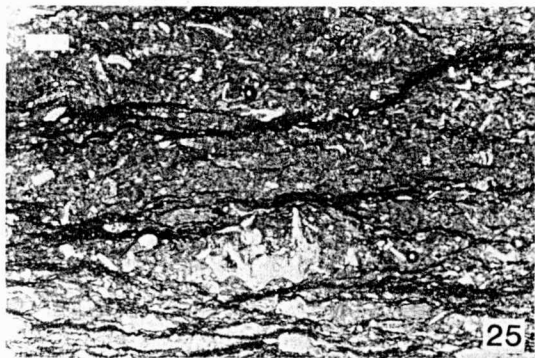


Table 3. Dolomite concentrations in seams. Numbers (e.g. #30) refer to insoluble residue samples (Table 2); sample 2 is not listed in the table. * indicates that the correction factor (Table III-A) yields a negative figure; this sample probably has a few percent dolomite.

SAMPLES	WT. % DOLOMITE
1 core #30	33
2 outcrop	3
3 outcrop #91	5
4 core #57	0*
5 core #44	21
6 outcrop #124	11
7 outcrop #121	15

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Contrasts Within and Between Clay-rich Zones and Limestone Beds

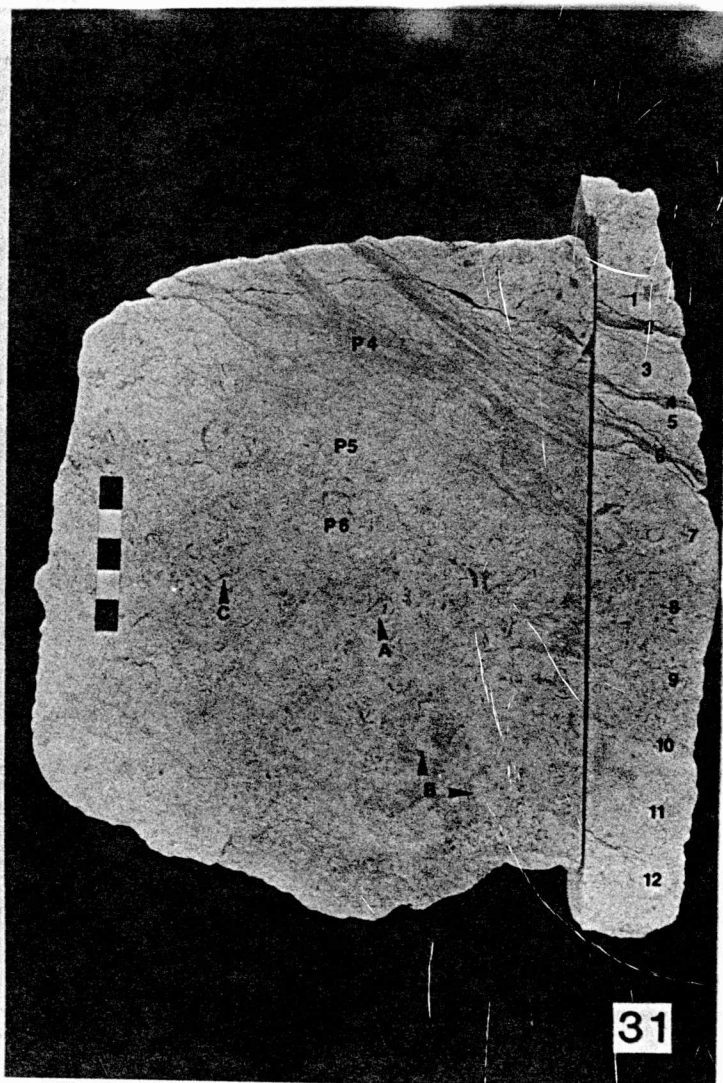
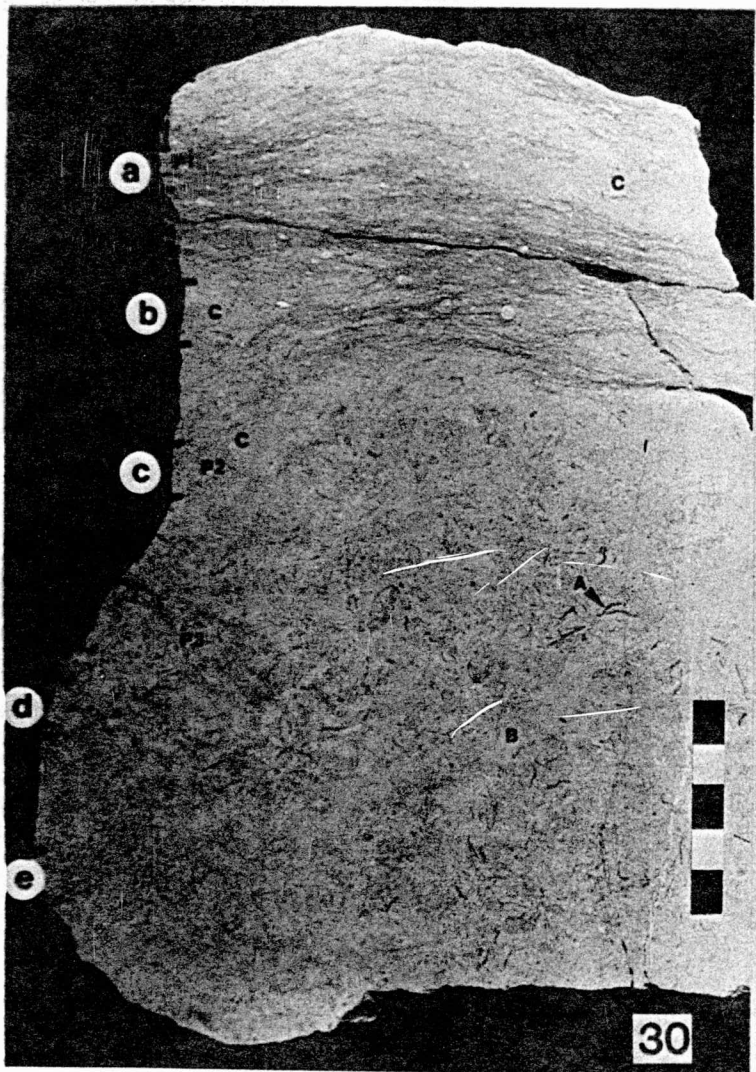
As previously described, zones can vary in form from a single seam with uniform concentration of clay to an interval with diffuse to concentrated seams interspersed with limestone. This interspersed limestone contains a slight to marked increase in lime mud, decrease in the abundance of fossil molds, and an increase in clay content as compared to adjacent limestone beds. This change in lithology is most pronounced in the Stoner Limestone and in a few zones in the Plattsmouth Limestone (Figs. 30, 31). In these examples the limestone bed away from the zone is mottled, with muddy areas, probably burrows, interspersed with less muddy areas containing loosely packed peloids and fossils in a sparry matrix (Figs. 30, 31, 32). Fossil molds of phylloid algae, gastropods, and bivalves are common. In contrast, limestone near and within the zones is rich in lime mud, contains increased insolubles, and has few or no fossil molds (Figs. 30, 31, 33). Fossils in these limestone intervals are more commonly broken and interpenetrant (Fig. 34) than in the adjacent limestone beds. Point counts (Table 4) emphasize differences in fossil content between seams, muddy limestone immediately adjacent to them, and limestone beds. Seams contain no molds and an average of twice as many calcitic fossils as adjacent limestone (Table 4). Such possible remnants of fossil molds as crushed micrite envelopes were not observed in seams or limestone. There is no distinct change in the types of calcitic fossils from limestone to seam; crinoids,

Figure 30.

Sample with a distinct difference in texture and composition adjacent to and within a thick zone with diffuse, wispy seams (top of sample). Limestone below the zone contains abundant molds of fossils (predominantly phylloid algae (A)), and muddy burrows (B) in a matrix that is less muddy (Fig. 32). Limestone immediately adjacent to and within the zone (C) is muddier, more nonmoldic, and richer in insolubles than the the limestone bed below. Intervals a to e correspond to insoluble residue samples (Table 2, 92 to 96). P1 to P3 mark general locations of point counts (Table 4). Scale bar marked in centimeters. Sample from locality 5, Plattsmouth Limestone.

Figure 31.

Sample similar to the sample in Figure 30, with a distinct change in texture and composition adjacent to and within the zone. Limestone above and below the zone contains abundant molds of fossils (A) and muddy burrows (B) in a sparry matrix. Some of the burrow fill is fractured (C), but fractures do not extend into the surrounding limestone. Limestone associated with the zone contains more lime mud and clay and fewer molds than the limestone above and below the zone. Intervals 1 to 12 correspond to insoluble residue samples listed in Table 2 (125 to 136). P4 to P6 correspond to point-count intervals (Table 4). Scale bar marked in centimeters. Sample from locality 13, Stoner Limestone.



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Figure 32.

Photomicrograph of mottled limestone in sample pictured in Figure 30, with fossil molds (A), areas that are muddy to peloidal (B), and areas with calcite spar and distinct peloids (C). Scale bar equals 1 mm. Sample from locality 5, Plattsmouth Limestone.

Figure 33.

Photomicrograph of limestone within zone in sample pictured in figure 30, characterized by a muddy to faintly peloidal texture and scattered calcitic fossils. Scale bar equals 1 mm. Sample from locality 5, Plattsmouth Limestone.

Figure 34.

Photomicrograph of limestone within a zone, with interpenetrant (A) and broken (B) fossils. Scale bar equals 1 mm. Sample from locality 5, Plattsmouth Limestone.

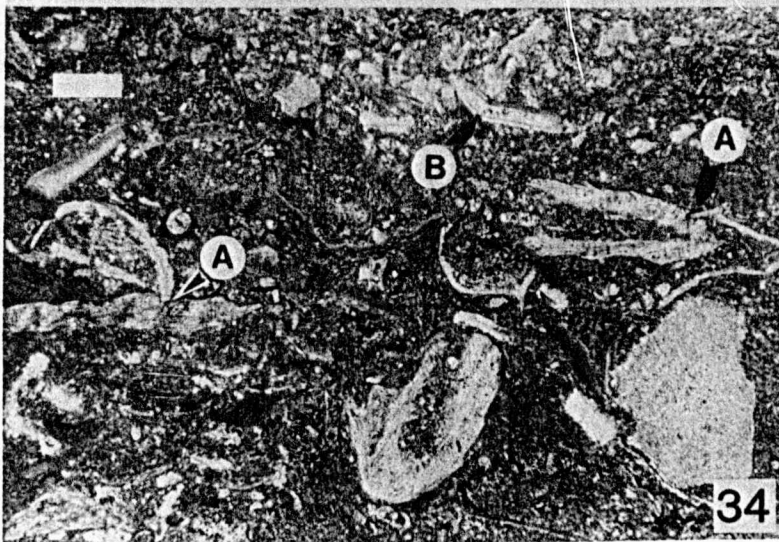
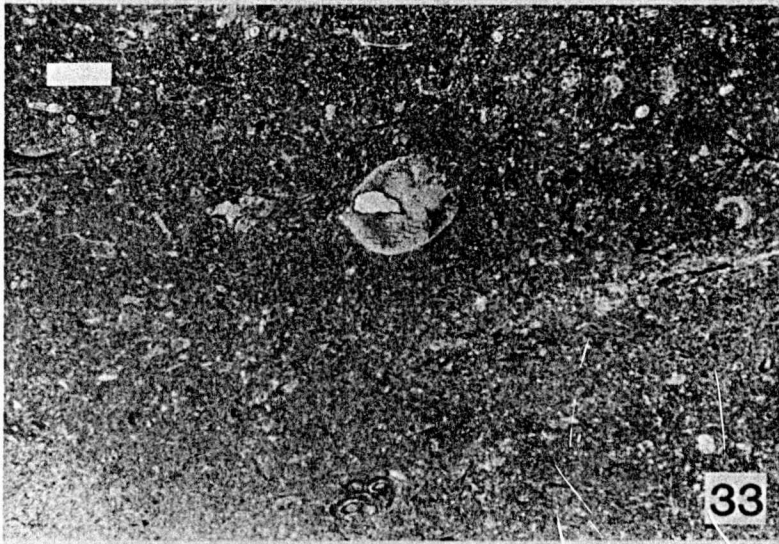
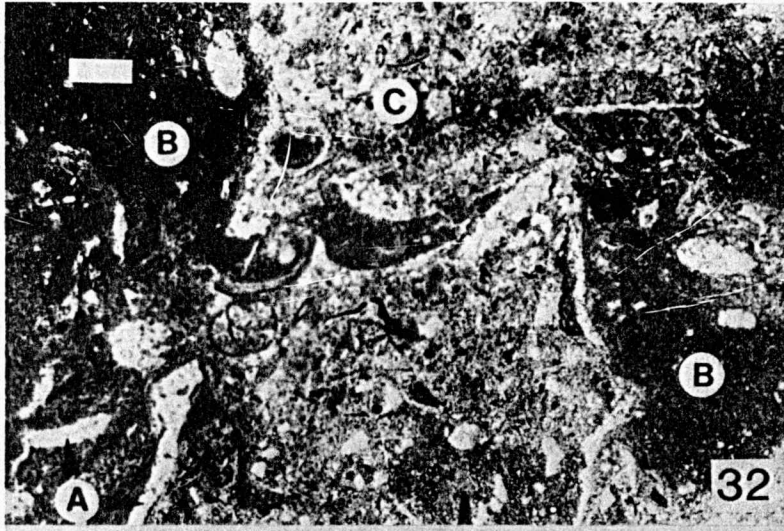


Table 4. Point count results for seams, limestone immediately adjacent to diffuse seams (LS NM), and limestone beds (LS). Point counts P1 to 3, P4 to 6 correspond to intervals in samples pictured in Figures 30 and 31 respectively; and point counts P11 to 14 correspond to intervals in the core pictured in Figure V-A. Values are percentages (top figure) from 400 point counts. The lower figure is the percentage of the particular fossil to the total number of calcitic fossils in the point count. *1 includes such other fossils as other foraminifera and ostracodes. *2 are primarily small fossil fragments that are too degraded for identification, most probably brachiopod or bryozoan fragments. *3 seam matrix consists of clay, organic matter, dolomite, and lime mud (in diffuse seams); limestone matrix consists of limestone and minor dolomite. *4 total percentage of calcitic and moldic fossils. *5 total percentage of calcitic fossils. Insoluble residue values were previously determined and are included to aid later interpretation. *6 indicates estimated weight percent of insoluble residue (samples taken within about one centimeter of the point-count interval). Seams contain an average of two times as many calcitic fossils as adjacent limestone (SD of 0.5, n of 7).

COMPONENTS	P1	P2		P3	P4	P5		P6	P7		P8
	SEAM	LS	NM	LS	SEAM	LS	NM	LS	LS	NM	LS
CRINOID	3.25 21.0	0.25 4.2		0.25 4.0	4.0 48.5	1.0 22.2		3.75 46.9	2.5 25.6		1.25 35.7
BRYOZOAN	3.75 24.2	0.75 12.5		2.0 32.0	2.0 24.2	1.25 27.8		2.5 31.2	2.5 25.6		0.75 21.4
BRACHIOPOD	4.75 30.6	2.25 37.5		1.25 20.0	0.75 9.1	0.5 11.1		0 0	0.5 5.1		0 0
FUSULINID	0 0	0.25 4.2		0.25 4.0	0 0	0.5 11.1		0 0	2.75 28.2		0.5 14.3
OTHER *1	1.25 8.1	1.25 20.8		2.0 32.0	1 12.1	1.25 27.8		1.75 21.9	1 10.3		0.5 14.3
UNKNOWN *2	2.5 16.1	1.25 20.8		0.5 8.0	0.5 6.1	0 0		0 0	0.5 5.1		0.5 14.3
FOSSIL MOLDS	0	0.75		13.75	0 0	1.75 7		8.25 33	0.5 2		10.5 42
MATRIX *3	84.5	93.25		80.0	91.75	93.75		83.75	89.75		86.0
TOTAL FO.*4	15.5	6.75		20.0	8.25	6.25		16.25	10.25		14.0
TOTAL FO. W/O MO. *5	15.5	6.0		6.25	8.25	4.5		8.0	9.75		3.5
INSOLUBLE RESIDUE	31%	10.0%		3.5%	25%	4.5%		2.5%	4.0%		2.5
				est.*6	est.	est.		est.			

Continued on following page.

COMPONENTS	P9 SEAM	P10 LS NM	P11 SEAM	P12 LS	P13 SEAM	P14 LS
CRINOID	3.5 17.7	2.0 22.2	1.5 18.2	0.75 16.7	0.75 14.3	0 0
BRYOZOAN	4.0 20.3	1.75 19.4	1.75 21.2	1.5 33.3	0.5 9.5	0.25 9.1
BRACHIOPOD	9.25 46.8	4.25 47.2	3.0 36.4	1.5 33.3	3.5 66.7	2.0 72.7
FUSULINID	0.5 2.5	0 0	0 0	0 0	0 0	0 0
OTHER *1	0.5 2.5	0.75 8.3	0.5 6.1	0.5 11.1	0 0	0.5 18.2
UNKNOWN *2	2.0 10.1	0.25 2.8	1.5 18.2	0.25 5.6	0.5 9.5	0 0
FOSSIL MOLDS	0 0	0.75 3	0 0	10.0 40	0 0	14.5 58
MATRIX *3	80.25	90.25	91.75	85.5	94.75	82.75
TOTAL FO. *4	19.75	9.75	8.25	14.5	5.25	17.25
TOTAL FO. W/O MO. *5	19.75	9.0	8.25	4.5	5.25	2.75
INSOLUBLE RESIDUE	23% est.	7.0% est.*6	25%	5.0%	27%	8.0%

bryozoans, and brachiopods are the most abundant fossils and occur in roughly the same percentages in seams and limestone (Table 4).

Composition of insoluble residues in seams and adjacent limestone is similar, with clay the most abundant constituent and lesser amounts of quartz silt, organic matter, silicified fossils, and pyrite. Insoluble residues of the seams contain larger, more concentrated masses of organic matter than the insoluble residues of the limestones; however, the ratio of organic matter to total insolubles varies little (mean of 10 (SD of 4, n of 32) weight percent in seams versus a mean of 11 (SD of 4, n of 63) weight percent in limestones, Table 2 and Appendix IV).

Clay-rich zones in the Plattsmouth, Stoner, and Ervine Creek limestones differ in form and composition. Zones in the Stoner Limestone generally contain numerous seams and well-defined microstylolites (Figs. 20, 21, 22). Zones in the Plattsmouth Limestone tend to be more concentrated, with microstylolites that are diffuse to distinct (Figs. 14, 15, 23). The Ervine Creek Limestone and the Plattsmouth Limestone (core, locality 10) (Figs. 19, 24) are characterized by concentrated to diffuse seams with few distinct microstylolites. The datum bed differs significantly in form and composition from the other zones, as summarized in Table 5.

TABLE 5. Comparison between datum bed and other clay-rich zones

	Datum bed	Other zones
Zone shape and continuity	Roughly uniform thickness with gradational top and sharp base; thickens laterally; was correlated for approximately 130 km.	Changes laterally from a single seam to multiple seams; zones can be discontinuous but some are correlated for approximately 70 km.
Insoluble residue content	Predominantly clay; up to 90 weight percent.	Composition similar to datum bed; mean of 27 weight percent in seams.
Chemical compaction features	No chemical compaction features observed.	Contain microstylolites, and interpenetrant and truncated fossils.
Fossil content	Very few fossils; no fossil molds.	Fossils more abundant in seams than in adjacent limestone; few or no fossil molds.

INTERPRETATIONS

Primary Characteristics of Clay-rich Zones

Clay

The datum bed contained a high primary clay content, as indicated by the clay-filled burrows below the bed. It is less clear, however, that the other zones contained such a primary increase in clay, because mechanical and chemical compaction and burrowing tend to mask any original increase. Limestone associated with zones commonly has more clay than the adjacent limestone (Figs. 30, 31). This transitional clay-rich limestone is likely to be an indication of a higher initial clay content in the zones. The amount of clay originally in zones can be estimated by comparing the abundance of calcitic fossils in the seams with the abundance of calcitic fossils in adjacent limestones. The abundance of calcitic fossils and the ratio of moldic to calcitic fossils were probably similar in the primary zones and the adjacent limestone, as suggested by the evidence of burrowing (see p. 44). The seams that were point counted (Table 4) contain about twice as many calcitic fossils as the adjacent limestone, suggesting that concentration of the seams was doubled as the result of dissolution of lime mud. These seams contain 23 to 31 weight percent of insolubles (Table 4), so the initial concentration of insolubles in the seams prior to chemical compaction may have ranged from approximately 12 to 16 weight percent.

Clay-rich zones can be correlated for considerable distances

(Figs. 17, 18), suggesting widespread influx of clay or reduction in supply of carbonate sediment. The datum bed thickens to the south (Fig. 18), suggesting an influx of clay from a southern source, although it cannot be identified in southernmost exposures (localities 11 and 12, Fig. 6). Other zones do not thicken laterally; however, the greater amount of clay in the zones probably resulted from influx of clay because 1) no hardgrounds were observed, whereas pauses or reductions in carbonate supply that are not the result of an influx of clay may result in the formation of hardgrounds (cf. Kennedy and Garrison, 1975), and 2) influxes of clay occurred, as indicated by the lateral continuity and thickening of the datum bed. In addition, the regional depositional environment favors the occurrence of detrital pulses, with sources of sediment from the Ouachita Mountains to the south, and possibly from highlands to the east (Fig. 4, see also Wanless et al. 1970; Heckel 1977, 1980, 1984; Ball 1983; Ball 1985). The composition of insoluble residue in the clay-rich zones and adjacent limestone beds is similar, suggesting a similar source.

Other Primary Characteristics

Seams and some adjacent limestones (e.g. Figs. 30, 31) lack fossil molds; it is possible, however, that lack of molds is due to diagenesis (see p. 45). Limestone within and immediately adjacent to some zones is commonly slightly muddier than adjacent limestone beds, suggesting a primary depositional change. The muddy, compact character of limestone within the zones, however, may have resulted

in part from mechanical compaction that was greater than in adjacent limestone beds (see p. 47). The datum bed contains few fossils, suggesting that the clay influx caused decreased biologic productivity or possibly diluted the fossils. The lack of fossil molds in the datum bed could be due to the change in environment associated with the large influx of clay or to diagenesis (see p. 45).

Diagenetic Modifications

Burrowing

Limestone beds underwent thorough burrowing, as indicated by mottling and lack of laminae. The clay-rich zones were probably also burrowed, as limestone associated with the zones is muddy to slightly mottled with an even distribution of fossils. Thorough burrowing of a thin seam with an initially high percentage of clay could result in formation of a broad zone with slightly higher clay content than adjacent limestone beds (cf. Carney 1981). Zones with an irregular shape characterized by diffuse to concentrated seams that enclose limestone nodules and that die out in the limestone beds may have resulted from varying degree of burrowing. Incomplete burrowing could result in an irregular distribution of clay and thus possibly influence later diagenesis.

Differential Lithification

Lithification may have been retarded in clay-rich zones, as suggested by the lack of molds of fossils within and adjacent to seams. Delayed lithification of zones may have allowed mechanical compaction to destroy the molds after or during leaching but prior to their being filled with calcite spar. Lack of molds could also have resulted from a change in depositional environment associated with formation of the zones, such as influx of clay or increased lime mud; however, a change in environment cannot explain the abrupt decrease or total lack of molds in the zones in view of the following: 1) burrowing that probably occurred in the zones should have at least partially homogenized any primary differences in abundance of fossils that may have occurred as the result of depositional changes, transporting some of the aragonitic fossils into the zone; 2) calcitic fossils such as crinoids, brachiopods, and bryozoans are the most abundant fossils and occur in roughly the same percentages in seams and limestones (Table 4). This suggests that there was little change in fauna associated with development of the zones or thorough burrowing and therefore probably a similar primary ratio of calcitic to aragonitic fossils in seams and limestones.

Several other observations provide additional support of differential lithification. 1) Broken and interpenetrant fossils are observed in the muddy, nonmoldic limestone immediately adjacent to a few seams (Fig. 34), suggesting that delayed lithification allowed increased mechanical compaction. Interpenetrant grains are the

result of chemical compaction, but chemical compaction would not have occurred without initial mechanical compaction of grains. 2) Limestone associated with some zones has a muddy, compact texture, whereas the limestone beds adjacent to these zones commonly have a mottled texture that suggests loose packing, with sparry, peloidal areas interspersed with muddy areas. This difference in texture suggests increased compaction and denser packing, resulting in a muddier texture; however, a possible depositional change cannot be ruled out. 3) In one example (Fig. 31), muddy burrow-fill in the limestone bed is fractured, indicating that these muddy intervals underwent earlier lithification than adjacent limestone and were later fractured due to differential mechanical compaction. In contrast, muddy limestone immediately adjacent to and within the diffuse zone (Fig. 31) is not fractured, even though this limestone was presumably subjected to stress that was uneven and locally severe due to the proximity to dissolution sites. This lack of fracturing suggests that the zones were less lithified and therefore deformed without fracturing.

The cause of poor lithification in the zones is not clear. Zones probably contained a higher clay content than adjacent limestone beds, suggesting that clay retarded lithification in some manner. Clay may have decreased the permeability of the sediment to cementing fluids or inhibited the growth of cement by interfering with recrystallization of calcite (Bausch 1968; Marschner 1968; Zankl 1969). Growth of cement is favored on substrates of similar

mineralogy (Bathurst 1975, p.428), so it is possible that limestone containing more clay will be less lithified than adjacent cleaner limestone.

Mechanical Compaction

Mechanical compaction of clay-rich zones may have destroyed fossil molds and probably resulted in denser packing of constituents in limestone immediately adjacent to seams, as discussed above. In addition, the breakage of fossils within the seams is due to mechanical compaction following removal of material by chemical compaction.

The effect of mechanical compaction on the shape of the limestone beds is not clear. The total relief in outcrop along the limestone beds appears to be a combination of the form of the zones, diffuse to concentrated, and preexisting shape of the limestone beds. The shape of the limestone beds may have resulted from such bed forms as ripples, since peloidal lime mud can be transported by currents (Enos and Perkins 1979). The random distribution of relief on the bedding surfaces (Fig. 9), however, and the evidence of bioturbation in the limestone beds suggest that primary bedforms were not responsible for the bedding shape. Mechanical compaction of layers subjected to variations in lithification, see Differential Lithification above, might produce limestone beds with an irregular shape. Differential compaction around chert nodules contributed to the irregular shape of limestone beds in some intervals of the Plattsmouth Limestone (Fig. 7).

Chemical Compaction

Clay-rich zones in the Plattsmouth, Stoner, and Ervine Creek limestones, with the possible exception of the datum bed, were compacted chemically. Evidence of chemical compaction includes interpenetrant and truncated fossils and microstylolites. Some microstylolites may be primary sedimentary features (McHargue and Price 1982; Pratt 1982); however the observed truncation of fossil grains in contact with microstylolites and the sutured form of some microstylolites, suggestive of sutured stylolites, indicate origin by dissolution. Zones in the Plattsmouth core and in the Ervine Creek Limestone generally lack distinct microstylolites and contain diffuse to concentrated accumulations of clay (Figs. 19, 24). These accumulations of clay, however, were also concentrated by dissolution because they contain partially dissolved fossils, and some can be traced into microstylolites. Fine-grained calcite may be preserved in diffuse seams (Fig. 29), although fine-grained calcite is typically absent in concentrated seams, presumably having been destroyed by dissolution or replacement by dolomite. Although the datum bed lacks evidence of dissolution, it is possible that the high concentration of clay in the bed is partly the result of dissolution of minor amounts of lime mud. It is unlikely that the datum bed underwent much dissolution, as burrows adjacent to the bed are filled with clay of similar concentration. Dissolution in the datum bed may have removed some fossils; however, fossils in concentrated seams in other zones are at most only partly dissolved.

Microstylolites and thicker accumulations of clay occur in

intervals that apparently underwent delayed lithification and that contained a greater clay content than adjacent limestone beds. Variations in clay content may have influenced the degree and form of chemical compaction as indicated by zones containing differing amounts of clay that are characterized by differences in chemical compaction features (e.g. Figs. 30, 31). The observations do not indicate conclusively whether the zones were lithified or unlithified when chemical compaction occurred, although the presence of interpenetrant grains and the lack of fracturing in limestone immediately adjacent to seams suggests poor lithification. Less lithification would allow more mechanical compaction, possibly leading to chemical compaction.

Although variations in the concentration and form of zones are probably mainly the result of lateral and vertical variations in clay content and possibly degree of lithification, several minor factors may also be important. For example, differences in grain type or abundance in the zones may have controlled the degree of dissolution in some seams. The lime mud in the seams was most susceptible to dissolution, followed by fossils consisting of multiple crystals of calcite (bryozoans, brachiopods, and fusulinids). Crinoid fragments, composed of a single large crystal of calcite, were the most resistant to dissolution. In addition, chert nodules or large fossils in the zones probably reoriented chemical compaction (Fig. 7).

The close association of dolomite and microstylolites suggests

that dissolution along the microstylolites created conditions suitable for dolomitization (cf. Wanless, 1979). Further study of the origin of dolomite is needed, however, as it was recently observed (personal observation, and B. P. Stephens 1985, pers. comm.) that dolomite that is similar in size and composition to dolomite in the seams is very common in argillaceous limestone not associated with seams in the upper portion of the Plattsmouth Limestone and the superjacent Kereford Limestone.

Proposed Origins of Clay-rich Zones

The origin of the clay-rich zones is most consistent with a sedimentary origin characterized by small influxes of clay, possibly derived from the Ouachita Mountains or from eastern highlands. Burrowing resulted in distribution of clay over a broad, irregular zone. Lithification was retarded within the zones, possibly due to the abundance of clay. Less lithification allowed more mechanical compaction than in adjacent limestone beds, resulting in denser packing of constituents, destroying fossil molds prior to filling with calcite cement, and possibly leading to chemical compaction. Differential mechanical compaction contributed to the wavy shape of the limestone beds. Chemical compaction, characterized by interpenetrant and truncated fossils as well as microstylolites and thicker accumulations of clay, resulted in final modification of the zones. The initiation, final degree, and form of chemical compaction were probably controlled by the amount and distribution of clay and possibly the degree of lithification.

The datum bed differs in form and composition from all other zones, suggesting a somewhat different origin. Unlike other zones, the datum bed was characterized by a high initial clay content, which caused differences in later diagenesis. The high clay content in the datum bed was probably the result of an influx from a southern source, the most likely source being the Ouachita Mountains (Fig. 4). The greater clay content caused a reduction in the abundance of skeletal organisms and retarded lithification. Less lithification

resulted in more mechanical compaction, possibly destroying fossil molds, although lack of molds could also be due to the general decrease in abundance of fauna. The datum bed, unlike other zones, lacks evidence of chemical compaction, although it is possible that chemical compaction was partially responsible for the large amount of clay in the bed.

DISCUSSION

Clay-rich zones in the Plattsmouth, Stoner, and Ervine Creek limestones are similar in form, constituents, and origin to zones described by Arthur and Fischer (1977), Garrison and Kennedy (1977), Scholle (1977), Ricken (1986), and Bathurst (1987) (Table 6). Zones described by Wanless (1979) and Marshak and Engelder (1985) (see also Logan and Semeniuk 1976), are also similar in form and constituents to zones described in this study, as indicated in particular by the presence of microstylolites. Zones in the units studied, however, have a initial depositional origin.

Primary Characteristics of Clay-rich Zones

Most workers (Table 6) have suggested that clay-rich zones originally contained slightly more clay than adjacent limestone beds, with evidence of the higher clay content based on such observations as clay-rich burrows in the limestone adjacent to zones (e.g. Arthur and Fischer 1977; Ricken 1986). In contrast, Bathurst (1987)

Table 6. Studies of clay-rich zones, with factors important in development of zones. Works are grouped on the basis of similar origin (see also Table 1). The results of this study are included for comparison. Mathews (1978) did not discuss the origin of clay-rich zones in detail but is listed because he also examined zones in the Plattsmouth Limestone. "A" equals primary factors; "B" equals secondary or modifying factors; "?" indicates that the factor may have been important or was important in some cases. * indicates either clay influx or less carbonate production; results in a higher clay content in the zones than in adjacent limestone beds. *1 burrowing; important either in redistributing clay (1), or altering the lithology of the sediment independent of redistribution of clay (2). *3 indicates less burrowing than in adjacent limestone beds. *2 indicates chemical compaction was possibly dependent on mode of stress; i.e., shear or overburden stress with high or low strain possibly in combination with changes in lithology (3), particularly variations in clay content (Appendix I).

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WORKERS		FACTORS IMPORTANT IN DEVELOPMENT OF ZONES						
		DEPOSITIONAL CHANGES		Burrowing *1	Differential Lithification	Mechanical Compaction	Chemical Compaction	Variations in stress *2
		Increased Clay*	Changes in Texture and Fauna					
Hattin (1971)		A		B (2) 3	B	B		
Mathews (1978)		A			B	B		
Wilson & Jordan (1983)		A			B	B	B?	
Arthur & Fischer (1977)		A		B (1)		B?	B	
Bathurst (1987)		A?	A?	A?(2) B(1)	B	B	B	
Garrison & Kennedy (1977)		A	A?		B	B	B	
Ricken (1986)		A		B (1)	B	B	B	
Scholle (1977)		A?	A?		B	B	B	
Logan & Semeniuk (1976)		(3)					B	A
Marshak & Engelder (1985)		(3)					B	A
Wanless (1979)		A? (3)					B	A
This study	datum bed	A			B	B	B?	
	Other Zones	A		B (1)	B	B	B	

observed no clear evidence of a higher primary clay content in the zones. A number of workers, in particular Barrett (1964), Garrison and Kennedy (1977), Scholle (1977), and Bathurst (1987), suggested that factors other than clay, such as variations in sedimentation rate, degree of bioturbation, or changes in texture, may have initiated development of the zones that they studied.

The clay-rich zones examined in this study are characterized by fewer fossil molds and slightly more lime mud than adjacent limestone beds; however, the results suggest that these factors were at least partly the result of mechanical compaction and were not of primary importance in development of the zones. Zones and adjacent limestone beds may have differed in degree of burrowing; however, there is no evidence that variations in burrowing initiated development of the zones. There is no evidence of a change in the rate of sedimentation associated with the zones except possibly the higher clay content.

Modifications of Clay-rich Zones

Limestone beds and clay-rich zones were burrowed, probably with redistribution of clay within zones. In other studies, almost all workers have noted that limestone beds are burrowed, and Arthur and Fischer (1977), Ricken (1986), and Bathurst (1987) (see also Garrison and Kennedy 1977) recognized that burrowing had also occurred in zones, resulting in redistribution of sediment.

Clay-rich zones in the units studied underwent later lithification than adjacent limestone beds as suggested by evidence

of more mechanical compaction, consistent with the observations, in particular, of Garrison and Kennedy (1977), Ricken (1986), and Bathurst (1987). The absence of fossils molds within zones characterized by chemical compaction has not been previously reported. It is possible that changes in abundance of molds of fossils were overlooked in other studies or that the limestones examined contained no fossils that were primarily aragonite. Variations in abundance of molds of fossils have been noted in some limestone intervals not associated with clay-rich zones; for example Wolfe (1968) observed fossil molds filled with calcite spar in a chalk unit adjacent to other units that contained few or no molds, although there was little difference in abundance of calcitic fossils. His units that lacked molds contained evidence of more mechanical compaction than the moldic unit, with deformation of sedimentary structures and breakage of fossils. Wolfe (1968) suggested that these mold-free units were probably subjected to later lithification, allowing molds to be destroyed by mechanical compaction prior to filling with calcite spar.

The causes of differential lithification remain largely unknown. Variations in lithification may have resulted from variations in rate of sedimentation or degree of bioturbation that influenced exposure to cementing fluids (Shinn 1969; Garrison and Kennedy 1977; Bathurst 1987; see also Hattin 1971). No evidence of seafloor cementation was seen in the units studied. Observations that zones in some chinks and pelagic limestones are less lithified when

accompanied by a high clay content has led several workers (Kennedy and Garrison 1975; Scholle 1977; Ricken 1986) to suggest that clay may have inhibited cementation in zones, possibly by interfering with recrystallization of calcite (Ricken 1986, p.120).

Most workers, in particular Garrison and Kennedy (1977) and Bathurst (1987) suggested that mechanical compaction resulted in breakage and rearrangement of grains in zones, as observed in this study. Wilson and Jordan (1983) suggested that limestone beds and adjacent zones in shelf limestones were subjected to differential mechanical compaction, resulting in bedding with an irregular, wavy shape (cf. Mathews 1978). In contrast, Wanless (1979, 1982) suggested that mechanical compaction is not important in clay-rich zones, and that such features attributed to mechanical compaction as breakage and rearrangement of fossils are the result of mechanical flowage or shear during chemical compaction (Wanless 1982; cf. Pratt 1982).

Clay-rich zones examined in this study and in studies of other units are characterized by such similar features of chemical compaction as interpenetrant grains and microstylolites. Chemical compaction in zones in the Plattsmouth, Stoner, and Ervine Creek limestones was apparently influenced by clay content, although degree of lithification may have also been important. Garrison and Kennedy (1977), Scholle (1977), Buxton and Sibley (1981) (see also Shinn and Robbin 1983) suggested that chemical compaction that resulted in the formation of microstylolites was favored in poorly lithified sediment because mechanical compaction would cause greater stress on grains and lead to dissolution, although Garrison and Kennedy (1977) also

suggested that a high clay content enhanced chemical compaction. In contrast, Oldershaw and Scoffin (1967), Nelson (1978), Wanless (1979), and Bathurst (1987) suggested that clay was probably the primary factor promoting chemical compaction and that the degree of lithification, if discussed, was unimportant or of less importance.

Recognition of chemical compaction features in clay-rich zones not confined to intervals with primary changes in lithology (Logan and Semeniuk 1976; Wanless 1979; Marshak and Engelder 1985) suggests that variations in clay content rather than variation in lithification may be the more important factor. The conclusion that clay enhances dissolution has generally been based on the observed association of dissolution features with argillaceous limestone or zones containing increased clay content (e.g. Garrison and Kennedy, 1977; Wanless, 1979). Workers have generally cited the theoretical work of Weyl (1959) to support this conclusion. Weyl (1959) suggested that clay aids dissolution by its ability to enhance diffusion of material in solution away from the dissolution sites, thereby promoting dissolution. Wanless (1979) and Marshak and Engelder (1985) observed dissolution features only in limestone containing at least 10 percent clay, the lowest amount of clay thought sufficient to connect "dissolution sites at grain boundaries with the free-fluid system" (Marshak and Engelder 1985, p. 357). Ten percent clay is roughly the same clay content that was probably present in zones in this study prior to dissolution.

Zones examined in this study contain microcrystalline dolomite

that may have resulted from chemical compaction. Similar dolomite was observed by Wanless (1979) and Logan and Semeniuk (1976); no other workers have recognized preferential concentrations of dolomite in zones. According to Logan and Semeniuk (1976) and Wanless (1979, 1982; see also Ricken, 1986), the dolomite formed as a product of dissolution within the zones. Some aspects of the origin of dolomite, in particular a source of Mg, were not thoroughly examined (cf. Pratt 1982).

Datum Bed

The datum bed has a different origin than other zones, and is similar in lithology and origin to the zones described by Hattin (1971) and Wilson and Jordan (1983) (Table 6). Hattin's detailed study of shaly chalk beds in the Cretaceous of Kansas and Colorado is of particular interest because of the clear evidence of differential lithification and the absence of fossil molds in the beds. Hattin (1971) suggested that the beds were characterized by a high clay content resulting from influx of clay. Reduced burrowing, or the higher rate of sedimentation, may have limited the exposure of sediment to cementing fluids, resulting in retarded lithification. Less lithification resulted in more mechanical compaction, as indicated by deformation of burrows. Hattin observed few or no fossil ammonites preserved as molds filled with calcite spar in the shaly beds, although molds of ammonites are common in adjacent limestone beds and the other fauna differed little in abundance.

Hattin suggested that the lack of molds in the shaly beds indicated dilution of ammonites during periods of greater influx of clay. The shaly beds, however, underwent considerable mechanical compaction, so it is possible that the molds were destroyed during mechanical compaction as suggested in this study.

CONCLUSIONS

Clay-rich zones in the Plattsmouth, Stoner, and Ervine Creek limestones are typically 1 to 10 cm thick and separate limestone beds that are typically 10 to 40 cm thick. Zones in the Plattsmouth Limestone commonly change shape laterally from thinner portions generally consisting of a single seam with a uniform distribution of clay to thicker portions with one or more distinct seams or diffuse to wispy seams with microstylolites. Zones in the Stoner Limestone are similar to zones in the Plattsmouth Limestone but contain fewer thick accumulations of clay and contain numerous distinct microstylolites. Zones in the Ervine Creek Limestone resemble zones in the Plattsmouth, particularly zones in the core, with wispy seams or patchy accumulations of clay and few distinct microstylolites.

Seams contain a range of 10 to 40 weight percent of insoluble matter, with calcitic fossils that are commonly interpenetrant and truncated. Seams also commonly contain remnant lime mud and microcrystalline dolomite. Zones can be traced laterally within an outcrop, and most zones in the Plattsmouth Limestone can be traced for approximately 70 km. Adjacent limestone beds are commonly skeletal wackestone, mottled by burrowing, with wavy to irregular bedding and a low percentage of insoluble residue (4.5 weight percent). Limestone immediately adjacent to and within some zones differs from the limestone beds, with few or no fossil molds, greater amount of insoluble residue, and a muddier texture. One clay-rich zone, the datum bed, lacks chemical compaction features, contains up

to 90 weight percent insoluble residue, and consists of a roughly planar seam that was traced for approximately 130 km.

Origins of Clay-rich Zones

Clay-rich zones probably formed due to small influxes of clay derived from the Ouachita Mountains to the south or possibly an eastern source. The clay was redistributed by burrowing, perhaps resulting in an initial clay content in the range of 10 to 15 weight percent.

Evidence of more mechanical compaction in the clay-rich zones than in adjacent limestone beds suggests that lithification was retarded in the zones. Reduced lithification may have been the result of greater clay content, which inhibited cementation.

Mechanical compaction in the zones resulted in breakage of fossils, loss of fossil molds, and denser packing of constituents. Mechanical compaction may have led to chemical compaction; however the degree of lithification at the time of chemical compaction is not clear. Irregular mechanical compaction, the result of variable lithification, probably contributed to the wavy to irregular shape of the limestone beds.

Chemical compaction, characterized by such features as microstylolites, thicker accumulations of clay, and interpenetrant and truncated fossils, was the final stage of diagenetic modification. The occurrence, degree, and form of chemical compaction in the zones was controlled by the amount and

distribution of clay and possibly degree of lithification and to a minor degree by variations in grain size and type. The irregular shape of some limestone beds is due to irregular chemical compaction, with formation of discontinuous or wispy seams and patchy accumulations of clay. Dolomite is closely associated with microstylolites and thicker accumulations of clay, suggesting that dissolution created conditions suitable for dolomitization.

Datum Bed

The different form and composition of the datum bed is attributed to a greater influx of clay than in other zones. This influx of clay probably originated from a southern, Ouachita Mountains source. The presence of few benthic organisms suggests that the high clay content of the bed decreased biologic productivity or that organisms were diluted by high rate of sedimentation. Clay probably retarded lithification and subsequent mechanical compaction probably destroyed molds of fossils and resulted in the irregular shape of the bed. Such evidence of chemical compaction as microstylolites and interpenetrant and truncated grains was not observed in the datum bed; it is possible, however, that the high clay content of the bed was partially the result of dissolution of residual lime mud.

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APPENDIX I

BRIEF REVIEW OF CHEMICAL COMPACTION

Chemical compaction is the general term for processes that are characterized by dissolution, with consequent compaction and concentration of insolubles. Most workers attribute chemical compaction features to pressure solution, although the general term chemical compaction is probably more applicable as pressure is not necessarily the most important factor. In very general terms, pressure solution is the process whereby grains under stress in an aqueous solution dissolve at their points of mutual contact; as material is removed in solution an aqueous film termed a solution film will form between the grains, allowing stress to be transmitted between the contacts and serving as a pathway for removal of the dissolved ions (Weyl 1959; Kerrich 1977; Rutter 1983; however see Bathurst 1975, p. 466-468). Weyl (1959, p. 2016-2019) suggested that clay between grains can enhance pressure solution because the clay provides multiple pathways of diffusion for the removal of material in solution, increasing the rate of diffusion and therefore the rate of dissolution. Pressure solution generally increases with depth; however, several studies have suggested that pressure solution is strongly influenced by the composition of pore waters (Neugebauer 1973; Nelson 1978; Meyers 1980). Fluids that are undersaturated with respect to calcite enhance dissolution of grains, possibly allowing the formation of pressure-solution features even at very shallow

depths (Nelson 1978, p.765).

Chemical Compaction Features

Three types of features are typically attributed to chemical compaction: 1) stylolites; 2) interpenetrant or sutured grains; and 3) microstylolites (Wanless, 1979), which are also called solution seams (Garrison and Kennedy 1977) horsetails (Mossop 1972), or other terms. The origin of microstylolites by chemical compaction has not been completely accepted; some (McHargue and Price 1982; Shinn and Robbin 1983) have suggested that microstylolites may be primary sedimentary features, possibly modified by mechanical and chemical compaction. Stylolites and interpenetrant grains (Fig.I-A) are most commonly observed in limestones (e.g. Stockdale 1922; Park and Schot 1968; Wanless 1979; Buxton and Sibley 1981), and some sandstones (e.g. Lerbekmo and Platt 1962; Sibley and Blatt 1976; Houseknecht 1984). Interpenetrant grains are generally assumed to form in sediment that was mechanically compacted prior to cementation (Wanless 1979; Buxton and Sibley 1981), whereas stylolites form in cemented intervals that probably contained little clay (Stockdale 1943; Dunnington 1954; Wanless 1979; Buxton and Sibley 1981). Microstylolites (Fig. I-A) have only recently received detailed study (Garrison and Kennedy 1977; and in particular Wanless 1979). Wanless (1979) described microstylolites as thin, undulating clay films with 20 to 40 micrometer relief that are usually grouped into microstylolite swarms, with individual microstylolites braiding around small limestone clots and remnant fossils. Microstylolites

Figure I-A.

Three types of chemical compaction features.



STYLOLITE



**INTERPENETRANT
GRAINS**



MICROSTYLOLITES

are commonly difficult to recognize, as they branch and anastomose in an irregular fashion and may have diffuse boundaries with the adjacent limestone, e.g. Wanless 1979, Figure 7. Microstylolites may merge into thicker concentrations of clay (clay seams of Wanless 1979), with selective removal of more soluble material such as lime mud and consequent concentration of coarser and less soluble grains (Garrison and Kennedy 1977; Wanless 1979). Microstylolites and interpenetrant grains are common in many clay-rich zones (Wanless 1979; Bathurst 1987).

Possible Factors Controlling Chemical Compaction In Clay-rich Zones

Workers that recognize chemical compaction features in clay-rich zones generally suggest three major factors that could control chemical compaction: 1) degree of lithification, 2) amount and distribution of clay, and 3) variations in mode of stress perhaps in combination with minor changes in lithology. Garrison and Kennedy (1977), Scholle (1977), Buxton and Sibley (1981) (see also Shinn and Robbin 1983) suggested that the formation of microstylolites is favored in limestone intervals that are poorly lithified, with increased mechanical compaction in these intervals possibly leading to dissolution. In contrast, microstylolites are also present in some zones that cut across primary bedding (Wanless 1979; Marshak and Engelder 1985; see also Logan and Semeniuk 1976), suggesting that the rocks were lithified when chemical compaction occurred.

Clay may be the most important factor influencing chemical compaction. Clay may retard lithification (Bausch 1968; Marschner 1968; Zankl 1969; Buxton and Sibley 1981), thereby having an indirect effect on mechanical and chemical compaction, as discussed above. In addition, clay may directly promote or hamper dissolution. More clay in limestone generally favors the formation of microstylolites rather than stylolites (Wanless 1979). According to Wanless (1979) the clay retards fluid migration and acts as a glide surface, inhibiting the formation of sutured stylolites. Clay is generally thought to have a textural rather than chemical role in promoting solution (Weyl 1959, p. 2016-2017; De Boer 1977, p. 254; Marshak and Engelder 1985, p. 357; see also Bayly 1986). Pressure solution is enhanced by increased diffusion of material in solution away from the solution point (Weyl 1959; De Boer 1977), and clay provides numerous diffusion pathways increasing the rate of diffusion and thereby the rate of dissolution. Marshak and Engelder (1985) suggested that the highly charged surfaces of clays can retain water films even under high stress, allowing dissolution to occur within cleavage domains composed of microstylolites in some limestones that are tectonically deformed. According to Marshak and Engelder (1985, p. 357) at least 10 weight percent of clay is needed to "permit interconnectivity of dissolution sites at grain boundaries with the free-fluid system" (cf. Wanless 1979). Clay probably does not have a chemical role in dissolution by altering water chemistry to promote dissolution, because clay appears to enhance dissolution of both quartz and calcite (Marshak and Engelder 1985; see also De Boer 1977, p. 254-

255). In contrast, Shinn and Robbin (1983, p. 614) noted that "Enhancement of dissolution by clays has not been demonstrated."

Mode of stress; i.e., shear or overburden stress with high or low levels of strain may be important in determining the zone of dissolution in tectonically deformed limestones and possibly limestones not subjected to tectonic stress (Logan and Semeniuk 1976; Wanless 1979; Marshak and Engelder 1985; see also Rutter 1983). According to Marshak and Engelder (1985), closer cleavage spacing (with domains composed of microstylolites) will result from higher levels of strain, whereas at lower levels of strain the cleavage is farther apart and more dependent on minor changes in lithology. Logan and Semeniuk (1976 p. 45-56) suggested that different forms of chemical compaction features and the spacing between these features are dependent largely of the mode of stress, ranging from overburden to shear stress.

In related studies, several workers have developed theoretical models to explain how chemical compaction could occur at roughly regular intervals in a homogeneous limestone. Nelson (1983) suggested that stylolites occur at predictable intervals in a rock as the result of an interaction between stress, mechanical properties of the rock, and rock petrology. According to Nelson (1983, p. 317), "stylolites could occur at stress gradients within a rock which are due to the physical make-up or internal geometry of the body." Merino et al. (1983, p. 360) developed a kinetic theory suggesting that stylolites and "pressure-solution seams" (microstylolites) will

occur at very roughly predictable and uniform intervals (few micrometers to tens of centimeters) in initially uniform rocks under stress. Pressure solution will occur at specific intervals due to an interaction between dissolution, diffusion, reprecipitation, and very minor changes of porosity. According to Bayly (1986), stylolites may form due to very minor inhomogeneties in the rock. With increased stress, localized dissolution will begin in the rock, especially at areas that are slightly rich in clay. Fluid movement normal to stress will interconnect these local points of dissolution, creating layering and eventually leading to the formation of stylolites.

APPENDIX II. LOCATIONS OF SECTIONS

- Locality 1 -- S1/2, SW1/4, Sec.7, T8S R21E; Leavenworth County; active quarry Plattsmouth Limestone; producer N.R. Hamm Quarry, Inc., Perry, Kansas.
- Locality 2 -- C, S1/2, Sec.2, T9S R21E; Leavenworth County; active quarry Plattsmouth Limestone; N.R. Hamm Quarry, Inc., Perry, Kansas.
- Locality 3 -- W1/2, NW1/4, Sec.7, T10S R21E; Leavenworth County; active quarry Plattsmouth Limestone; Martin Marietta Aggregates, Topeka, Kansas.
- Locality 4 -- SW1/4, Sec.6 and NW1/4, Sec.7, T11S R21E; Leavenworth County; inactive quarry Plattsmouth Limestone.
- Locality 5 -- C, Sec.35, T11S R19E; Jefferson County; active quarry Plattsmouth Limestone; N.R. Hamm Quarry, Inc., Perry, Kansas.
- Locality 6 -- SW1/4, Sec.1, T13S R18E; Douglas County; active quarry Plattsmouth Limestone; Killough, Inc., Ottawa, Kansas.
- Locality 7 -- N1/2, SW1/4, Sec.35, T13S R18E; Douglas County; active quarry Plattsmouth Limestone; N.R. Hamm Quarry, Inc., Perry, Kansas.
- Locality 8 -- C, NE1/4, Sec.15, T15S R18E; Douglas County; active quarry Plattsmouth Limestone; Killough, Inc., Ottawa, Kansas.
- Locality 9 -- NE1/4, Sec.33, T16S R17E; Osage County; active quarry Plattsmouth Limestone; Killough, Inc., Ottawa, Kansas.
- Locality 10 -- NE1/4, NE1/4, Sec.11, T21S R15E; Coffey County; core Plattsmouth Limestone; stored at Kansas Geological Survey.
- Locality 11 -- W1/2, SE1/4, Sec.25, T29S R12E; Elk County; inactive quarry Plattsmouth Limestone.
- Locality 12 -- C, Sec.33, T33S R11E; Chautauqua County; active quarry Plattsmouth Limestone; Sedan Limestone Co., Inc., Sedan, Kansas.
- Locality 13 -- E1/2, SW1/4, Sec.13, T16S R19E; Franklin County; active quarry Stoner Limestone; Killough, Inc., Ottawa, Kansas.
- Locality 14 -- SW1/4, Sec.7, T12S R17E; Shawnee County; active quarry Ervine Creek Limestone; Martin Marietta Aggregates, Topeka, Kansas.

APPENDIX III. X-RAY DIFFRACTION AND MICROPROBE ANALYSES

All samples were analyzed with a Rigaku Geigerflex x-ray diffraction unit using a Cu tube operated at 40 kv and 20 ma. Samples were ground with a mortar and pestle to pass a 75 micrometer sieve. The intensities of calcite and dolomite {104} reflections were measured by counting maximum peak intensity for 100 seconds (Royse et al. 1971). The ratio of dolomite intensity to dolomite plus calcite intensities was used to determine weight percent of dolomite (Royse et al. 1971). These figures represent the relative proportions of dolomite and calcite in total carbonate in a sample (Table III-A). The insoluble portion of the samples (Table 2) must be considered to obtain true weight percent of dolomite (Table III-A and Table 3). According to Lumsden (1979), methods based on the comparison of calcite and dolomite {104} reflections are subject to substantial error when the dolomite is nonstoichiometric. Each percent increase of Ca in excess of stoichiometric dolomite causes a two-percent overestimation of the amount of dolomite in a sample. Therefore, dolomite stoichiometry was determined for the samples (Lumsden 1979, and Lumsden and Chimahusky 1980). Dolomite stoichiometry was also determined by electron microprobe analysis of dolomite rhombs in one sample from a seam (Table III-A). The stoichiometry correction was applied to the values of weight percent dolomite (Table III-A). This correction method probably has significant error, as sample 4 (Table III-A) yields a negative number, so that the values of weight percent of dolomite are probably only rough estimates.

TABLE III-A. Dolomite stoichiometry and weight percent of dolomite

SAMPLES	MOLE % CaCO ₃	WT. % DOLO.*1	WT.% DOLO.*2
1 core #30	58	60	44
2 outcrop (*3)	57	18	4
3 outcrop #91	55 (56.6 *4)	17	7
4 core #57	58	14	?
5 core #44	58	45	29
6 outcrop #124	56.5	29	16
7 outcrop #121	56.5	39	26

Mole percent CaCO₃ in dolomite from samples of seams, and values of weight percent of dolomite before (*1) and after (*2) correction for stoichiometry. Numbers (#) correspond to numbers in insoluble residue table (Table 2); *3 indicates that this sample is not listed in table 2. *4 denotes microprobe results.

APPENDIX IV. METHODS FOR DETERMINING WEIGHT PERCENT OF INSOLUBLE
RESIDUE AND WEIGHT PERCENT OF ORGANIC MATTER IN RESIDUE

Sampling Techniques

Most of the samples to be used for determination of weight percent of insoluble residue were taken from the core (Fig. V-A), as the core is easy to section and samples can be taken with precision from seams and adjacent limestone. Samples were also taken from a quarry exposure of the Plattsmouth Limestone (Fig. 7) and from selected hand samples of the Plattsmouth, Stoner, and Ervine Creek limestones (Table 2). The sample size depended on the size of features but was generally not smaller than 1 cubic cm. Samples were generally taken every centimeter or every other centimeter if the limestone or seam was uniform in composition. Limestone samples taken adjacent to seams did not generally include any portion of the seams; i.e., any thin seams or microstylolites were avoided or cut out.

Laboratory Techniques--Insoluble Residue

The samples were crushed to approximately 5 mm diameter in a small jaw mill, washed with distilled water to remove dust, and dried overnight in an oven at 105° C. Samples were cooled to room temperature in a desiccator. Approximately 1.5 g of each sample was placed in a 90 ml centrifuge test tube and dissolved in concentrated (36 percent) HCL to remove all carbonate minerals. A sample size of

1.5 g was of sufficient size to allow several repetitions and still generate enough residue for accurate weighing. Digestion was aided in some cases by placing the test tube into an ultrasonic cleaner. Completion of digestion was verified by the addition of more acid. Samples were centrifuged at approximately 2000 RPM for 10 minutes, and the acid was carefully decanted. An insignificant amount of material was lost during decantation. The sample was then flushed with distilled water in the same tube to remove excess acid and recentrifuged. The fluid was again decanted, and the residue was washed into preweighed 10 ml ceramic crucibles (if the residue was to be also used for the determination of weight percent of organic matter) or preweighed 10 ml glass beakers, and dried overnight at 105° C. The samples were cooled in a desiccator, and weighed in the crucibles or beakers to determine weight percent insoluble residue. Three splits of each sample from two slabs (Table 2, hand samples 5-2 and 2-1) were analyzed and the results averaged; all other values are single analyses. The results were rounded to the nearest 0.5% for samples of limestone and nearest 1% for samples from seams, as limited replication of samples suggests a precision of plus or minus 0.5 weight percent for limestone samples and plus or minus 1 to 2 weight percent for samples from seams. The increased variability in seam results is due to inhomogeneities in seams. Silica and minor pyrite add to the insolubles in some samples, but samples containing a significant amount of silica were avoided because values would not indicate depositional conditions. Average weight percentages of

insoluble residue was determined for seams and limestone; one value was used for each seam or limestone bed. Values determined for multiple samples from a seam or limestone bed were averaged. Limestone values included only samples that lacked visible accumulations of clay (39 total values), whereas seam values included only samples with a uniform accumulation of clay (27 total values).

Laboratory Techniques--Organic Matter

Determination of the weight percent of organic matter in a residue sample is an extension of the insoluble residue process. After final weighing, the insoluble residue in a ceramic crucible is placed in a muffle furnace for 1 hour at 500°C. The weight loss is organic matter that is burned away. The results were rounded to the nearest 1%. The accuracy of this process is unknown, although this method compares favorably to the hydrogen peroxide method of organic removal, as determined in a sample test summarized below (Table IV-A). Determination of weight percent of organic matter was limited to 96 samples (Table 2) due to time constraints. The average weight percent of organic matter was determined for 32 values from seams and for 63 values from limestone.

TABLE IV-A. Determination of weight percent of organics using two techniques

SAMPLES	WT. % ORGANICS	
	Heat	H2O2
Seam, 4 splits, 22% ins.*	27	28
-----	-----	-----
Ls., 4 splits, 7.0% ins.*	14	17
-----	-----	-----

Determination of weight percent of organic matter in insoluble residue samples from a seam and adjacent limestone bed, * indicates the weight percent of insoluble residue. Each sample was split into four fractions; two were subjected to heat treatment as described above, and the other two placed in warm (approximately 60°C) hydrogen peroxide for one week.

APPENDIX V -- SAMPLE LOCATIONS IN CORE FOR DETERMINATION
OF WEIGHT PERCENT OF INSOLUBLE RESIDUE AND
ORGANIC MATTER

Figure V-A.

Core of Plattsmouth Limestone (locality 10), showing locations of samples for determination of weight percent of insoluble residue and weight percent of organic matter; values are listed in Table 2. P11 to P14 indicate point-counted intervals (Table 4). Some samples (e.g. 44, 74) were cut to avoid limestone or accumulations of clay, as indicated by dotted pattern. Core is marked at 10-cm intervals; samples were taken from intervals at the base of the section to approximately 2.6 m above the base. The upper one third of the datum bed is shown at the 1.8- to 1.9-m interval (sample 51). Note the large sutured stylolites at the 1.9-m marking.

