

**KANSAS GEOLOGICAL SURVEY
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**PROJECT PANGEA WORKSHOP
MAY 23 – 28, 1992
Lawrence, KS, USA
Field Trip Guidebook**

Part 1 – Lower Permian, Central Kansas

Part II – Upper Pennsylvanian, Eastern Kansas

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INTRODUCTION TO LOWER PERMIAN (WOLFCAMPLAN) CYCLES OF KANSAS

Global Sedimentary Geology Program
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Introduction to Lower Permian (Wolfcampian) cycles of Kansas

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Permo-Carboniferous Cyclothem

Repeated sedimentary cycles were first recognized in the Pennsylvanian of Illinois by Udden (1912) and later generalized by Weller (1930) into an idealized cycle. Moore (1931) was the first to describe the more complex cyclic pattern of the Pennsylvanian (lower Virgilian) of Kansas and Nebraska. The term "cyclothem" was introduced by Wanless and Weller (1932) to describe the Pennsylvanian cyclicity of the Illinois Basin, and was subsequently applied to the first description of Permian cyclicity within the midcontinent by Jewett (1933). Moore (1936) introduced the concept of "megacyclothem," or cycles of cyclothem, based on his work on the Virgilian cycles of Kansas. This concept was similarly adopted by several workers to describe cyclic sequences of the lower Permian (e.g. Hattin, 1957), and eventually the entire sequence was divided into megacyclothem (Moore, 1964).

The facies sequence of Permian cyclothem described by Jewett (1933) began with red and green variegated mudstones, followed by a thin limestone or calcareous zone, a gray to yellow fossiliferous shale, and lastly by a thick interval of limestone beds. This description was modified and elaborated by Elias (1937) who placed all the major facies encountered within Permian cycles into an idealized depth-related sequence (Fig. 1). All the facies of this idealized cyclothem were never encountered in any single cyclothem, and some predicted facies transitions rarely if ever occurred. The actual cycles identified by Elias within the Lower Permian were essentially the same as those recognized by Jewett.

A number of detailed sedimentary and paleontological studies of individual cyclothem and their member-scale lithologic units were completed following the initial description and interpretation of late Paleozoic cyclicity. The Grenola Limestone (Lane, 1958), Beattie Limestone (Imbrie, 1955; Laporte, 1962; Imbrie et al. 1964), Wreford Limestone (Hattin, 1957), and Red Eagle Limestone (McCrone, 1963) were all the focus of investigation. In all these cases, however, the variegated mudstones were largely ignored and depositional and paleoecologic interpretations were confined to the fossil-bearing marine units.

Presently, the most widely accepted cyclothem model is that of Heckel (1977) which, like the earlier model of Wanless and Shepard (1936), assumes primary eustatic control. His typical "Kansas-type cyclothem" consists of 1) a sandy

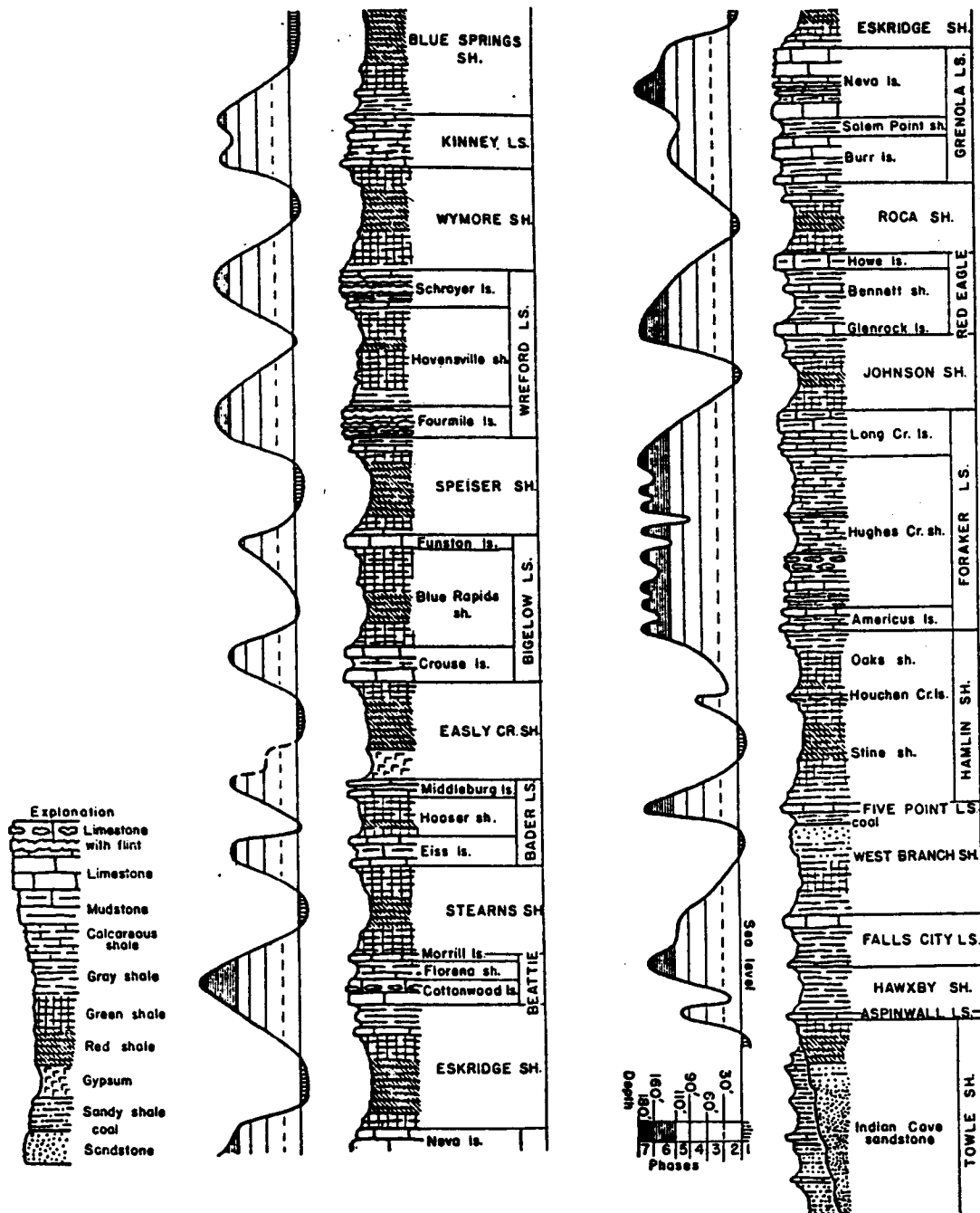


FIGURE 1 -- Sealevel curves interpreted by Elias (1937) for the Admire, Council Grove and Chase Groups. Fusulinid-bearing limestones were interpreted as the deepest water facies. Note the difference in cycle complexity between the Foraker and Grenola limestones, though these units have similar lithologic variability.

"outside shale" unit deposited under primarily terrestrial and shallow marine conditions and typically containing coal beds; 2) a thin "transgressive" limestone unit; 3) a black, often phosphatic, "core" shale representing deepest marine conditions; 4) a thick, multistoried "regressive" limestone unit; and 5) a return to an "outside shale" at the top (Fig. 2). Although based primarily on the Upper Pennsylvanian (Missourian) strata of eastern Kansas, it has become a paradigm for Permo-Carboniferous cycles in general. However, a thorough test of Heckel's "Kansas-type" cyclothem model within the Lower Permian section has yet to be made.

Lower Permian cycles bear certain general similarities to Missourian cyclothem but there are significant differences as well. The "outside shales" are highly calcareous and dominated by red and green mudstones with multiple stacked paleosols (Joeckel, 1991; Miller *et al.*, 1991). Coal beds are present only rarely, and occur as very thin localized deposits. Gypsum is a significant component of limestone and mudstone facies and becomes increasingly common upward through the Lower Permian sequence, locally forming beds up to one meter thick in the subsurface. Chert nodules and layers, some replacing evaporites, are also characteristic of Permian limestones (West *et al.*, 1987). The dark gray to black organic-rich "core shales" of the Pennsylvanian are largely absent in the Permian, being replaced in position by gray, often fossiliferous shales. The significance of these probably climate-controlled facies changes for eustatic cycle models have yet to be adequately addressed.

The Early Permian was a time of major climatic change upon which the cyclothem were superimposed. Gondwana glaciation was waning in the Early Permian (Crowell, 1978; Veevers & Powell, 1987), and there was a consistent trend toward increased aridity and continentality in North America. These long-term climate trends are recorded by the increased proportion of red terrigenous clastics, evaporites, and carbonates within the Lower Permian relative to the Upper Pennsylvanian. The trend toward increased aridity begun in the Late Pennsylvanian can also be followed in the paleobotanical record (Phillips & Peppers, 1984; Phillips *et al.*, 1985; Cross & Phillips, 1990). Such changes are consistent with paleogeographic reconstructions showing the mid-continent drifting into dry latitudes during this time (Rowley *et al.*, 1985; Scotese, 1986; Witzke, 1990) (Fig. 3).

Eustatic Sealevel Change

The glacio-eustatic model of cyclothem development was first proposed by Wanless and Shepard (1936) for the Pennsylvanian, and was soon followed by the classic paper by Elias (1937) on Lower Permian sealevel cycles. Eustatic models for Permian cyclothem have largely rested upon the bathymetric interpretation of particular marine units. Elias (1937) based his sealevel curves on the interpretation of fusulinids as deep water foraminifers. Although actual cycles often did not closely match the ideal facies sequence, smooth curves were

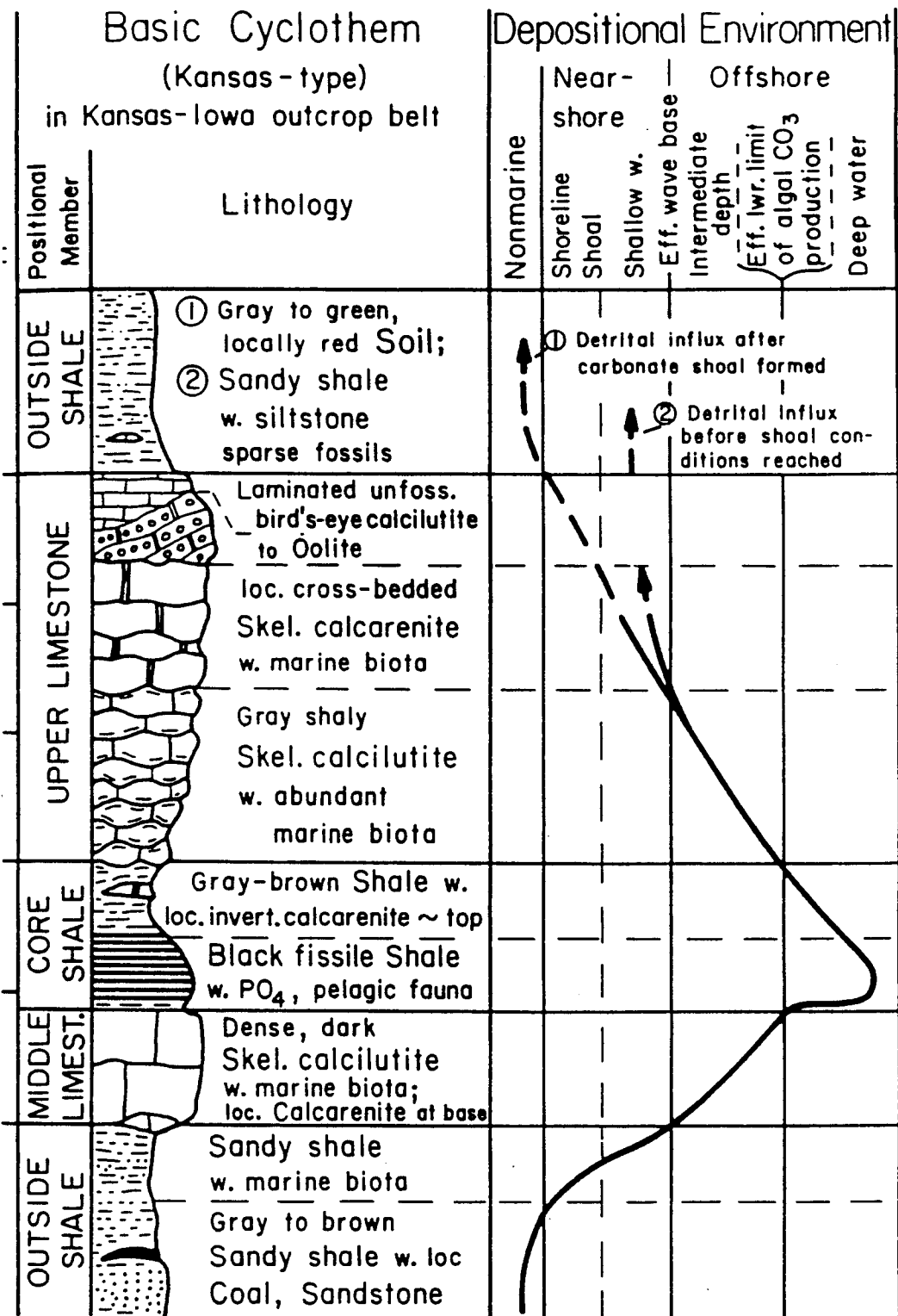


FIGURE 2 – Kansas-type cyclothem model of Heckel (1977) based on the Upper Pennsylvanian (Missourian) strata of eastern Kansas. This model assigns deepest water conditions to phosphate and conodont-bearing black shales.

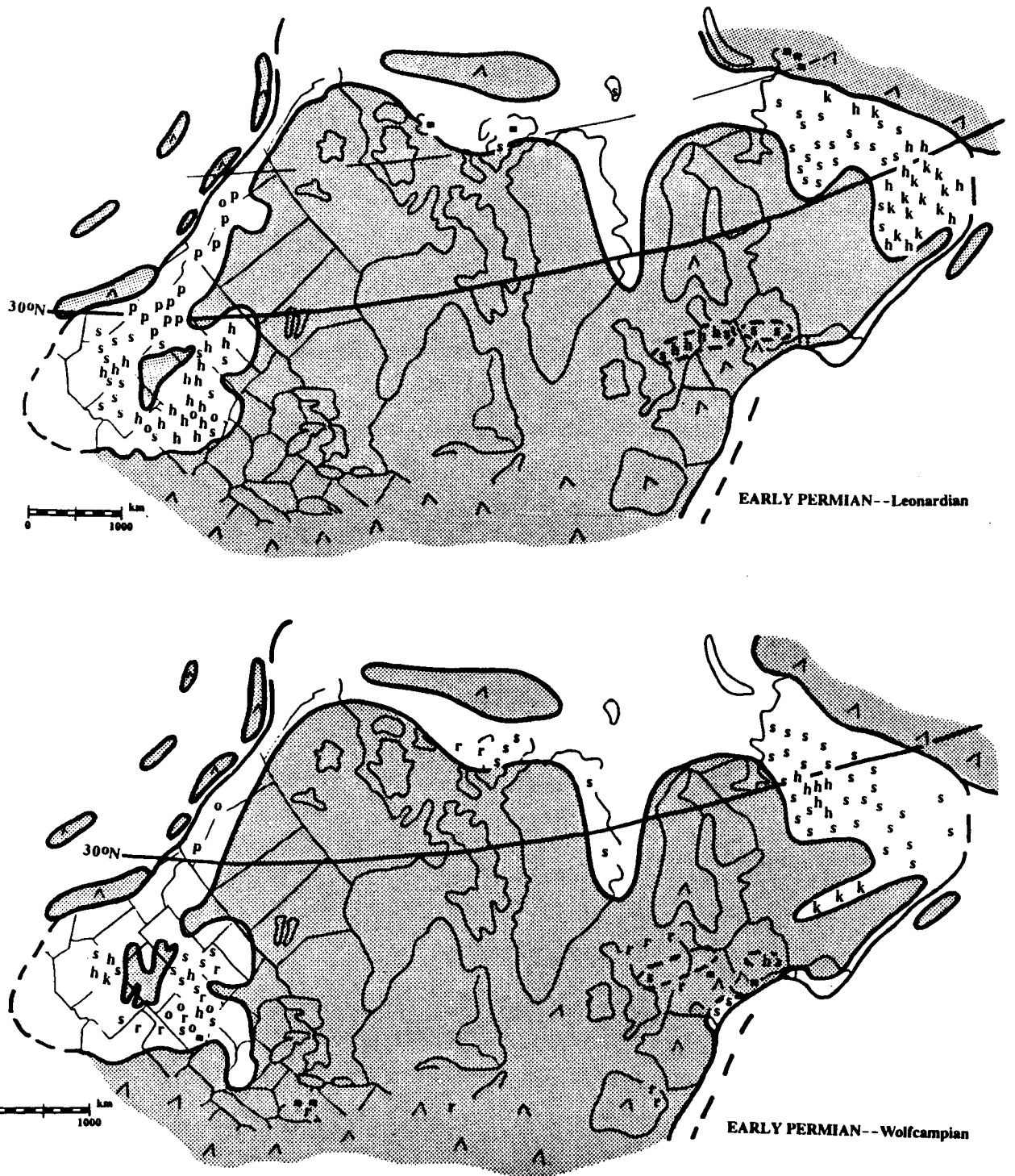


FIGURE 3 -- Interpreted paleogeography for Early Permian of Euramerica. Wolfcampian map includes Asselian, Sakmarian, lower Rotliegendes; Leonardian map includes Artinskian, Kungurian, upper Rotliegendes (from Witzke, 1990).

drawn nonetheless and fusulinid-bearing units were invariably placed at the transgressive peaks of sealevel curves. This resulted in very different curves being drawn for cycles of similar lithologic complexity. Compare, for example, the sealevel curves for the Foraker and Grenola limestones in Figure 1.

In redefining and reinterpreting Pennsylvanian cyclothem, Heckel (1977) has similarly focussed attention on a specific marine facies. Black, typically phosphatic, conodont-rich shales are interpreted as representing upwelling circulation during times of maximum transgression (Heckel & Baesemann, 1975). The thin limestones which commonly underlie these "core shales" are viewed as recording transgressive conditions, and the thicker overlying limestones as recording regressive conditions (Fig. 2). Limestones not associated with core shales are interpreted as accessory units that are not integral to the general cycle pattern. The reliance of this model on a particular facies for defining the inflection points on cyclothem sealevel curves becomes a liability in the Lower Permian where such facies are rare or absent. Also black phosphatic shales are subject to alternative depositional interpretations which do not require deep offshore conditions (Wenger & Baker, 1986). In addition black shales exhibit a variety of facies, some of which are interpreted as shallow water (Zangerl & Richardson, 1963; Coveney *et al.*, 1991).

The absolute magnitude of sealevel fluctuation recorded by Pennsylvanian-Permian cycles has always been a matter of dispute. Elias' (1937, 1964) estimate of 60 meters for the deepest water facies of Permian cycles was disputed by Imbrie and others (1964) and McCrone (1964). These workers placed maximum water depth at less than 20 meters based primarily on a reinterpretation of fossil evidence and the recognition of abundant sedimentary indicators of shallow water. Heckel's (1977) model, if applied to the Lower Permian, would predict water depth fluctuations of more than 100 meters, far in excess of those proposed by Elias, returning the debate full circle.

Cycle Hierarchies

The increasing recognition of hierarchies of cycles by stratigraphers is providing a needed context within which processes at different temporal scales can be analyzed and compared. The work of Vail and others (1977) established a hierarchy of depositional sequences composed of first (225-300 my), second (20-90 my), and third (7-13 my) order levels, which are major onlap-offlap sequences bounded by unconformities that are recognized globally. This hierarchy was further expanded downward by Busch and Rollins (1984) and Busch and West (1987) as a result of their studies of Pennsylvanian sequences of the Appalachian Basin. Cyclothem were integrated into this scheme as fifth order cycles, and genetic packages down to sixth-order cycles (PAC's of Goodwin and Anderson, 1985) were recognized. These sixth-order cyclic units are viewed by some as equivalent in temporal scale to the parasequences of sequence stratigraphy. Barron and others (1985) and Kauffman (1985, 1988) have proposed a similar

hierarchy in which fifth to seventh-order cycles are based on Milankovitch orbital parameters. A number of regional stratigraphic studies have utilized a hierarchical approach to understand the depositional dynamics of sedimentary basins (Aigner, 1985; Brett & Baird, 1986; Brett, et al., 1990; Goldhammer, et al., 1990).

Interest in cyclothem-scale patterns has largely diverted attention from possible smaller scale cyclic patterns which may prove to be very significant. Meter-scale (sixth-order) cycles have been recognized within the Pennsylvanian of the midcontinent (West & Busch, 1985; Busch et al., 1985; Suchy & West, 1991). These cycles are also readily recognized features of the Lower Permian in outcrop and core. Several recent detailed studies of specific members and formations within the Council Grove Group have focused on these cycles as the basis for correlation and paleo-environmental reconstruction (Bogina, 1986; F. Barrett, 1989; T. Barrett, 1989; Clark, 1989; Cunningham, 1989). Correlation of such higher-order cycles provides a very fine time-stratigraphic framework for the reconstruction of lateral facies relationships and the evaluation of models of cycle generation.

Preliminary work has indicated the occurrence of a yet finer scale of cyclicity that may provide even higher-resolution correlation on a local scale. Regular alternations of clay-rich and clay-poor units within limestones, and the stacking of paleosols within variegated mudstones, both occur at a scale of 30 to 50 cm . These cycles may be a response to periodic fluctuations in clastic influx controlled by short-term climate cycles. Whatever their cause, their presence is a ubiquitous and prominent feature of Lower Permian rocks at the outcrop and in core.

Discontinuity surfaces are very abundant within the Lower Permian, associated in many cases with sharp lithologic contacts. Until recently, however, most attention has focused on facies rather than the surfaces which bound them. Understanding the nature and temporal duration of these surfaces is critical both for defining cycle patterns and periodicities, and for interpreting their environmental significance. The environments under which depositional hiatuses form may also be completely distinct from those during deposition of the underlying and overlying lithologies. Subaerial exposure surfaces may develop on marine sediments and be overlain by marine sediments as well, with the discontinuities themselves the only record of the intervening nonmarine conditions. The presence of such surfaces places important constraints on any proposed model of cyclothem development, and on any proposed eustatic sealevel curves. An assessment of the amount of time represented by discontinuities is also critical for testing cyclic depositional models, because it is now generally recognized that more time is represented by surfaces than sediment, particularly at small time scales (Ager, 1981; Dott, 1983). Cycle periodicities will thus tend to be overestimated and sedimentation rates underestimated, perhaps by several orders of magnitude, if the nondepositional

and erosional hiatuses are not given adequate consideration (Sadler, 1981; Algeo & Wilkinson, 1988).

Paleosols and Paleoclimate

One potentially valuable type of bounding surface has received almost no attention – that of paleosols. Though the study of paleosols has increased significantly in the last ten years, Permian paleosols are essentially unstudied despite their potential for stratigraphic and paleoclimatic interpretation. In recent years a number of studies of Paleozoic paleosols and paleokarst have appeared in the literature: Ordovician (Feakes & Retallack, 1988), Silurian (Kahle, 1988), Devonian (Allen, 1986; McPherson, 1979), and Carboniferous (Walls *et al.*, 1975; Harrison & Steinen, 1978; Riding & Wright, 1981; Wright, 1982; Goldhammer & Elmore, 1984; Prather, 1985; Schutter & Heckel, 1985; Ettensohn *et al.*, 1988; Joeckel, 1989). Despite the dominance of nonmarine sedimentation in the Permian, paleosols of this period are some of the least studied (Smith, 1990 being one of the few). Presently, only one study inside the continental U.S. has undertaken an analysis of Permian paleosols (Joeckel, 1991).

Paleosols have been used with success as paleoclimate indicators (Bown & Kraus, 1981; Retallack, 1983), but their potential remains largely untapped. Preserved soil horizonation, pedogenic structures, root casts, carbonate accumulation, clay infiltration fabrics, and other soil features provide the basis for paleosol classification (Retallack, 1990) (Fig. 4). To date, at least six morphologically distinct paleosols within the measured stratigraphic section have been tentatively identified to the suborder level. These paleosols belong to the following soil orders: Entisols (2), Aridisols (2), Inceptisols, and Vertisols (Soil Survey Staff, 1990). Each paleosol type retains a diversity of features which reflects the past soil-forming environment. Once identified, paleosol types provide insight into both climate trends and rates of sediment aggradation. Given similar parent materials, climate and time are crucial variables controlling soil development (Birkeland, 1984). Morphological characteristics of paleosols (e.g. clay translocation, chemical leaching, grain weathering) are indicators of specific pedogenic processes that assist in reconstructing former climatic conditions. Also, paleosols often contain evidence of former vegetation and fauna that is useful for paleoenvironmental interpretation. The value of paleosols as a means of assessing stratigraphic completeness and the time represented by nondeposition and soil formation has been discussed by Retallack (1984) and Kraus and Bown (1986).

Models used to reconstruct climatic and environmental systems of the late Paleozoic in the midcontinent have been based primarily on marine stratigraphic units in the geologic record. These models were constructed with limited terrestrial data although nonmarine facies often account for major portions of the cyclothemic sequences. For much of the Lower Permian, paleosols are the predominate stratigraphic units within nonmarine facies. The

TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking edges	spheroidal with slightly interlocking edges	rounded and spheroidal but not interlocking
USUAL HORIZON	E, Bs, K, C	Bt	Bn	Bt	Bt	A	A
MAIN LIKELY CAUSES	initial disruption of relict bedding; accretion of cementing material	swelling and shrinking on wetting and drying	as for prismatic, but with greater erosion by percolating water, and greater swelling of clay	cracking around roots and burrows; swelling and shrinking on wetting and drying	as for angular blocky, but with more erosion and deposition of material in cracks	active bioturbation and coating of soil with films of clay, sesquioxides and organic matter	as for granular; including fecal pellets and relict soil clasts
SIZE CLASS	very thin < 1 mm	very fine < 1 cm	very fine < 1 cm	very fine < 0.5 cm	very fine < 0.5 cm	very fine < 1 mm	very fine < 1 mm
	thin 1 to 2 mm	fine 1 to 2 cm	fine 1 to 2 cm	fine 0.5 to 1 cm	fine 0.5 to 1 cm	fine 1 to 2 mm	fine 1 to 2 mm
	medium 2 to 5 mm	medium 2 to 5 cm	medium 2 to 5 cm	medium 1 to 2 cm	medium 1 to 2 cm	medium 2 to 5 mm	medium 2 to 5 mm
	thick 5 to 10 mm	coarse 5 to 10 cm	coarse 5 to 10 cm	coarse 2 to 5 cm	coarse 2 to 5 cm	coarse 5 to 10 mm	not found
	very thick > 10 mm	very coarse > 10 cm	very coarse > 10 cm	very coarse > 5 cm	very coarse > 5 cm	very coarse > 10 mm	not found

DESCRIPTIVE SHORTHAND FOR LABELING PALEOSOL HORIZONS

Category	New Term	Description	Old Term
Master Horizons	O	Surface accumulation of organic materials (peat, lignite, coal), overlying clayey or sandy part of soil	O
	A	Usually has roots and a mixture of organic and mineral matter; forms the surface of those paleosols lacking an O horizon	A
	E	Underlies an O or A horizon and appears bleached because it is lighter colored, less organic, less sesquioxides, or less clayey than underlying material	A2
	B	Underlies an A or E horizon and appears enriched in some material compared to both underlying and overlying horizons (because it is darker colored, more organic, more sesquioxides or more clayey) or more weathered than other horizons	B
	K	Subsurface horizon so impregnated with carbonate that it forms a massive layer (developed to stage III or more of Table 4)	K
	C	Subsurface horizon, slightly more weathered than fresh bedrock; lacks properties of other horizons, but shows mild mineral oxidation, limited accumulation of silica carbonates, soluble salts or moderate gleying	C
	R	Consolidated and unweathered bedrock	R
Gradations Between Master Horizons	AB	Horizon with some characteristics of A and B, but with A characteristics dominant	A3
	BA	As above, but with B characteristics dominant	B1
	E/B	Horizon predominantly (more than 50%) of material like B horizon, but with tongues or other inclusions of material like an E horizon	A&B
Subordinate Descriptors	a	Highly decomposed organic matter	—
	b	Buried soil horizon (used only for pedorelict horizons with paleosols; otherwise redundant)	b
	c	Concretions or nodules	cn
	e	Intermediately decomposed organic matter	—
	f	Frozen soil, with evidence of ice wedges, dikes, or layers	f
	g	Evidence of strong gleying, such as pyrite or siderite nodules	g
	h	Illuvial accumulation of organic matter	h
	i	Slightly decomposed organic matter	—
	k	Accumulation of carbonates less than for K horizon	ca
	m	Evidence of strong original induration or cementation, such as avoidance by root traces in adjacent horizons	m
	n	Evidence of accumulated sodium, such as domed columnar peds or halite casts	sa
	o	Residual accumulation of sesquioxides	—
	p	Plowing or other comparable human disturbance	p
	q	Accumulation of silica	si
	r	Weathered or soft bedrock	ox
s	Illuvial accumulation of sesquioxides	ir	
t	Accumulation of clay	t	
v	Plinthite (in place, pedogenic laterite)	—	
w	Colored or structural B horizon	—	
x	Fragipan (a layer originally cemented by silica or clay, and avoided by roots)	x	
y	Accumulation of gypsum crystals or crystal casts	cs	
z	Accumulation of other salts or salt crystal casts	sa	

FIGURE 4 -- Classification of soil peds (stable aggregates of soil material) and descriptions of the basic types of paleosol horizons (from Retallack, 1988).

terrestrial climatic and biologic record provided by these paleosols, when used in conjunction with the sedimentology and paleontology of the marine facies, provide a much more accurate reflection of Permian paleoclimatic conditions and fluctuations.

If eustatic sealevel change alone is insufficient to explain the observed facies transitions and cycle patterns, climate change may provide an important forcing mechanism. Climate cycles have been invoked by several workers (Barron et al., 1985; Fischer et al., 1985; Hattin, 1985; Kauffman, 1986) to explain decimeter- to meter-scale periodicities within the Cretaceous. A model for climatic control over facies development within Carboniferous cycles has been proposed by Cecil (1990) based on a comparison of Mississippian and Pennsylvanian cycles in the Appalachian Basin (Cecil et al., 1985; Donaldson et al., 1985). In this model, clastic sediment transport is predicted to be highest in seasonal wet-dry climates and lower in both arid and tropical wet climates. Carbonates and evaporites accumulate during arid and semiarid conditions, and mappable coal beds form during relatively wet climates when clastic influx is low. These climate-driven depositional processes may function at more than one temporal scale, responding to long-term climatic changes within the Permo-Carboniferous as well as short-period Milankovitch climatic oscillations. This model also predicts a progressive change in paleosol types with increasing aridity from leached soils (Oxisols and Inceptisols) to Vertisols and Aridisols (Cecil, 1990). Paleosols, in fact, provide a valuable independent test of this climate model.

Overview of Council Grove Group Stratigraphy

The focus of this portion of the guidebook is the stratigraphic interval from the Grenola Limestone through the Wreford Limestone of the Council Grove Group (Fig. 5). This interval was chosen because the sedimentary cycles contain the full range of facies encountered within the Lower Permian section. The Grenola Limestone includes the last widespread occurrence of black shales, and the Wreford Limestone represents the first highly cherty limestone of the midcontinent Permian. A wide range of carbonate facies occurs within this interval, including marine bioclastic packstones and wackestones, fusulinid packstones, algal wackestones, tidally laminated carbonate mudstones, and molluscan limestones. Variegated mudstones include subaerial facies with a wide diversity of pedogenic structures as well as marine facies with moderately diverse faunas. The marine fossil assemblages of this interval have been well documented by previous workers (Lane, 1958, 1964; Imbrie, 1955; Laporte, 1962; Imbrie et al., 1964; Hattin, 1957; McCrone, 1963).

The cycles of the Council Grove Group are broadly similar to those of the Missourian upon which the "Kansas-type" cyclothem model of Heckel (1977) is based. The sequence of red and green variegated mudstone or "outside shale", thin marine limestone, dark gray "core shale", and thick multistoried limestone is a repeated pattern at a scale of 10-20 meters. This is the scale at which Lower

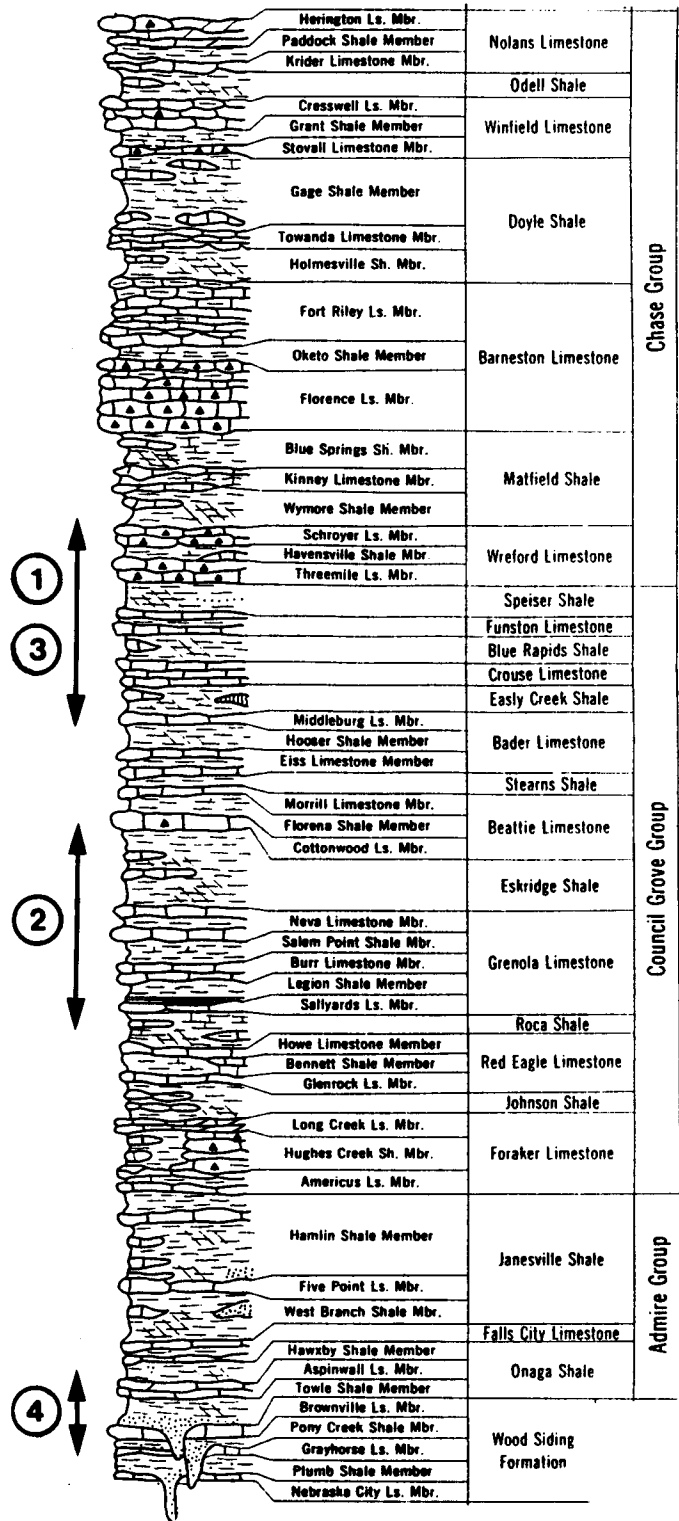


FIGURE 5 – Formation and member-scale units of the Admire, Council Grove and Chase Groups in Kansas (from Zeller, 1968). Arrowed bars with circled numbers indicate the stratigraphic intervals to be examined at each of the field stop localities.

Permian cyclothems were originally described by Jewett (1933) and Elias (1937). However, preliminary field work has revealed that this same pattern is also present within stratigraphic intervals only a few meters thick (Miller, 1991). Within the Grenola cyclothem for example, the "Kansas-type" cyclothem facies pattern has been recognized at three distinct temporal scales within the same stratigraphic interval at the same locality (see Stop 2).

Meter-scale cycles are both ubiquitous and prominent within the studied interval, being especially well developed in the more marine portions of the cyclothems. These small-scale cycles are bounded by discontinuity surfaces and can be defined as subsequences or parasequences (PAC's of Goodwin and Anderson, 1985) depending on the environmental interpretation of specific facies. A yet smaller scale of cyclicity is also evident. These 30-50 cm thick cycles manifest themselves as regularly-spaced shale interbeds or clay-rich zones within limestones, and as stacked paleosols within the variegated shales. Such decimeter-scale cycles have also been recognized within Pennsylvanian cyclothems, and one recent study (McNeice, 1987) correlated clay-rich zones within one limestone unit for a distance of over 70 kilometers. These small-scale cycles may be similar in origin to the limestone-marl alternations of the western interior Cretaceous which have been interpreted as recording Milankovitch climate cycles (Barron *et al.*, 1985; Hattin, 1985).

Discontinuity surfaces bound meter-scale cycles and mark the contacts of many lithologic units (Miller *et al.*, 1991). These discontinuities include marine flooding surfaces, condensed horizons, and subaerial exposure surfaces. Flooding surfaces are typically associated with intraclastic beds or condensed skeletal lags. Condensed beds are represented by skeletal lags which may be phosphatized and particularly by bone beds rich in fish debris. Subaerial exposure is recorded by a wide range of surfaces including paleosols, rooted horizons, calcretes, mudcracked horizons, and microkarstic surfaces. These surfaces, which have been largely overlooked in the past, have important implications for both the delineation and interpretation of cycles.

A great variety of pedogenic features have been recognized within the Council Grove Group including color horizonation, root casts and molds, rhizocretions, well-developed blocky and columnar ped structures, caliche nodules and calcretes, pedogenic slickensides, pseudoanticlines, and *in situ* brecciation. Stacked sequences of truncated paleosols typify the non-marine portions of the variegated mudstones. Multiple columnar carbonate horizons within the lower Eskridge Shale and very uniform red and green color banding in rooted blocky mudstones within the Speiser shale record repeated paleosol units. The delineation and characterization of paleosol horizons, together with the record of flooding surfaces and condensed beds, makes possible a very fine-scale stratigraphy for the variegated mudstones. The identification of paleosols is also crucial to reconstructing both spatial and temporal changes in the soil forming environment. Consistent changes in paleosol morphology upward

through the section would strongly suggest climatic trends, given relatively homogeneous parent materials. Preliminary work does indicate such patterns are present within several outside shale units. Aridisols are more characteristic of the lower portions of variegated mudstones, while vertisols occur near their tops. Such a trend could be generated by a short-term climate trend toward increasing, though still seasonal, precipitation.

STOP 1 Scenic Drive (K-408): Crouse, Funston, and Wreford cycles

Location: Sec. 15, T.10S., R.7E., Riley County

Contributors: Keith B. Miller and Thomas J. McCahon

Introduction

Stop 1 is located on Scenic Drive 1.2 mi. north of the intersection with K-18. This stop offers a continuous exposure of the upper Council Grove Group from the Bader Limestone through the Wreford Limestone at the base of the Chase Group. Six cyclothem sequences equivalent to the cycles defined by Elias (1937) occur within this stratigraphic interval. Four of these cycles will be examined in detail -- the Crouse, Funston, Three Mile, and Schroyer cycles. The latter three were grouped together by Moore (1964) to form a "megacyclothem." The Crouse Limestone marks the top of another megacyclothem that includes the underlying Middleburg and Eiss cycles.

The general facies pattern of Lower Permian cyclothem is well displayed at this locality. Variegated mudstones with extensive paleosol development are abruptly overlain by thin transgressive carbonates typically containing intraclasts, skeletal debris that may be phosphatized, and bone fragments. Above these are gray to yellowish gray shales followed by thick limestone units which may show evidence of subaerial exposure at the top. The internal complexity of these formation- to member-scale units can be examined in detail. Each of the variegated mudstones contains several flooding surfaces which define widely traceable stratigraphic units. Similarly, the limestones contain traceable meter- to decimeter-scale internal units.

A wide variety of pedogenic features can be observed within this stratigraphic interval. Paleosols are easily identified in the field using soil horizons, rooting, and pedogenic structures. Many paleosol profiles are truncated but some are nearly complete. The latter provide the best opportunity for paleoclimatic and environmental interpretation.

Stratigraphy and Facies Descriptions

The stratigraphic interval described here begins with the Easley Creek Shale which can be divided into three distinct stratigraphic units (Fig. 1-1). The base of the Easley Creek is marked by a mudstone breccia of pale olive (10Y6/2) clasts in a grayish red (10R5/2) matrix. Both the mudstone matrix and the clasts show evidence of having been subjected to pedogenic processes. This breccia corresponds to a 1.8 meter-thick gypsum bed in the subsurface, and thus probably represents a solution collapse breccia. Above this breccia is an interval of light

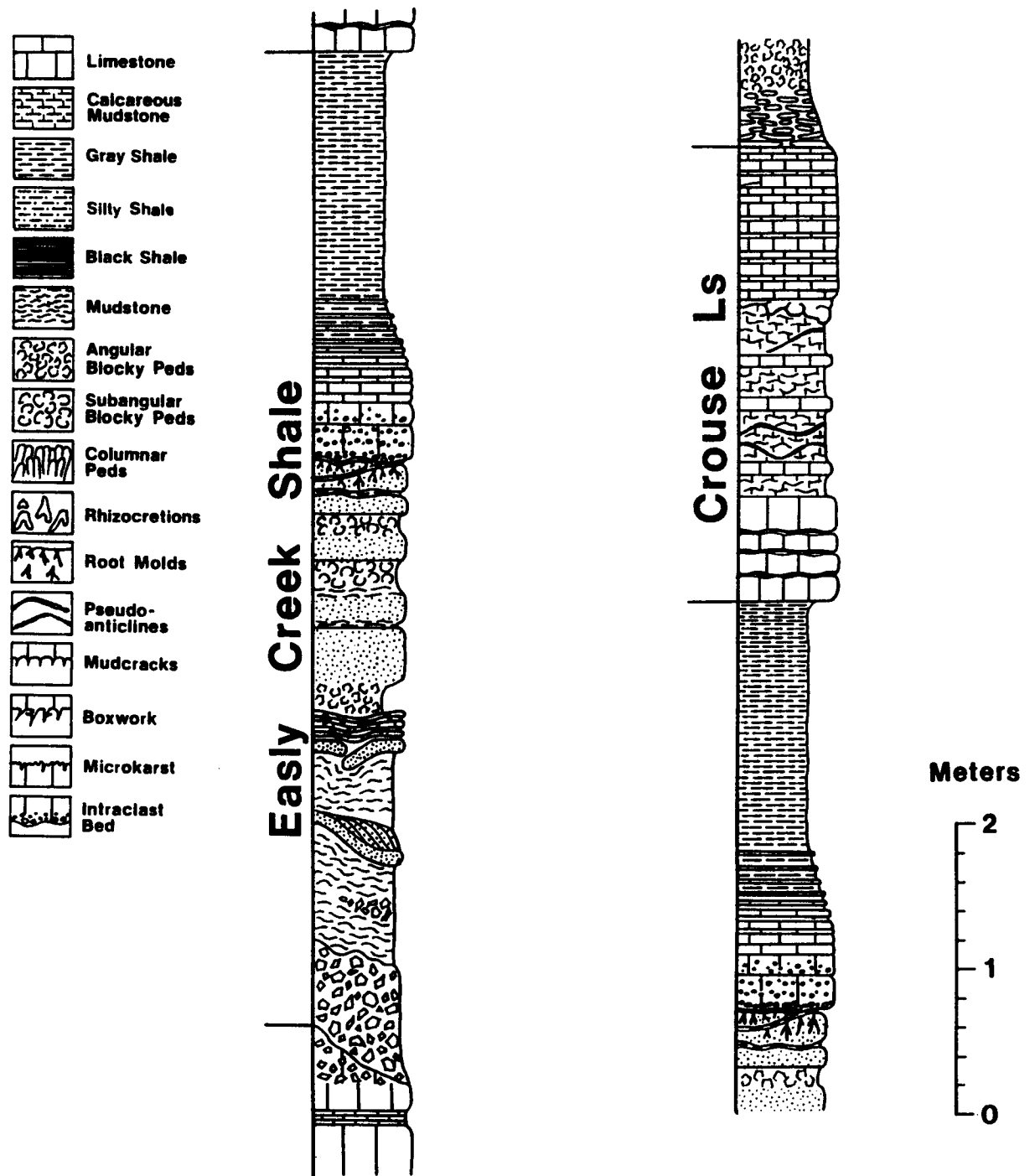


FIGURE 1-1 -- Measured stratigraphic columns for the Easy Creek Shale and Crouse limestone at Scenic Drive (K-408) roadcut. The key to unconventional symbols is shown to the left.

greenish gray (5GY8/1) and light brown (5YR6/4) mudstone that shows extensive synsedimentary deformation and becomes increasingly silty upward. Within this mudstone a 10 cm thick sandstone bed has broken and foundered into the underlying mudstone. Depressions formed by the foundering of this bed are filled by sigmoidally cross-bedded sand indicating that the deformation resulted from the syndepositional solution of the underlying gypsum bed. This lower portion of the Easley Creek is capped by thin calcareous beds containing root traces and plant debris. The next major interval is represented by a series of alternating pale greenish yellow (10Y8/2) to grayish yellow (5Y8/4) mudstone and siltstone beds. These decimeter-scale units also display incipient soil development with angular to subangular peds. A rubbly, rooted silty mudstone with a poorly developed columnar ped structure caps this second stratigraphic interval. Sharply overlying the rooted horizon is a 50 cm-thick intraclastic limestone containing rounded granule to pebble-size micrite clasts. These clasts occur in graded layers together with disarticulated and fragmented brachiopod shells, bivalves, and pyramidellid gastropods. The intraclastic limestone grades into interbedded limestone and shale. The thin limestone beds are highly fossiliferous with abundant brachiopod shell debris (with articulated productids common), ramose bryozoans, small crinoid ossicles, algal-coated grains, and ostracodes. These grade into an interval of medium gray (N5) shale with a low diversity fauna of lingulids and pectinid bivalves.

Above the Easley Creek Shale is the Crouse Limestone (Fig. 1-1) which also contains three widely traceable stratigraphic intervals (West, 1972; Voran, 1975; West & Twiss, 1988). A lower wackestone to packstone interval is characterized by pyramidellid gastropods and bivalves. This interval consists of decimeter-scale beds separated by thin shale partings. The uppermost of these beds is highly vuggy. The middle Crouse is a highly calcareous, silty mudstone to shale. Undulatory carbonate-filled fractures and a rubbly zone at the top of this interval may indicate a period of subaerial exposure. The upper interval of the Crouse is a thin-bedded, horizontally laminated, dolomitic micrite with pavements of ostracodes. West and Twiss (1988) have interpreted the facies succession of the Crouse as a shallowing-upward sequence from a shallow subtidal to supratidal environment.

The top of the Crouse marks the beginning of the next cyclothemic sequence. The variegated mudstone of the overlying Blue Rapids Shale is divisible into four intervals marked by sharp flooding surfaces (Fig. 1-2). Resting on brecciated micrite from the Crouse, the lowest interval preserves a nearly complete paleosol profile with well-developed color horizonation, angular blocky ped structure, pedogenic slickensides, and carbonate rhizcretions. This paleosol is sharply overlain by a calcareous mudstone containing ostracodes and fish bone. This mudstone in turn lies at the base of another similar, well-preserved paleosol profile, itself abruptly overlain by a laminated mudstone containing ostracodes, fish bone and granule-size intraclasts. The next interval of greenish gray (5GY6/1) mudstone, though different in appearance, also shows evidence of

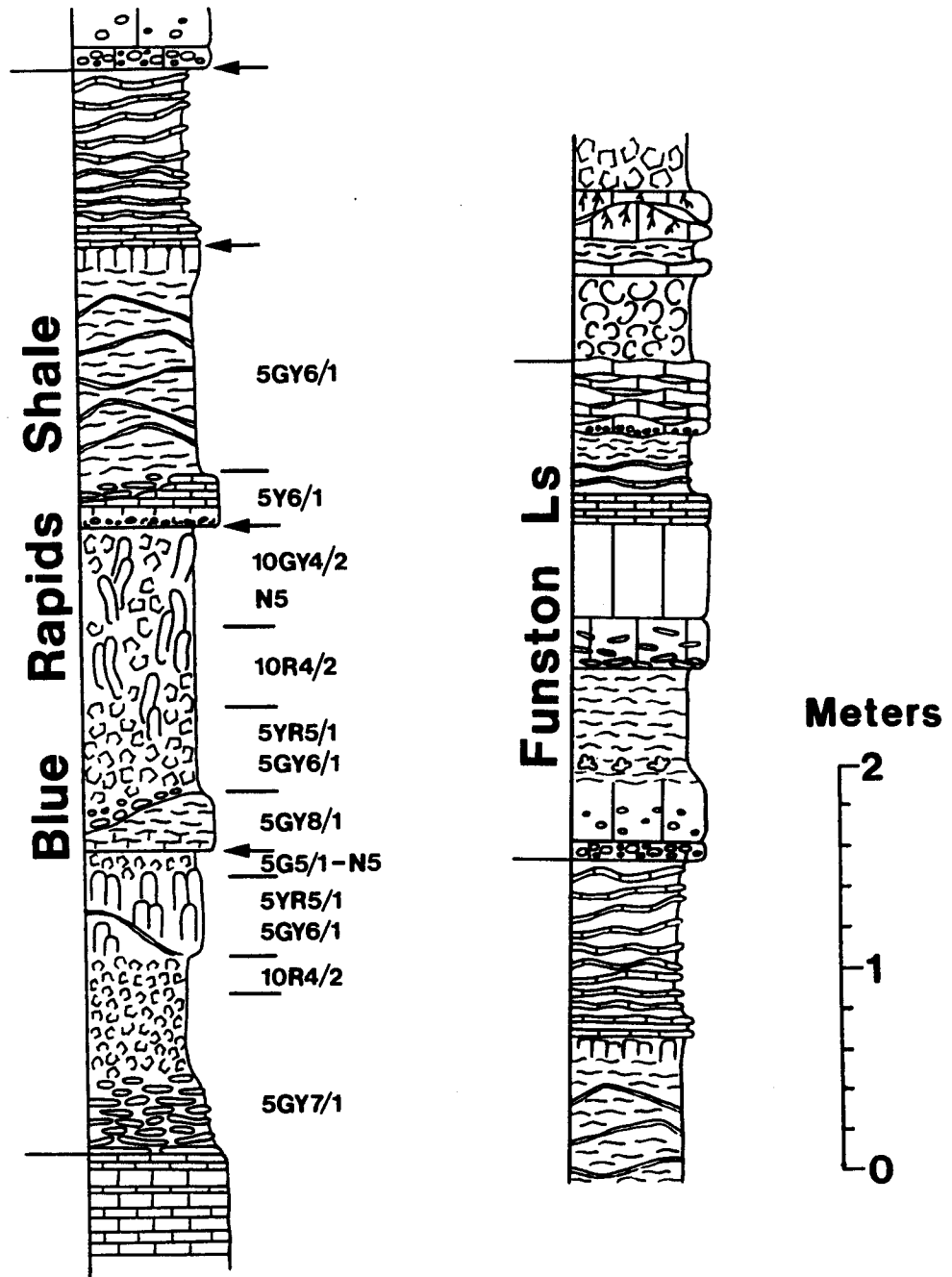


FIGURE 1-2 -- Measured stratigraphic columns for the Blue Rapids shale and Funston limestone at Scenic Drive (K-408) roadcut. Munsell color designations are given for paleosol horizons within the Blue Rapids shale. Arrows mark flooding surfaces.

pedogenesis. The most prominent pedogenic structures are abundant pseudoanticlines. A horizontally laminated carbonate bed truncates this paleosol and is followed by an interval of dusky yellow green (5GY5/2) shale with thin, wavy carbonate bands.

The base of the Funston Limestone (Fig. 1-2) is marked by a prominent flooding surface. Resting on this surface is a 40cm-thick argillaceous packstone containing abundant granule-size mudstone clasts and fragmented and abraded skeletal debris. Fossils include pyramidellid gastropods, ostracodes, productid brachiopods, bryozoans, and crinoid ossicles. This limestone grades upward into an unfossiliferous, grayish yellow (5Y8/4) mudstone which is horizontally laminated in its lower part and contains botryoidal silica geodes. A second wackestone to packstone unit has platy micrite intraclasts at its base. It is highly recrystallized, with abundant moldic porosity and small solution voids. Identifiable fossils include ostracodes and pyramidellid gastropods. Above this limestone is a light greenish gray (5GY7/1) mudstone with well-developed pedogenic slickensides indicating subaerial exposure and incipient soil development. This is sharply overlain by a third argillaceous limestone with granule-sized green mudstone clasts at its base.

The third cyclothem sequence begins with the Speiser Shale, a variegated mudstone similar in many respects to the Blue Rapids Shale. The Speiser Shale is divisible into four intervals (Fig. 1-3). The lowest interval is a paleosol profile truncated by an ostracode bearing argillaceous limestone that is extensively rooted. Above is a spectacular red and green banded interval of stacked and truncated paleosols. These paleosols have angular to subangular ped structures and abundant dendritic root mottles. This interval is sharply overlain by a thin-bedded mudstone with granule-sized green mudstone clasts. Above this flooding surface is a light greenish gray (5GY7/1) mudstone with prominent pseudoanticlines and abundant concertina root traces up to 3 cm in diameter. The upper ~1 meter of this interval probably represents a nearly complete paleosol profile. A packstone of comminuted skeletal debris abruptly overlies this paleosol and marks the base of the uppermost interval of the Speiser Shale. Above is a highly fossiliferous medium light gray (N6) calcareous shale grading into a more fissile and less fossil-rich shale. Fossils include brachiopods (particularly productids which can be found articulated and in life position), bivalves, ramose and fenestrate bryozoans, and crinoid ossicles.

The Three Mile limestone is the first prominent chert-bearing limestone in the Council Grove Group. It contains four distinct units at this locality (Fig. 1-4). At the bottom is a wackestone to packstone containing irregular beds of chert. Productid shell debris and crinoid ossicles are abundant. This is overlain by a fissile calcareous shale that grades upward into an argillaceous limestone and wackestone. Fossils include brachiopods, crinoid ossicles, fenestrate and ramose bryozoans, and ostracodes. Articulated productids occur within the shaley interval. The wackestone contains a chert bed, as well as isolated chert nodules

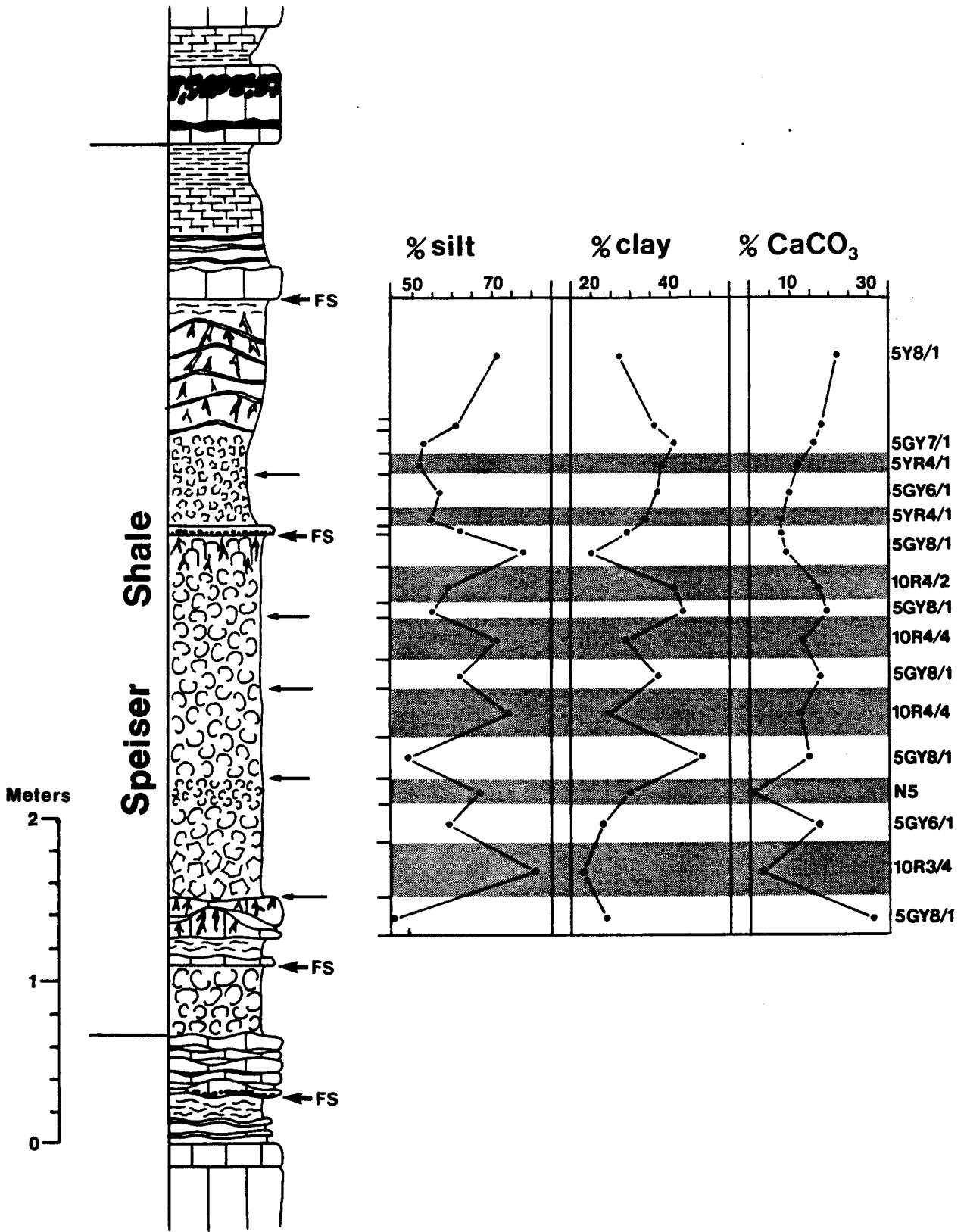


FIGURE 1-3 -- Measured stratigraphic column for the Speiser Shale at Scenic Drive (K-408) roadcut. The percent silt, clay and carbonate is given for each paleosol horizon. Munsell color designations are shown to the right --shaded horizons are reddish or gray, non-shaded horizons are greenish gray. Heavy arrows mark flooding surfaces (FS), and thin arrows mark sharp boundaries between paleosols horizons indicating truncation of the soil profile.

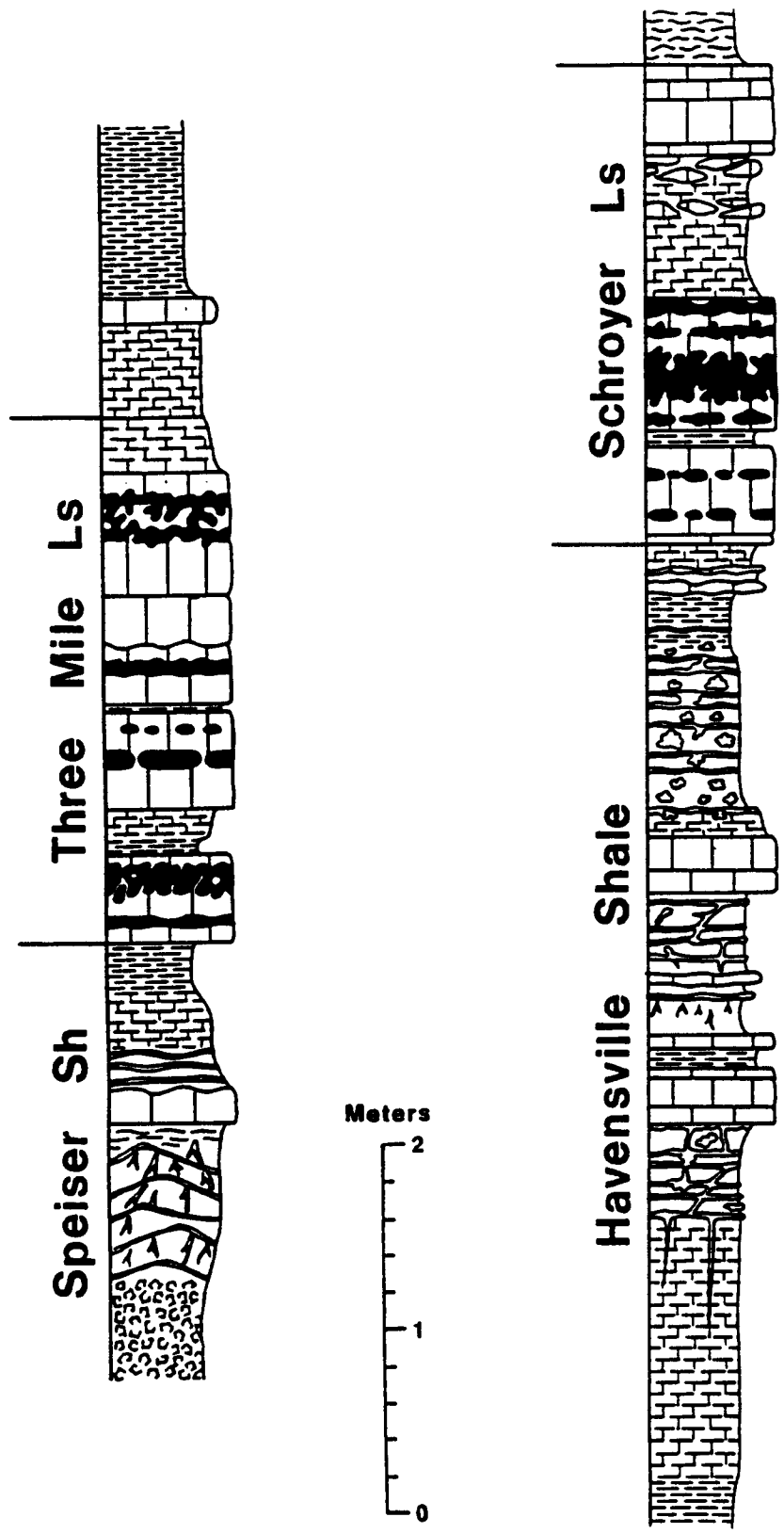


FIGURE 1-4 -- Measured stratigraphic columns for the Three Mile limestone, Havensville shale and Schroyer limestone at Scenic Drive (K-408). Chert beds and nodules are indicated in black.

with radial length-slow calcedony formed by the replacement of gypsum nodules (West, et al., 1987; Twiss, 1991). A thin clay parting separates the next limestone unit containing little chert, but abundant small solution cavities. Fossils within this wackestone include brachiopods, small bivalves and crinoid ossicles. Hattin (1957) found that this portion of the Three Mile limestone thickens to 7.5 meters in central Kansas and contains abundant fenestrate and ramose bryozoans. The uppermost unit of the Three Mile limestone is a highly cherty wackestone that grades upward into an argillaceous packstone. The diverse fossil assemblage includes crinoid ossicles, ramose and fenestrate bryozoans, brachiopods and trilobites.

The fourth and final cyclothem begins with the top of the Three Mile limestone. The Havensville shale, however, is very different from any of the previously described "outside shales" (Fig. 1-4). Its contact with the underlying limestone is gradational rather than abrupt, and evidence of subaerial exposure does not occur until higher in the section. A fossiliferous calcareous shale at the base is succeeded by a thick interval of medium gray (N5) calcareous shale/mudstone that is poorly fossiliferous except for pectinid bivalves near the top. At the top of this interval is a 50cm-thick calcareous mudstone with a "boxwork" structure of irregular botryoidal carbonate bands and vertical carbonate-filled fractures, some extending up to 60 cm into the underlying mudstone. This structure probably developed as a result of desiccation during extended periods of subaerial exposure. Above this boxwork is a wackestone with a graded layer of shell debris marking a flooding surface at its base. This wackestone is overlain by medium light gray (N6) calcareous shale and mudstone with abundant ostracodes and chonetid brachiopods. Root traces and the development of an angular blocky ped structure in the upper olive gray (5Y4/1) part of this interval indicates another extended period of exposure. This rooted horizon is followed by a second ~50 cm-thick boxwork interval capped by an argillaceous wackestone with brachiopod shell debris, ramose and fenestrate bryozoans, crinoid ossicles, and ostracodes. The medium light gray (N6) calcareous mudstone above contains abundant thin irregular bands of silica, silica nodules, and large quartz-filled cauliflower-shaped geodes. The shape of these silica bands and nodules and their internal "chickenwire" texture suggests that they formed by the replacement of gypsum. Tiny lath shaped molds of gypsum crystals are also locally abundant.

The Schroyer limestone is both the capping unit of the fourth cyclothem described here and of the megacyclothem that began with the top of the Crouse Limestone. It is another highly cherty limestone, and can be divided into four units (Fig. 1-4). The bottom unit is a micrite with layers of ellipsoidal chert concretions and abundant small solution voids. Abruptly overlying this is a shaley layer grading upward into a massive wackestone with prominent irregular chert beds. Fossils include brachiopods (productids and Composita occur as articulated specimens), ostracodes, crinoid ossicles, and ramose and fenestrate bryozoans. Above is a fossiliferous calcareous mudstone that becomes

rubbly and nodular toward the top. Many articulated productids occur near the top of this interval. The upper unit of the Schroyer is a recrystallized wackestone to packstone with abundant solution voids and moldic porosity. A thin packstone of ellipsoidal osagia grains marks the top.

Paleosol Description and Interpretation

The paleosols of the Blue Rapids and Speiser shales deserve further discussion because of their possible environmental significance. The three nearly complete paleosols of the Blue Rapids Shale with preserved E, B, and C horizons are especially noteworthy (Fig. 1-2). The first has a well developed carbonate accumulation (Bk) horizon with abundant rhizcretions that is relatively shallow. The overlying paleosol, while similar, contains a much more diffuse carbonate horizon which lies lower in the profile indicating a relatively greater intensity of leaching. The grayish red (10R4/2) horizons in the middle of both of these paleosols record oxidation under fairly well drained conditions, with the underlying greenish gray horizons (5GY7/1) probably indicating the average position of the water table. The vertic structure of the upper paleosol, with its abundant pseudoanticlines, indicates the expansion and contraction of the soil in a seasonal wet/dry environment. The absence of a red oxidized horizon suggests more poorly drained conditions.

The truncated paleosol profiles of the middle Speiser are much more difficult to interpret. Erosional truncation of paleosol profiles can be recognized by sharp contacts between horizons, in contrast to the diffuse or mottled contacts expected within a profile. Despite this truncation, both clay illuviation and carbonate concentration can be recognized in these paleosols (Fig. 1-3). Like the lower Blue Rapids paleosols, they were well enough drained to develop red oxidized horizons above the water table. The uppermost paleosol of the Speiser has a very well developed vertic structure with prominent pseudoanticlines or gilgai. This would again suggest a highly seasonal wet/dry environment like that for the upper Blue Rapids paleosol. This upward trend from drier, better drained soils to vertic, poorly drained soils is a common pattern within the "outside shales" of the Council Grove Group. Such a trend could be generated by a short-term climate trend, or by paleogeographic factors such as increased proximity to the paleoshoreline.

STOP 2 (optional) Fort Riley Boulevard (K-18): Grenola cycle

Location: Sec. 23, T.10S., R.7E., Riley County

Contributors: Keith B. Miller and Thomas J. McCahon

Introduction

Exposed along this roadcut are the paleosols of the upper Roca Shale, the thin Sallyards limestone, Legion shale, Burr limestone, Salem Point shale, Neva limestone, and the variegated paleosols and carbonate units of the Eskridge Shale. All the stratigraphic units from the Sallyards limestone through the Neva limestone are members of the Grenola Limestone Formation. The earlier work by both Elias (1937) and Moore (1964) considered the Grenola to be a single cyclothem. Recognition of several subaerial exposure surfaces within the Grenola makes this interpretation no longer tenable.

The Eskridge Shale is interesting both for its internal stratigraphy and the spectacular development of some of its paleosols. The paleosols of this unit are also the only ones of the midcontinent Permian which have been previously studied (Joeckel, 1991). Because the Eskridge is not easily accessible at this locality, the description of the Eskridge Shale presented here is from a roadcut on Anderson Avenue at the intersection with Scenic Drive and Kimball Road just north of Stop 1.

The stratigraphic interval exposed at this locality is significant for several reasons. Firstly, the hierarchical pattern of depositional cycles characteristic of the Council Grove Group is very clearly displayed at this locality. Numerous condensed beds, flooding surfaces, and subaerial exposure surfaces reveal a complex cycle pattern within cyclothem-scale units. Secondly, the Grenola Limestone contains the last widespread black "core shales" within the Pennsylvanian/Permian, and thus is more similar to the "Kansas Type" cyclothem model. And lastly, the Virgilian/Wolfcampian boundary has recently been moved upward to the base of the Neva Limestone to be compatible with accepted biostratigraphic criteria (Baars, 1990; Baars et al., 1990). This section therefore contains the newly redefined Pennsylvanian/Permian boundary of the midcontinent.

Stratigraphy and Facies Descriptions

The upper portion of the Roca Shale exposed here contains perhaps three paleosol profiles (Fig. 2-1). These have very well developed angular blocky ped structure, root traces, and carbonate rhizcretions. The uppermost paleosol contains a calcrete (K) horizon up to 45 cm thick. These carbonate-rich profiles are indicative of semi-arid conditions. The Roca paleosols are abruptly overlain

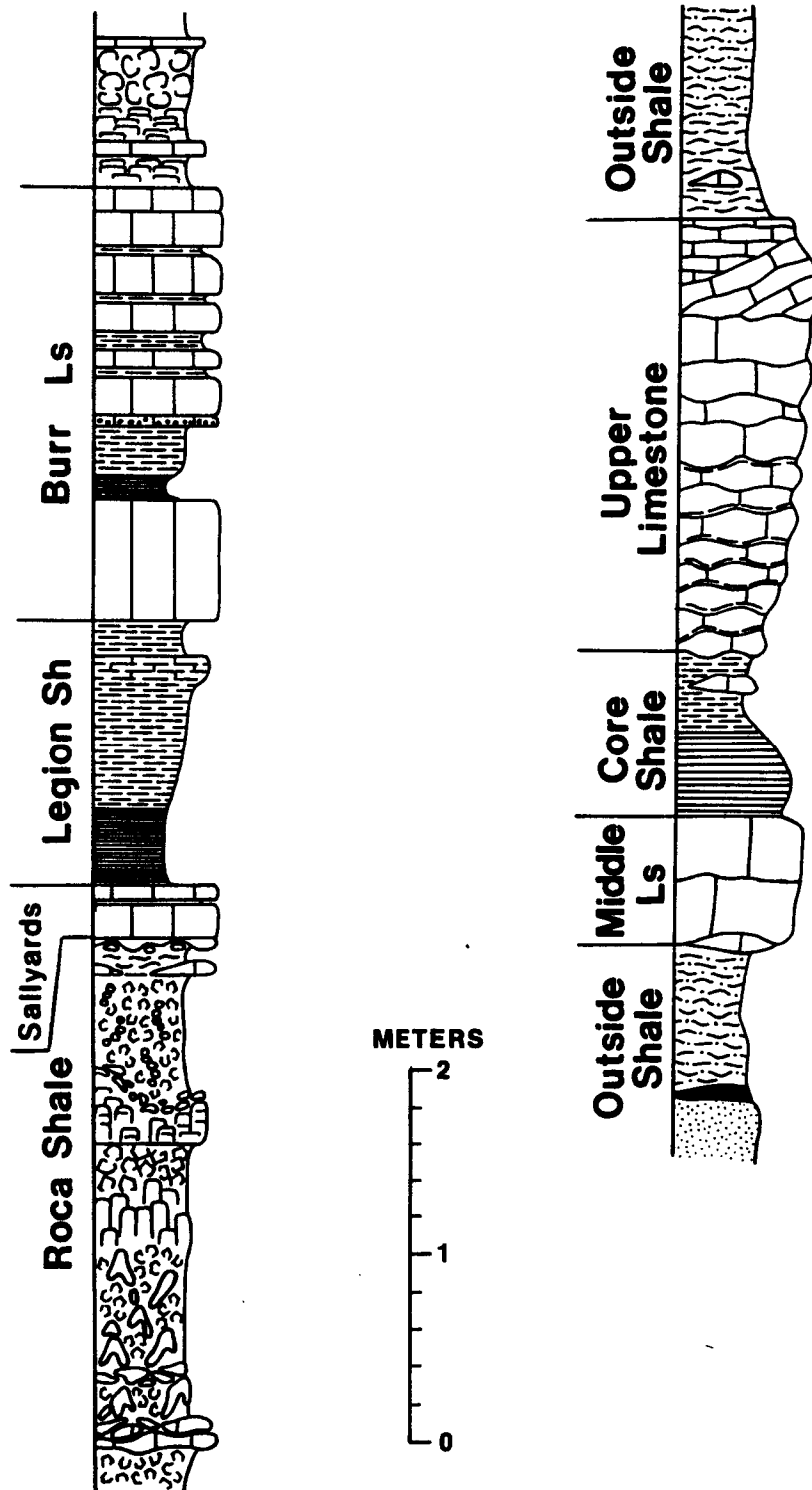


FIGURE 2-1 – Measured stratigraphic column for the Roca Shale, Sallyyards limestone, Legion shale, and Burr limestone at Fort Riley Blvd (K-18) roadcut. The Kansas-type cyclothem model of Heckel (1977) is shown to the right for comparison. Note that this cyclothem pattern is present at two different scales. See text for discussion.

by the Sallyards limestone, a thin wackestone containing small bivalves, brachiopods, and crinoids. Above this limestone is the Legion shale which grades upward from a fissile dark gray (N3) shale to a siltier and less fissile light olive gray (5Y6/1) shale. Small burrows are common throughout, and ostracodes occur toward the top together with some plant debris.

The Burr limestone consists of three distinct units (Fig. 2-1). The lower unit is a packstone to wackestone containing brachiopods, bivalves, pyramidellid gastropods, fenestrate bryozoans, crinoid ossicles and echinoid spines. Articulated, life-position brachiopods, particularly productids, occur at the top. Sharply overlying this limestone is a fissile black (N1) shale with fine phosphatic skeletal debris at the base. This black shale grades upward into a medium dark gray (N4) shale with pavements of ostracodes, tiny pectinids and myalinids. The upper unit of the Burr is composed of decimeter-thick micritic limestones separated by thin argillaceous or shaley intervals. The base of the upper Burr has a thin condensed bed of phosphatized skeletal material, particularly pyramidellid gastropods, and fish teeth. The middle part of the unit contains abundant fish bone (?) debris and ostracodes which are frequently concentrated within burrow structures. Also abundant on some bedding planes are Permophorus-type bivalves. At the top of the Burr is a layer of highly fragmented and abraided shell debris.

Above the Burr limestone is the Salem Point shale which is a deceptively complex and heterolithic interval (Fig. 2-2). At the base of the Salem Point is a greenish gray (5GY6/1) silty mudstone with poorly developed platy to subangular blocky peds. (However, in the subsurface, a ~60 cm thick gypsum bed overlies the Burr.) The upper portion of the mudstone is horizontally laminated and has well developed large desiccation cracks with polygons 30 cm or more across. This exposure surface is overlain by a micrite, in part laminated and containing horizons of rip-up clasts. Resting on a sharp contact above this thin limestone is a fissile dark gray (N3) shale that grades upward into a silty light gray (N7) to light olive gray (5Y6/1) shale. Plant debris are abundant particularly within silty laminae. Ostracodes, small bivalves, and small burrows are also abundant. At the top of this shale is a calcareous mudstone with a very well developed horizon of columnar ped structures, and lenses of light olive gray (5Y6/2) mudstone with fine angular blocky peds and root traces. This interesting horizon may have developed in response to a soil forming environment with a high flux of sodium. Such saline conditions are consistent with the presence of gypsum lower in the interval. Truncating this paleosol is a highly burrowed argillaceous packstone with fragmented skeletal debris including brachiopods and crinoid ossicles. This limestone is in turn sharply overlain by another fissile grayish black (N2) shale grading upward to a medium gray (N5) shale. At the base of this shale is a bone bed up to several centimeters thick with skeletal debris and abundant conodonts. The first appearance of the conodont species Streptognathodus barskovi in this horizon is used by Baars and others (1990) to mark the base of the Permian. Lingulid brachiopods occur in the black shale

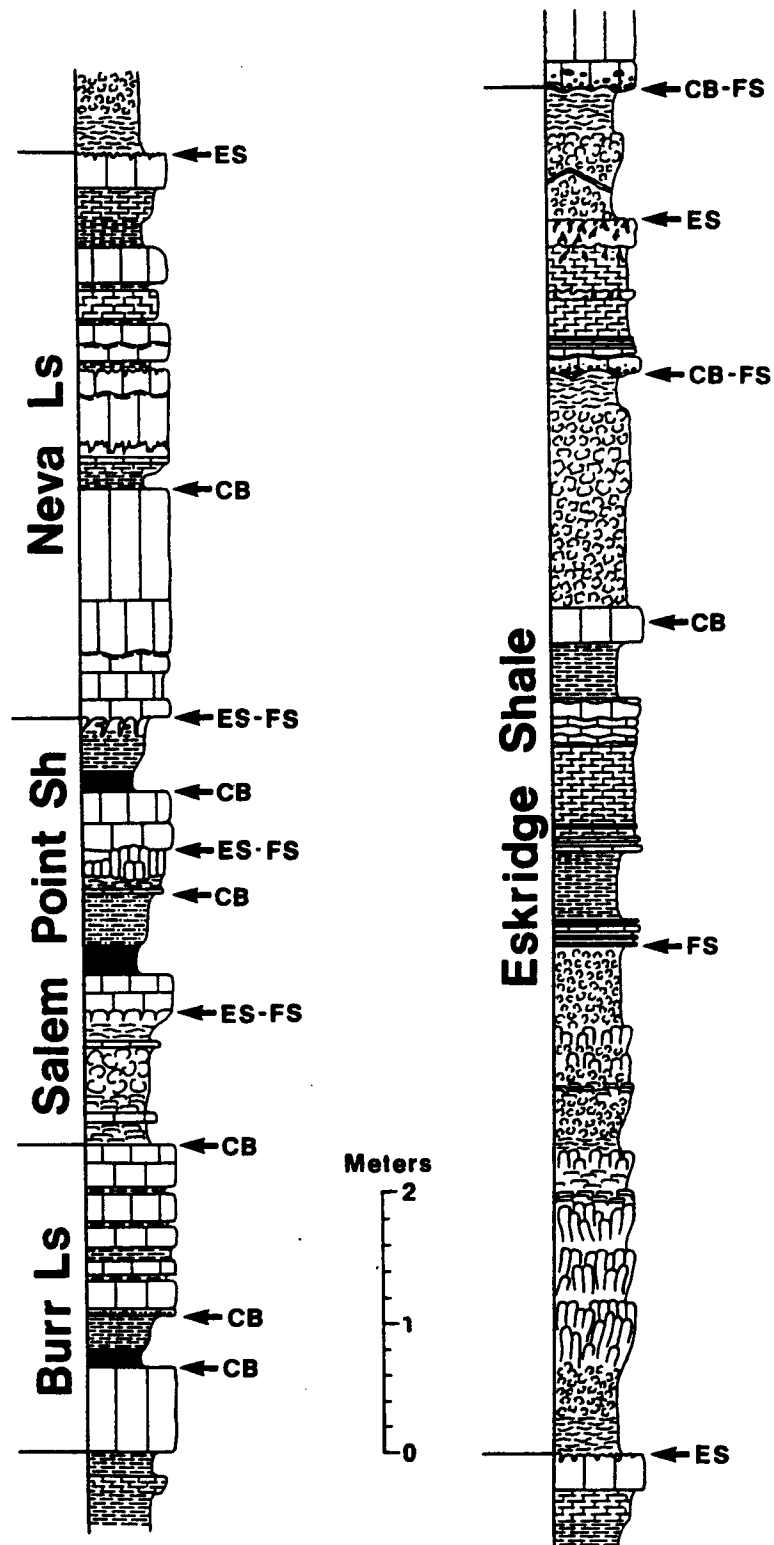


FIGURE 2-2 -- Measured stratigraphic column for Burr limestone, Salem Point shale, and Neva limestone (Grenola Limestone) at Fort Riley Blvd (K-18). Eskridge Shale column was measured at the intersection of Scenic Drive and Anderson Avenue near Stop 1. The arrows mark the important hiatus surfaces: (FS) flooding surfaces, (ES) exposure surfaces, and (CB) condensed beds. The Grenola Limestone could be divided into as many as 10 shallowing upward parasequences.

above. Plant debris is also present and increases in abundance upward. At the top, this interval becomes a silty calcareous mudstone with lingulids, plant debris, small bivalves and large Chondrites-like burrows. Boxwork carbonate fracture fillings extending down from the overlying Neva limestone possibly record another subaerial exposure surface.

The base of the Neva (Fig. 2-2) is a silty wackestone with shelly layers of brachiopods and crinoid ossicles. Above this basal unit is a thick massive algal wackestone with silty laminated layers. The limestone is very vuggy especially in its lower part. The large branching phylloid algae of this interval is associated with abundant fenestrate bryozoans (many with little fragmentation), productid and Composita brachiopods, and crinoid ossicles. Sharply overlying this massive unit is a thin dark shaley interval with a bone bed containing conodonts and skeletal debris at the base. Fusulinids occur within this argillaceous interval which was therefore interpreted by Elias (1937) as the deepest water facies within the Grenola cyclothem. The upper part of the Neva Limestone consists of four cycles of alternating argillaceous limestone or calcareous shale and micritic limestone. The first of these limestones is poorly fossiliferous and stylolitic with small gypsum crystal molds. The others are packstones with brachiopods, crinoid ossicles, echinoid spines, bryozoans, bivalves and ostracodes. The top of the Neva is dolomitic with a microkarstic upper surface and possible root traces.

The Eskridge Shale is a thick mudstone formation that is divisible into four stratigraphic intervals (Fig. 2-2) recognizable at least as far as the Nebraska border (Joeckel, 1991). The lowest interval is a red and green variegated mudstone with spectacularly developed pedogenic structures. In addition to angular blocky ped structures and root traces, these paleosols have horizons of dense carbonate rhizcretions which are grown together to produce a structure similar to columnar peds. These rhizcretion horizons are stacked in units a few decimeters thick. The top of this paleosol sequence is grayish green (10GY5/2) to yellowish gray (5Y7/2) in color indicating more poorly drained conditions as at the top of the Blue Rapids and Speiser shales. A thin basal lag of ostracodes and pyramidellid gastropods marks a flooding surface at the base of the next interval of light olive gray (5Y6/1) to light gray (N7) calcareous mudstone. Above this lag are several thin limestone beds with unfragmented myalinids, pectens, and Derbyia brachiopods. An argillaceous packstone caps this calcareous interval. This condensed bed contains abundant ostracodes, fine skeletal debris (productid spines, crinoid ossicles) and fish bone. Well developed angular blocky ped structures and pedogenic brecciated fabrics are present in the variegated red and green mudstones that comprise the next interval of the Eskridge. This interval of paleosols is also truncated by a flooding surface overlain by an intraclastic carbonate containing granule- to cobble-sized mudstone clasts, pyramidellid gastropods, productid spines and shell fragments. The calcareous mudstones above are poorly fossiliferous except for pavements of Derbyia and productid brachiopods. The upper portion of this calcareous interval is intensely rooted and overlain by a grayish green (10GY4/2) paleosol with angular blocky peds and

possible pseudoanticlines. The Eskridge Shale is capped by a condensed phosphatic bed at the base of the Cottonwood Limestone. This bed contains mudstone clasts up to 10cm in diameter, phosphate nodules, bone fragments, and skeletal debris (pyramidellid gastropods, ostracodes, and brachiopods).

Hiatal Surfaces and Cycle Patterns

The abundance and variety of discontinuities within cyclothem-scale depositional packages reveals the internal complexity of these large-scale cycles. Of particular interest and significance is the presence of subaerial exposure surfaces within the limestone and gray shale facies. For example, each of three shale-to-limestone cycles (parasequences) within the Salem Point shale of the Grenola cyclothem contain subaerial exposure surfaces (Fig. 2-2). These exposure surfaces include a mudcracked horizon, a zone of columnar pedogenic structures, and a horizon of boxwork structure. All three of these surfaces are overlain by a marine limestone thus superimposing a marine flooding surface on the exposure surfaces. Such double discontinuities have important implications for any proposed model of cycle formation. Within this same stratigraphic interval, condensed beds tend to occur at the contact of limestone beds with overlying black to dark gray shale. These are highly comminuted skeletal lags with an abundance of fish bone and conodonts.

The internal stratigraphy of the variegated "outside shales" is nearly as complex as the limestone and "core shale" facies. Marine flooding surfaces occur at the base of calcareous intervals and are commonly marked by intraclastic beds of reworked mudstone pebbles and caliche nodules or by skeletal lags. The presence of flooding surfaces within variegated shales and of exposure surfaces within otherwise marine facies suggests that depth may not be the only, or even the primary, control on facies development. A similar conclusion was reached earlier by Laporte and Imbrie (1964) based on their work on the overlying Beattie and Wreford cyclothem.

The problem of delineating cycles is particularly evident within this stratigraphic interval. If Heckel's (1977) "Kansas type" cyclothem model is used, two cyclothem would be recognized within the Grenola Limestone (Fig. 2-1). The first would include the Sallyards limestone, Legion shale, and Burr limestone, and the second would include the upper Salem Point shale and Neva limestone. However, this assignment is not without problems. For example: the Sallyards limestone could be considered a "transgressive limestone" with the Legion shale representing the "core shale;" alternatively, the lower Burr limestone could be designated the "transgressive limestone" and the black shale above the "core shale." The expected facies pattern is actually present at several different temporal scales. This can be seen within other lower Permian cyclothem as well. An alternative approach is to divide the interval into shallowing upward parasequences with flooding surfaces at their bases. Up to 10 parasequences could be defined within the Grenola Limestone in this way (Fig. 2-

2). However, the definition of such cycles is dependent on the relative significance given to individual surfaces and to the environmental interpretation of certain facies. For example, the dark gray to black shales could record accelerated deepening following initial transgression, or shallowing into near shore lagoonal or estuarine environments.

STOP 3 I-70, 3 miles west of Frontage Road Exit 323: Crouse, Funston, and Wreford cycles

Location: Sec. 30, T.11S., R.9E., Riley County

Contributors: Keith B. Miller and Ronald R. West

Introduction

This roadcut exposure is located almost at the crest of the Nemaha Anticline, and therefore provides an opportunity to view the facies changes associated with this paleotopographic high. It also enables the stratigraphic significance of different lithologic units and discontinuity surfaces to be assessed. A major objective of the detailed measurement of stratigraphic sections is to identify those surfaces which have widespread chronostratigraphic significance.

Two closely spaced roadcuts on the north side of I-70 expose much of the interval viewed at Stop 1. The westernmost cut includes the Middleburg limestone, Easley Creek Shale, and Crouse Limestone. The eastern cut begins in the upper part of the Blue Rapids Shale, and extends through the Funston Limestone, Speiser Shale, Three Mile limestone, and Havensville shale to the base of the Schroyer limestone.

Stratigraphy and Facies Descriptions

Surprisingly, the Easley Creek Shale has nearly the same thickness and internal stratigraphy here as at Stop 1 (Fig. 3-1). It begins with a mudstone breccia of green mudstone clasts in a reddish matrix. This is overlain by a red and green variegated mudstone with pedogenic structure followed by a massive silty mudstone. As at Stop 1, this first interval is capped by a rooted calcareous unit. The interval above consists of two mudstone to calcareous siltstone intervals with poorly developed pedogenic structure. This silty interval is truncated by an intraclastic limestone essentially identical to that previously described from Stop 1. Bone fragments and pieces of charcoal occur within this condensed bed in addition to pyramidellid gastropods, ostracodes, and small mounds of calcareous tubes of uncertain affinity. This grades into a highly fossiliferous shaley packstone with abundant bryozoans, brachiopods, pectinid and myalinid bivalves, ostracodes, and algal-coated grains. The poorly fossiliferous shale above is not well exposed.

Though the Easley Creek Shale is essentially unchanged, the Crouse limestone shows significant thinning over the Nemaha Anticline (Fig. 3-2). The lower Crouse is similar to its appearance at Stop 1 with decimeter-scale beds separated by shaley partings and a vuggy upper part. The fauna is similar with ostracodes in addition to pyramidellid gastropods and bivalves. Nearly all of the

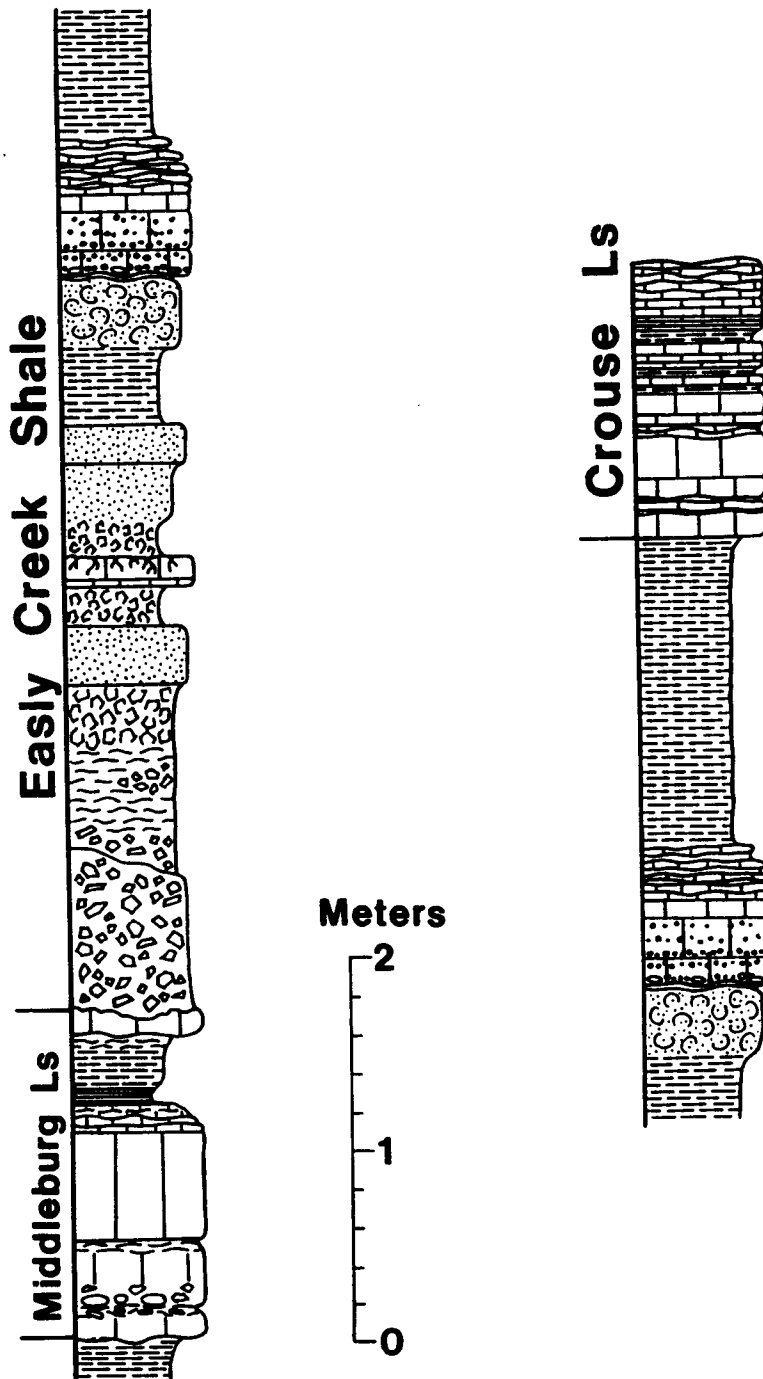


FIGURE 3-1 -- Measured stratigraphic columns for Middleburg limestone, Easy Creek Shale, and Crouse limestone at I-70 roadcut east of Manhattan. Compare with measured section from Stop 1 (Fig. 1-1).

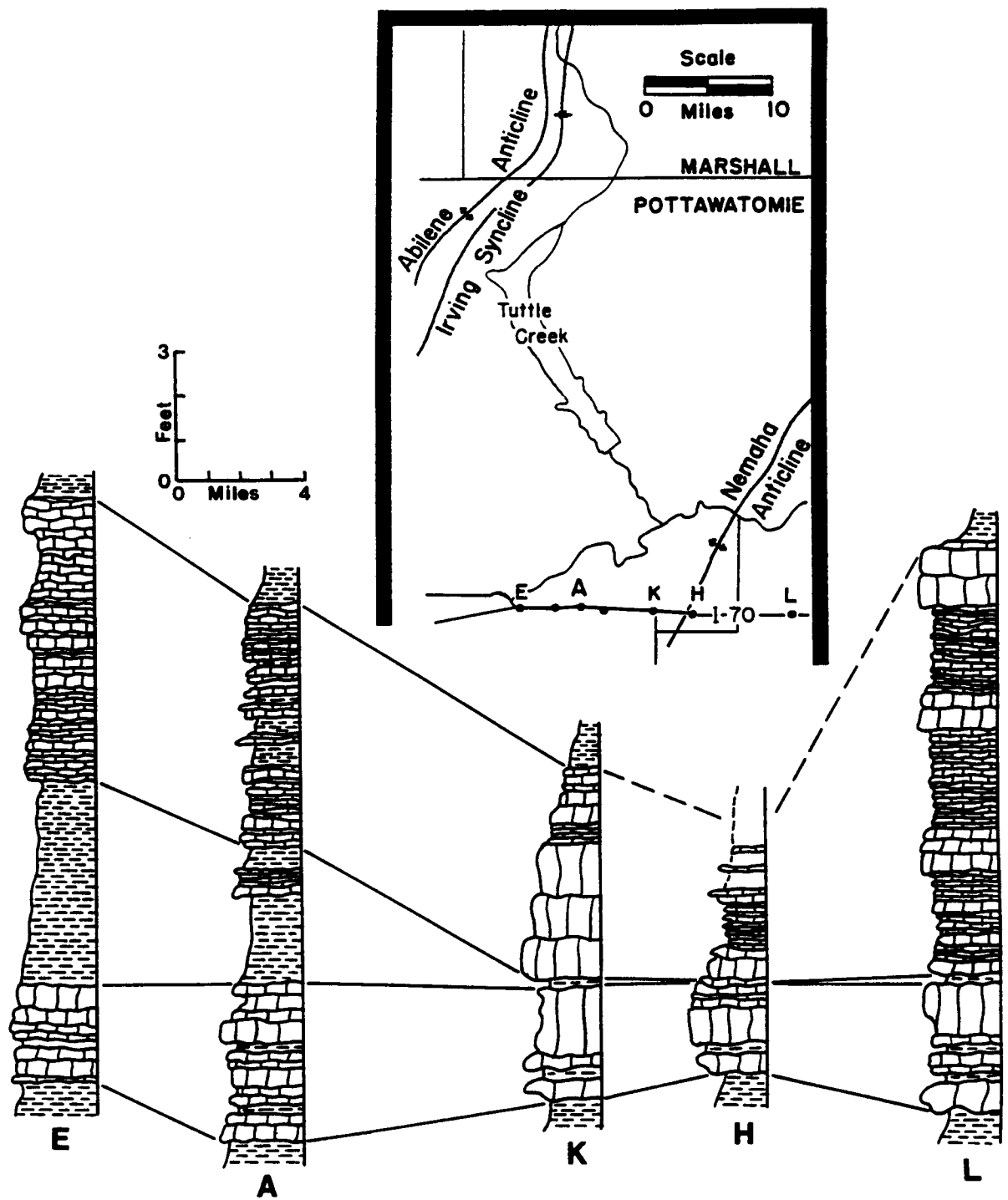


FIGURE 3-2 -- Correlated sections of the Crouse limestone across the Nemaha Anticline showing lateral changes in its three distinctive units. Stop 3 is shown as locality H on the map inset. Note the thinning, and eventual loss, of the middle shaly unit of the Crouse over the anticline.

thinning of the Crouse is accomplished by the reduction of the middle shaley interval to a few centimeters of silty micrite (West & Twiss, 1988). The upper Crouse consists of thickening upward packages of horizontally-laminated, dolomitic micrite with abundant lath-shaped gypsum molds and occasional ostracod pavements.

Most of the Blue Rapids Shale is covered at this locality. Immediately below the Funston Limestone, the Blue Rapids is an olive black (5Y2/1) to olive gray (5Y4/1) shale. The Funston is thinner at this locality and divisible into only two intervals (Fig. 3-3). The lower interval has a highly recrystallized wackestone at its base with unidentified skeletal debris and abundant botryoidal silica geodes. Above is a platy micrite grading into calcareous mudstone. As at Stop 1, the second interval is a micrite to wackestone with platy intraclasts and brecciated beds at its base, and fine skeletal debris including pyramidellid gastropods. This recrystallized limestone contains small silica geodes and abundant fine root molds that decrease downward. This intensely rooted zone is apparently stratigraphically equivalent to the uppermost Funston limestone and lowest Speiser Shale at Stop 1.

The Speiser Shale at this locality is very different in appearance from variegated paleosols present at Stop 1, and much thinner. However, the major distinctive intervals and their bounding surfaces are still easily recognized (Fig. 3-3). The lowest interval of the Speiser consists of a stacked series of truncated dusky yellow (5Y6/4) to pale olive (10Y6/2) paleosols with fine angular blocky peds and fine dendritic root traces. These are separated by mm-thick gray layers that contain plant debris, fine skeletal debris, and bone. The uppermost paleosol contains a very well-developed horizon (Bk) of carbonate rhizcretions that are locally densely spaced. The entire series of paleosols is only 90 cm thick here, but is stratigraphically equivalent to 2.25 meters of red and green paleosol horizons at Stop 1. Abruptly truncating this interval is a prominent intraclastic limestone with angular micritic clasts and ostracodes (?). Above this bed, layers of rounded granule-size carbonate grains alternate with mudstone and shale for several decimeters. This same flooding surface is represented at Stop 1 by a single horizon of granule-size mudstone clasts. Overlying the intraclastic unit is a light olive gray (5Y5/2) shale with abundant plant material and ostracodes that grades upward into a grayish olive (10Y4/2) mudstone with angular blocky peds. The next flooding surface is marked by a brecciated and rubbly micrite overlain by packstone beds with ostracodes, pyramidellid gastropods, bivalves, brachiopods and echinoids. Above is a very fossiliferous medium dark gray (N4) to medium light gray (N6) shale with crinoids, bryozoans, pectinid bivalves, ostracodes, and a variety of brachiopods. At the upper contact of the Speiser Shale with the Three Mile limestone are unusual concave-up tepee-like structures commonly having large cauliflower masses of chert at their crests. These structures and associated vertical silica-filled fractures may indicate subaerial exposure.

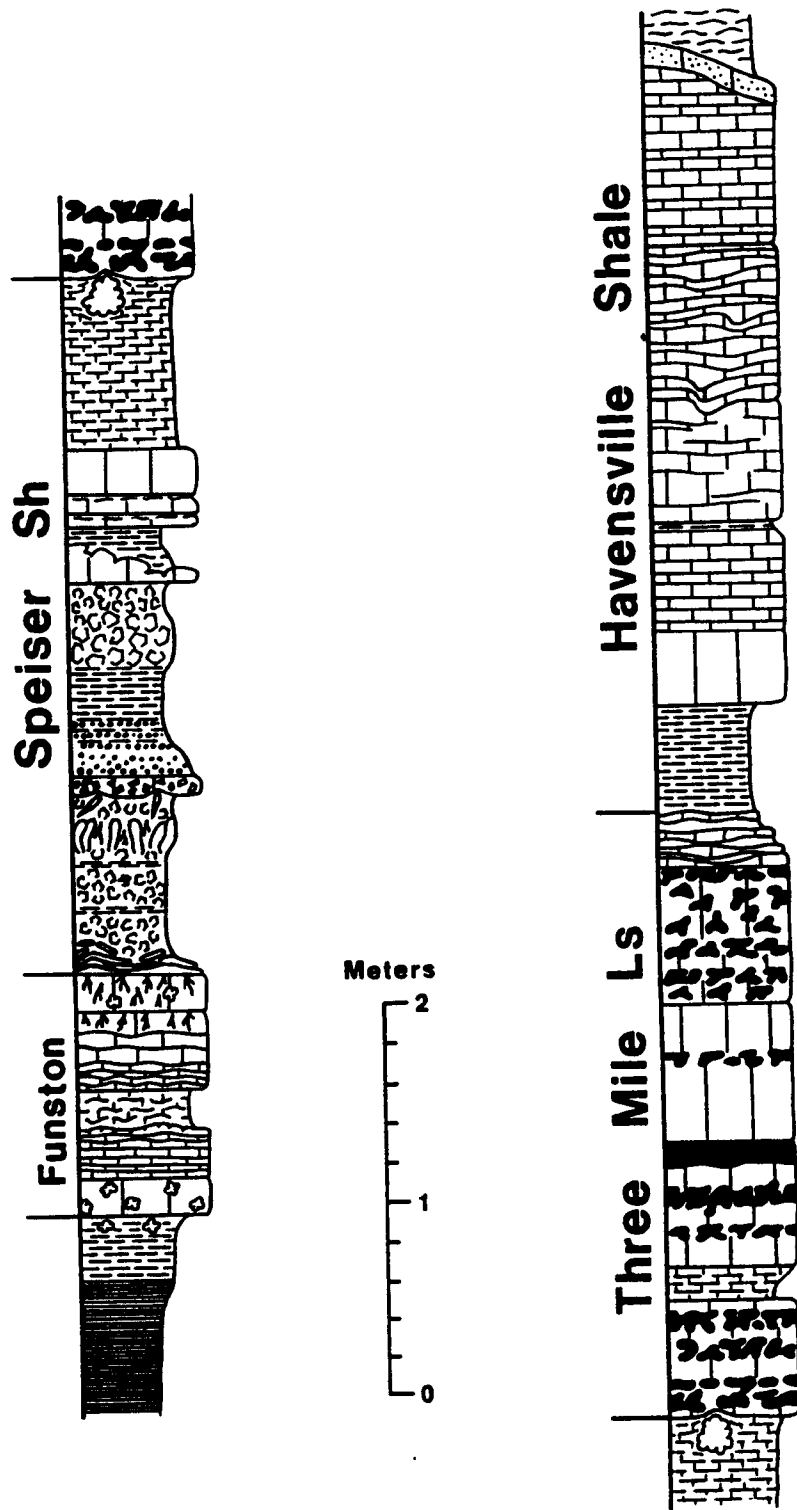


FIGURE 3-3 -- Measured stratigraphic columns for the Funston limestone, Speiser Shale, Three Mile limestone, and Havensville shale at I-70 roadcut east of Manhattan. Chert beds and nodules shown in black. Note the presence of the thick bedded bioclastic limestone in the lower Havensville, and compare with measured section from Stop 1 (Fig. 1-4).

The Three Mile limestone is almost identical in thickness, lithology and fossil content to its occurrence at Stop 1. The same four distinct units are present: two lower cherty units separated by a thin calcareous shale, a chert-poor unit with abundant small solution voids, and an upper highly cherty unit grading into a fossiliferous shale (Fig. 3-3). Fossils include abundant bryozoans, crinoids, echinoids, and brachiopods. Branching burrow structures filled with skeletal debris occur in distinct horizons and may have formed by the infilling of open burrow structures during high energy events ("tubular tempestites" of Wanless *et al.*, 1988). The similar branching morphology of many nodular chert layers indicates that they represent the selective silicification of these burrows.

The most dramatic facies change between Stop 1 and Stop 3 is within the Havensville shale. The poorly fossiliferous calcareous shale in the lower Havensville at Stop 1 is locally replaced over the crest of the Nemaha Anticline by a thick fossiliferous packstone (Fig. 3-3). This packstone is divisible into three main units: a lower unit with 5-8 cm-thick graded beds of skeletal debris, a middle unit with wavy irregular, locally disturbed beds, and an upper unit of 5-8 cm-thick graded beds. The fossil content of all three units is similar, with brachiopods (productids, chonetids, Composita, Derbyia), gastropods, pectinid and myalinid bivalves, crinoid ossicles, and ramose and fenestrate bryozoans. Wood fragments, fossil leaves and charcoal occur in the lower and upper units. Of special interest within this thick packstone is the observation of the internal truncation of these three units. From west to east across the roadcut exposure each of the three units can be seen to pinch out under the overlying unit which increases in thickness (Fig. 3-4). The whole sedimentary package is, in turn, truncated and bevelled from east to west by a thin silty bed with oriented wood and plant fragments. The impression is of a series of "channels" cut and filled with transported bioclastic debris. The upper Havensville shale is present above, though covered, and capped by the cherty limestone of the Schroyer at the top of the outcrop.

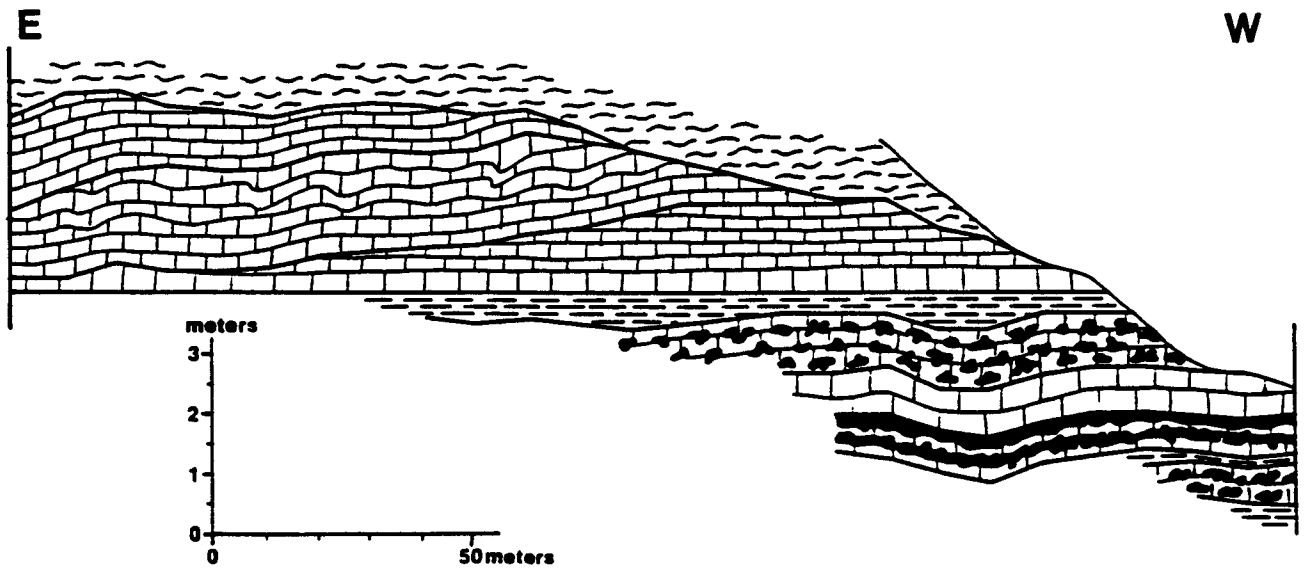


FIGURE 3-4 – Measured profile of the roadcut on the south side of I-70 at Stop 3 showing the Three Mile limestone and overlying Havensville shale with the base of the bioclastic limestone of the Havensville drawn as datum. Note the cut and fill geometry of the three units within the bioclastic limestone, and the east-to-west truncation of the entire limestone (measured by Kelly Greene).

STOP 4 (Optional) I-70, 0.5 miles west of Maple Hill Exit: Pony Creek Shale, Brownsville Limestone, Towle Shale, and Aspinwall Limestone

Location: C South line Sec. 26, T.11S., R.12E., Wabaunsee County

Contributors: R. R. West and R. Matsumoto

Introduction

The three important aspects of this stop are: 1) the previously defined Pennsylvanian-Permian boundary is clearly visible, 2) the basic "Kansas" cyclothem seen in the Missourian is not present here, and 3) the facies mosaic recorded by a very small (thin) and subtle, but important, genetic event within the Pony Creek Shale Member.

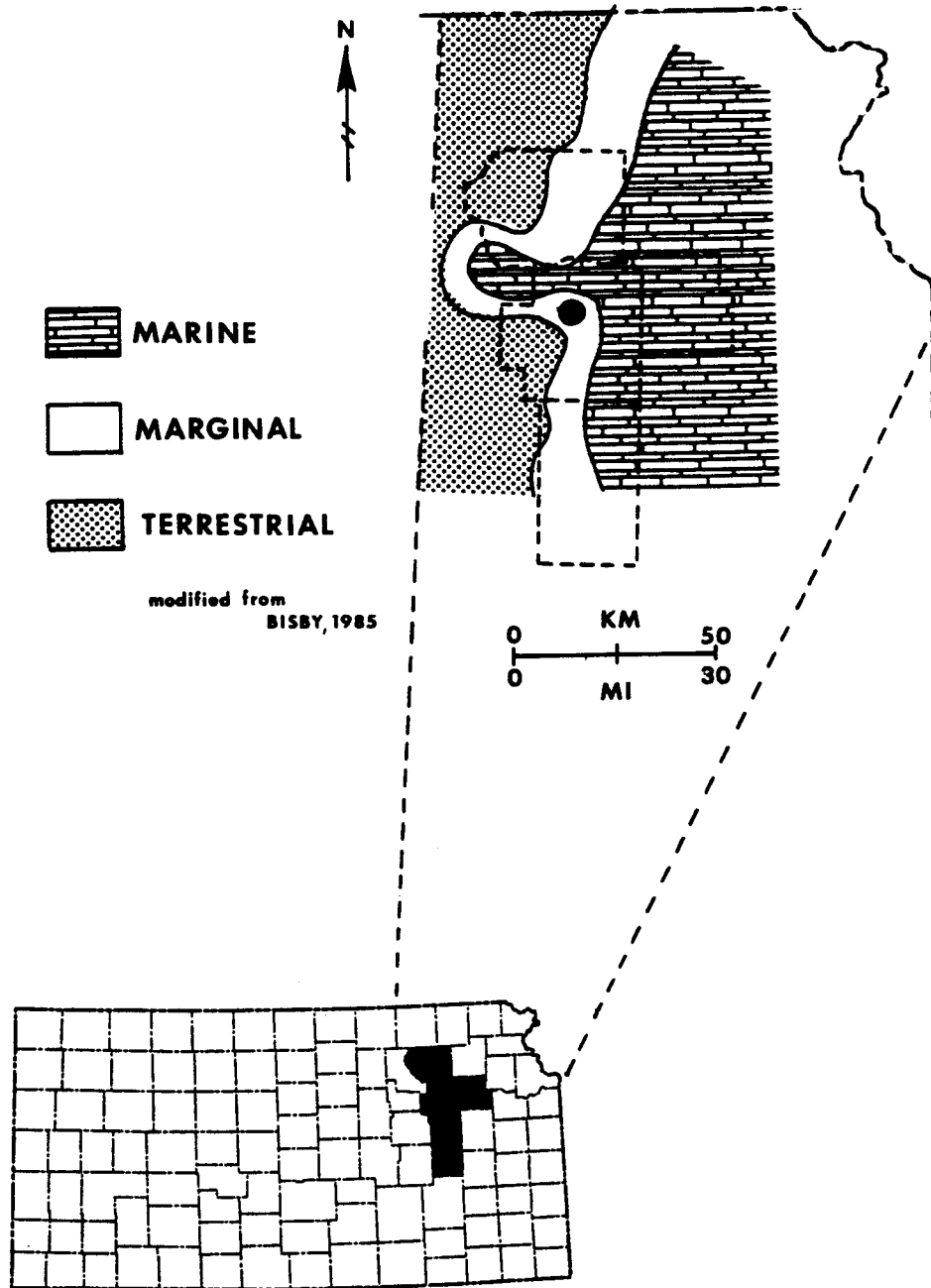
The Pennsylvanian-Permian contact is exposed on both sides of I-70 at this locality. This exposure is located on the west flank of the Brownville Syncline, an asymmetrical structure in the Forest City Basin, and on the east flank of the Nemaha Anticline. The depositional environment is marginal marine as determined by Bisby (1985) and shown in Figure 4-1. Dominantly terrestrial environments occur to the west along the Nemaha Anticline with dominantly marine environments eastward in the Brownville Syncline.

The stratigraphic sequence exposed here extends from the Grayhorse Limestone Member of the Wood Siding Formation, which crops out low in the road ditch at the west end of the exposure, to the Aspinwall Limestone Member of the Onaga Shale at the top of the outcrop (Fig. 4-2). Besides the Grayhorse and Aspinwall, the other stratigraphic units exposed, in ascending order, are: Pony Creek Shale Member and Brownville Limestone Member, both of the Wood Siding Formation, and the Towle Shale Member of the Onaga Shale.

Stratigraphy and Facies Descriptions

The systematic boundary between the Pennsylvanian and Permian was previously placed at the top of the Brownville Limestone Member (i.e., at the top of the Wood Siding Formation). Placement of the boundary at this position was based on what have been considered major changes in the "aspects" of the fossil assemblages in the rocks above and below this position (Moore, 1940; Moore, 1949; and Mudge and Yochelson, 1962). The Brownville Limestone Member is a conspicuous lithostratigraphic unit and is easily recognized across Kansas, but the significance of the biotic change is debatable (Mudge and Yochelson, 1962).

In this part of the stratigraphic sequence (upper Wabaunsee and lower Admire groups), the typical "Kansas" cyclothem of Heckel (1977) is difficult, if



modified from
BISBY, 1985

FIGURE 4-1 -- Location of Stop 4 relative to inferred depositional environments of Wood Siding and Onaga Shale Formations (from Bisby, 1985).

not impossible, to recognize, and may not exist. In this area, the basic lithologies of these Upper Pennsylvanian rocks are siltstones, claystones, mudstones, and sandstones. Limestones are commonly thin and a minor part of the sequence. Close examination of these sequences reveals that they record numerous small-scale events (Bisby, 1985, 1986). In the area studied to date (north-central Kansas), some of these are allogenic events that record sea-level and/or climate change. Indeed, the paleogeography suggested by the correlation of these events is reflected in the differences in the biotic diversity of some of the dominantly marine units, such as the Brownville Limestone Member (Bisby, 1985, 1986).

One of the genetic events recorded by this sequence of rocks reveals an interesting facies mosaic at this locality. This genetic event is represented by an 8-to-11cm interval, about 3 m below the top of the Brownville Limestone Member. A total of 30 stratigraphic sections were measured and described along a 300 m transect (Fig. 4-2A). Across this thin interval, the environment of deposition is inferred to have changed from a nonmarine muddy environment to a marginal marine environment (low intertidal to very shallow subtidal) and back to a higher intertidal to nonmarine environment. The uppermost depositional environment is represented by an interval of heavily oxidized ironstone nodules and crusts in an unfossiliferous mudstone (West & Matsumoto, 1986). The low intertidal to very shallow subtidal part of this thin sequence is represented by a 2 cm thick tempestite that overlies a 1 cm thick, clayey carbonate mudstone (West & Matsumoto, 1986). It is within this clayey carbonate mudstone that the facies mosaic is conspicuous. From west to east, along this 300 m roadcut exposure, this clayey carbonate mudstone records a change from a Glossifungites ichnofacies (sec. E) to a Trypanites ichnofacies (sec. P and BB) (Fig. 4-2B). Across the valley to the west (sec. EE), a nonmarine-to-marginal marine quartz sandstone correlates with this horizon. This facies transition is reasonable in terms of the paleotopography at the time of deposition of these units (Bisby, 1985, 1986). Probably, the clayey carbonate mudstone, as it dried and cracked, provided flat pebbles, cobbles, and shingles that were colonized by components of the Trypanites ichnofacies. The inferred sequence of events that led to the storm deposit and its hiatus pebbles and cobbles is, in general, similar to a genetic sequence described by Fürsich (1979) from the Jurassic, and a pebbly to reworked hardground described from the Ordovician of Ontario by Brett & Brookfield (1984). The lateral relationships between sands and Glossifungites and Trypanites ichnofacies along the offshore islands of the Georgia coast (described by Pemberton & Frey, 1985; West *et al.*, 1990) are a reasonable modern analog for this horizon within the Pony Creek Shale Member at this locality.

Note: This field stop description was taken with only minor modifications from the guidebook compiled by R.K. Pabian and R.F. Diffendale, Jr., 1989, Late Pennsylvanian and Early Permian cyclic sedimentation, paleogeography, paleoecology, and biostratigraphy in Kansas and Nebraska: Guidebook for field trip in conjunction with the 1989 annual meeting of the Geological Society of America, St. Louis, Missouri, 75 p.

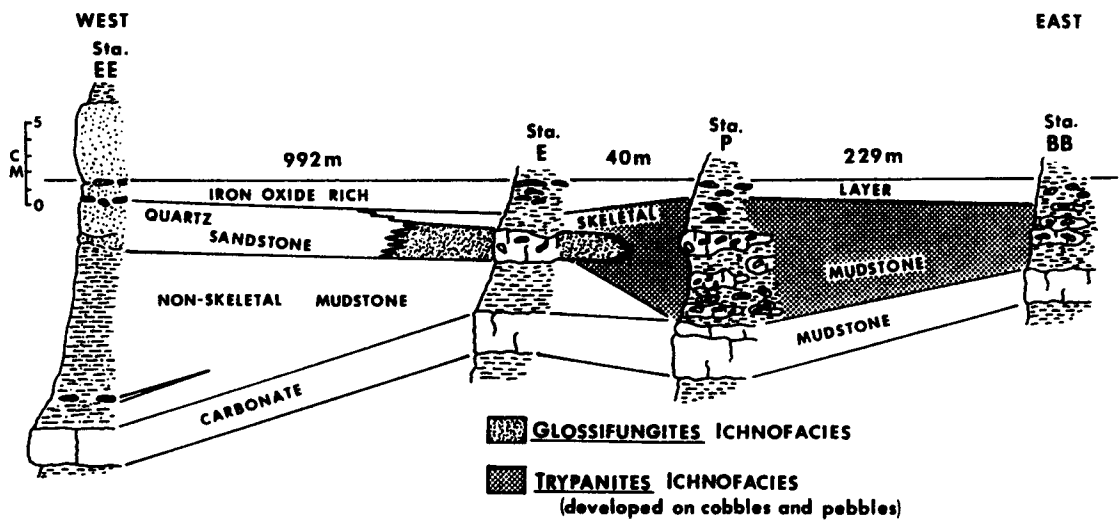
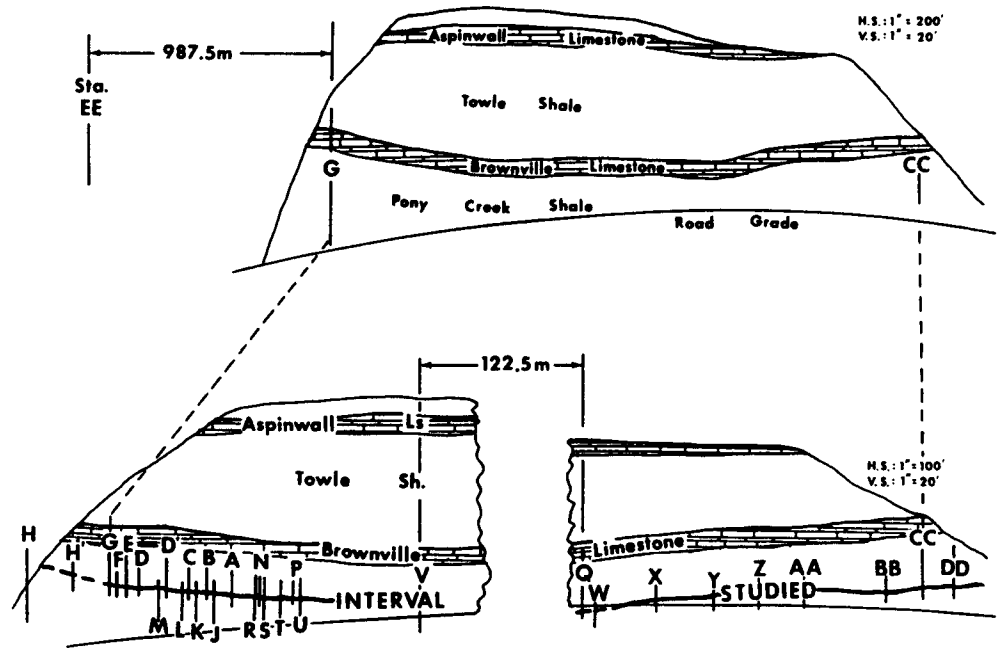


FIGURE 4-2 -- A) Vertical profile of exposure at Maple Hill I-70 roadcut showing locations of sections measured across discontinuity surface. B) West-to-east stratigraphic cross section showing facies mosaic along hiatus.

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**UPPER PENNSYLVANIAN (VIRGILIAN
AND MISSOURIAN) CYCLOTHEMS IN THE
LAWRENCE, KANSAS AREA**

**Global Sedimentary Geology Program
A Commission of the International Union of Geological Sciences
PROJECT PANGEA**

May 28, 1992

prepared and compiled by Lynn Watney

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FIELD STOPS

- Stop 1 Clinton Lake Spillway:
 upper Lawrence Shale and Oread Limestone

- Stop 2 Roadcuts along I-435 near Holliday Road exit:
 Chanute to Stanton Limestone

- Stop 3 I-70/I-435 Interchange:
 Bonner Springs Shale and Plattsburg Limestone

Introduction to Pennsylvanian portion of field trip

by *W. Lynn Watney*,
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Acknowledgements

Much of the introduction and stops 2 and 3 were adapted from Watney, W.L., French, J.A., and Franseen, E.K., 1989, Sequence Stratigraphic interpretations and modeling of cyclothems in the Upper Pennsylvanian (Missourian), Lansing and Kansas City Groups in eastern Kansas: 41st Annual Field Trip, October 14 and 15, Kansas Geological Society, 211 p. Credits for these stops are given at the beginning of each stop.

Appreciation is extended to Jennifer Sims for assistance in electronic text transfer and to Lea Ann Davidson for wordprocessing.

Forward

This field trip is held in conjunction with the Lawrence meeting of **PROJECT PANGEA**. The objective of the field trip is to provide an opportunity to examine cyclothem strata of the Upper Pennsylvanian and to discuss causal mechanisms of Pennsylvanian cyclothem sedimentation. Another objective of the field trip is to permit interaction among participants on the outcrop to further explore the perspectives and insights provided by the varied expertise of the participants. We hope that you will participate in the discussion of approaches to describing and analyzing geologic data such as that seen and described on this field trip that will be helpful in constraining geologic interpretations and increasing accuracy and precision of geological predictions.

Logistics and organization of field trip

Field stops

Fig. 1 identifies the field stops for the day-long field trip. Fig. 2 is a regional map of the bedrock geology of the Mid-Continent. Fig. 3 the regional structural setting for the field trip using the present-day configuration of the Precambrian surface. Additional maps are provided in the descriptions of the stops to orient readers to the local surroundings. The stratigraphic section seen during the course of this field trip is illustrated in fig. 4. These sections are annotated with the stratal interval seen on each stop. Virgilian strata from the upper Douglas and lower Shawnee Groups are the focus of stop 1. Strata from the Missourian Lansing Group are seen in stops 2 and 3. Carbonate and siliciclastic intervals will be examined from these intervals.

Stop descriptions include orientation information and an introduction to the regional and local perspectives of the stop. Significant surfaces useful in sequence-stratigraphic interpretation are annotated on measured sections on stops 2 and 3 using standard symbols. A profile of natural gamma radiation is provided in stops 2 and 3 to facilitate correlation to the subsurface. The gamma-ray profiles were acquired with the use of a hand-held gamma scintillometer. Recorded values are in counts per second. The gamma-ray profiles in stop 2 are correlated to gamma ray-neutron logs from wells in the immediate vicinity to illustrate the feasibility of using wireline logs in sequence-stratigraphic work and to illustrate stratigraphic changes in the vicinity of the stop.

The sequence stratigraphy of the Missourian Lansing and Kansas City Groups is the object of continuing study at the Kansas Geological Survey supported by a grant from the Department of Energy. The goal of this work is to establish quantitative process-response relationships and detailed correlations that will facilitate development of improved stratigraphic models of the Missourian strata. These studies are being conducted in concert with reservoir studies to assist industry in optimizing exploration and development strategies as applied to similar reservoirs. Additional stratigraphic correlation studies currently are underway in the Desmoinesian, Missourian, and Virgilian strata at the KGS supported by grants from the USGS, DOE, and industry. Considerations of climatic controls is timely for these continued investigations.

Petroleum-reservoir analogue development in the Lansing and Kansas City Groups

This trip was prepared mostly by members of the Petroleum Research Section at the Kansas Geological Survey. One of our objectives is to understand and predict natural resources associated with these strata, therefore a few paragraphs included here to further describe the petroleum reservoir analog study underway on the Lansing and Kansas City Groups.

Sites in southeastern Kansas are serving as near-surface analogues where depositional models for petroleum reservoirs contained in similar rocks in the subsurface are being refined and tested. Southeastern Kansas is providing an opportunity for improved reservoir modeling because: 1) the stacking geometries of unconformity-bound depositional sequences are significantly affected over short distances resulting from notable depositional topography and basin subsidence; 2) large grainstone and phylloid algal carbonate buildups are constrained in three dimensions; 3) siliciclastic- and basinal-facies sequences equivalent to the northern carbonate-dominated shelf cycles occur at the surface and in the shallow subsurface due to stratal geometries and the dip of the strata relative to the outcrop; 4) the area is well suited to economical seismic, coring, logging, and surface examination, facilitating interdisciplinary investigation; 5) both sandstones and carbonates examined are targets of oil and gas exploration and development in the western and southern portions of the study area as well as in western Kansas (Watney et al., 1989).

Combined surface and subsurface mapping indicates that the belts of Missourian phylloid algal buildups in southeastern Kansas (Heckel and Cocke, 1969) and broad, thick ooid-shoal complexes in western Kansas (Watney, 1985a) developed along an east-west trend across southern Kansas. These facies coincide with a southern shelf margin that extends across southern Kansas bordering both the shelfward extensions of the Arkoma and Anadarko basins, which were active during the Missourian. Lower Missourian algal buildups form elongate, regionally extensive bank complexes in southeastern Kansas ranging from 6 to 19 mi (10–30 km) wide, which can be three times the thickness (100 ft; 30 m) of the entire cyclothem on the northern shelf (Watney, et al., 1989). The ooid-shoal complex of western Kansas forms a broader progradational belt some 100 mi (160 km) wide due to less abrupt change in depositional slope (Watney, 1985a and b). Phylloid algal mounds are more isolated but important in limited stratigraphic intervals in western Kansas (Ebanks and Watney, 1985). Likewise, ooid shoals are present, but less abundant, and are isolated within specific stratigraphic zones in eastern Kansas.

The idea of a widespread, layercake stratigraphy in midcontinent strata is seriously compromised when the regional setting is considered. Moreover, deciphering these stratal packages in areas of varying levels of stratigraphic and sedimentologic resolution and composition ultimately will provide the means to identify and quantify the controlling processes.

Cratonic sedimentation is characteristically episodic and the stratigraphic record is compartmentalized by natural breaks. Surfaces that reflect either pauses in sedimentation or abrupt facies dislocation can be visually identified and imaged with common subsurface tools. Recognition of such surfaces provides a practical means of delineating temporally distinct strata. Sequence stratigraphy provides concepts and methods useful in interpreting the processes responsible for deposition of units within these time-equivalent sedimentary packages. We believe this approach can be effectively and practically applied in the midcontinent. However, testing of concepts, refinement of methodology, and application of new technology is needed in order to make sequence stratigraphy and sedimentary modeling practical tools for predicting characteristics of petroleum reservoirs. Paleoclimate may play a key role in influencing sedimentation. Detailed paleogeographic reconstructions based on recognition and mapping of time-distinct depositional sequences provides a means for prediction through extrapolation or interpolation. We envision this approach to be immediately promising in exploration, and as more information is obtained, parameters become better constrained, and models become more sophisticated, we see the use extended to coal- and petroleum-development geology.

The cyclic Pennsylvanian and Lower Permian strata of the midcontinent are of appropriate thickness and distribution to provide a practical framework for sequence analysis using surface exposures, cores, wireline logs, and very high resolution seismic profiling. Moreover, the subsurface data base for these strata in the midcontinent, which spans a broad shelf-to-basin setting, provides superb three-dimensional control. In excess of 150,000 wells exist in Kansas alone. Recent developments in regional biostratigraphic correlation corroborate the effects of oscillations of regional processes. Regional correlations of individual depositional sequences provide strong support for the feasibility of establishing and analyzing regional sequence architecture as a means of providing parameters for computer simulation.

Oil and gas resources in Missourian rocks in midcontinent

Carbonate and sandstone reservoirs have been the petroleum-producing zones in more than 50% of the successful development and exploration wells in Kansas since 1970. The ultimate recovery from Pennsylvanian rocks in the midcontinent is estimated to be nearly 9 billion barrels of oil (BO; Rascoe and Adler, 1983). Non-associated natural gas produced from Pennsylvanian reservoir rocks from the midcontinent now totals some 32 trillion ft³. At least one-fifth of Kansas' estimated 2.4 billion barrels of unswept mobile oil (BPO/Toris data base) and 8.7 billion barrels of residual (immobile) oil remain in existing Pennsylvanian reservoirs. These reservoirs also contain over 23% of the original-oil-in-place. Oil and gas reservoirs occur in characteristically stacked, commonly thin, discontinuous strata consisting of phylloid algal, chaetetid, and crinoid-bryozoan carbonate buildups, grainstone shoals, and quartz sandstones. Variable diagenetic processes and subtle structural deformation have created additional complexities in reservoir development and hydrocarbon trapping. Heterogeneity and marked compartmentalization of strata occur at all scales in the Missourian reservoirs (fig. 5). An estimated one-fourth of the oil and 40% of the natural gas ultimately produced in this region will come from smaller Pennsylvanian fields. Nearly 30% of all new oil is produced from Lansing and Kansas City reservoirs in Kansas (Watney et al., 1989).

Fields producing from the Lansing and Kansas City groups are commonly found on structural highs both large and small, in part, because these reservoirs have been the primary exploration targets. Many of these structures were also positive topographic features that affected reservoir development, either through localization of favorable depositional environments (such as grainstone shoals or phylloid algal buildups), or

through early diagenesis related to subaerial exposure (DuBois, 1985; Ebanks and Watney, 1985; Watney, 1980, 1984; Watney and French, 1988).

We believe the optimum approach to reservoir analysis involves an interdisciplinary approach coupled with quantitative process modeling of stratigraphic units associated with the reservoirs. Sedimentary models are increasingly being based on concepts of sequence stratigraphy. The models require an integrated geoscience data base that ranges from the large scale (such as tectonic history) to the small scale (e.g., the application of chemical stratigraphy, biostratigraphy, and paleoecology).

Regional geologic setting

During Missourian and Virgilian the large supercontinent Pangea was in the final stages of formation (fig. 6). The Ouachita Mountains bordering the midcontinent on the southeast formed along the suture zone created by the collision of Laurasia with Gondwana (fig. 7, Rascoe and Adler, 1983). Broad, active patterns of subsidence, accompanied by more restricted uplifts, occurred on the craton during this collision creating very favorable sediment-accommodation potential during the Pennsylvanian (Houseknecht and Kacena, 1983; Kluth and Coney, 1981a and b; Thomas, 1985).

Shelf areas were subsiding less rapidly and sediment-accumulation rates were relatively high during the Permo-Pennsylvanian. Thicknesses of these strata account for 45–75% of the Paleozoic sedimentary column on the shelf area in Kansas, even though the Permo-Pennsylvanian represents only 23% of Paleozoic time. Overall it was a period of significant subsidence and burial of sediments on the shelf, producing a high-fidelity sedimentary record.

The distribution of uplifts within the craton is notable in that most are oriented at a high angle to the orogenic belt. The prominent Amarillo–Wichita uplift (Oklahoma), Nemaha uplift (Kansas), and Central Basin platform (Texas) all occupy locations corresponding to the axes of lower Paleozoic basins (Ham and Wilson, 1967) which, in turn, formed above, or adjacent to, relict Cambrian or Proterozoic crustal features (Keller et al., 1983). Timing of orogenic deformation was diachronous along the length of the Ouachita orogen. The span of time was sufficiently brief to mirror the broadly coeval deformation of the foreland basins, including the Anadarko and Arkoma basins (Kluth and Coney, 1981a and b).

The Ouachita Mountains were an active thrust belt, and the Arkoma basin was the associated foreland basin during the Missourian. Siliciclastic progradation from the Ouachitas episodically filled the Arkoma basin and occasionally reached onto the carbonate platform to the north into southern Kansas (fig. 7). The Arkoma basin was nearly filled with detrital sediments by Missourian time due to diminished subsidence, as compared to peak subsidence during climactic orogenic activity during Atokan time (Houseknecht and Kacena, 1983). In contrast, the southern margin of the western shelf along the Anadarko basin was never affected by similar siliciclastic influx, but underwent episodic carbonate shelf-margin progradation and retreat.

The areal variation of average subsidence rates on the shelf during the Missourian conforms to basin development in the southern midcontinent (fig. 8; Kluth, 1986). The average subsidence rates vary considerably from shelf to basin, ranging from more than 0.3 m (1 ft)/ka in the basin to less than 0.05 m (0.17 ft)/ka on the northern shelf. Backstripped subsidence curves for sites in northern and southern Kansas indicated slower rates ranging from 0.01 up to 0.04 m/ka. These rates are similar to those determined by Klein and Kupperman (1992). The average subsidence includes episodic thrust-induced subsidence, characterized by pulses of rapid downwarp followed by longer periods of slower subsidence. The precise duration of these episodes is not well known.

Comparisons are made on this field trip of eastern Kansas with the Missourian rocks on the western Kansas shelf, where a major share of petroleum is produced from the Lansing and Kansas City groups (fig. 15). Subsidence patterns are similar in western Kansas but are influenced by a different tectonic element than in southeastern Kansas. Thus, precise tectonic parallism can not be assumed. The Anadarko basin, which was responsible for subsidence along the western Kansas shelf, is a hybrid foreland basin that partially owes its subsidence to overthrusting of crustal blocks now exposed in the Wichita Mountains in western Oklahoma. Uplift of the Amarillo–Wichita–Arbuckle mountains beginning in the Early Pennsylvanian (Atokan) coincides with the onset of significant subsidence and definition of the Anadarko basin (Brewer et al., 1983). Some 8–9 km (5–6 mi) of northward thrusting in the Wichitas are indicated by deep-reflection seismic profiling (Brewer et al., 1983). Thrusting is attributed to the plate collision along the Ouachitas, perhaps ultimately linking with tectonic events in the Arkoma basin. Uplift along the mountain front is recorded as major episodes of conglomerate progradation into the southern margin of the Anadarko basin (Ham and Wilson, 1967). These episodes appear to have each lasted several million years and led to considerable subsidence in the basin and adjoining shelves.

Subsidence rates during the Virgilian continued at moderate levels across the Kansas shelf and actually increased in northern Kansas compared to the Missourian (fig. 9). Tectonic activity along the Ouachita Mountains diminished during the Virgilian while subsidence in the Anadarko basin was sufficient to foster sediment-starved conditions in the Oklahoma and Texas Panhandles (fig. 10).

During Missourian and Virgilian time the Anadarko basin was at its maximum development; subsidence was estimated to have exceeded 2 m (7 ft)/Ka (Dickinson and Yarborough, 1979). Maximum subsidence in the western Anadarko basin situated immediately south of the western Kansas shelf is recognized by sediment-starved conditions (Galloway et al., 1977; Kumar and Slatt, 1984; Rascoe and Adler, 1983). Fig. 11, prepared by George Moore (unpublished, circa 1974), provides an excellent depiction of this sediment starvation in the western Anadarko basin during Missourian time. Eastern limits of the basin in proximity to the Ouachita Mountains received reciprocally deposited siliciclastic sediments similar to the Arkoma basin. Estimated relief across the shelf margin in the Anadarko basin during the Late Pennsylvanian was estimated at 1,100 ft. (335 m; Kumar and Slatt, 1984).

Subsidence creates accommodation space for sediments and produces a complex signal in the sedimentary record, which is the focus and livelihood of basin modelers. The complexities of this subsidence history must be understood and accounted for in any enlightened attempts at quantitative reservoir modeling.

Cyclothem concept

General nature of Upper Pennsylvanian (Missourian) stratigraphy

Upper Pennsylvanian (Missourian, Kasimovian, early Stephanian) strata of the midcontinent United States are characterized by thin cyclical successions of variable percentages of carbonate and siliciclastic rocks, with thicknesses of less than 75 ft (25 m) to 150 ft (50 m). Comprehensive overviews of Pennsylvanian cyclic sedimentation are found in Merriam (1964) and Heckel (1977, 1984, 1985). Cycles of sedimentation or “cyclothem” developed on shelf areas of the midcontinent generally have thin but widespread transgressive basal lithofacies overlain by thicker regressive strata (fig. 12, Heckel, 1977). These cyclothem are commonly separated from bounding strata by surfaces that are commonly associated with diagenetic and textural features indicative of subaerial weathering (Watney and Ebanks, 1978; Watney, 1980; Prather, 1981; Schutter and

Heckel, 1985; Goebel et al., 1989). Variations in thickness, areal extent, and lithofacies in typical cyclothems suggest varying degrees of marine inundation of the craton (Heckel, 1980, 1984, 1986; Watney, 1984). Additional omission surfaces that define distinctive subcyclothem sequences are commonly imbedded within many cyclothem successions on the shelf. Cyclothems are considered to be the same as fifth-order (T-R) units (Busch and Rollins, 1984; Busch et al., 1985) with durations between 300 and 500 Ka. The order hierarchy describes the relative timing of cyclical patterns in the rocks and has connotations as to causal mechanisms (table 1).

Cyclothems are widespread on the shelf areas, but regional interbasinal correlations were not possible until recently because their time spans were shorter than the resolution levels of accepted biostratigraphic information. However, current investigations by Boardman and Heckel (1989) on independent comparisons of ammonoid, conodont, fusulinid, and coral groups provide correlations between 13 major Virgilian and Missourian cyclothems in the eastern shelf of the Midland basin and the northern midcontinent (fig. 13, Boardman and Heckel, 1989). Correlations reflect synchronous marine inundation in both areas.

Foraminiferal, ammonoid, and conodont zones have also been used by Ross and Ross (1987) to extend correlations of similar Pennsylvanian marine inundations globally (fig. 14). Both Boardman and Heckel (1989) and Ross and Ross (1987) attribute the sea-level fluctuation to late Paleozoic continental glaciation.

Middle (transgressive) limestone

Using the nomenclature of Heckel (1977), the lowermost bed of the cyclothem is the middle or transgressive limestone (fig. 12). The name middle limestone results from maintenance of R. C. Moore's (1936, 1949) nomenclatural scheme for Virgilian megacyclothems.

The middle limestone is a widespread transgressive deposit that is typically a few feet thick or less. These units were deposited in environments that ranged from the shoreline to below wavebase. Most preserved beds consist of subtidal marine wackestones. Middle limestone thickness ranges from relatively thick (50 ft [15 m]), to very thin, to absent, as will be seen on the field trip. Normally, however, middle limestones are less than 3 ft (1 m) thick.

Core shale

The core shale overlies the middle limestone in the typical Kansas cyclothem (fig. 12). Core shales are typically thin, about 1–3 ft (0.3–0.9 m) and, like the middle limestones, are areally extensive. Some core shales are black and organic rich (>4% carbon) and commonly contain phosphate nodules. The black core shales are readily recognizable in surface exposures and are frequently excellent subsurface markers due to their high natural gamma radioactivity. For example, the Hushpuckney and Stark shales in the lower Kansas City Group can be traced throughout the outcrop belt from Iowa and southward deep into siliciclastic cycles in the Arkoma basin south of Tulsa. They also extend over 400 mi (640 km) to the west into western Kansas and eastern Colorado where they can be readily identified through their strong radioactive response on gamma-ray logs. Nevertheless, the black shales abruptly change to gray, fossiliferous shales along the upper shelf in northwestern Kansas and thin gray shales over the Central Kansas uplift, a long-term positive element.

Wanless (1964) used these black shales, which are also common to a number of Middle Pennsylvanian cyclothems, to physically correlate siliciclastic-dominated cyclothems in Illinois with equivalent, more marine-dominated successions in the western midcontinent. Although biostratigraphy is now verifying some

of these correlations, Wanless emphasized that a particular cyclothem could be distinguished through correlation of the core shale regardless of the variation in the remaining succession of sediments.

The origin of the black core shales has been vigorously debated. Heckel (1977) reemphasized the significance of the regional correlatability demonstrated by Wanless and stressed that this lateral continuity, coupled with the faunal composition and presence of nonskeletal phosphate, made the black shale the deepest-water deposit of the cyclothem. In the western craton, along the outcrop belt, the indigenous fauna is composed primarily of conodonts, ammonoids (from the southern exposures), and dissociated fish debris suggesting very slow sediment-accumulation rates. Minor elements such as uranium and various other metals are also abundant in the black shale along with phosphate. Heckel (1977, 1985) has proposed that the water column in which black shale accumulated contained a thermocline leading to quasi-estuarine circulation and upwelling, which accounts for the conspicuous phosphate. Water depths would necessarily be deep to accommodate formation of a long-term, stable thermocline.

Boardman et al. (1984) provide a paleoecologic model that relates faunal communities to dissolved oxygen, which is in turn related to a depth-defined bottom oxycline associated with vertical stratification resulting from the thermocline. Sufficient depths and stratification can result in anoxic bottom waters where sapropels typically accumulate. Accumulation rates would be slow and duration of black-shale deposition would be long in a deep, stratified water column.

In contrast, workers such as Zangerl and Richardson (1963), Merrill (1973), Maples (1986), and Coveney and Martin (1983) have provided paleontologic and inorganic and organic geochemical evidence that supports a shallow-water origin and rapid sediment accumulation over a relatively short term compared to the previous model for certain Middle Pennsylvanian black shales in the Illinois and Appalachian basins.

The apparent controversies in interpreted depth, rate of sediment accumulation, and duration of black-shale deposition are addressed in Coveney et al. (1991). A knowledge of the water depth represented by core shales is critical to our understanding of the changes in relative sea level that occurred during cyclothem deposition. The proper interpretation of relative sea-level change and dissolution of core-shale accumulation is important with regard to process-response modeling.

Upper (regressive) limestone

The upper or regressive limestone of Heckel (1977) is commonly the thickest bed within cyclothem on the carbonate platform (fig. 12). This unit ranges from less than 10 ft (3 m) to more than 100 ft (30 m) in thickness. The upper limestone contains the major petroleum reservoirs of the Lansing and Kansas City groups. Reservoirs occur in skeletal grainstone and oolitic facies, phylloid algal buildups, and structural and diagenetic traps created by fracturing and dissolution.

Lithofacies and early-diagenetic features of the upper limestones indicate a general shallowing-upward succession. Although the general Kansas cyclothem model of Heckel (1977) indicates a continuous gradual shallowing upward, observed facies successions and their correlation suggest fluctuations in water depth within an overall shoaling trend (Heckel, 1986). The relative importance of local (autogenic) controls, e.g., progradation and aggradation and subsequent local shallowing versus regional (allogenic) controls, such as eustatic sea level change, on the deposition of these generally complex shallowing-upward successions is another topic of intense interest and discussion. We will explore some of these variations on the trip. In general, individual upper limestones can be recognized and traced across widespread areas of the carbonate shelf, including into western Kansas, some 400 mi (640 km) west of the surface exposures.

While most upper limestones can be correlated from eastern to western Kansas where they are also bounded by the core shales, the upper limestones thin substantially and change facies markedly into the northern extension of the Arkoma basin. Siliciclastic sedimentation from the south became increasingly important as the Arkoma basin progressively filled. The "Layton" sandstones are an example of such a siliciclastic unit.

Some upper limestones exhibit more obvious evidence for episodic deposition than others, e.g., the Winterset Limestone, which is punctuated by thin, widespread shale beds, versus the more massively bedded Bethany Falls Limestone. Some of the internal beds and bounding surfaces within the upper limestones are interpreted to result from short-term events (e.g., storm deposits) or represent local aggradation and progradation processes with limited lateral extent. Other stratal units within the upper limestone are correlative over large distances and suggest an allogenic cause, e.g., shale-bounded packages within the Winterset Limestone extending over 50 mi (80 km) along the outcrop.

Outside shale

The outside shale, the uppermost unit of the Kansas-type cyclothem, exhibits considerable variability among different cyclothem (fig. 12). These stratal elements are locally thin or missing in southwestern Kansas due to an apparent lack of siliciclastic influx. Where siliciclastics were available, thicknesses of other outside shale units may be as much as 300 ft (91 m) in eastern Kansas. Thicker packages of shale, sandstone, and siltstone represent deltaic siliciclastic influx in shallow-marine conditions. These deltaic deposits contain invertebrate-rich horizons, thin limestones, channel sandstone, and paleosols. The platform deltaic deposits form broad aprons of mainly shale extending for tens of miles. The sediments composing the outside shales in the Kansas City area were apparently derived from the east and northeast. Accordingly, outside shales of the lower Kansas City Group are typically thin, blocky mudstones with paleosol features, also common in the thin outside shales of central and southwestern Kansas. In southeastern Kansas outside shales become very thick and complex in character, preserving events that do not occur to the north.

The platform deltaic units thicken and thin locally along their margins, producing marked changes in depositional topographic relief that affected subsequent deposition. Some of this relief is probably due to late-stage erosional downcutting into the deltaic platform (e.g., Stops 2 and 4). Carbonate buildups in superjacent units occupy positions along these local breaks in slope.

Deltaic progradation and accumulation of thick outside shales occur when sufficient accommodation space is available. Deltaic influx on the northern shelf occurred late in a cycle while the shelf was still submerged.

In some cases, siliciclastic detritus in the upper Kansas City and Lansing groups reached the east-central Kansas shelf prior to extensive subaerial exposure and paleosol development on the upper limestones. Relative sea level fell in late stages of deltaic sedimentation leading to local erosion and channeling of the deltaic wedges, occasionally downcutting into the underlying limestones. Concurrent with the channeling events, but more widespread, is the development of paleosols that are only now being recognized as significant bounding surfaces separating temporally distinct stratigraphic sequences. Evidence for subaerial exposure is much more apparent in outside shales without siliciclastic influx, e.g., the blocky mudstones, or on the surfaces of the upper limestone.

Widespread subaerial exposure is clearly evident in most outside shales and on the tops of many of the upper limestones (Watney and Ebanks, 1978; Schutter and Heckel, 1985; Goebel et al., 1989). In many cases the outside shale (at least the lower portion) is a paleosol capping the carbonate. Moreover, these paleosols can be traced across the northern carbonate shelf from Iowa to southeastern Kansas; they also are present westward in cores through the subsurface of western Kansas and southwestern Nebraska. Spatial trends of subaerial exposure have also been recognized on the shelf (Watney, 1980). Areas interpreted to be higher

shelf locations generally exhibit evidence of more intense subaerial weathering and commonly early meteoric diagenesis (Watney and Ebanks, 1978; Watney, 1980; Heckel, 1983).

Current investigations in southern Kansas indicate that subaerial surfaces can be traced to conformable surfaces on the lower shelf and basin that show no evidence of exposure. When paleosols are present they provide a critical, temporal break in the sedimentary record. However, problems remain in the distinction and correlation of these surfaces regionally, particularly in thick outside shale sections where paleosols are not easily recognized.

Causal mechanisms for cyclothem development

Contrasting and widespread facies changes in cyclical sequences indicate a significant contribution from allogenic controls (Heckel, 1977; Watney, 1984, 1985a; Boardman and Malinky, 1985; Heckel, 1986). Glacial-eustatic control has been invoked most often by those who subscribe to allogenic causes for stratal cyclicity (Wanless and Shepherd, 1936; Wanless and Cannon, 1966; Crowell and Frakes, 1975; Heckel, 1977; Crowell, 1978; Denton and Hughes, 1983; Heckel, 1986; Crowley et al., 1987; Veevers and Powell, 1987). The analogue used in these arguments is the sea-level change associated with advance and retreat of Pleistocene continental glaciers. These Pleistocene glacial advances and retreats produced high-frequency sea-level changes with magnitudes on the order of 330–500 ft (100–150 m), periodicity around 100,000 years, and rates of sea-level change around 10 m (33 ft)/thousand years (Ka; Donovan and Jones, 1979).

Autogenic causes, due to internal feedback mechanisms that operated within the depositional system, are also argued to have produced these same cyclothem strata, e.g., Duff and Walton (1962), Donaldson (1974), Ferm (1975), Brown (1972), and Galloway and Brown (1973). All of these studies dealt with strata dominated by deltaic sedimentation and heavily influenced by local (autogenic) sedimentary processes, thereby limiting the potential for correlation between individual delta systems. However, even in these areas of significant autogenic control, recent studies, e.g. by Brezinski, (1984), and Busch and Brezinski (1984) in the Upper Pennsylvanian strata of the Appalachians; West and Busch (1985), and Busch and West (1987) in the Lower Permian of Kansas, find distinct vertical variations in biotic diversity within relatively homogeneous lithologies, which may indicate temporally distinct sedimentary rocks that can be correlated over widespread areas. Boardman and Malinky (1985) recognize regional, interdeltaic genetic units defined by thin, darker marine shales on the eastern shelf of the Midland basin that are analogous to the core shales of the northern midcontinent. Boardman and Heckel (1989) have now correlated these Midland basin shales and their associated sedimentary packages with their equivalents in the northern midcontinent, strengthening the argument for a eustatic control that affected areas on an interbasinal scale. Brown (1989) has also invoked a eustatic component for the generation of Pennsylvanian and Lower Permian strata along the eastern shelf of the Midland basin.

The role of climate control on generation of cyclothems has been considered in the past, but without a recent analog model. Swann (1964) proposed a subtle climate-control hypothesis invoking changing precipitation to explain more complex carbonate-terrigenous clastic cyclothems of the Chesterian in the Illinois basin. Cecil et al. (1985) and Cecil (1990) proposed that repetitions in siliciclastic and chemical rocks is related to paleoclimate cycles probably operating in combination with other processes such as eustasy and tectonics. The basis of this conclusion is founded on studies of Recent environments thought to be analogous to conditions under which the Pennsylvanian cyclothems were deposited.

Klein and Kupperman (1992) and Klein (1992) have joined in this active area defining causal mechanisms of cyclothems, estimating combinations of eustasy, tectonics, and climatic factors thought responsible for generation of these cyclothems.

Application of sequence-stratigraphic concepts

Overview

Modern sequence-stratigraphic concepts have been vigorously used as an excellent method to subdivide, map, and correlate sedimentary rocks. Mapping includes depiction of stratal geometries and paleogeography. The approach of sequence stratigraphy has a long heritage, but it has been significantly refined with the advent of seismic stratigraphy and improved depositional-facies interpretation. Basic definitions of some of the sequence-stratigraphy terms are included at the end of this section.

Sequence-stratigraphic analysis can provide crucial information about the genesis of stratigraphic units through analysis of stacking geometry (fig. 15, Haq et al., 1987). Some aspects that can be addressed, as pointed out by Vail (1987), include:

- Relatively deep water leads to preservation of depositional topography. Sedimentary onlap onto an irregular depositional surface can be used to characterize submarine topography.
- Stratal patterns can be used to quantify minimum paleowater depths by analyzing height of prograding clinofolds.
- Extent of inundations (onlap) onto a shelf and the lower basinward extent of subaerial exposure can be used to quantify the relative sea-level change or rise associated with inundation. Some inundations have been correlated on a global basis from which a eustatic sea-level curve can be inferred.
- Apparent truncation and downlap indicate sediment starvation. Truncation occurs along top-set beds beneath a type 1 sequence boundary and downlap is associated with basinward terminations of sedimentary wedges.

The application of sequence stratigraphy to cratonic Paleozoic strata presents considerable challenges due to 1) limited accommodation potential on platform areas; 2) slow, episodic sediment-accumulation rates and limitations in sediment preservation; and 3) difficulty in establishing independent methods of correlating parasequences.

Shelfward (platform and shallow-ramp) portions of cratonic Paleozoic depositional sequences commonly consist of parallel to subparallel beds with limited potential for the expression of local relief. Depositional sequences in a shelf setting thus are characterized by numerous local and regional truncations and facies changes involving thin, but commonly mappable, beds.

Expected stratal geometries on the shelf include: subtle onlap and offlap, local wedges of fluvial deposits and buildup of carbonate deposits, and subtle changes in sediment-surface elevation due to concurrent structural deformation.

In general, the shelf (platform or ramp) preserves a better record of sea-level high-stand events than does the sediment-starved setting in the basin. In contrast, the basin and shelf margin preserve a better record of sea-level low-stand events while contemporaneous subaerial exposure or nondeposition dominates the shelf.

Sequence-stratigraphic analysis can be accomplished without seismic profiles, if adequate rock and wireline-log data are available. The general approach to sequence-stratigraphic analysis as it is being applied to the midcontinent Pennsylvanian is described as follows:

1) Vertical-sequence analysis:

- a) Describe strata in terms of depositional environment and relative water depth (relative sea-level change) and evidence for shallowing or deepening trends; identify potential marker beds (thin distinctive units to aid in correlation)
- b) Describe surfaces: bedding planes (frequency and nature; distinguish diagenetic from depositional); association of surfaces with facies dislocation; ranking of facies dislocation according to water-depth change; establish evidence of subaerial exposure or prolonged nondeposition, e.g., hardground developed in subaqueous marine environment
- c) Draw profiles of sections providing interpretation of genetic units and water depth; genetic units consisting of
 - * *flooding or transgressive units* (usually associated with base of depositional sequence; usually thin limestone or coal on shelf areas in Pennsylvanian depositional sequences) of
 - * *condensed sections* (may be associated with accumulation of organic matter, e.g., black shale or hardgrounds);
 - * *shallowing-upward unit* (shallowing carbonate or siliciclastic succession or combination; thickest and most complex component of a sequence; frequently associated with multiple parasequences
 - * *paleosol development* (may represent sequence or possibly parasequence boundary if it forms a surface).

2) Correlation between localities

- a) Establish correlations of marker beds and surfaces, utilizing lithostratigraphic, paleontologic, geophysical, or geochemical data (preferably through continuous or detailed systematic sampling).
- b) Identify the depositional sequence(s). Correlate major genetic units and bounding surfaces associated with a depositional sequence using all information available.
- c) If possible, extend control to the 3rd-dimension and over more extensive areas of shelf, shelf margin, and into basin to address stratal geometries in more comprehensive manner and evaluate allogenic and autogenic causal mechanisms (eustatic, subsidence).

The temporal distinction of sedimentary sequences also provides the data base to

- a) define detailed paleogeography;
- b) address rates, duration, and magnitude of events responsible for sedimentation;
- c) possibly improve the ability to predict facies for economic development.

Recognition of sequence-stratigraphic components in Upper Pennsylvanian cyclothems

Flooding unit

The flooding unit is either absent or thin (zero to several 10's of feet thick) with a sharp basal contact (fig. 16). It is readily identified through vertical-sequence analysis in outcrop or core. The flooding unit commonly is succeeded by deeper marine strata. Lithologies include calcareous sandstones and siltstones with nearshore affinities (northwestern Kansas) and thin carbonate units that reflect deepening conditions, e.g., a generally shoal-water strata occur at the base and are overlain commonly by normal marine strata at the top that were likely deposited below normal and storm wave base. Clam borings, pyritization of skeletal debris, and preservation of small to moderate amounts of organic debris are common components of the carbonate-flooding units. The lower contact usually separates distinctly different depositional facies resulting in *facies dislocation*, e.g., a paleosol beneath a marine limestone. Carbonate buildups, although uncommon in this unit, are spectacularly developed locally. Carbonate mounds that developed during deepening events, and locally kept pace with rising base level thicken abruptly to over 50 ft (15 m; e.g., the Captain Creek Limestone, Heckel, 1975). In contrast, the flooding unit may only consist of a few inches of bioclastic-shell packstone or other shallow-water marine-carbonate rock. Heckel (1984) has ascribed variations in thickness of the transgressive limestone (his term for the flooding unit) to varying rates of inundation of the shelf and to differences in the slope of the surface that is being inundated.

Widespread coals capped by invertebrate skeletal lag or limestone locally are characteristic of some flooding units (fig. 16). Marine sandstones and siltstones that compose the flooding unit also include reworking of underlying deposits or renewed detrital deposition. Whether erosion or deposition occurs during deepening was likely dependent on steepness of depositional slopes (energy level), climate, marine-circulation patterns, and rate of deepening.

Results from studies of Holocene coastal sedimentation provide important analogues to the Pennsylvanian flooding units. The Holocene work suggests that at a certain threshold rate of deepening, effective carbonate sedimentation can decrease significantly (Neumann and Macintyre, 1985). Sedimentation does not keep up with rapidly increasing water depth, probably due, in part, to loss of opportunities for sediment progradation and aggradation, e.g., inundation of delta and estuary formation or rates of deepening exceeding effective carbonate-accumulation rate (Heckel, 1984).

Hallock and Schlager (1986), in their studies of Holocene carbonate settings, conclude that reefs and most carbonate-sediment-producing organisms flourish in nutrient-deficient systems. However, these organisms undergo significant reduction in sediment production during increasing nutrient supply, which often occurs during submergence of a carbonate shelf. Flooding is thought to produce a biotic crisis due to nutrient excess. While increased nitrate and phosphate would stimulate growth of some organisms, other more deleterious

effects apparently lead to net decreased sediment production, e.g., reduced water transparency limiting the depth range for some corals and calcareous algae, and consequently reduced sediment production.

Hallock and Schlager (1986) have identified criteria for recognizing changes in nutrient excess conditions in the sedimentary record: nondeposition (hiatal) surfaces, bioerosion such as clam borings, and reduced redox potential encouraging preservation of organic matter. The carbonate surface is commonly covered by fine-grained siliciclastics if conditions of nutrient excess persist. The net result is reduced sedimentation during flooding, contributing what is referred to as lag time. This is precisely what is observed in the Pennsylvanian strata.

The sensitivity of a carbonate platform to flooding is a function of local conditions. For example, the euphotic zone, below which reefs composed of zooxanthellate corals will not survive, ranges from 170 m (561 ft) in the Gulf of Aqaba to 18 m (59 ft) around Barbados (Hallock and Schlager, 1986; fig. 17). The shallower the euphotic zone, the more susceptible the area is to diminished CaCO₃ accumulation during flooding events. Thus, in spite of the fact that short-term reef growth has been estimated at rates in excess of 10 m (33 ft)/Ka, environmental conditions must remain nearly constant while accommodation space must be increased in order for these rates to be maintained.

Neumann and Macintyre (1985) and Adey et al. (1977) further describe the widespread rapid drowning associated with the early Holocene eustatic rise due to glacial melting. Neumann and Macintyre (1985) suggest that the reefs were "shot in the back" by their lagoons. Some reefs essentially "give up" during the rapid rise (~8m [26 ft]/ka) in sea level. Stratigraphic evidence noted by these workers for drowning includes bored hardgrounds, ferromanganese-oxide accumulations, phosphates, and glauconite separating neritic from overlying deeper water deposits. The nutrient influx and increased organic productivity led to reduced water clarity. This could effectively lead to a shallowing of the euphotic zone. Thus the euphotic zone, i.e. zone of carbonate production, could be dependent on the rate of sea level rise. Oscillatory sea level fluctuations in even shallow water could lead to retardation or termination of carbonate production.

The Pennsylvanian midcontinent seaway was a tropical inland sea with limited connection to the open ocean (Heckel, 1977). Conditions probably favored high nutrient supply during marine flooding due to freshwater runoff contributing terrestrial organic matter and inorganic compounds to the marine realm. The tendency for water stratification due to an equitable climate promoting a stable water column supports conditions of lowered oxygen and preservation of organic matter. For these reasons, the effective depth of the euphotic zone may have been shallow in the interior Pennsylvanian seaway and perhaps quite variable, especially in the areas of detrital influx. Flooding units may be linked to the overlying condensed sections through the nutrient excess potentially created by the flooding process.

Condensed section

Core shales in the midcontinent are similar to other condensed sections, often shales, that have been referred to as the "starved-basin facies" (Scholle et al., 1983; fig. 16). Organic-rich units are deposited under dysoxic to anoxic conditions. Black or gray shales can also result from rapid episodic changes in oxygen level due to organic productivity or water circulation. As suggested above, the condensed section may simply be represented by a diastemic surface such as a hardground. As in the case of the upper Virgilian strata, the black shale is lacking. Rather, the condensation in sedimentation in the upper Virgilian may be represented by a surface in a limestone or marine shale.

Dysoxic conditions result in accumulation of gray, dark-gray, or olive-green shales or siltstones. Anoxic conditions may result in the accumulation of black shales. Whereas the black shales are laminated, the gray

shales are variably burrowed. These gray shales, albeit thin (< 1 ft [0.3 m]), typically precede and succeed the black shale, if the latter is even developed, or are found laterally equivalent to a black shale.

Unlaminated gray or green fossiliferous siltstones and claystones are commonly deposited in landward positions or on bathymetrically higher elevations in positions equivalent to extensive black shales (Watney, 1984). The condensed sections are relatively thin, usually under 2 to 3 ft (0.6–0.9 m) in thickness. However, exceptions occur as the condensed section grades laterally to localities where suspension sedimentation was significant, such as in the Ouachita siliciclastic depositional sequences. Contacts with adjoining strata are usually abrupt, but gradations do occur with shale and carbonate lithologies. Most of the black shales on the upper carbonate-dominated shelf are regionally widespread.

Biota in the Upper Pennsylvanian black shales in the western midcontinent is limited to nektonic and nektobenthic organisms, abundant pelagic organisms, and rare benthic forms. Large amounts of conodonts and fish debris are common, but these shales generally lack benthic marine invertebrates. The microstratigraphy is complex as indicated by interlayered bioturbated zones, thin carbonate layers, and marked variations in minor elemental composition. Uranium concentrations in black shales ranges from < 20 ppm to more than 250 ppm, accounting for most of the high natural gamma radiation emitted by black shales.

Nonskeletal phosphate (apatite) is common as assorted nodules and laminae in black shales. Abundant and diverse radiolarians, nautiloids, and fish debris have been found in the nodules in black shales in eastern Kansas (Kidder, 1985). The source of the phosphate could be planktonic organisms, fecal material, or perhaps solution and suspension from river water.

Greatly reduced sedimentation rates for the condensed section are suggested by 1) commonly abundant phosphate, 2) high concentrations of normally sparse pelagic fossils, 3) horizontal orientation of clay minerals composing the shale (suggesting dilute suspension sedimentation; James, 1970), and 4) elevated concentrations of minor elements such as uranium.

The widespread nature of most of the black shales on the shelf and in the basin suggests that the shales represent uniform conditions developed synchronously such as in deep water, or in a time-transgressive manner during rapidly deepening conditions. While lithofacies such as sandstone and carbonates thin in a basinward direction, black shales persist across the shelf and into the basin. Black shales observed in the lower Missourian converge in the basin in areas of sediment starvation to form stacked condensed sections separated by very thin intervening dark, skeletal wackestones and gray shales and siltstones. A number of process models have been proposed to explain black-shale deposition, namely upwelling and quasi-estuarine circulation (Heckel, 1977), upwelling through Ekman transport (Parrish, 1982), halocline (Demaison and Moore's Black Sea model with freshwater influx, 1980, or basinal brine upwelling, Hite, 1978), and thermocline (Rossignol-Strick, 1982; Heckel, 1985).

The dysoxic facies contain limited, but distinctive faunas that have been interpreted as an assemblage related to depth (Boardman et al., 1984). Biotic assemblages reflecting similar dysoxic conditions are commonly found in other Paleozoic shales. Perhaps these biotic zones may be affected by unfavorable water chemistry, or high organic-matter productivity, in addition to simple oxygen depletion due to water depth and isolation of the bottom water column, i.e. not necessarily depth controlled.

As previously stated, stratigraphic, sedimentologic, paleontologic, and geochemical evidence from a variety of settings supports *both* shallow- and deep-water origins of black shales. Accumulation of black shales is dependent on developing a prevailing bottom anoxia that is tied to the rate of the production of organic matter and preservation potential of organic matter versus amount of oxygenation of the water column or sediment.

The higher the influx of organic matter, the more oxygen that will be consumed. Bottom stagnation may not be a prerequisite if abundant organic matter is available due to high organic productivity. Whereas favorable conditions for black-shale accumulation occurred frequently during the Pennsylvanian across the greater United States midcontinent, equivalent cyclothemic units on the Russian platform, although containing open-marine carbonates, do not contain black shales. If water depths between the two shelves were similar, then water depth may not have been the only critical factor in generation of black shales.

Freshwater runoff flowing over the surface of marine waters that were flooding the shelf could provide limited, temporary stratification of the water column, particularly under tropical conditions. Input of large amounts of terrestrial organic matter and high nutrient supply could also be provided by runoff to generate abundant marine-organic matter. Woody-plant material has been found in both the Hushpuckney and Stark shales in eastern Kansas and Oklahoma, attesting to the input of terrestrial organic matter. Moreover, mixed terrestrial and marine macerals of organic matter occur in these shales (Hatch and Leventhal, 1985). Tropical conditions favoring thermal stratification would assist in developing a pycnocline. The epeiric sea in the midcontinent was only open to the ocean through a connection in the Dalhart basin in west Texas, thus limiting open exchange with normal oceanic waters. Basinal brines may also have formed in the Anadarko basin, possibly fed episodically by the influx of brines during lowstand shelf bypassing or during early flooding of the shelves that contained evaporites on the western craton, e.g., Minnelusa Formation of Wyoming and adjacent areas. A combination of different factors between locations likely may have facilitated preservation of organic matter during rising sea level. Rising water levels could have led to conditions favoring nutrient excess such as organic productivity and water stratification. Furthermore, the thickness of the bottom anoxic layer may have been variable, thus accounting for the loss of some black shales over topographic highs.

Shallowing-upward stratal unit

This unit composes the thicker portion of the Pennsylvanian sedimentary sequences (fig. 16). Lithologies are highly variable ranging from fluvial-deltaic sandstone, marine sandstones and shales, to shallow-water carbonates. Thickness of these shallowing-upward, siliciclastic-dominated units range from a few feet to more than 100 ft (30 m), while carbonate successions vary from a few feet to 10's of feet thick.

Depositional facies reflect a range of depositional environments that varies from subaerial, intertidal, to below storm-wave base. Basinal carbonates are argillaceous and commonly organic-rich; marine macrofossils and trace fossils are common to abundant.

Common shallowing-upward facies seen on this field trip include

a) *open-marine carbonate* with normal marine biota

1) clear-water carbonate

- i) low to moderate energy—commonly phylloid algal wackestone or packstone ('mound rock') or crinoid-bryozoan-brachiopod wackestone; sedimentation rates are judged to be moderate to high, the latter during mound development
- ii) high energy—bioclastic and oolitic grainstones; sedimentation rates interpreted as high as long as favorable conditions existed and accommodation space for accumulation was available.

- 2) Turbid-water and deeper water carbonate deposits
 - i) argillaceous bioclastic mudstone and wackestones with dispersed silt and clay, macerals of organic matter, and wispy shale seams and microstylolites; sedimentation rates are judged to be low because of marginal conditions for carbonate accumulation; facies typically have undergone significant, apparently long-term compaction; porosity is typically low;
 - 3) restricted, shallow-marine and clear-water carbonate sediment
 - i) laminated, fenestral, mudcracked, stromatolitic lime mudstone and dolomicrite; sparsely fossiliferous, trace fossils common; sedimentation rates are interpreted as moderate to high as long as accommodation space was available.
- b) *siliciclastic-dominated regressive*
- 1) below wave base to subaerial deposits; fluvial-deltaic, marine sandstones, siltstones, and shales; locally and episodically high sedimentation rate, but quickly diminished by rise in base level.
 - i) southern shelf (early Missourian) (south of Tulsa)—fluvial and deltaic sandstones and shales with limited marine section; sedimentation rates are moderate to very high; significant topographic relief and clastic wedge development;
 - ii) depositional basin (early Missourian) (Tulsa to Coffeyville, Kansas)—delta-front, tractive sandstones and suspension-load sedimentation; predominately marine interval; accumulation rates likely very high along the prograding edge of an active delta; sediment-starved along middle shelf, indicating deeper water conditions with limited traction and suspension sediment load and too deep for carbonate accumulation;
 - iii) Northern carbonate-dominated shelf—shale of variable thickness on top of shallowing-upward limestone; thin lenticular sandstones in shale; local shale-dominated deltaic platforms up to several hundred feet (60 m) thick developed in some intervals covering areas ranging up to several thousand square miles (5,000 km²); thin paleosols (blocky claystones) and isolated, rare channels as evidence of subaerial exposure and sediment bypassing on the shelf into the basin.

Paleosols and other evidence for subaerial exposure

Diagnostic criteria for subaerial exposure and paleosol development are examined on the trip because of their importance in defining sequence boundaries (fig. 15). Significant subaerial exposure, weathering, and paleosol development occurred over extensive areas of the shelf following deposition of the shallowing-upward stratal unit or at the tops of parasequences within a sequence. Paleosols form a veneer on top of depositional sequences on the shelf areas of most Missourian strata in western Kansas (Watney and Ebanks, 1978; Watney, 1984) and extend across much of eastern Kansas (Schutter and Heckel, 1985; Goebel et al., 1989). Early meteoric diagenesis consisting of both dissolution and cementation events is pervasive on the shelf, e.g., extensive dissolution of oolites produced broad expanses of oomoldic porosity in western Kansas (Watney, 1984). An improved understanding of the patterns and causes of cementation and dissolution events during diagenesis, such as the work of Goldstein et al. (1989), will provide an important facet in developing a predictive model for porosity development during subaerial exposure.

In general, correlating subaerial-exposure surfaces is difficult. The lack of clear, definitive evidence of subaerial exposure may be due to spatial variations of processes involved in even a single weathering event, resulting in subtle, nondiagnostic products, or paleosols of complex origin containing mixed preservation features. Proximity of paleosols to the flooding unit of the overlying sequence leads to a high potential for their erosional truncation. However, evidence is sufficient to conclude that paleosols characteristically form extensive bounding (hiatal) surfaces to most sequences on the shelf. Recent coring shows that these hiatal surfaces merge with conformable surfaces in the basin or on lower parts of the shelves that were apparently still submerged during lowered sea levels. Heckel (1986) has identified such a relationship associated with the sequence boundary between the Wyandotte and Iola limestones in a mid- shelf and lower-shelf setting.

Subaerial exposure surfaces clearly separate younger sequences from older sequences, thus providing excellent temporal definition of the sequences. Examples of a well-developed paleosol horizon and subaerially exposed surface is seen at stop 4.

Detrital-rich paleosols are composed of blocky mudstones. Weathering features are common in the upper portions of the underlying parent material on which these blocky mudstones are developed, e.g., dissolution channels and cavities in limestone. Missourian-age paleosols are carbonate-rich, indicating carbonate accumulation due to a net moisture deficiency in the local soil environment, whereas other paleosols indicate more moist conditions. Interpreting soils is complex in features to be recognized in the field and laboratory, in classification and nomenclature, and in assessing the relative contribution of potential agents responsible for the formation of the soil. Climate, local relief, vegetation, parent material, time, and multiple events all can affect the type of soil developed.

Most of the paleosols observed on the trip appear to have been affected by multiple stages of formation. Preservation probably favors only the more resistant components. Also, subaerial exposure features are preferentially preserved in topographically low areas and may not be representative of the paleosol as a whole.

Diagnostic features commonly present in paleosols include

- 1) rhizoliths (rootlets);
- 2) ped surfaces in the blocky mudstones (fig. 18, p. 12, from Retallack, 1988);
- 3) color mottling or isolated horizons of color and textural variation in the mudstone due to differential oxidation and hydrolization of iron, and redistribution and formation of clay minerals (illuviation);
- 4) micritic carbonate nodules or casement around rhizoliths, or carbonate crusts (calcrete).

Paleosols rich in calcium carbonate are referred to as *caliche*, defined as a strataform to irregular deposit, formed primarily of calcium carbonate, with concretionary, pisolitic, banded or massive structure that is formed in the soil or subsoil of arid and semiarid regions (Gonzalez-Bonorino and Terruggi, 1952). Missourian sequences in northwestern Kansas are commonly capped by chalky caliches found in red paleosols or as laminated calcrete at the top or near the top and filling in the carbonates (Watney, 1980, 1984). Their abundance in western Kansas is indicative of drier conditions than in southeastern Kansas which fits with paleoclimatic reconstructions (Heckel, 1980). While varying from area to area, these paleosols appear to be shelfwide developments.

In contrast to caliche, the following are some of the identifying criteria for paleosols developed under moist, subaerial conditions, provided sufficient time has elapsed for soils to develop;

- 1) terra rossa (red residuum dissolved from carbonate dissolution);
- 2) paleokarst and solution piping, commonly plugged with clay of paleosol or wall-rock debris;
- 3) well-developed clayey soil profile exhibiting illuviation.

Some paleosols exhibit relationships of both wet and dry attributes. Dubois (1985) describes karsting as prevalent in topographically lower areas at the top of the Dennis Sequence in southwestern Nebraska. Solution piping extends through the carbonate (> 20 ft, 6 m). Proximity to the water table and greater residence time of water in the low areas are likely reasons for karsting. Topographically higher locations contain caliche paleosols indicative of locally drier conditions (Dubois, 1985).

Sequence-stratigraphy terminology

Summarized here is terminology utilized in sequence-stratigraphic interpretations as presented by Haq et al. (1987; fig. 15) and for a carbonate shelf by Vail (1987; fig. 19). This terminology, generally after Van Wagoner et al. (1987) unless otherwise specified, will be utilized throughout the text and during the course of the field trip where applicable.

Depositional sequence: the fundamental unit of sequence stratigraphy. A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Mitchum, 1977). They have predictable stratal patterns and lithofacies and thus provide a new way to establish a chronostratigraphic correlation framework based on physical criteria (Vail, 1987).

Hiatal surface (unconformity): separates rocks of different ages and does not cross other chronostratigraphic surfaces. In addition, the duration along a hiatal surface varies, thus time lines merge along the surface, but do not cross it. Therefore, the hiatal surface is not diachronous. The strata bound by an unconformity are also not diachronous, but temporally distinct. However, the strata constrained by bounding hiatal surfaces were not necessarily deposited at the same time.

Marine-flooding surface: a surface that separates younger from older strata, across which there is evidence of an abrupt increase in water depth.

Parasequences: relatively conformable successions of genetically related beds or bedsets within a depositional sequence, each bounded, in most cases, by a marine-flooding surface and their correlative surfaces. Parasequences are progradational and therefore the beds within parasequences shoal upward. Stacking patterns of parasequences in parasequence sets are progradational, retrogradational, or aggradational depending on the ratio of depositional rates to accommodation rates. Examples of parasequences sets and geometries are provided in Figures 20 and 21.

Sequence boundaries: regional hiatal surfaces, either subaerial or subaqueous, that are characterized by regional onlap of strata above the surface and truncation of strata below.

Type 1 sequence boundary: characterized by subaerial exposure and concurrent subaerial erosion, a basinward shift of facies, a downward shift in coastal onlap, and onlap of overlying strata. A type 1 sequence boundary develops when there is a relative fall in sea level (e.g., rate of eustatic sea-level fall is greater than the rate

of subsidence at the depositional shore-line break; labeled SB1 in fig. 15). The type 1 sequence boundary of shelfal Pennsylvanian rocks is the stratigraphically highest regional subaerial surface of each depositional sequence. Parasequences also can have an upper subaerial surface which is not as extensive in a basinward direction as the upper bounding surface.

Type 2 sequence boundary: marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional-shoreline break, onlap of overlying strata landward of the depositional shore-line break; lacks a basinward shift in facies. The Type 2 sequence boundary is an unconformity in landward positions (labeled SB2 in fig. 15). A Type 2 sequence boundary is interpreted to form when the rate of eustatic sea-level fall is less than the rate of basin subsidence, so that no relative fall in sea level occurs at the shoreline position.

Transgressive surface: the first significant marine-flooding surface across the shelf within the sequence (labeled TS in figs. 15 and 19). This appears to be most difficult to identify on a seismic section but is easy to identify in the rocks.

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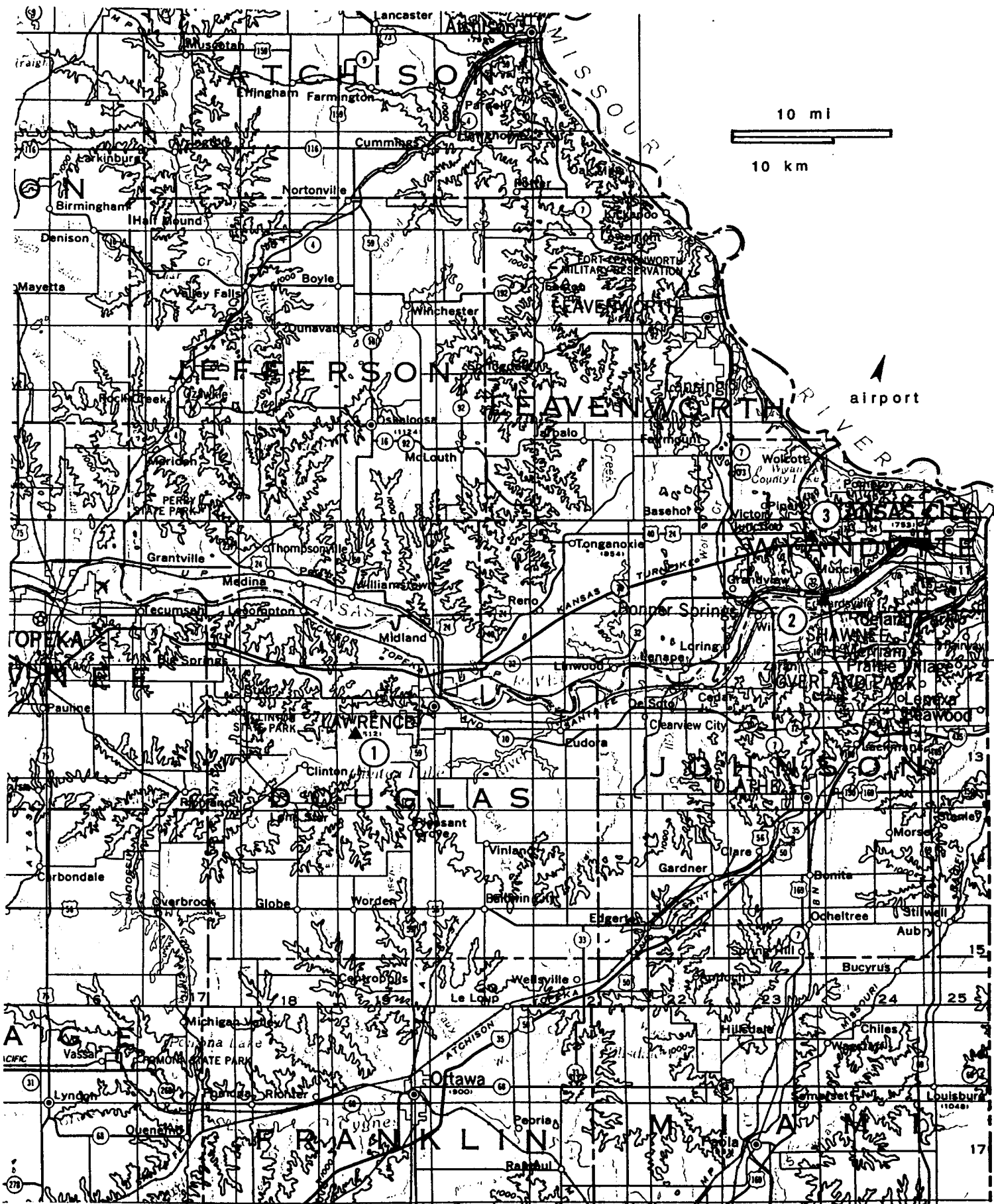


FIGURE 1—Index map of eastern Kansas showing stops on field trip (numbers and triangles), index of well locations (letters) used to make regional cross section found in fig. 4, and hatched area in southeastern Kansas delimiting area mapped in figs. 5-13.

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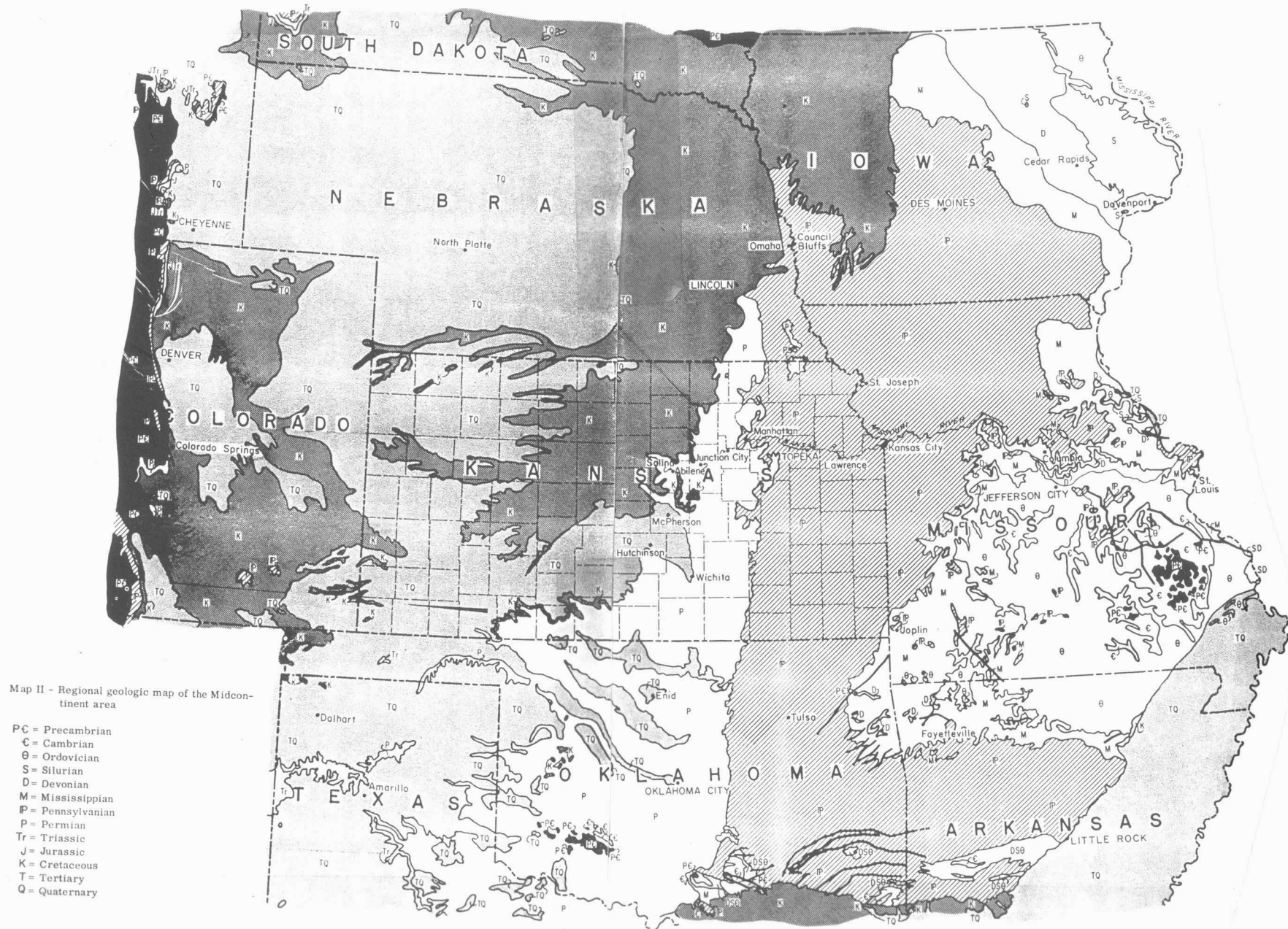
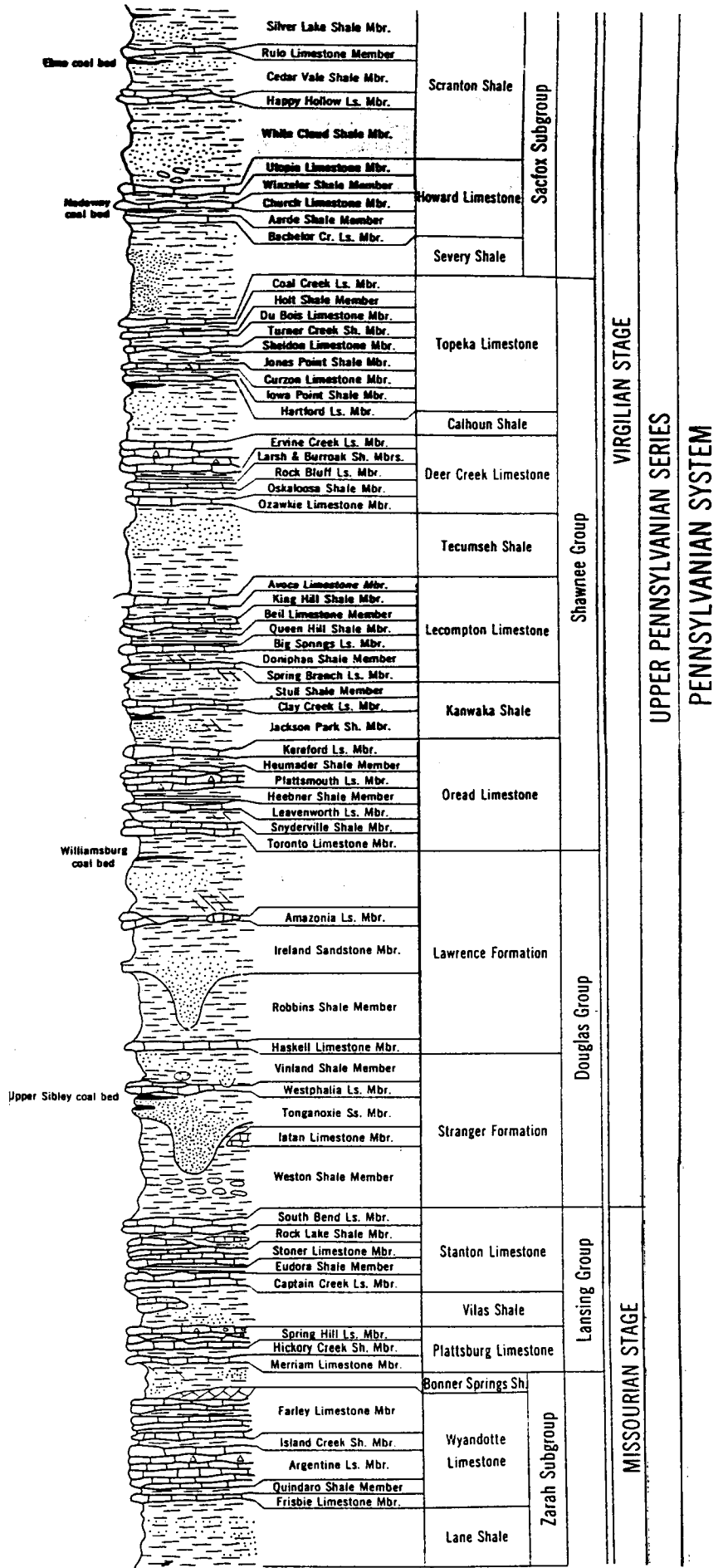
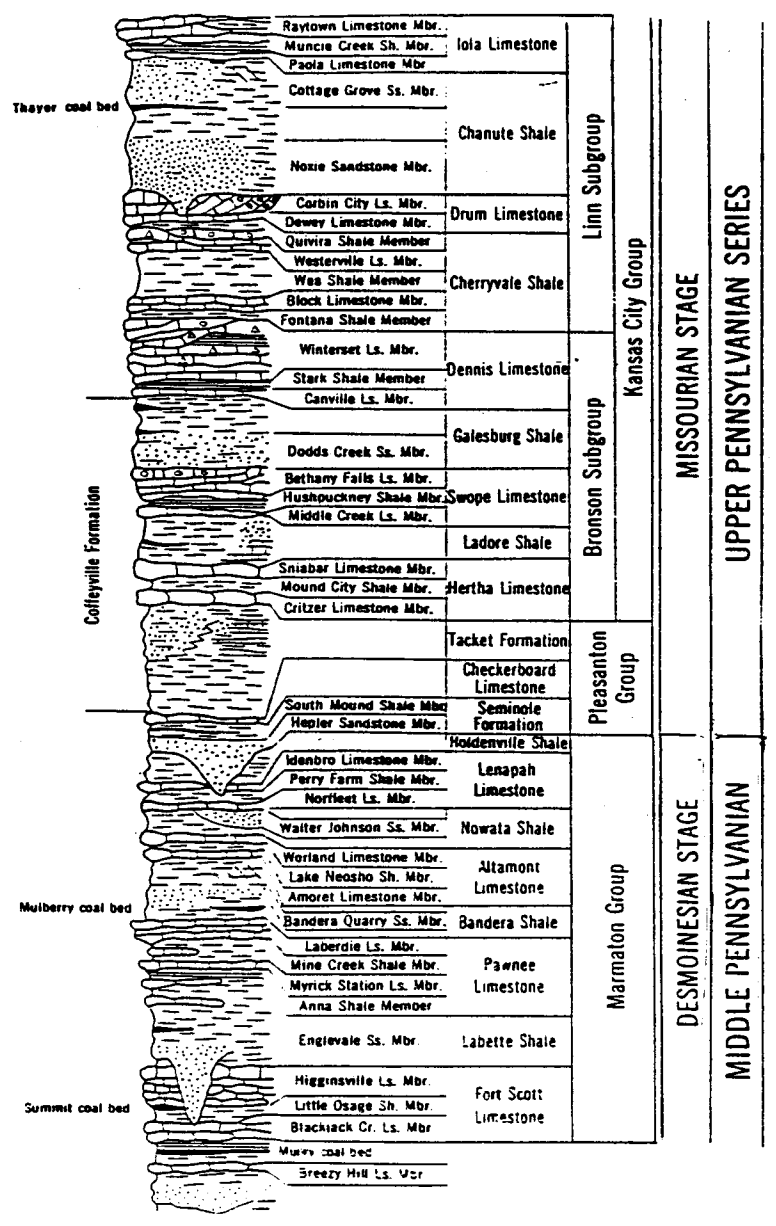


FIGURE 2-Bedrock geologic map of Mid-Continent region (Moore and Merriam, 1959).

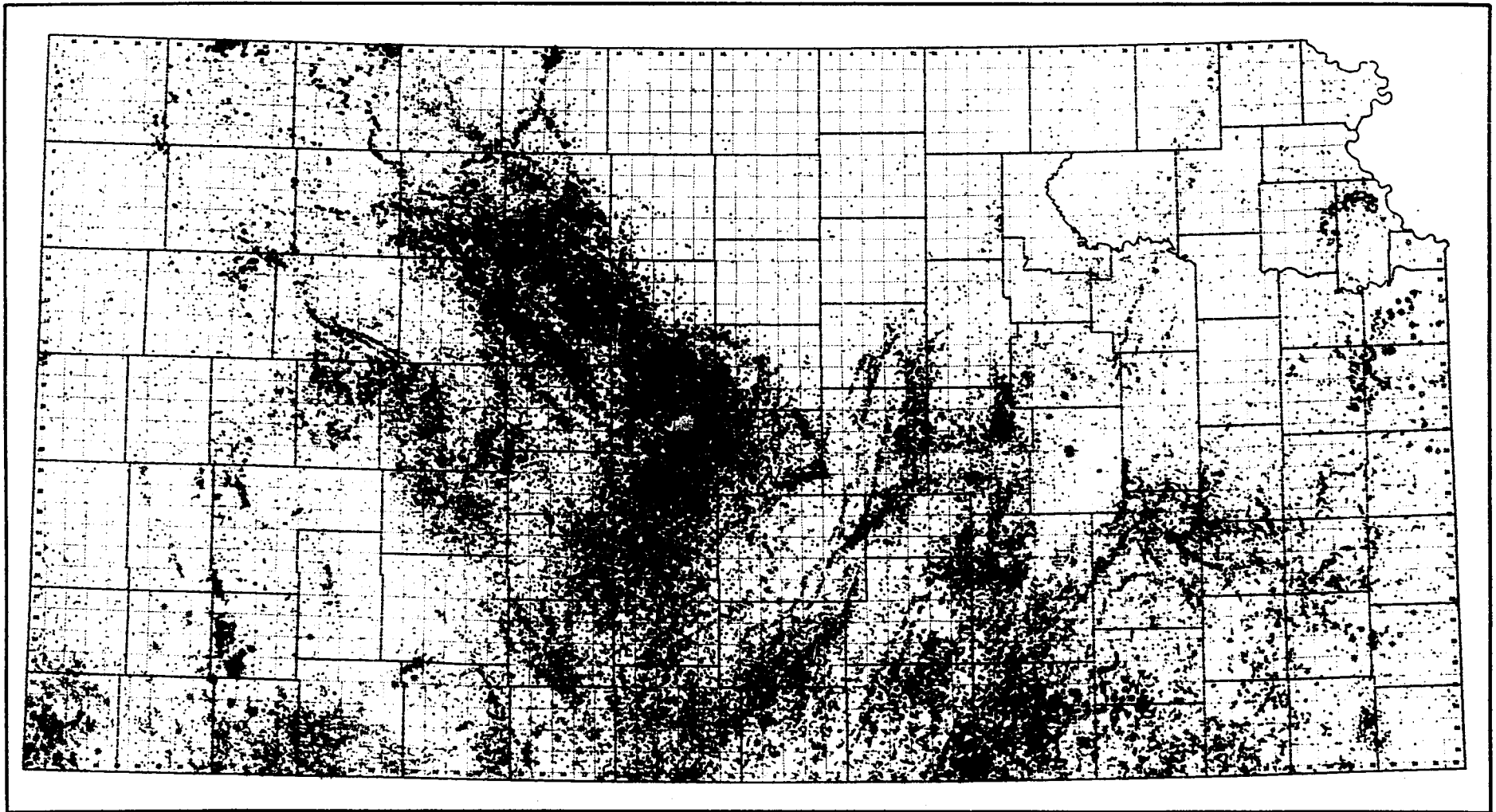
FIGURE 4—Stratigraphic sections that will be examined on the field trip showing formal stratigraphic nomenclature and major lithologies. Intervals examined at each stop are indicated.

Field Stops





WELLS PENETRATING AND PRODUCING FROM LANSING-KANSAS CITY



IV-33

FIGURE 5-Wells penetrating and producing from Lansing and Kansas City Groups in Kansas.



FIGURE 6—Hemisphere of globe showing Euramerica and location of midcontinent during Pennsylvanian (Ross and Ross, 1987).

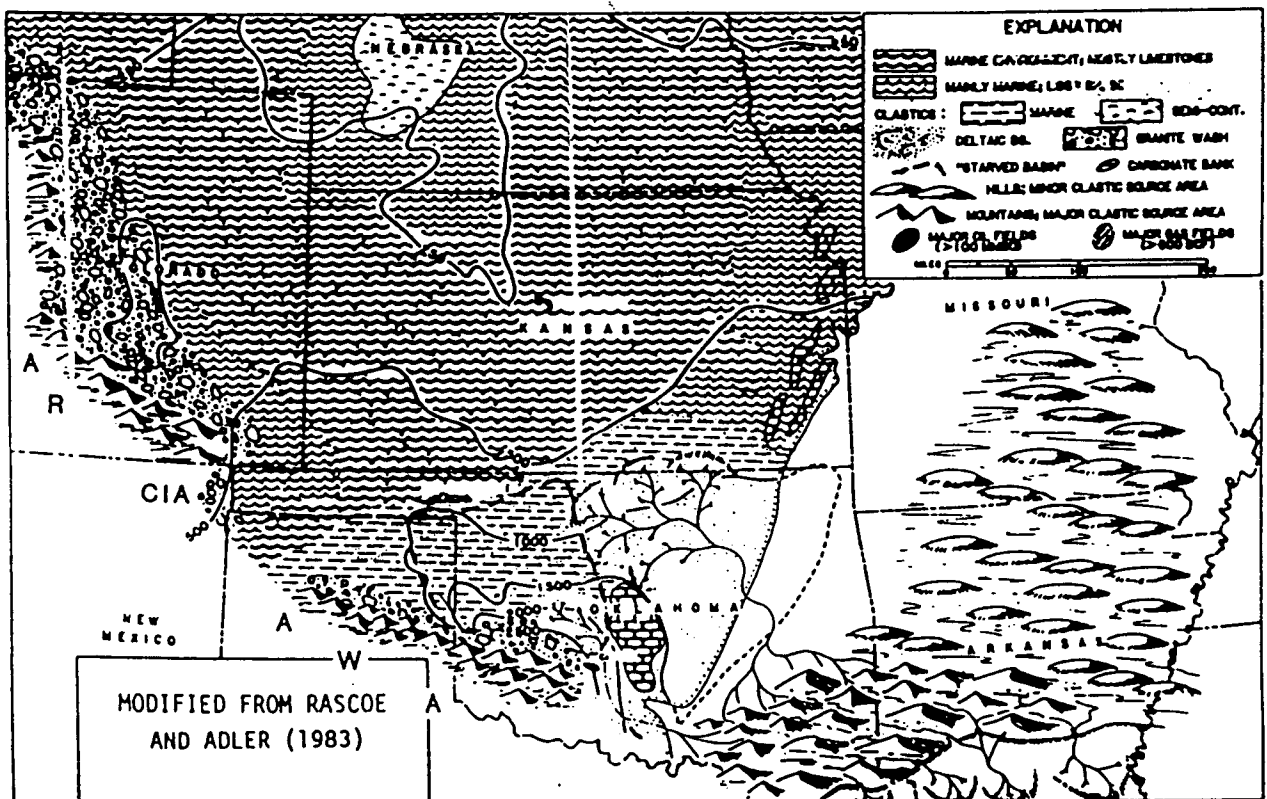


FIGURE 7—Lithofacies, paleogeography, and isopach map of strata deposited during Missourian (Pennsylvanian) in southern mid-continent (Rascoe and Adler, 1983).

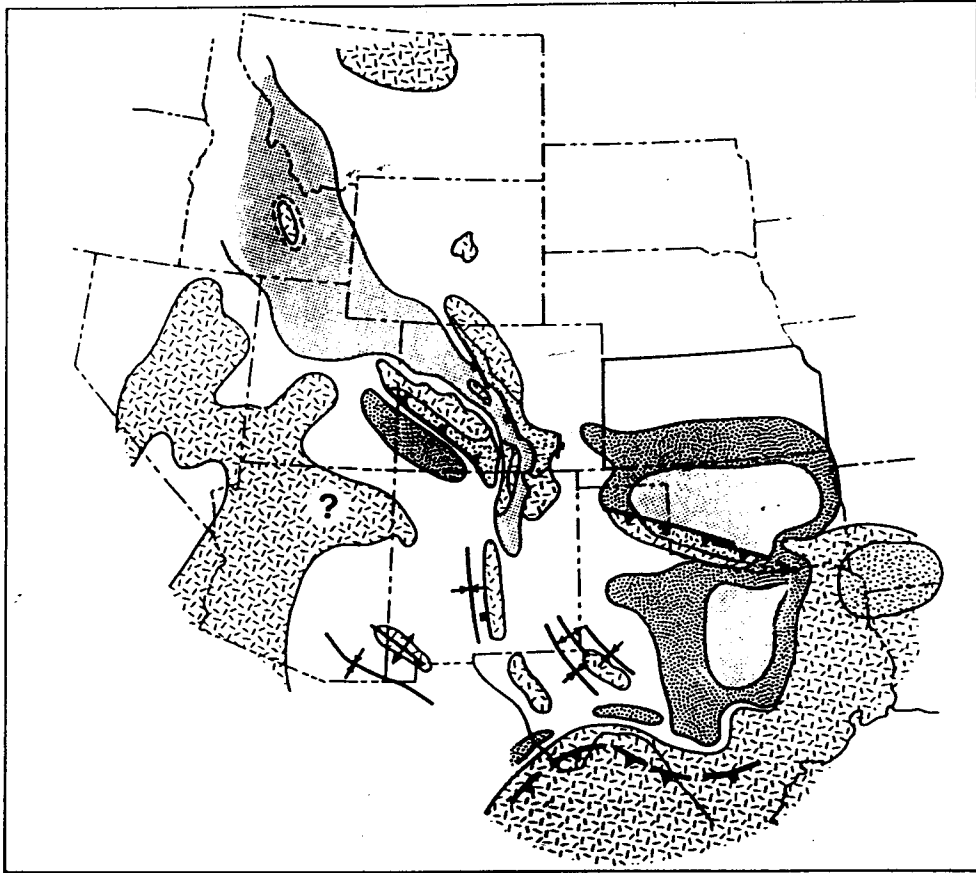


FIGURE 8—Missourian tectonic features with average subsidence rates for Missourian time: white areas = < 0.05 to 0.2 m/ka; dark stippled pattern = > 0.05 to 0.2 m/ka; and lighter stipple = > 0.2 to 0.3 m/ka. Subsidence in Arkoma basin in waning stages during the Missourian (Kluth, 1986).

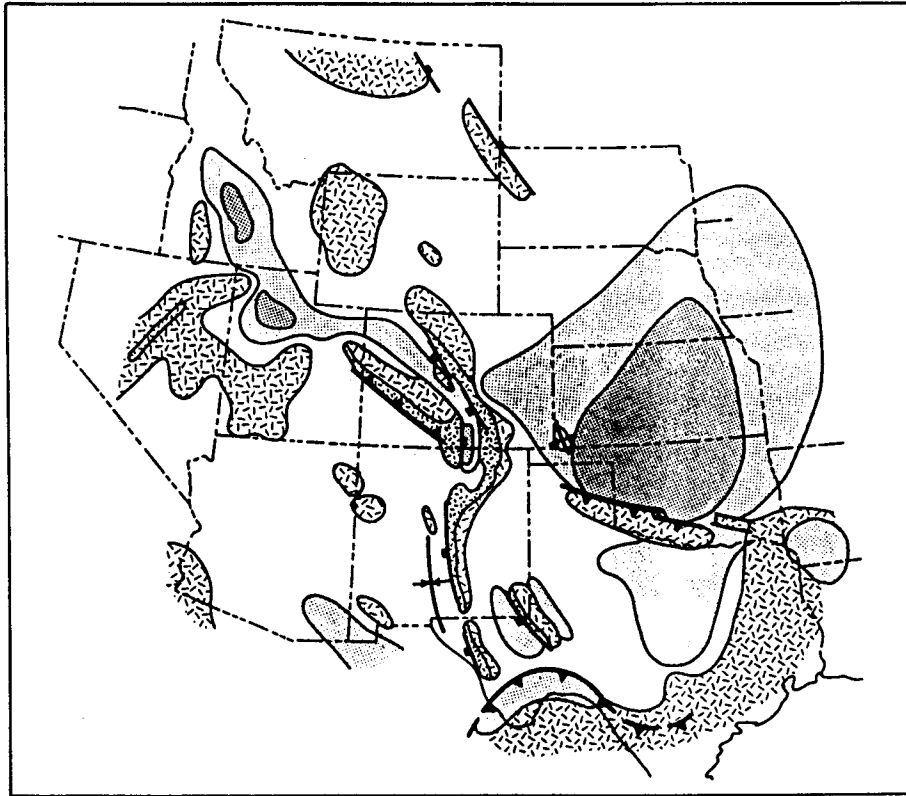


FIGURE 9-Virgilian tectonic features with average subsidence rates for Virgilian time (as fig. 8) (Kluth, 1986).

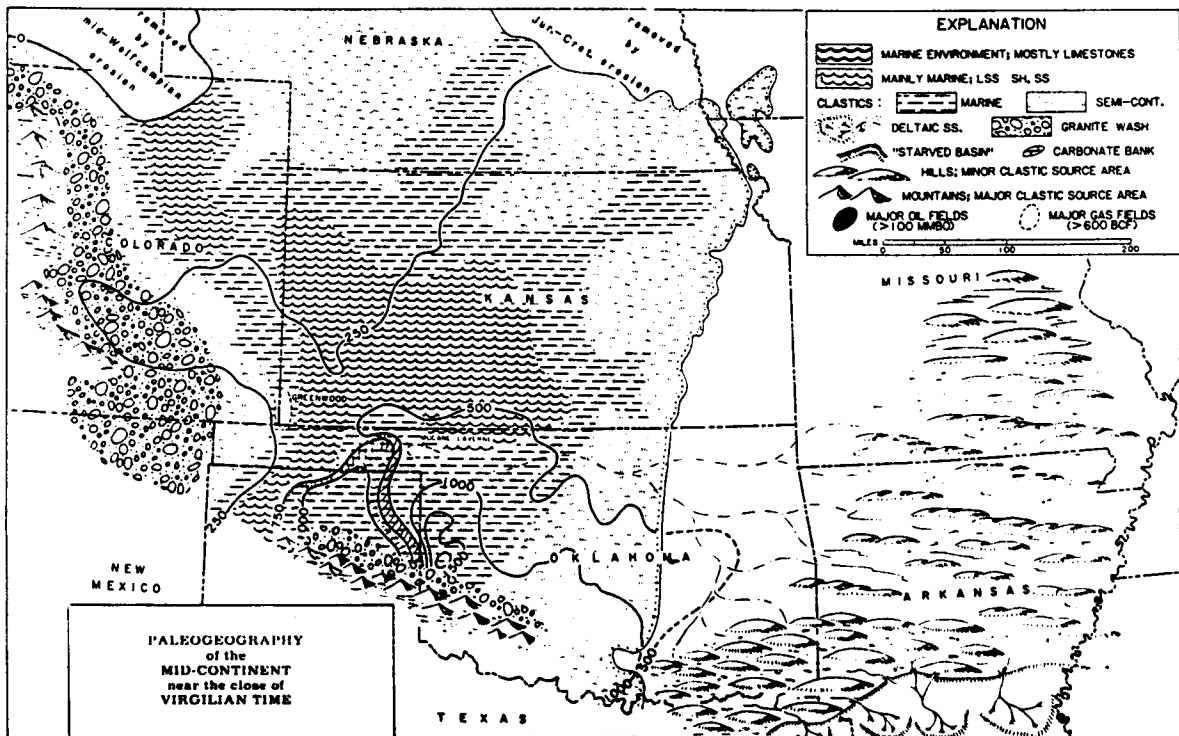


FIGURE 10-Lithofacies, paleogeography, and isopach map of strata deposited near close of the Virgilian in southern mid-continent (Rascoe and Adler, 1983).

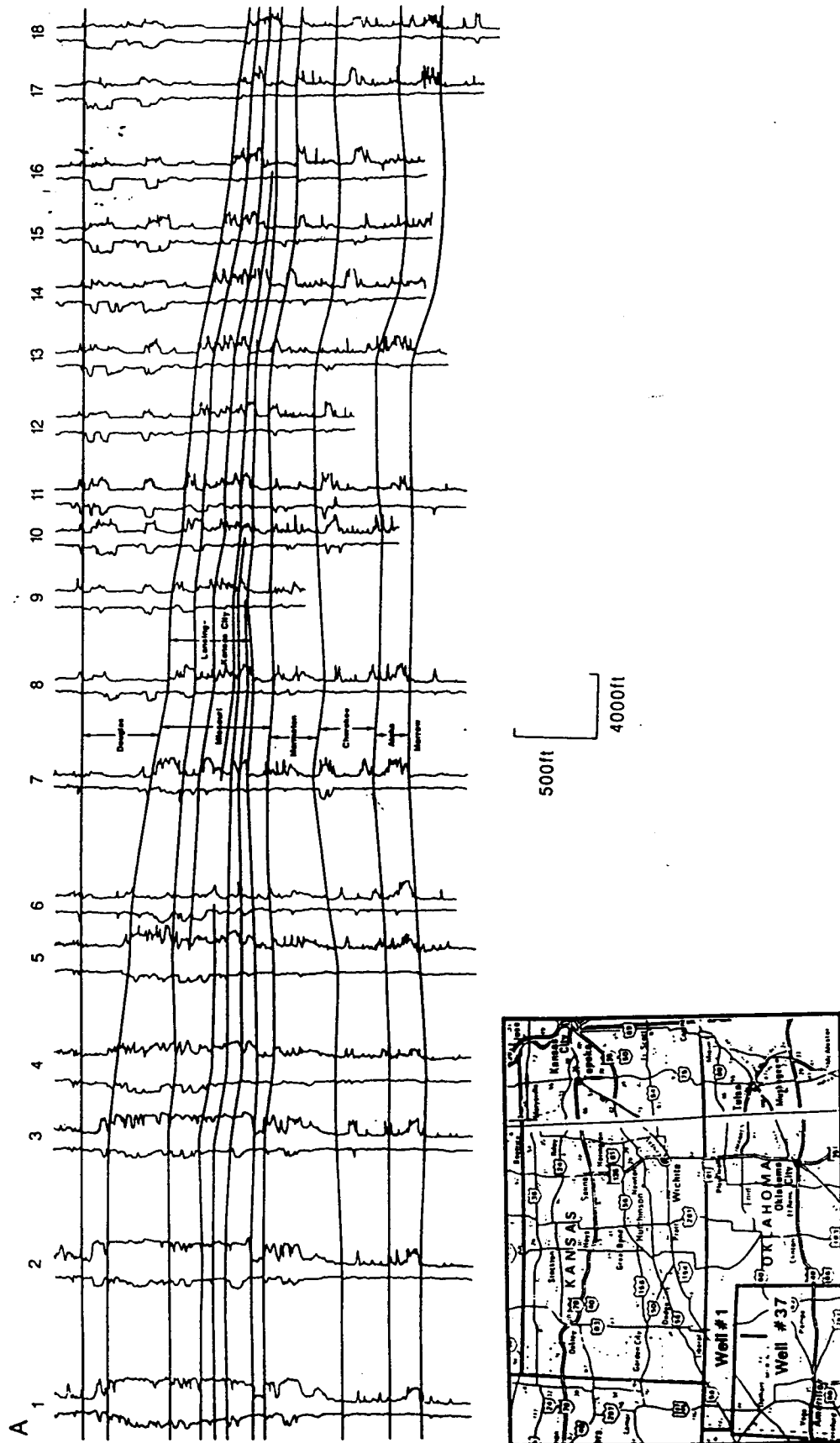
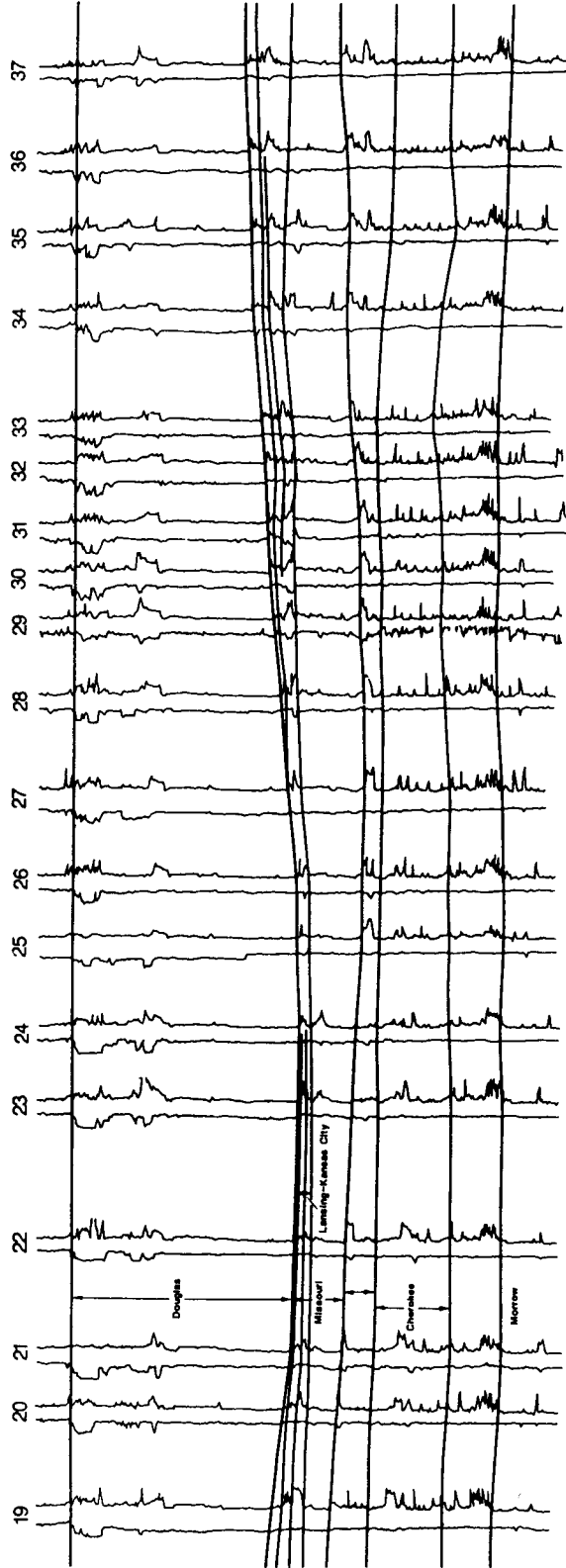
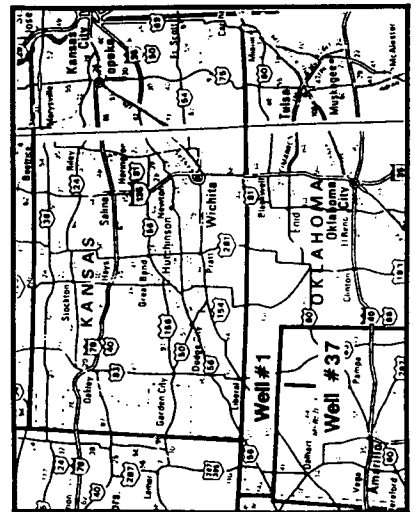


FIGURE 11—Stratigraphic wireline-log cross section across shelf edge of northwestern Anadarko basin in Hansford County, Texas. Datum is Virgilian Heebner Shale (from George Moore, circa 1974).

A'



500ft
4000ft



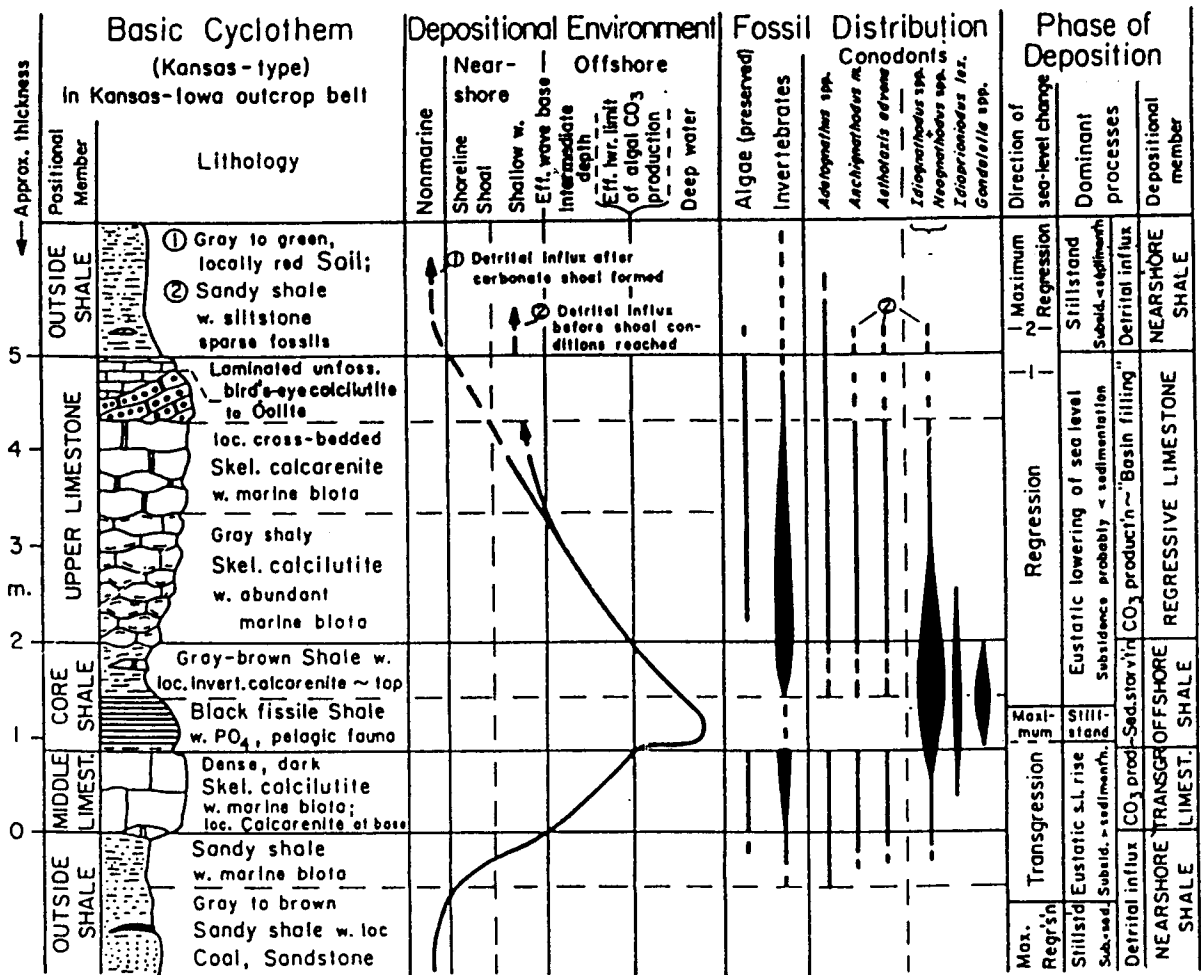


FIGURE 12—Basic Kansas cyclothem characterizing carbonate-dominated strata in the northern midcontinent shelf (Heckel, 1977, 1989).

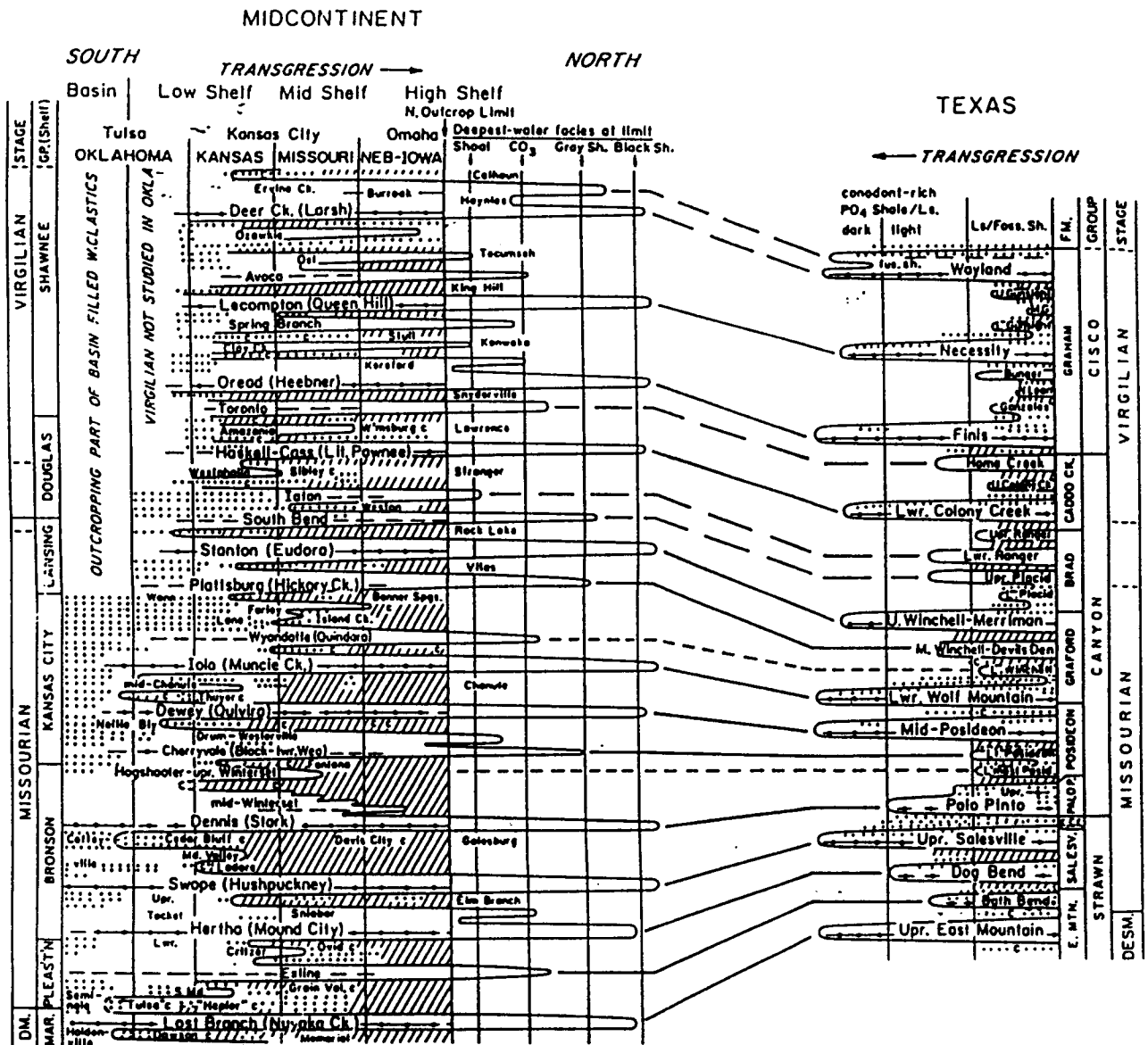


FIGURE 13—Glacial-eustatic sea-level curves for early Upper Pennsylvanian succession in north-central Texas and midcontinent correlated using biostratigraphy. Curves depict maximum inundations based on occurrence of black shale and low stand based on extent of subaerial exposure (Boardman and Heckel, 1989).

TABLE 1—HIERARCHY OF ROCK CYCLES RELATING TO RELATIVE CHANGE IN SEA LEVEL.

1st order (highest)	Duration	
	225–300 Ma	Plat movement and volume of ocean basin (Paleozoic–Mesozoic)
2nd order	20–90 Ma	Stoss cratonic sequences plate movement-tectonic syntheses of Chang (1975)
3rd order	7–13 Ma	Cloetingh's (1988) intraplate response to changing stress patterns; rates = 0.01 to 0.1 m/ka (slow) (gradual)
4th order	0.6–3.6 Ma	Mesothem of Ramsbottom tectonism-thrust loading
5th order	300–500 ka	Orbital parameters and climate (also lower orders); Pennsylvanian cyclothem
6th order	50–130 ka	PAC (punctuated aggradational cycles)—Goodwin and Anderson (1985); Pleistocene glacial-interglacial (rates 2–10 m/ka)

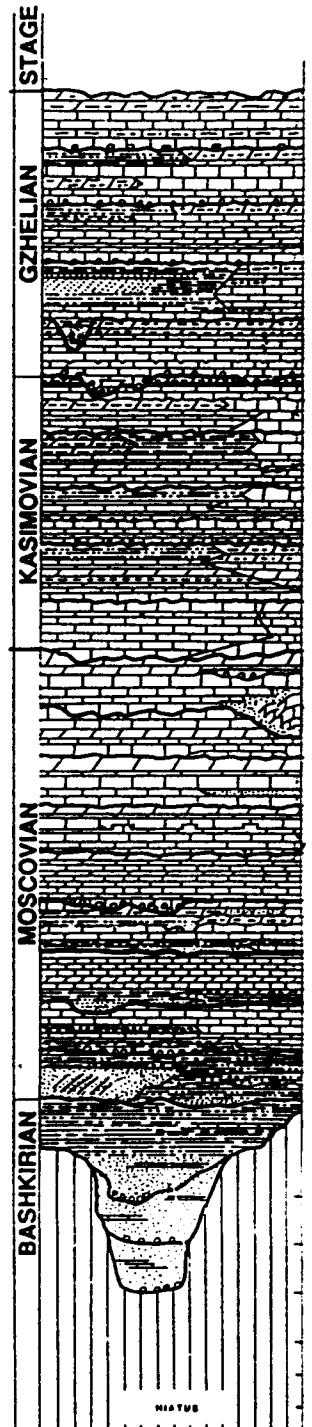


FIGURE 14—Stratigraphic section of carbonate-dominated Middle and Upper Carboniferous shelf cyclothem on Russian platform. Kasimovian is equivalent to Missourian and earliest Virgilian (Ross and Ross, 1988).

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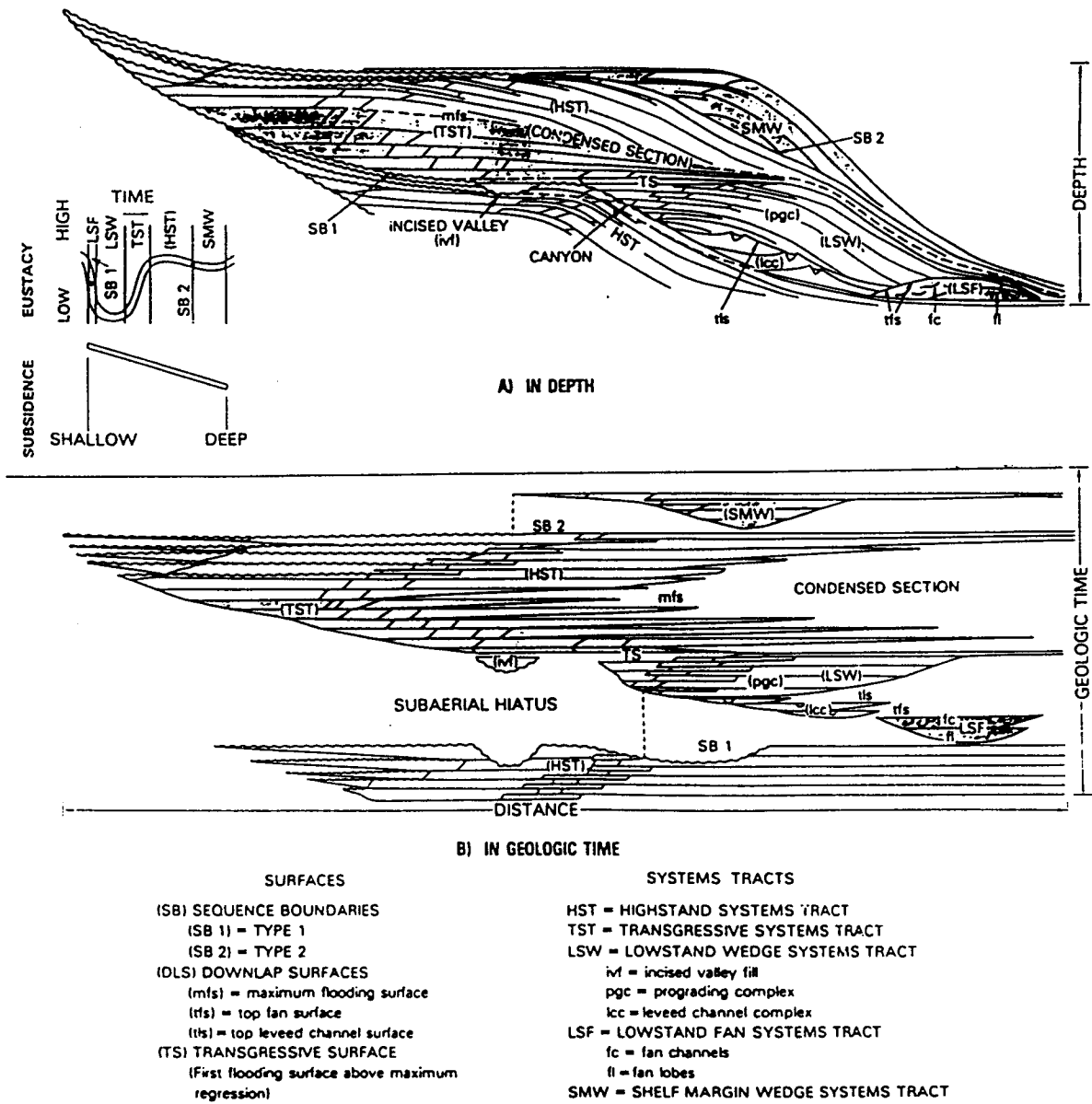


FIGURE 15—Depositional sequence deposited along shelf margin due to oscillation in sea level and constant subsidence (Haq et al., 1987). Stratal units and surfaces are defined further in appendix A.

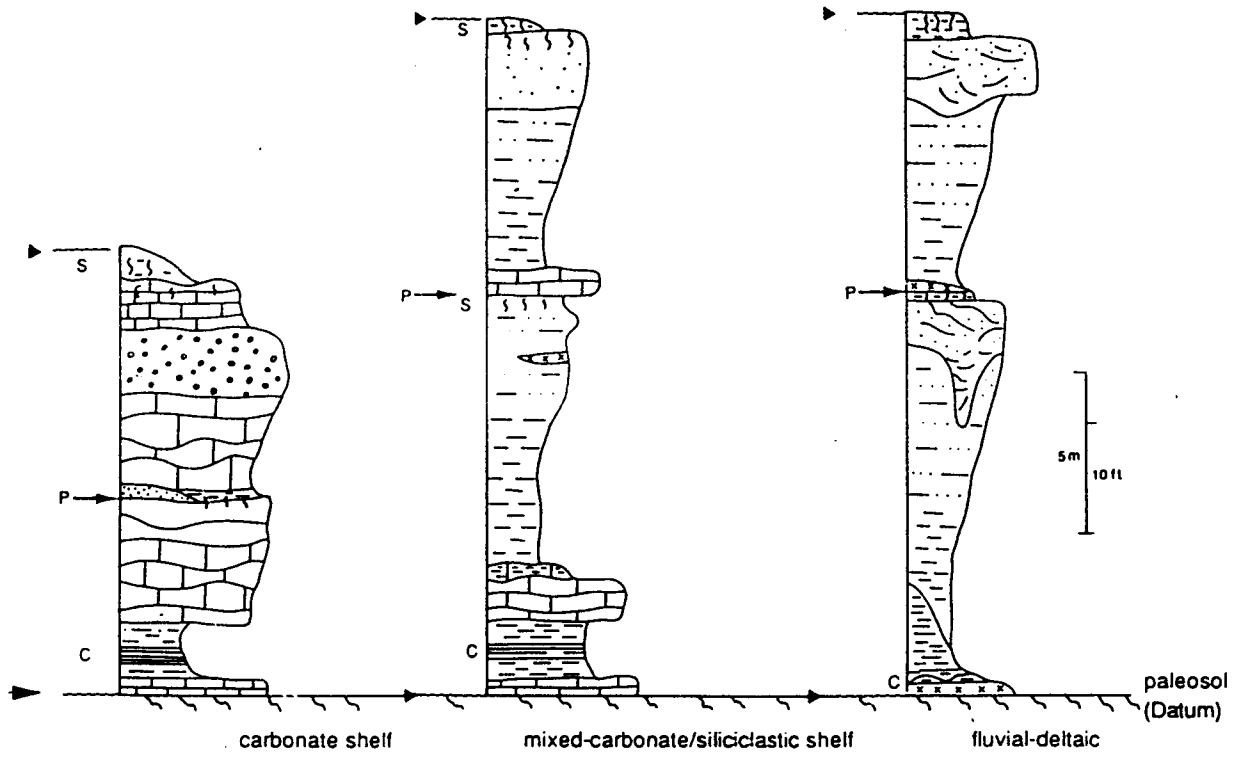


FIGURE 16—Vertical profiles of selected types of depositional sequences observed in Pennsylvanian strata of the midcontinent. Simple shallowing-upward sections shown.

11-43

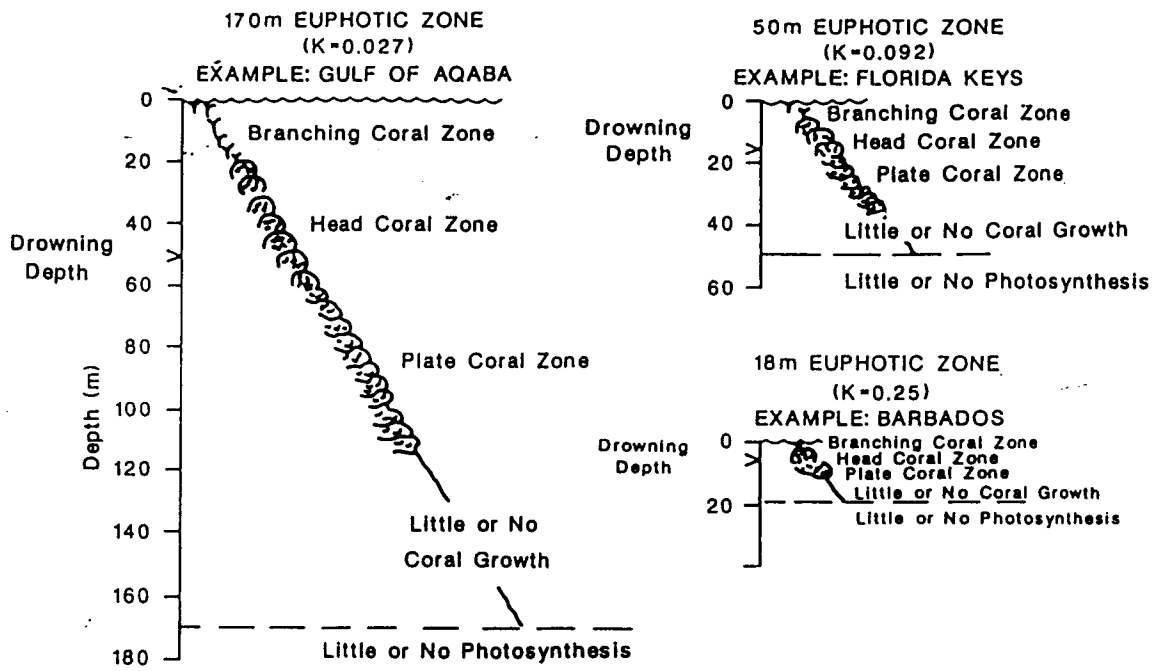


FIGURE 17—Illustrations showing influence of water clarity on zooxanthellae [sic] (zoochlorellate) corals. "K" is the extinction coefficient of light. Drowning depth shown is approximate submergence depth required to physically drown that reef (Hallock and Schlager, 1986).


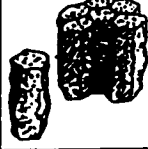

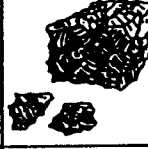
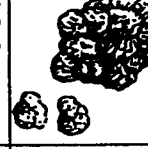
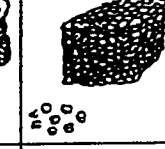

TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	lobular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking edges	spheroidal with slightly interlocking edges	rounded and spheroidal but not interlocking
USUAL HORIZON	E, Bs, K, C	Bt	Bn	Bt	Bt	A	A
MAIN LIKELY CAUSES	initial disruption of relict bedding; accretion of cementing material	swelling and shrinking on wetting and drying	as for prismatic, but with greater erosion by percolating water, and greater swelling of clay	cracking around roots and burrows; swelling and shrinking on wetting and drying	as for angular blocky, but with more erosion and deposition of material in cracks	active bioturbation and coating of soil with films of clay, sesquioxides and organic matter	as for granular, including fecal pellets and relict soil clasts
SIZE CLASS	very thin < 1 mm	very fine < 1 cm	very fine < 1 cm	very fine < 0.5 cm	very fine < 0.5 cm	very fine < 1 mm	very fine < 1 mm
	thin 1 to 2 mm	fine 1 to 2 cm	fine 1 to 2 cm	fine 0.5 to 1 cm	fine 0.5 to 1 cm	fine 1 to 2 mm	fine 1 to 2 mm
	medium 2 to 5 mm	medium 2 to 5 cm	medium 2 to 5 cm	medium 1 to 2 cm	medium 1 to 2 cm	medium 2 to 5 mm	medium 2 to 5 mm
	thick 5 to 10 mm	coarse 5 to 10 cm	coarse 5 to 10 cm	coarse 2 to 5 cm	coarse 2 to 5 cm	coarse 5 to 10 mm	not found
	very thick > 10 mm	very coarse > 10 cm	very coarse > 10 cm	very coarse > 5 cm	very coarse > 5 cm	very coarse > 10 mm	not found

FIGURE 18—Classification of soil peds (stable aggregates of soil material). Soil material bounded by cutans (clay skins or illuviation argillans). Clay has washed down into and lined cracks within soil.

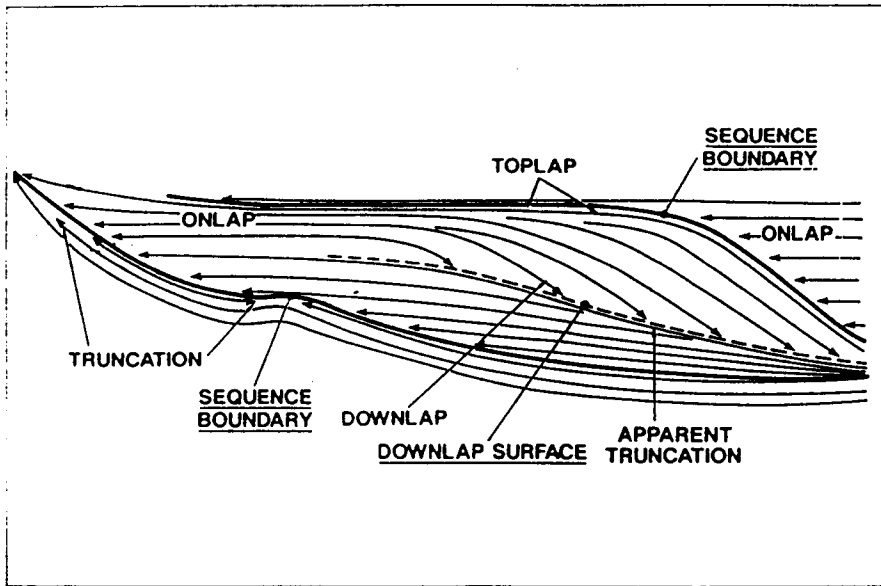


FIGURE 19—Types of discontinuities in a depositional sequence (from Vail, 1987).

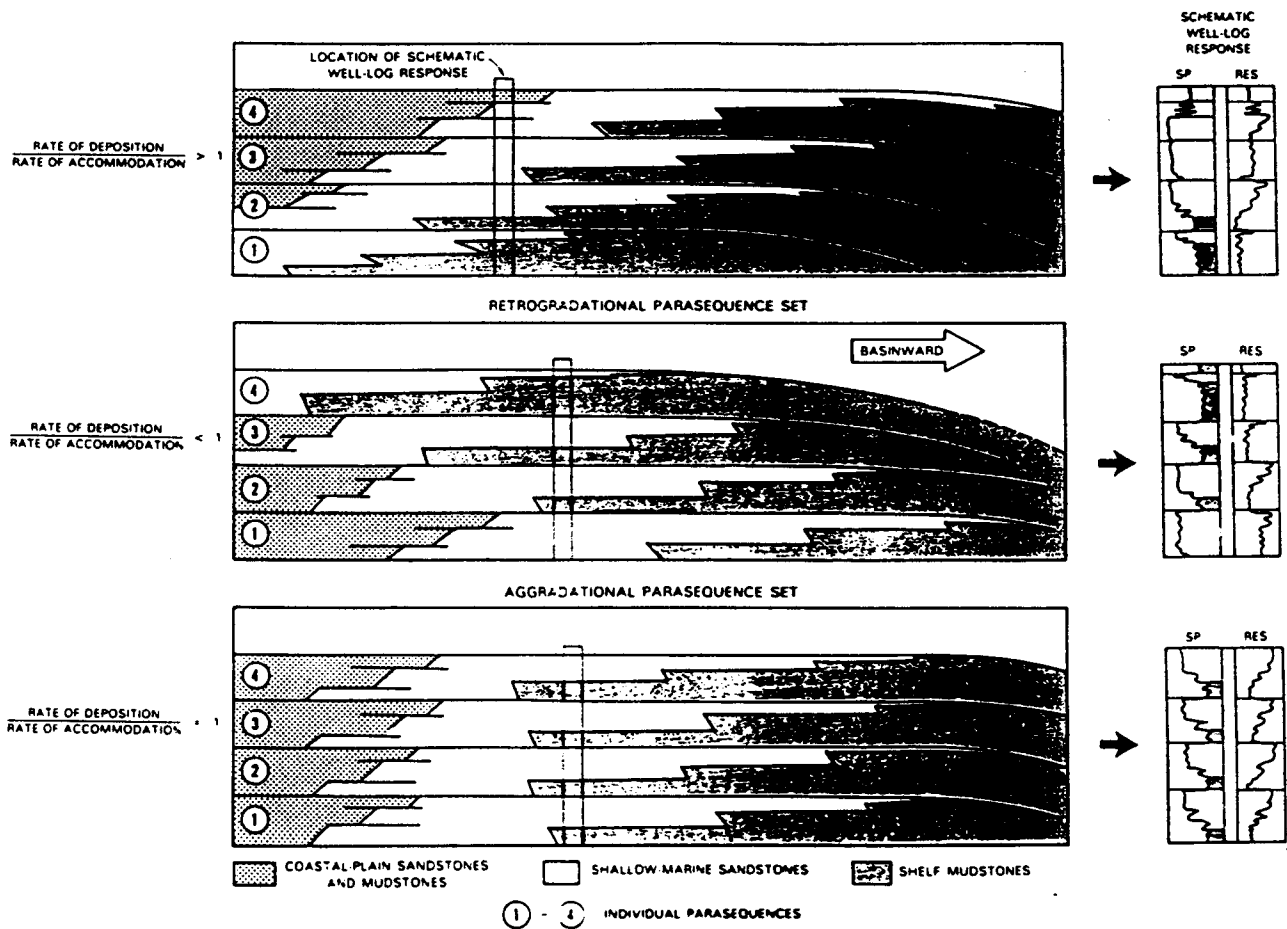


FIGURE 20—Examples of progradational, retrogradational, and aggradational parasequence sets for shelf with schematic well-log response (from Van Wagoner et al., 1987).

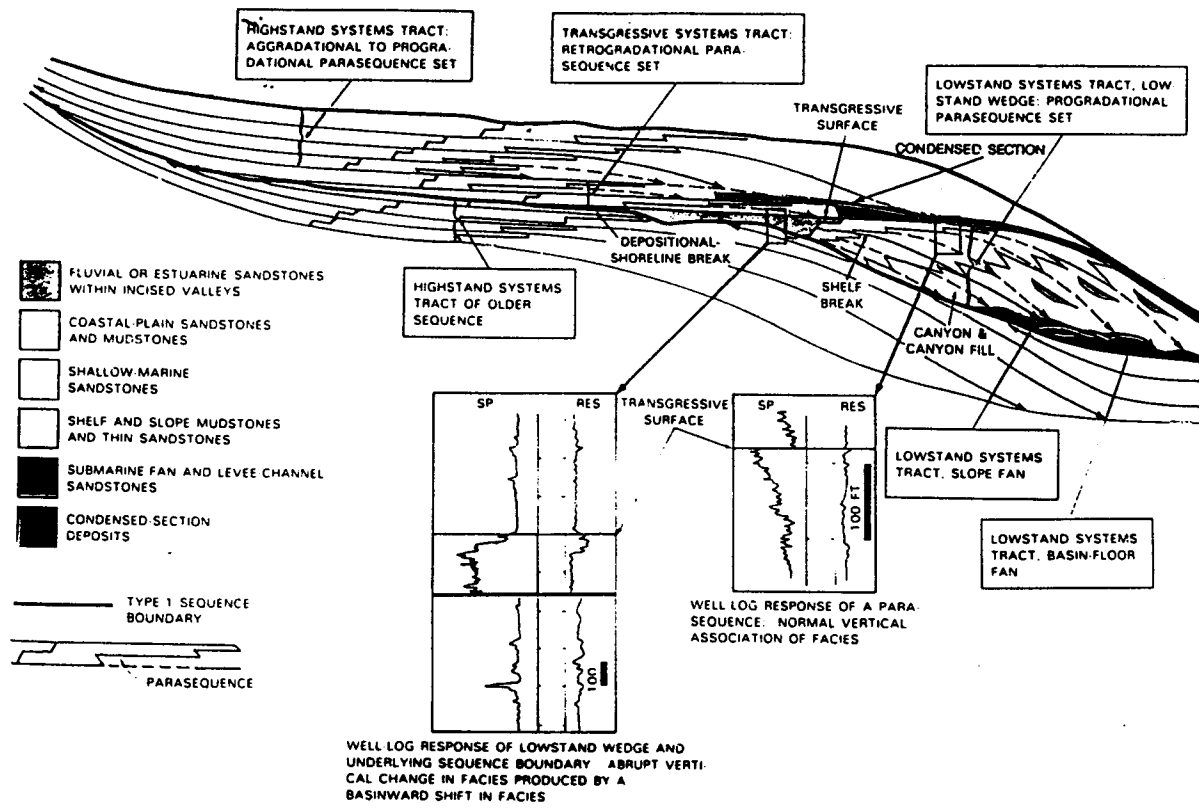


FIGURE 21-Example of parasequence geometries in context of crossing a type 1 sequence boundary (from Van Wagoner et al., 1987).

Stop 1 Clinton Lake Spillway: upper Lawrence Shale and Oread Limestone

Contributors: *Lynn Watney and Bryan Stephens*

Introduction

The gentle eastward-sloping upland surface in the vicinity of Lawrence is interrupted by several parallel northeasterly trending hills or cuestas resulting from differential erosion of slightly westward-dipping (approx. 25 ft./mi.) Pennsylvanian limestones and shales. Although local anticlines, synclines, and small faults may disrupt this shallow westerly dip, it provides for broad exposures of strata along valleys carved by rivers flowing east down regional slope. Mount Oread, the hill on which the University of Kansas rests, is capped by the Oread Limestone. The same strata are exposed here on the north face of the spillway near Clinton Lake dam on the Wakarusa River, 3.5 mi (5.5 km) west of Lawrence (fig. 1-1). The interval from the Plattsmouth Limestone down to the Amazonia Limestone Member of the Lawrence Shale is well exposed on the spillway wall (fig. 1-2). The measured section at this locality is provided in Fig. 1-3.

The Oread Limestone, originally described by Haworth (1894), consists, from base to top, of the Toronto Limestone, Snyderville Shale, the thin Leavenworth Limestone, the black Heebner Shale, the thick Plattsmouth Limestone, Heebner Shale, and Kereford Limestone. The Oread Limestone according to Moore (1936) is part of a megacyclothem, a succession of distinctive shale-limestone couplets repeated in several successive formations. Moore identified five limestone members in the idealized megacyclothem. The lower limestone is the Toronto, followed by the middle limestone (Leavenworth), the upper limestone (Plattsmouth), super limestone (Kereford), and finally the fifth limestone (Clay Creek) at the top of the cycle (fig 1-4). The inside or core shale is the Heebner Shale. Moore suggested that a marine transgression peaked during accumulation of the Plattsmouth Limestone based on abundance of fusulinids. The lower, super, and fifth limestones are not always present in a single megacyclothem, but are compositely expressed in the four late Missourian and early Virgilian megacyclothem successions.

Heckel (1977) describes a simpler cyclothem consisting of four components: the middle limestone, core shale, upper limestone, and outside shale. Maximum regression is associated with the outside shale (i.e., Kanwaka) and maximum transgression is recorded by the core shale (i.e., Heebner). The Toronto Limestone of the Oread Limestone (the lower limestone in Moore's megacyclothem classification) may represent an intermediate marine inundation separate from the transgression accounting for the Oread cyclothem (Troell, 1969). The upper surface of the Toronto has occasional solution fissures and piping filled with shale. Fragments of Toronto Limestone are also found infrequently at the base of the overlying Snyderville Shale. Together this suggests that the top of the Toronto was at least subjected to weathering and perhaps was subaerially exposed. The pattern of intermediate and major marine cycles is not unexpected, if these marine inundations are driven by glacial eustasy.

The presence and the extent of subaerial exposure due to relative sea level fall is also a key component relating to the mechanism affecting sedimentation. The individual paleosols observed in these cyclothem are often very extensive and can be traced laterally over the outcrop and into the subsurface. The magnitude and duration of sea level fall and the climatic conditions associated with the paleosol are critical components to interpretation of the cycles.

Channels and valley cuts are common throughout the Pennsylvanian section in the mid-continent. Mudge (1956) describes 27 occurrences of channels from the outcrops of Lower Permian and upper Virgilian strata. The incisions cut down as deep as 110 feet into underlying strata. Lins (1950)

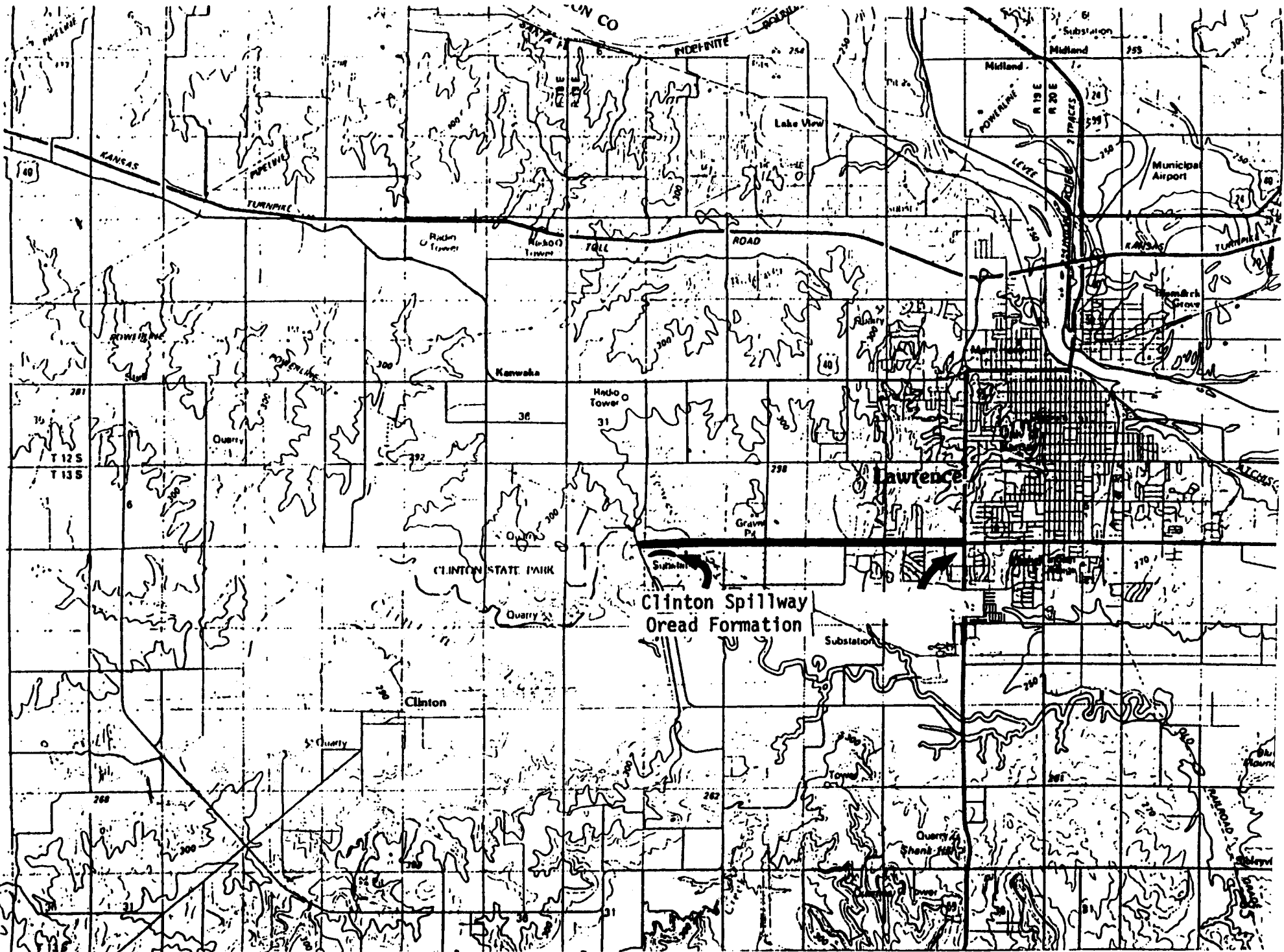
describes a valley filled by the Tonganoxie Sandstone in the Virgilian-age Douglas Group that is present in the vicinity where it is up to 80 feet deep and approximately 20 miles wide. These incised valleys are now being considered as lowstand incised valleys and when combined with the marine inundation together reflect considerable fluctuations in relative sea level. During an incision there was an extensive emergent upland surface over which paleosols formed.

Another way to examine the cycles is through sequence stratigraphy. The exposure surfaces are

A measured section (fig. 1-3) of the Clinton Spillway is provided for reference to the first stop at a cut in the upper Douglas Group. The section begins with a shale and claystone found below the Amazonia Limestone member of the Lawrence Formation. Several horizons appear to have undergone subaerial weathering including the upper portion of the claystone beneath the Amazonia which is red in color. The Amazonia Limestone although a marine limestone, contains an autoclastic breccia and other evidence of probable subaerial weathering. The underclay is developed below the Williamsburg Coal and above the Amazonia. Additional evidence of oxidation occurs in the shale above the coal.

The Williamsburg coal is one of several coals developed in the upper portion of the Lawrence Formation. This upper Williamsburg coal is the more laterally continuous. The Amazonia Limestone is lenticular in the area.

FIGURE 1-1-Index map showing site of exposure on Clinton Lake Spillway.



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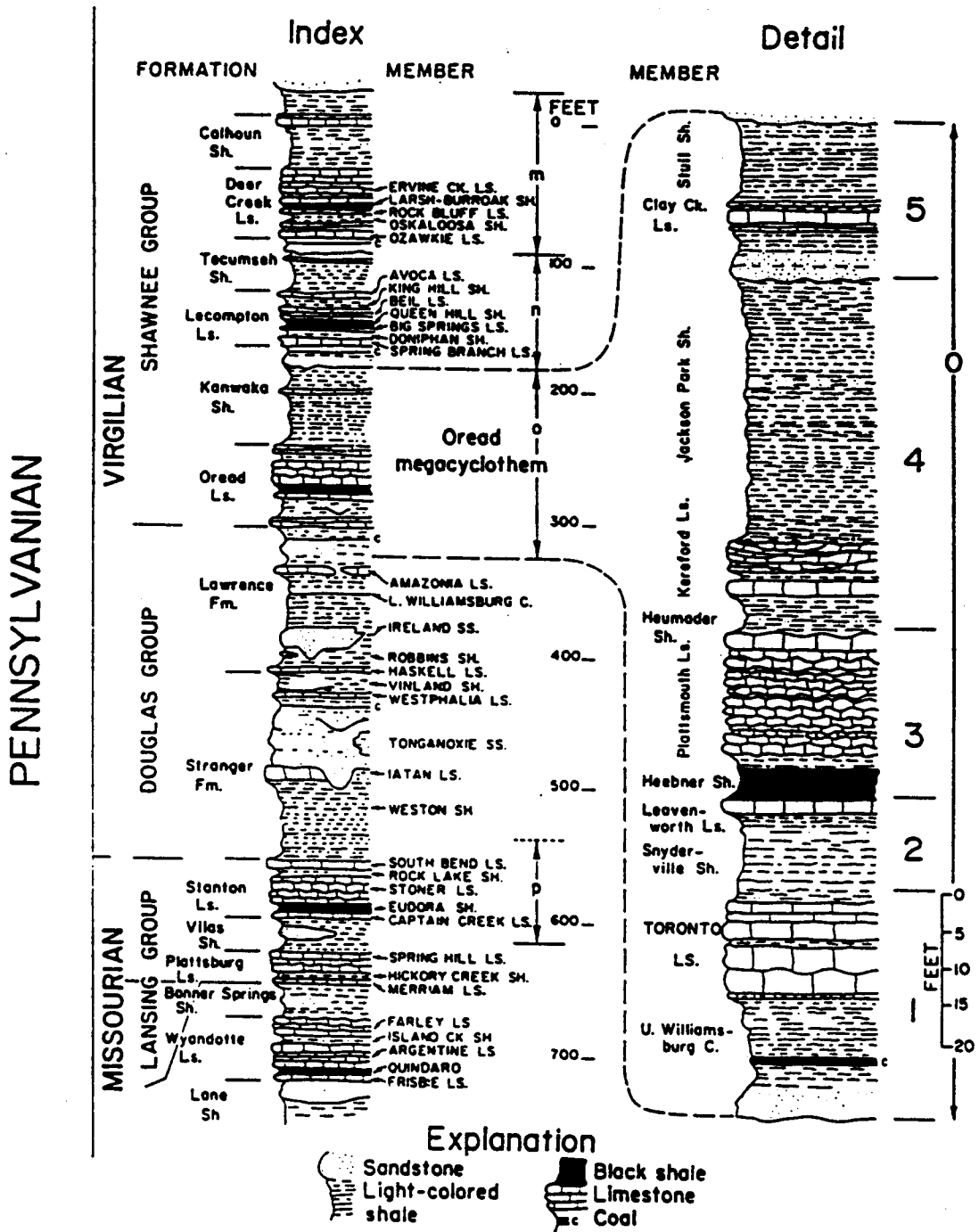


FIGURE 1-2-Stratigraphic position of the Oread Limestone and Oread megacyclothem (from Troell, 1969).

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Measured Section of Clinton Spillway
Douglas Co., Kansas

Vertical Scale :  1 m












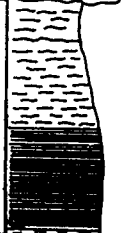







Group	Formation	Member	Lithology and Weathering Profile	Sed. Str. uct.	Rock Name	Fossils Particles	Color Fresh/ Weathered	Grain Size	Dia- genetic Features	Remarks				
Shawnee Group	Oread Limestone	Plattsmouth Ls. Mbr.			fusulinid packstone									
					fusulinid packstone		brown-rusty orange							
					skeletal packstone		gray							
				R	algal packstone-wackestone		tan			thin wavy bedding shale interbeds				
					cherty wackestone		gray			chert				
					fusulinid/crinoid packstone		gray-orange yellow							
				R	wackestone/packstone		rusty orange			rugose coral common				
					skeletal packst.-wackestone		gray			(chert)	chert concentrated on bottom of bed			
					skeletal packstone/wackestone		gray				whispy shale laminations			
					skeletal packstone/wackestone		gray				whispy shale laminations			
		Shawnee Group	Oread Limestone	Heebner Sh. Mbr.			clay shale		greenish yellow dark gray brown	clay		softer and less platy than shale below		
							black shale		black			hard platy phosphate nodules conodonts, sulfides 3 cm. soft shale at base		
				Toronto Ls. Mbr.		Leav	Leavenworth Ls. wackestone		dark gray-brown					
							clay shale		dark gry-brn					
							clay shale		dark gray	clay				
							micrite		tan				tube-like structures at top of bed filled with shale. Weather to tubes. pyrite	
							crinoid/fusulinid packstone/wackestone		light gray			algal omcolites - coated grains glauconite		
							crinoidal wackestone		greenish gray					

FIGURE 1-3-Measured section of upper Lawrence and Oread at Clinton Lake Spillway.

Shawnee Group	Oread Limestone		crinoidal packstone/wackestone	⊖ ~ ⊖ ~ ⊖	light greenish gray		whispy shale laminations
			skeletal packstone	~ ⊖ ⊖ ⊖	light gray -orange yellow		iron stains
Douglas Group	Lawrence Formation	Williamsburg Coal bed	skeletal wackestone	⊖ ⊖ ⊖ ⊖	light gray		iron stains
			wackestone	⊖ ~	light gray		
			mudstone/clay shale		gray		thin (1 cm.) silty laminations weathering to yellow color
			coal smut		black		
			mudstone		greenish gray greenish gray with maroon mottling		clayey light brown calcareous nodules cylindrical and branching
			Amazonia Ls. Mbr. micrite, silty Ls. & clay shale		greenish gray/orange yellow		solution breccia sheet cracks fitted clasts
			slightly silty clay shale		greenish gray lt. gray		maroon lenses around iron rich nodules soft thinly laminated
			clay shale		red		some v. fine silt platy laminated
			clay shale		greenish gray		weathers blocky
			siltstone		pale green-gray		micaceous thinly laminated in places red, iron hardened burrows

KEY TO SYMBOLS

- ⊖ brachiopods
- △ gastropods
- ⊖ crinoids
- ~ phylloid algae
- ⊖ fusulinid forams
- ∩ bivalves
- ∩ rugose coral
- ∩ conodonts
- ⊖ bryozoans
- ⊖ oncolites
- ⊖ coated grains

- ⊖ vug
- pyrite
- ⊖ shale interbeds
- ∩ burrows
- ∩ tubes
- ⊖ shale interbeds
- ⊖ phosphate nodules
- ⊖ chert
- ⊖ calcareous nodules
- ⊖ iron rich nodules

Stop 2 Roadcuts along I-435 near Holliday Road exit: Section from Chanute Shale to Stanton Limestone

Location: (W/2 NE sec. 6, T. 13 S., R. 22 E.)

Contributors: Lynn Watney, John French, Philip Heckel, and Evan Franseen

Introduction

These outcrops in the vicinity of Stop 2 (identified by the letters A, B, C, and D in fig. 2-1), are some of the best known continuous exposures of Missourian cycles. Limited time precludes our examining the entire sequence, so we will concentrate on the interval from the Chanute Shale through the basal Argentine Limestone (section 'A' of fig. 2-1). Fig. 2-2 (a, b, c, and d) is a composite measured section as prepared by Scott Johnsgard, 1984. The gamma-ray profile and relative water-depth curve are included in fig. 2-3 (a and b). A gamma ray-neutron log from a nearby well has been correlated to the lithologies of this exposure (fig. 2-4). Fig. 2-5 includes a photo of west-facing exposure at Stop 2. The Bonner Springs Shale presented in this measured section (fig. 2-2 c and d) will be the focus of Stop 3.

Stratigraphy

The *Chanute Shale* is a typical outside shale that records the influx of deltaic clastics. Approximately 40 mi (64 km) to the south, the Chanute is a thicker shale that includes sandstones and coal. This is not a homogeneous shale unit, but contains significant variability exposed at this stop. Irregular carbonate lithoclasts in a maroon blocky mudstone found near the top of the Chanute Shale suggest both subaerial exposure and erosion. The boundary between the Iola sequence (above) and the Dewey sequence is placed at this position.

The *Iola Limestone* is another excellent example of a typical Kansas cyclothem. It represents one of the greatest Missourian marine inundations of the midcontinent. The Iola consists, in ascending order, of

The *Paola Limestone*, which is a more typical thin (1 ft, 0.3 m) transgressive limestone than is the Captain Creek Limestone seen at Stop 1. The Paola Limestone is the marine-flooding unit of the Iola sequence. It is a skeletal calcilutite containing a diverse biota and represents abrupt and shelfwide marine flooding. It can be traced in the outcrop from Oklahoma to Iowa and westward in the subsurface to at least eastern Colorado some 400 mi (644 km) to the west.

The *Muncie Creek Shale* is the core shale of the Iola cyclothem and the condensed section of the Iola sequence. The black, phosphatic facies of this unit, 1.5 ft (0.46 m) thick, is inferred to represent minimal sediment influx during a period of low bottom-water oxygenation that occurred during rapid eustatic rise. It is one of only five black, phosphatic core shales of Missourian age that extend to the Iowa outcrop belt, which is located about 200 mi (322 km) to the north (Heckel, 1986).

The *Raytown Limestone* is the upper (regressive) limestone of the Iola cyclothem. It is a skeletal and phylloid-algal wackestone that was deposited in quiet water, probably below storm-wave base. The thin, lenticular packstone at the top may be a storm deposit, or may record the passage of wave base as relative sea level fell prior to deposition of the succeeding unit. No evidence for subaerial exposure is indicated here or at other sites in the Kansas City area and southward. Besides the lack of subaerial exposure to the south, the Iola and Argentine limestones converge in Miami County 25 mi (40 km) to the south as the intervening "Lane" Shale thins markedly. Sea level fell to an intermediate shelf

position between the Iola and Wyandotte sequences, rather than below the shelf margin as occurred with other major episodes of marine inundation. Ensuuing rise in sea level took place somewhere in the "Lane" Shale, its precise location yet to be found. This turnaround in sea level is tentatively a sequence boundary, resembling a Type 2.

The *Lane Shale* overlies the Iola Limestone. The "Lane" Shale is a typical outside shale that resulted from a northeasterly influx of siliciclastics. The terrigenous detritus probably resulted from progradation during eustatic stillstand and fall. Falling sea level or stillstand conditions would have provided time for the advance of these siliciclastics across the shelf. Nevertheless, sediment-accommodation space was sufficient for shallow-marine deltaic deposition. Thickness of the "Lane" Shale varies from 43 ft (13 m) at this stop to over 70 ft (21 m) about 10 mi (16 km) southeast of this outcrop to a pinchout only 7 miles (11 km) to the west of here. These lobate shale accumulations caused depositional topography conducive to formation of the overlying phylloid-algal buildups in the Wyandotte Limestone.

The *Wyandotte Limestone* overlies the "Lane" Shale. We will only examine the basal portion at this stop. In ascending order, the units within the Wyandotte Limestone seen here are

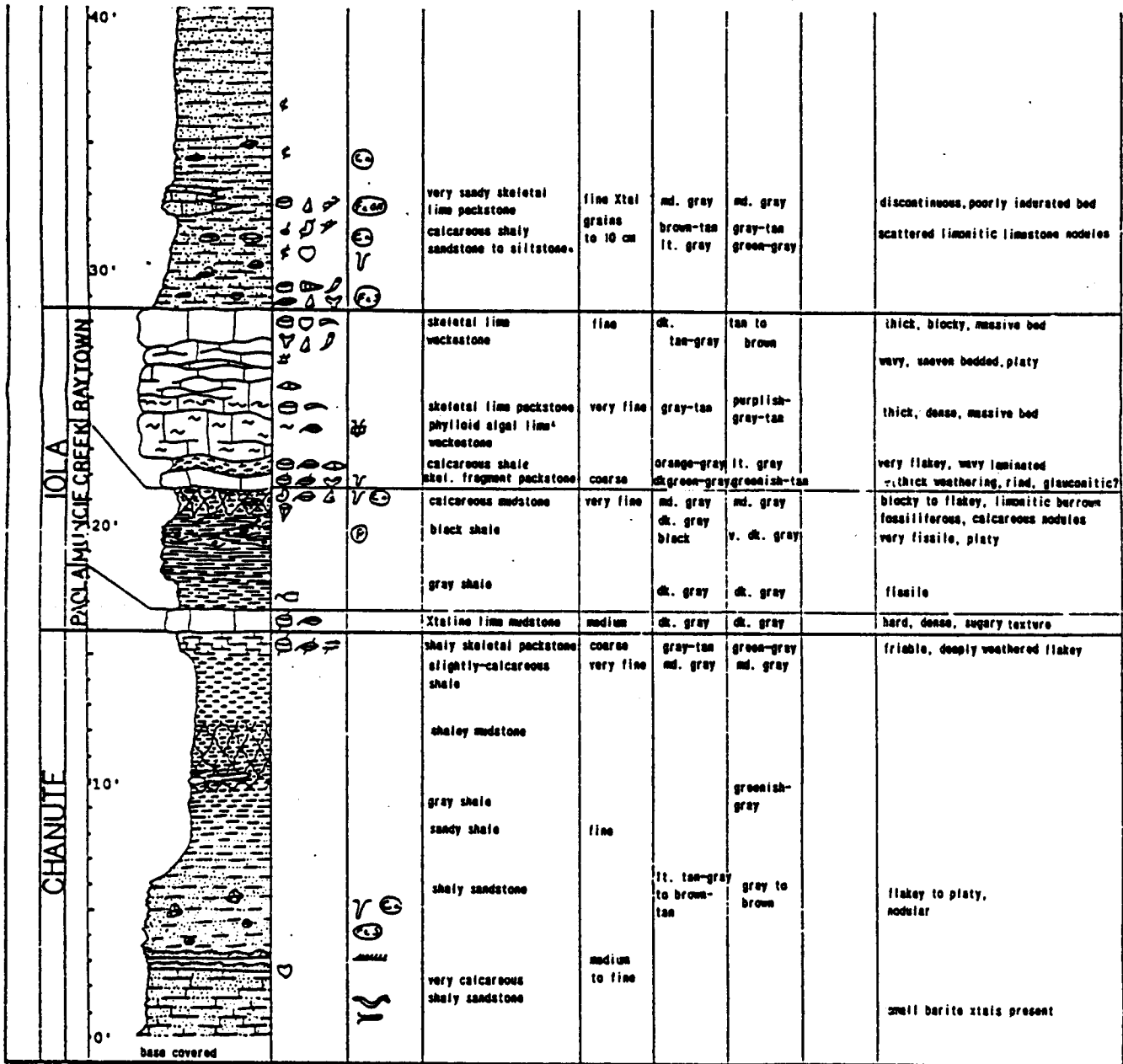
The *Frisbie Limestone* is the transgressive, or middle, limestone of the Wyandotte cyclothem. This unit represents a regional marine incursion (flooding unit of the Wyandotte sequence) that overstepped the "Lane" delta. Marine sedimentation extended beyond the Iowa outcrop belt some 200 mi (320 km) to the north. At this stop, near the center of the east slope, the Frisbie contains one excellent example of a number of discrete phylloid-algal buildups. Isolated phylloid-algal buildups are common in areas of moderately thick accumulations of the underlying "Lane" Shale (Arvidson, personal communication, 1989). These "mini" mounds are flanked by crinoidal grainstones. The phylloids are very obvious because they are unusually large. A systematic study of the Frisbie Limestone and the algal mounds done by George Coyle and Kevin Evans had been in preparation for publication. They describe what they believe are algae in growth position. In situ preservation of algae will be seen later on the field trip.

The *Quindaro Shale* is the core shale of the Wyandotte cyclothem and the condensed section of the Wyandotte sequence. It is thin (0.75 ft [0.23 m]) and dark gray (with low gamma radiation) at this stop. However, it becomes black (with high gamma radiation) where the underlying "Lane" Shale is relatively thin. Such lateral variations in these core shales are not uncommon; the Eudora Shale that was exposed at the first stop also varies from gray to black over distances of only a few miles. Such facies variations suggest that oxygen-deficient conditions were restricted in some cases to bottom waters in paleotopographically low areas. In a well located near this exposure, the shale is not distinguishable on the gamma-ray log (fig. 2-4). In addition to being thin and near the detection limit of the wireline gamma ray, the Quindaro Shale also has low- gamma radiation indicated by the surface measurements taken at this exposure (fig. 2-3b). Thus, the Frisbie Limestone cannot be distinguished from the Argentine Limestone on conventional gamma-ray logs.

The *Argentine Limestone* is the upper limestone of the Wyandotte cycle. It is 19 ft (5.8 m) thick at this location. This exposure is located in an area of moderately thick Argentine Limestone associated with a flank position on a lobe of the "Lane" delta. This unit consists mostly of phylloid-algal wackestone at this locality and is capped by 3 ft (1 m) of coated skeletal packstone. No subaerial exposure is noted on this surface.

The *Farley Limestone* is developed as two distinct units. Both units are notably thinner than they are several miles southwest of this location where they are phylloid-algal buildups, built farther down the flanks of the "Lane" delta. The Farley Limestones are of normal thickness, 7 ft (2.1 m) for the lower Farley and 9 ft (2.7 m) for the upper Farley. It is an intertidal and shoal-water facies, perhaps suggesting that location was more positive during deposition of the Farley Limestones than to the south. Best access to the Farley Limestone and the upper Argentine Limestone is on the west side of the road.

a



KEY TO SYMBOLS

FOSSILS		FOSSILS		PARTICLES		SED. STRUCT.		DIAGEN. FEAT.	
	Domei Stromat. Algae		Brachiopod, General		Limestone Lithoclast		Imbricate Grains		Stylolites
	Green, Cordicarian Algae		Spirifer Brachiopod		Shale Lithoclast		Vertical Burrow		Dolomitized Burrow
	Phylloid Algae		Productid Brachiopod		Pelletoid		Horizontal Burrow		Dolomite X-tals
	Plant Fragments		Lingulid Brachiopod		Calcite Grains		Spring		Chert Nodules
	Fusulinid		Colloid Cephalopod		Ooid		Ripple Scale X-lamin.		Selenite X-tals
	Encrusting Worm		Neutrofid		Ooid		Groove		Manganese Concretions
	Conularid		Gastropod		Coated Grain		Prod/Buonca		Phosphate Nodule
	Solitary Coral		Bivalve		Shell		Flute		Calcium Carbonate Nod.
	Penetrating Bryozoa		Crinoid		Fossil Fragments		Load Cast		Sphalerite
	Ramosse Bryozoa		Echinoid				Tracks and Trails		Pyrite/Markasite
	Encrusting Bryozoa		Shark Tooth				Feeding Traces		Limonite Nodule

FIGURE 2-2 (A, B, C, D)--Measured section of Lansing and Upper Kansas City groups at Johnson Drive and Holliday Drive interchanges prepared by Johnsgard (1984).

IF-57

C

BONNER SPRINGS	140'			shaly sandstone	fine	md. gray	pink-gray	platy to fissile
				sandy lithoclastic mollusc lim packstone	very coarse	md. brown	lt. gray	blocky, limonitic single channel(s) shaped bed
				shaly sandstone	fine	md. gray	md. gray to lt. gray	platy, fissile
				sandy shale	very fine			
				gray shale				
				shaly sandstone	fine			
				ripple laminated shaly sandstone	medium to coarse		lt. gray	very micaceous
				shaly sandstone	fine		md. gray	
				sandy shale gray shale	very fine			fissile, shaly
	FARLEY	120'			skeletal phylloid algal lime wackestone to packstone	very fine	gray-tan	pale pink-tan
				stromatolitic(?) skeletal lime wackestone	fine	tan-gray	md. tan	vague laminations
				shaly mudstone gray shale	very fine	md. gray	md. gray	fissile, flakey
				shaly siltstone				platy, micaceous
				shaly sandstone lime mudstone	fine medium	gray-brown	pinkish-brown	single, persistent bed flakey to fissile
				shaly sandstone shaly mudstone	fine very fine	md. gray	lt. gray	
				calcareous shale stromatolitic skeletal lime wackestone	fine medium	dk. brown orange to tan-gray	lt. brown orange-tan	very to nodular bedded, domal stromatolitic(?) laminae sparse oxides & calcite grains
				phylloid algal lime mudstone	fine	pink-tan to gray	pale pink-gray	
WANDOTTE ISLAND CREEK	100'			shaly sandstone	very fine	lt. gray	lt. gray	flakey
				coated grain packstone skeletal wackestone	very fine Xtal size very coarse grain size	tan-gray	brown-tan	3 even, distinct beds shells w/calcite, dolomite Xtals very bedded, "clay seams" present
				coated grain packstone skeletal lime mudstone	very fine		gray-tan	

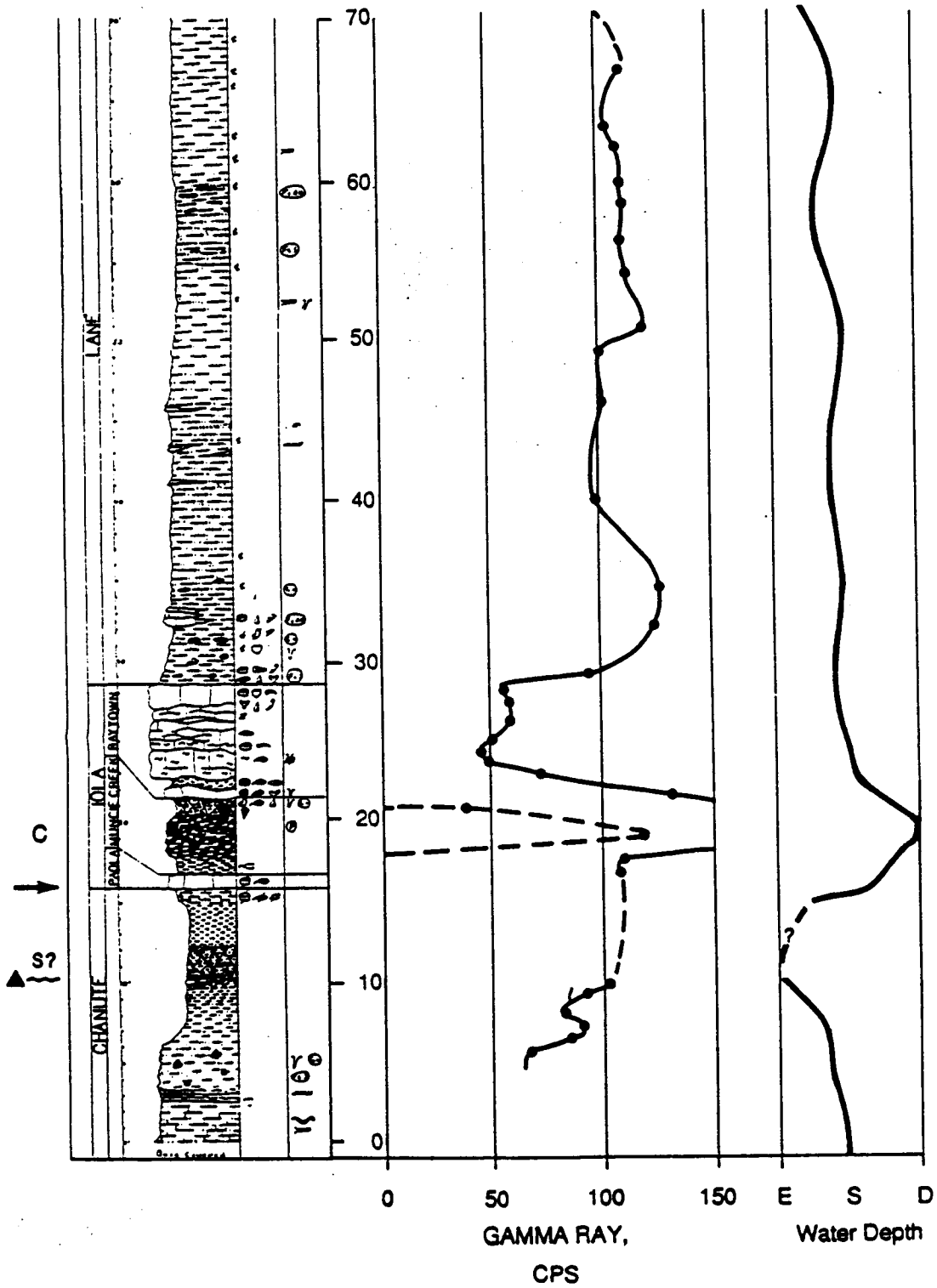
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d

Group	Formation	Lithology and Weathering Profile	Fossil and Particles	Sed. Struc. and Diag. Post.	Rock name	Crystal or Grain Size	Color		Sample and/or Photo #	Additional Remarks	
							Fresh	Weathered			
LANSING VILAS	STANTON	Top Covered			Skeletal lime wackestone	fine to medium	tan-gray	brown-tan to orange		slabby to platy iron stained, ferruginous very wavy bedded	
		100'			shaly lime wackestone		gray-tan	orange-tan			
		200'			blocky mudstone gray shale black shale gray shale	very fine	lt. gray-orange dk. gray black gray-tan	orange-tan md. gray dk. gray lt. gray		blocky, mottled flakey to fissile platy, very fissile	
	CAPTAIN CREEK/EUDORA	170'			skeletal lime wackestone skeletal lime mudstone skeletal coated grain lime wackestone	fine very fine fine	brown-tan brown-tan lt. gray-tan	brown-tan purple-tan		dense; 4 even, distinct beds	
					calcareous shale wavy laminated shaly sandstone	very fine medium to fine	tan lt. gray md. gray	tan md. to lt. gray		flakey, fissile very laminated, bioturbated very micaceous, carbonaceous	
	PLATTSBURG	MERRIAM/CORY CREEK - SPRING HILL	100'			ripple laminated shaly sandstone	fine	lt. tan-gray	greenish- lt. gray		slabby, even bedded, platy N 85 degree W (ripple marks)
						very sandy shale	very fine	lt. gray	v. lt. gray		platy, fissile, very micaceous
						sandy calcareous shale	fine	lt. brown	brown-tan		
						well-sorted lime wackestone very argillaceous lime wackestone	medium	lt. gray-tan md. gray	lt. brown orange-tan		single, even bed thick bedded, massive to shaly weathers to many thinner beds "clay seams" abundant
	MERRIAM/CORY CREEK - SPRING HILL	PLATTSBURG	100'			argillaceous skeletal lime wackestone skeletal lime wackestone	very fine medium	lt. brown lt. gray md. gray lt. gray	lt. brown lt. tan-gray lt. tan-gray md. gray		thin, uneven beds thick bedded, "clay seams" present
					calcareous shale	very fine	dk. gray	dk. gray		flakey	
					skeletal lime wackestone oolitic skeletal lime wackestone	fine medium	md. gray	lt. tan			
					calcareous siltstone shaly siltstone sandy siltstone	very fine	md. gray-brown lt. gray	orange-brown lt. gray		nodular, blocky, very impure flakey, micaceous	

a

STOP 3 HOLLIDAY DRIVE



Sequence Stratigraphy
 ▶ Sequence boundary
 — Flooding surface
 P — Parasequence flooding surface
 C Condensed section

— Erosional surface
 S Subaerial exposure

E = exposure
 S = shallow marine
 D = deep

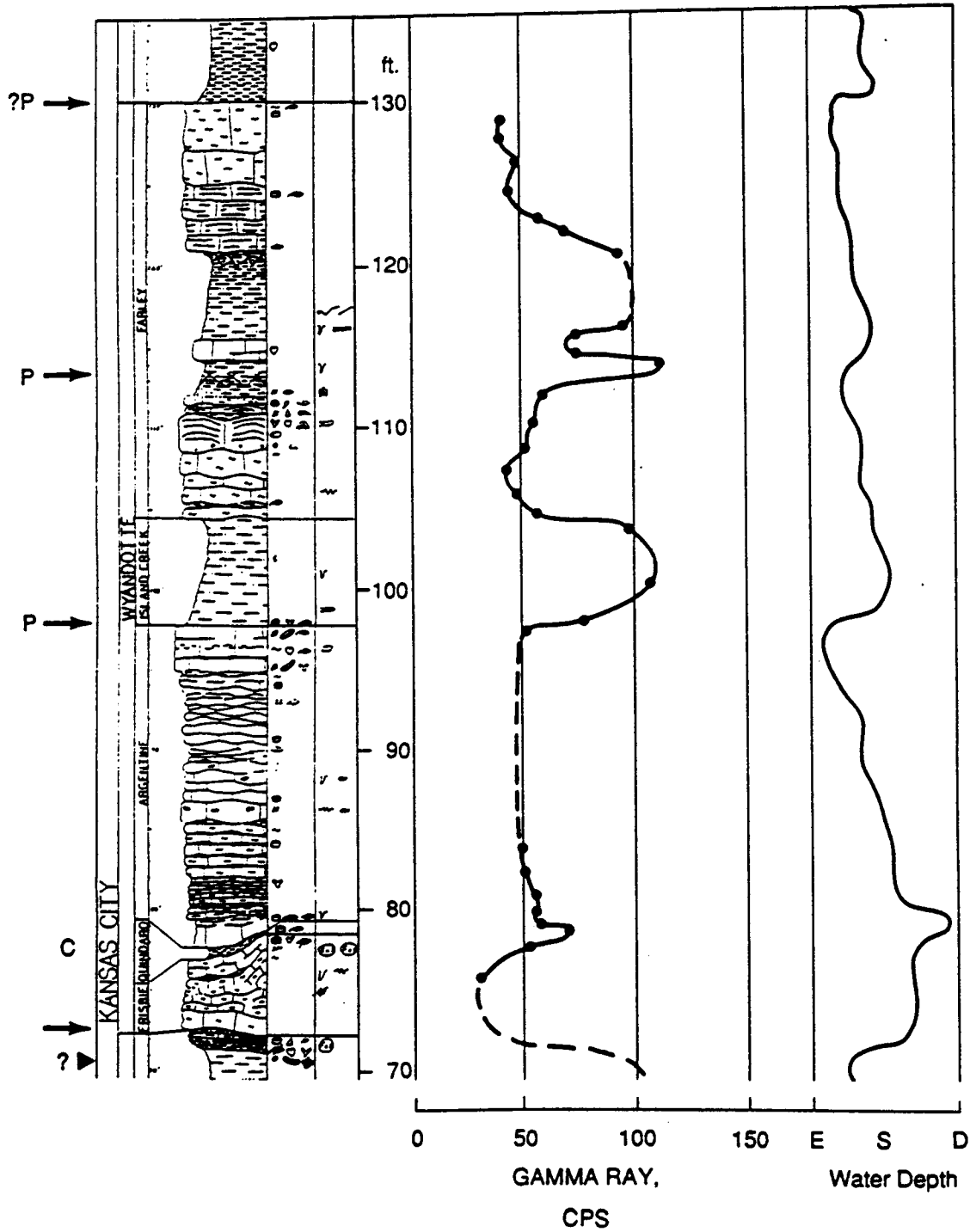
FIGURE 2-3 (A & B)—Stratigraphic section natural gamma-radiation profile, water-depth curve, and sequence classification (extreme left) for lower portion of measured section in fig. 2-2.

II-61

b

STOP 3

HOLLIDAY DRIVE



E = exposure
S = shallow marine
D = deep

II-62

SWSNW 8 T13S R24E

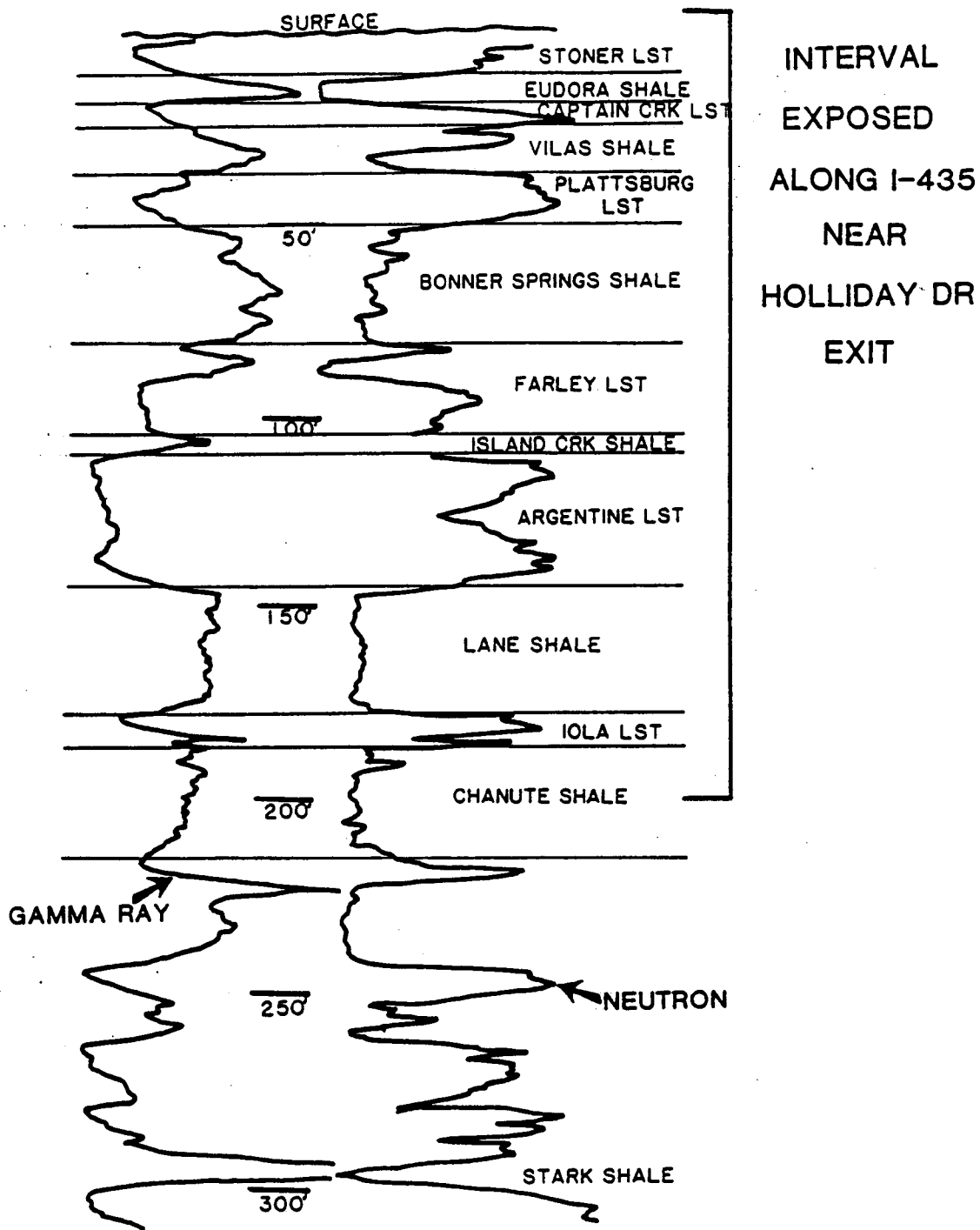


FIGURE 2-4-Correlation of formations in Lansing and Kansas City groups based on gamma ray-neutron log of well located near Stop 2.

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Stop 3 I-70/I-435 Interchange: Bonner Springs Shale and Plattsburg Limestone

Location: NE SW sec. 13, T. 11 S., R. 23 W., Wyandotte County, Kansas

Contributors: *Paul Enos, Derek Herman, Lynn Watney, and Evan Franseen*

Introduction

The depositional setting of the Bonner Springs Shale the outside shale of the Wyandotte Cyclothem. The Bonner Springs Shale also includes the boundary between the Wyandotte and Plattsburg sequences. The events which occur at and near this boundary is the focus of this stop. Erosional downcutting, channel sandstones, marine backfilling of erosional topography, and laterally extensive paleosol development near the top of the Bonner Springs Shale at Stop 3 provide an unusual opportunity to examine features not normally preserved at the top of a sequence on the shelf.

Local expressions of erosional topography in the Bonner Springs Shale have been described along some 80 mi (129 km) of outcrop in eastern Kansas running from Wyandotte County to Franklin County (Ball et al., 1963; Harris, 1985; and Enos and Herman, in ms.). This stop, #3, focuses on a spectacular example of multiple episodes of erosional scouring and backfilling in the Bonner Springs Shale. the Bonner Springs Shale in a more normal development with a capping paleosol.

A cross section prepared by Enos and Herman of measured sections at Stop 3 of the upper Farley Limestone, the Bonner Springs Shale, the Merriam Limestone, and the Spring Hill Limestone in the vicinity of the I-70 and I-435 interchange is shown in fig. 3-2. The index map (fig. 3-1) of the interchange locates the measured sections. Fig. 3-3 provides photos of the Bonner Springs Shale and adjacent units at and near Stop 4. We will make one stop along the northeastern cloverleaf to examine the more prominent and unusual channeling events in the Bonner Springs Shale. Please proceed with caution while on the roadside!

Stratigraphy

Commentary by Paul Enos and Derek Herman (excerpts from manuscript in preparation)

The section observed at Stop 3 includes the *upper Farley Limestone*, which is the unit locally truncated by the channel forms within the Bonner Springs Shale. The upper Farley Limestone averages 2.28 m (6.8 ft) thick and varies only ± 0.32 m (1 ft) in the local area. It is typically skeletal-lime packstone, but varies locally from skeletal mudstone to crossbedded ooid grainstone. Characteristic Farley fossils are brachiopods, (including *Composita*, productids), and bivalve fragments (locally including *Myalina*), phylloid-algal fragments, crinoid columnals, and fenestrate and ramose bryozoan and brachiopod spines. Encrusting organisms, probably worms and foraminifera, are abundant at Sections IX and VII (fig. 3-2). Coated grains are widely scattered in the unit but are concentrated only at Sections VII and IX.

The *Bonner Springs Shale* is a mixed bag of lithologies, as is typical of the thicker deltaic outside shales. In a typical section the Bonner Springs Shale in this area include olive-gray claystone through light-gray to olive-gray silty shale, to a discontinuous band of red to maroon-colored shale a meter or two below the top of the unit (Moore et al., 1951, p. 81; O'Conner, 1971, p. 20; Heckel, 1985, and Harris, 1985, measured sections). Siltstone and sandstone are widely distributed, particularly in the lower half of the unit. A calcareous paleosol is commonly developed above the maroon interval. This will be the focus of our next stop.

The thickness of the Bonner Springs in the vicinity is also extremely variable. Measurements in Wyandotte and northern Johnson County give an average thickness of $7.95 \text{ m} \pm 2.36 \text{ m}$ ($26.2 \pm 7.8 \text{ ft}$) in eight complete sections; the range is from 3.9 to 12.6 m (12.9–41.6 ft). Thinner intervals, down to 22 cm (9 inches), are truncated beneath the overlying Merriam Limestone.

The Bonner Springs Shale is largely unfossiliferous, but plant fragments occur locally within sandstone or nodular mudstone, and shelly fossils, including pectins, *Composita* and spiriferid brachiopods, high-spired gastropods, and shell fragments occur near the top of the shale and within some sandstones. Trace fossils include vague burrows in both shale and sandstone intervals; *Zoophycos* and *Protovirgularia* traces in channel siltstones; well-developed U-tubes in a nodular mudrock near the top and starfish impressions in blue-gray claystone in the lower half (location VII; Harris, 1985, p. 35).

The *Merriam Limestone* is the middle limestone of the Plattsburg cyclothem and the flooding unit of the Plattsburg Sequence. It ranges in thickness from 0.31 to 4.88 m (1–16 ft) in 23 measured sections. Normal thickness averages $0.88 \pm 0.33 \text{ m}$ ($0.9 \pm 1.1 \text{ ft}$). Lithologically, the basal portion is typically a packstone, but ranges from very argillaceous, nodular- weathering yellow limestone to ooid grainstone. The middle portion of the bed, below the most prominent shale break, is typically a skeletal packstone containing prominent coated grains or oncoids (traditionally "*Osagia*"). Wackestone and ooid or ooid grainstone are developed locally. An overlying shale bed or parting can be traced over most of the area. The top unit is one or two beds of skeletal packstone. Oncoids are locally prominent in this unit as well. Very argillaceous limestone caps, weathering yellow-brown, are developed at a few localities.

Although certain fossils or particles are particularly characteristic of the base, middle, or top portion of the Merriam, they do not define recognizable units, even locally. A wide variety of biota are developed throughout the interval or erratically in different portions. In order of decreasing abundance, these include: *Composita* brachiopods, crinoid columnals, gastropods, productid brachiopods, fenestrate bryozoans, fusulinids, bivalves, phylloid algae, spiriferid brachiopods, ramose bryozoans, echinoid fragments, brachiopod spines, solitary corals, encrusting bryozoans, pectins, encrusting worms, encrusting foraminifera, large scaphopods (to 5 cm [2 inches] long), and, very rarely, trilobites. A layer of *Composita* is locally prominent near the base of the Merriam and productids up to 5 cm (2 inches) wide are common in the middle portion of the unit in abnormally thick intervals. Prominent particles in the Merriam are oncoids and coated grains, ooids, peloids, unidentifiable skeletal debris, small carbonate and shale clasts, and sand grains locally at the base. Chert is present in some thickened intervals of the Merriam in the middle portion and burrows are prominent at the top, a characteristic noted statewide by McManus (1956).

The *Hickory Creek Shale* is a poorly developed core shale, probably the thinnest and palest in the entire Missourian Series. The unit is also the condensed section of the Plattsburg Sequence (fig. 3-2). The average thickness in 13 measured sections of "normal" development in Wyandotte and Johnson counties is $18.1 \pm 5.7 \text{ cm}$ ($7.2 \pm 2.3 \text{ inches}$); the range is from 7 to 27 cm (3–11 inches). Although the Hickory Creek is reported to contain a black, platy, carbonaceous zone in northern Johnson County and Wyandotte County (Newell, 1935, p. 72; Jewett and Newell, 1935, p. 181), we have not seen this development nor is it reported in this area by O'Connor (1971, p. 23), Mann (1957, p. 261) nor Ball et al. (1963, p. 13). The Hickory Creek is apparently nowhere developed as a black, fissile, phosphatic shale characterized by a "hot" gamma-ray response typical of core shales in the subsurface (Bryan Stephens, personal communication, 1987).

The Hickory Creek in Wyandotte and Johnson Counties is typically a dark-gray to olive-gray, flakey shale that weathers yellow to gray brown. It is sparsely fossiliferous, with a few crinoid columnals and brachiopods, although O'Connor (1971, p. 23) notes that it also contains abundant fenestrate bryozoans and fusulinids locally. A numerous but low-diversity molluscan fauna occurs in an anomalously thick Hickory Creek interval (Section V).

The bulk of the Plattsburg Formation consists of the regressive or upper *Spring Hill Limestone*, which ranges in thickness from about 3.1 to 7.1 m (10–23 ft) and averages 4.1 ± 1.2 m (13.5 ± 4 ft) in apparently complete sections in the area. It is predominantly skeletal wackestone, with lenses of grainstone and packstone. Characteristic fossils include abundant crinoid stems, productid, composita, and spiriferid brachiopods; fenestrate and ramose bryozoans; high-spined gastropods; a few corals; phylloid algae; and locally, orthocone nautiloids at the top.

Observations at I-70/I-435 Interchange

Taking it from the base up, the Bonner Springs Shale is fairly typically developed as a uniform, blue-gray shale with a few thin sandstone beds and the maroon marker bed near the top at section VII (fig. 3-2). Nowhere else in the exposures is the Bonner Springs typical. Northeast 300 to 850 m (1,000-2,800 ft, sections VIII-X, ramps E-N and N-E) the Bonner Springs interval is represented by up to 8.7 m (29 ft) of sandstone overlain by 1 m (3.3 ft) of sandy shale beneath a typical Merriam Limestone section (section IX). The upper bed of the underlying Farley Limestone Member is abnormally thin (0.75 cm [0.3 inch]) and shows very abrupt local relief with a bevel of 60 cm (24 inches) in thickness. A layer of lime-mud pebbles and bivalve shells plastered onto the Farley Limestone probably reflects reworking of the uppermost Farley prior to deposition of the sandstone. Small clasts of gray shale, less than 1 cm (0.4 inch) in diameter, are abundant throughout the sandstone, particularly in the base where beds of shale chips compose about half of the bulk. These shale clasts apparently represent the missing typical development of Bonner Springs Shale, ergo the victim of local erosion along with the top of the Farley Limestone.

The sandstone contains a few brachiopods (Harris, 1985), pectins, and high-spined gastropods. The overlying shale contains these fossils as well as fenestrate bryozoans and unidentified shell fragments. The sandstone is extensively ripple cross-laminated with a few festoon sets up to 30 cm (12 inches) thick. An excellent set of climbing ripple-drift cross-lamination is developed near the base. Current directions are persistently toward the east-southeast. Herringbone crossbedding is evident near the base, but no orientations could be measured.

This sandstone, which apparently eroded the entire Bonner Springs and beveled the top of the Farley Limestone, is truncated by a distinct hemi-channel form that removed all but 1.9 m (6.3 ft) of the sandstone in section X (fig. 3-2). The channel form is filled with 2.3 m (7.6 ft) of silty shale; silty, pebbly sandstone; and shale; it extends to the fossiliferous shale beneath the Merriam in Sections IX and VIII. This channel-form sand/shale sequence is in turn beveled by yet another hemi-channel form represented by abrupt westward thickening of the Merriam Limestone from 0.9 m (3 ft; possibly truncated by modern erosion) in section IX through 2.4 m (8 ft) in section VIII and 4.0 m (13 ft) in section X.

The nature of the Merriam expansion is best seen in sections VII, IV, and V where it clearly truncates a normal Bonner Springs Shale interval from 7.2 m to 1 m (23.7–3.3 ft) or less and may bevel the top of the Farley Limestone. An argillaceous interval at the top of the beveled Bonner Springs contains numerous pebbles of argillaceous limestone that are bored by tiny bivalves and heavily encrusted by worms and other organisms. These reworked pebbles, which may derive from the Farley Limestone or calcareous beds within the Bonner Springs, formed a lag in the base of the channel, where they were encrusted and bored.

The thickening of the Merriam involves some expansion of the uppermost limestone bed and an underlying, regionally persistent, intra-member shale; however, the most dramatic thickening is by introduction of numerous beds in the lower portion of the Merriam that are beveled, in a top-lap relationship against overlying beds. These beds contain abundant large (up to 5 cm [2 inches] wide) productids, tentatively identified as *Linoproductus*, *Echinochonus*, and *Juresania*, and an expansion of

the zone of abundant *Chonetes*, common near the base of the Merriam. These fossils are unbroken and many appear to be in life position.

The Hickory Creek Shale also thickens from 20 cm (8 inches) in section VII to 63 cm (25 inches) in section IV to 2.6 m (8.9 ft) in section V, its maximum known development in northeast Kansas. The lithology changes abruptly to a dark-gray, sooty-appearing, platy to flakey, calcareous shale. A low-diversity fauna of low-spined gastropods (*Trepostira* and, rarely, bellerophonitids), bivalves (*Palaeoneilo* and pectins), brachiopods, (*Composita*), and, rarely, crinoid columnals occurs in the lower part. Some of the bivalves and gastropods are pyritized.

Finally, the Spring Hill Limestone also thickens in section V to about 6 m (20 ft). In section MB, 700 m (2,310 ft) southeast., the Spring Hill is 3.9 m (12.9 ft) thick and in section II, about 1,200 m (3,960 ft) east, it measures 3.4 m (11.2 ft). Bedding is disrupted and somewhat thickened at the base of the wavy-bedded interval in the lower Spring Hill where the Merriam thickens in section VIII.

To summarize relations at the I-70/I-435 interchange, a typical section of Bonner Springs Shale was reduced to shale clasts in a thick sandstone, which also bevels the top of the underlying Farley Limestone. The narrow sandy body is in turn truncated by a hemi-channel form filled with shale and thin sandstone beds. This channel form is beveled by thickening of the Merriam Limestone into yet another channel form which trends northeast-southwest through sections VIII, X, and IV, where the Merriam rests directly on a truncated surface of normal Bonner Springs Shale. The dramatic thickening of the Merriam is through introduction of beds in the lower portion that top lap against the uppermost Merriam. The Hickory Creek Shale and Spring Hill Limestone also thicken above and westward of the thickest Merriam Limestone. The expansion is approximately five-fold in the Merriam Limestone, 13-fold in the Hickory Creek Shale, and nearly two-fold in the Spring Hill Limestone. Thus, although truncation of underlying units and top lap bedding are seen only in the Merriam Limestone, the entire Plattsburg Limestone thickens. In all, three channel forms are superposed, including that containing the very localized sandstone. Channelization was repeated through a sequence of depositional environments that formed a typical hemi-cycle of sandstone, shale, and limestone, all bearing marine fossils.

Interpretation of Bonner Springs Shale channels

The thick sandstone development, the shale-pebble clasts, and the abrupt lateral terminations within the Bonner Springs Shale at I-70/I-435 appear unique for outside shales (or any other unit) in this area. Elsewhere the Bonner Springs contains only thin, channel-form sand lenses or thin sandstone beds that appear continuous on outcrop scale. These striking lateral changes were discussed by Heckel (1985) and Harris (1985). Heckel (1985, p. 34) proposed that the thinning of the Bonner Springs was . . ."the slope of a subaqueous prodeltaic and delta front sequence that was stranded. . ." and that the sandstone in section IX was delta-front related sand. He noted evidence for subaerial exposure and possible soil formation toward the end of Bonner Springs deposition based on the maroon shale marker and regarded this as evidence of "...further eustatic withdrawal of the sea." Harris cited (1985, p. 35) a) the presence of mud cracks (primarily in the former quarry at Stop 2), "sandy lags" (section VIII), and conglomerates near the top of the Bonner Springs; b) the 5° slope of the Merriam-Bonner Springs contact (sections IV and VII) in contrast to an average slope of half a degree on the Mississippi Delta front; and c) truncation of the maroon zone (section IV) as evidence "that the upper surface of the Bonner Springs Shale is the result of [subaerial] erosion...along an unconformity."

We agree with Harris that the upper surface of the Bonner Springs is erosional, liberally sculpted by channels, both at and near the top, and with both Heckel and Harris that subaerial exposure near the close of Bonner Springs deposition is indicated by the data cited above. Marine transgression began, however, before the end of Bonner Springs deposition as indicated by marine fossils in the uppermost portion at a few localities. This marine interval is truncated along with the underlying subaerial nodular

carbonate and maroon shale. Moreover, the fill of each of the three superposed channels is marine. The sandstone contains a few brachiopods at the base as well as pectens and high-spired gastropods (sect IX, fig. 3-2). The overlying sand-shale sequence (sections X, IX, and VIII) contains Myalina clams, pectens, high-spired gastropods, and bryozoans. The Merriam contains an abundant marine fauna dominated by euryhaline brachiopods. The intra-Bonner Springs channels on I-435/Holiday Road also contain a marine fauna. Subaerial erosion of each channel would require yo-yo style oscillations of sea level.

Delta lobes are the traditional interpretation of sand bodies within outside shales and unusually thick silty-shale intervals. This interpretation fits the typical Bonner Springs, but the suite and succession of rock types, the ripple-drift and climbing ripple sets, the current reversals, and the small-scale festoons at the I-70/I-435 interchange are typical only of tide-dominated, high-destruct deltas (Miall, 1984), which are unlikely in the low-energy shallow seas of the midcontinent. The postulated slope on the delta front is clearly erosional as demonstrated by truncation of bedding within the Bonner Springs, including the maroon shale, and the superposition of multiple channels. Heckel's argument for a stranded delta seems unlikely. The origin of the Bonner Springs channels must be related to the superimposed thickened intervals of Merriam Limestone.

Interpretations of thickened intervals of Merriam Limestone

Several hypotheses are possible for the local expansion of Merriam Limestone, with or without concomitant thinning of the Bonner Springs. Positive relief on the Merriam could result from mud banks or carbonate deltas such as those in the modern Florida Keys (Enos and Perkins, 1979). A more likely alternative would be some relationship to linear oolite bodies in the Merriam of Franklin County (Ball et al., 1963). The scale, discontinuity, and general alignment of the oolite bodies suggest tidal oolite bars (Ball, 1967). The trend of the expanded intervals in Johnson and Wyandotte Counties, is comparable to that in Franklin County (north-northeast-south-southwest). However, the mud content of Merriam packstones and wackestones in the thick intervals rules out analogy with high-energy oolite shoals apparently represented by the crossbedded oolite bodies in Franklin County. In addition, the truncation of the underlying Bonner Springs Shale and other evidence of channelization presented above militates against any depositional configuration involving positive relief. The hemi-channel forms are interpreted as bonafide channels. It remains to identify the processes that formed them.

Processes responsible for channel formation

Channels could be incised into underlying units by fluvial, storm, or tidal erosion. Fill of the channels variously with sandstone, shale, and muddy limestone, each with exclusively marine or brackish fossils, limits the possibilities. Terrestrial processes would require repeated erosion without deposition, preservation of narrow channels, and repeated marine transgressions to fill the channels, each of which appears improbable even in isolation. Channelization in violent storms such as hurricanes is known (cf. Ball et al., 1967); however, it involves breaching of local barriers and does not produce elongate channels such as indicated for the Merriam. Also, deposits of violent storms are chaotic mixtures of mud and coarser clasts, typically in thin sheet-wash blankets (Hayes, 1967; Ball et al., 1967; Perkins and Enos, 1968) deposited in the upper flow regime. Storms would also fill any pre-existing channels with such chaotic deposits.

Each channel studied appears to truncate less erodible deposits, either more cohesive or coarser grained than those that fill the channel. This suggests that cut and fill were either in different environments or at different intensities. The presence of extensively bored and encrusted pebbles at the base of Merriam channels also suggests a finite period during which the channels were open before final filling. Apparently the channels were cut by rather ephemeral, strong currents and filled under different and varied sedimentary regimes. Tropical storm deposition is a possibility in the low latitudes of the

Pennsylvanian in the midcontinent (Heckel, 1983; Ziegler et al., 1979). In channels filled by carbonate or argillaceous deposits, however, the muddy texture of the sediment; its resolution into a number of distinct, well-defined beds; and the occurrence of brachiopods in growth position all attest to lack of strong currents during channel fill. Processes active over long periods are also indicated by the thick sequence of low-energy deposits. It cannot be demonstrated, however, that processes of long duration cut the channels.

Tidal currents appear to be the only common submarine process capable of producing the channel forms and marine sediments developed at the Bonner Springs–Plattsburg transition. Herringbone crossbedding developed locally in the sand-filled channel supports a tidal regime. The only direct evidence of currents during the deposition of the Merriam are the large-scale inclination and toplap in the lower beds (figs. 1, 10, 13). The initial limestone beds in the Merriam drape the channel wall (figs. 1, 13, 17, 18); they do not overlap as stated by Harris (1985). Subsequent beds terminate by toplap as the Merriam thins toward the channel margins. Toplap reflects building up to a base level, presumably either local wave base or sea level. The relatively thick, crossbedded ooid grainstone lenses in Franklin County and thin lenses of grain-supported ooids and oncoids in virtually all local Merriam sections reflect at least episodic agitation by strong currents. This suggests sea level as the control rather than wave base.

Is it reasonable to infer episodic high-tidal energy in the shallow “tideless seas” (Shaw, 1964) of the midcontinent? Repeated occurrences of crossbedded oolite near the tops of upper, regressive limestones throughout the Missourian (Moore et al., 1951; Heckel, 1983) are affirmative evidence. Skeletal rudstones in the Farley Limestone show opposing current directions, indicating tidal activity, and local channels at the base of the Captain Creek Limestone contain crossbedded conglomerates, a testimony of high energy (Enos et al., in ms.).

The uppermost shale and limestone beds in the Merriam thicken somewhat, but do not display toplap. This suggests continued presence of a shallow channel and a rise in base level with the transgression, as deduced by Heckel from the conodont assemblages (*in* Watney et al., 1985, p. 34). The persistence of channels would also explain thickening of the Hickory Creek shale and Spring Hill Limestone where the Merriam is thickest. Effective scouring of the channels almost certainly ceased early in Merriam deposition, as indicated by muddy lithologies and upward changes in bed geometry. Scouring was not a factor during maximum transgression represented by the Hickory Creek, a core shale (Heckel, 1985). Either channels were cut deep enough so that they were not completely filled during Merriam deposition, or differential compaction of the thicker channel fill maintained some relief during deposition of the other cyclothem members. Toplap in the lower Merriam indicates that the channel was filled to an effective wave base, but continued rise in sea level apparently removed this constriction.

Another possible mechanism for maintaining local relief is some kind of very local subsidence. Unlikely as this may seem, it would also explain why three channels come to be superposed through the normal cyclothem progression of depositional regimes. It could also explain a long, straight channel such as might extend from I-70/I-435 to K-10 at Cedar Creek, if some structural element such as an incipient fault controlled subsidence. However, it would not adequately explain the persistent and widespread occurrence of channels in Wyandotte and northern Johnson counties.

A more likely explanation is lateral funneling of currents by pre-existing relief developed by algal banks in the underlying Wyandotte Formation (Crowley, 1969). Crowley showed that the Bonner Springs reflects some inherited relief and this inheritance may have profoundly influenced currents and deposition even in the Stanton cyclothem that overlies the Plattsburg (Enos et al., in ms.).

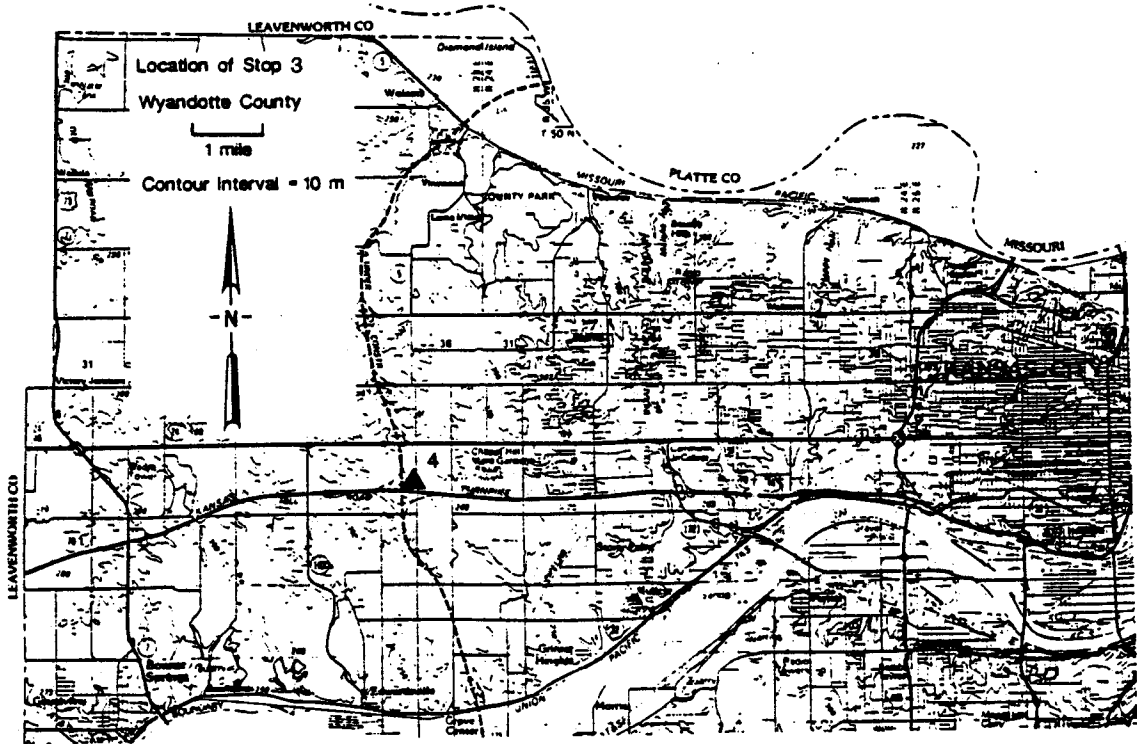
The change in lithologic character of the Hickory Creek Shale with the increase in thickness at I-70/I-435 interchange also suggests a depression on the sea floor. Local bathymetric highs have been called upon to explain the loss of black color, carbon content, and fissility within core shales where they projected through a pycnocline that produced anoxic conditions elsewhere on the sea floor (Heckel,

1977). The Hickory Creek is nowhere developed as a black, fissile, carbonaceous shale, but the *Trepostirid-Paleoneilo* assemblage in the thickened Hickory Creek contains forms closely related to those that occur under dysaerobic conditions at the top of the oxygen-minimum zone (Boardman et al., 1984). With no record of a regional pycnocline, the reduction in oxygen level probably reflects stagnation in a local depression, the relict channel. This thickened Hickory Creek Shale will be pointed out on the northeast corner of the interchange.

Discussion

The concentration of channels within and at the top of the Bonner Spring Shale suggests that the simple Irwin-Shaw model of seas transgressing over an essentially planar surface (Irwin, 1965; Shaw, 1964) is not invariably appropriate to transgression in midcontinent cyclothem. Disruptions in the normal transgressive sequence at the base of the superjacent Stanton cyclothem (Enos et al., in ms.) show that such interruptions are not unique, at least in the local area of Johnson and Wyandotte counties. Other local anomalies have been documented by the detailed stratigraphy of Philip Heckel and his students (cf. Heckel, 1986) and by ongoing work of Lynn Watney and John French, Kansas Geological Survey. Even the classic layer-cake stratigraphy of the midcontinent demonstrates many responses to local conditions such as depositional relief and therefore is not all "layer-cake."

a



b

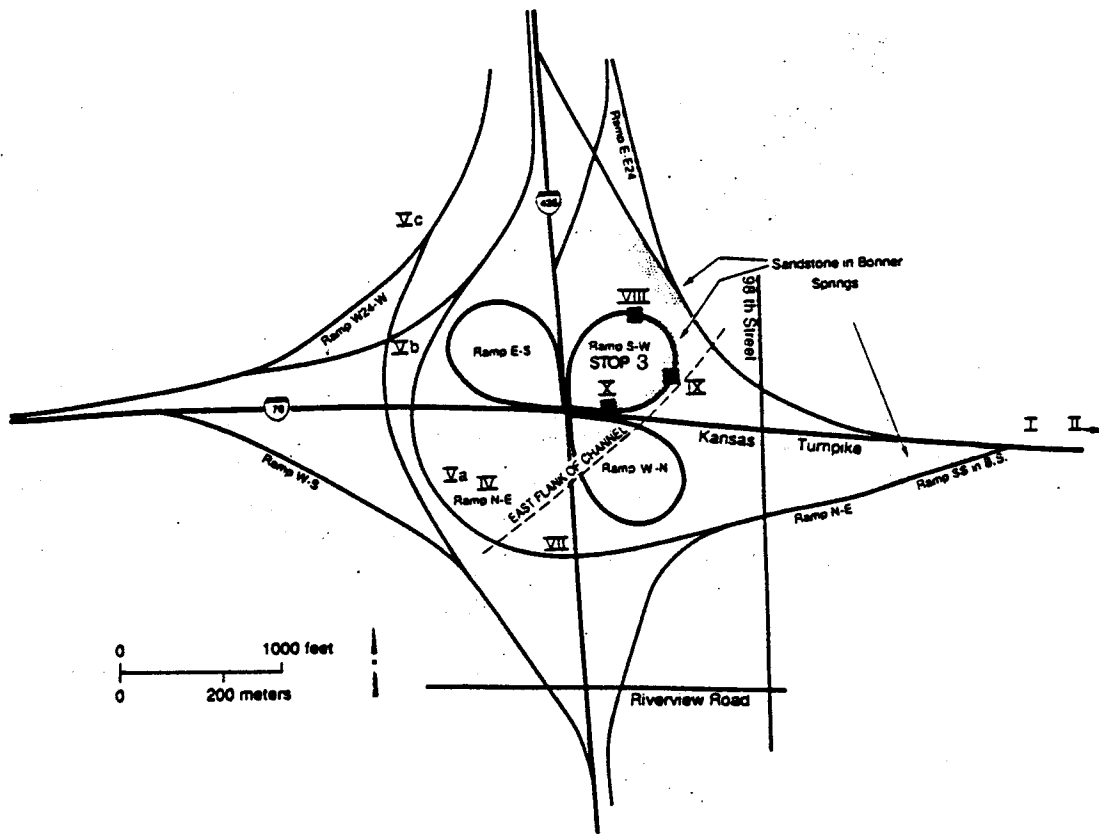


FIGURE 3-1 (A and B)--Location map for Stop 3 in Wyandotte County (A) and index map showing intersection with location of Stop 3 along northeastern cloverleaf of interchange of I-70 and I-435 and location of measured sections used in cross section (fig. 3-2a and b) identified with Roman numerals. Stippled pattern represents sandstones of Bonner Springs.

II - 21

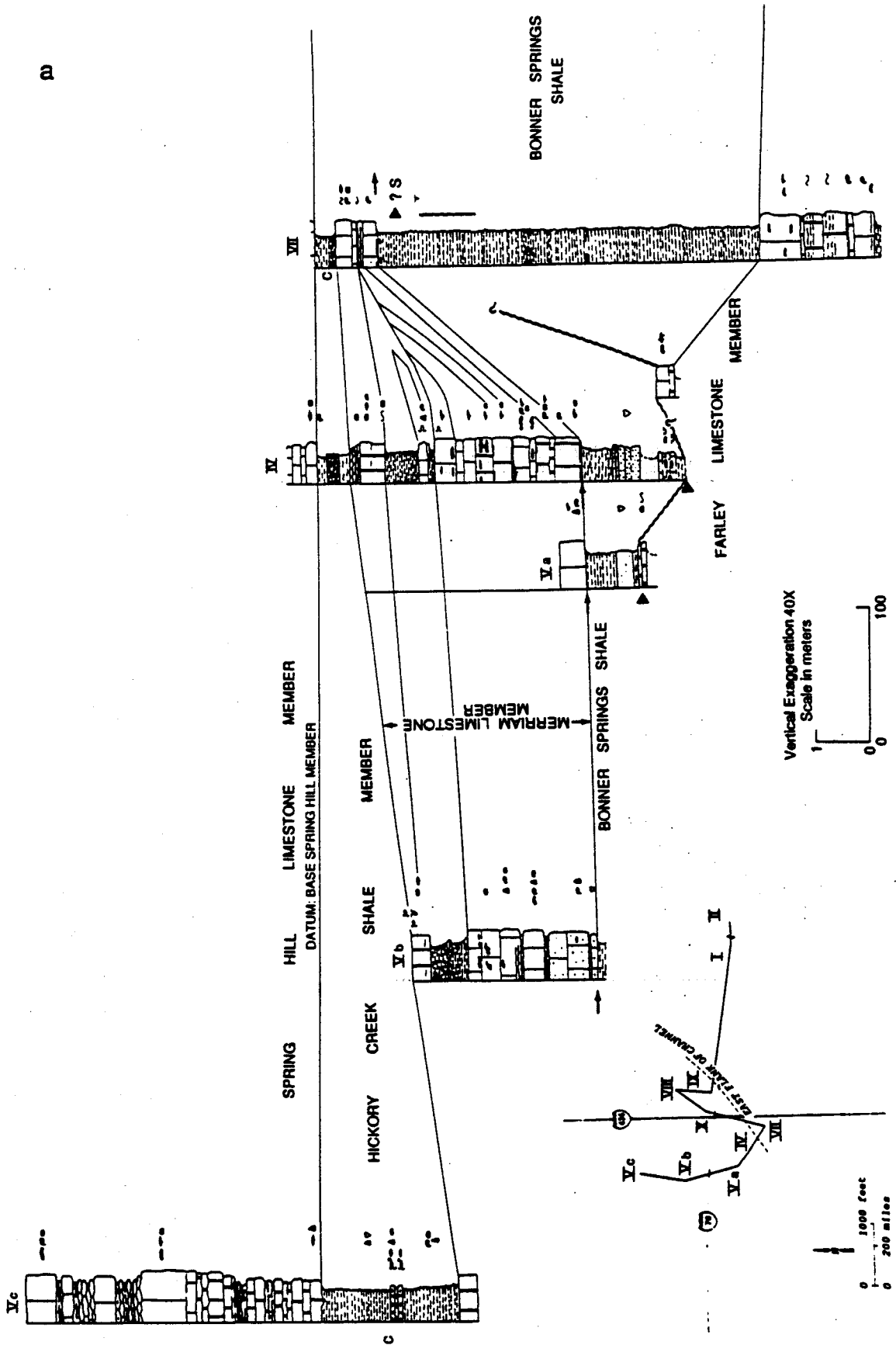
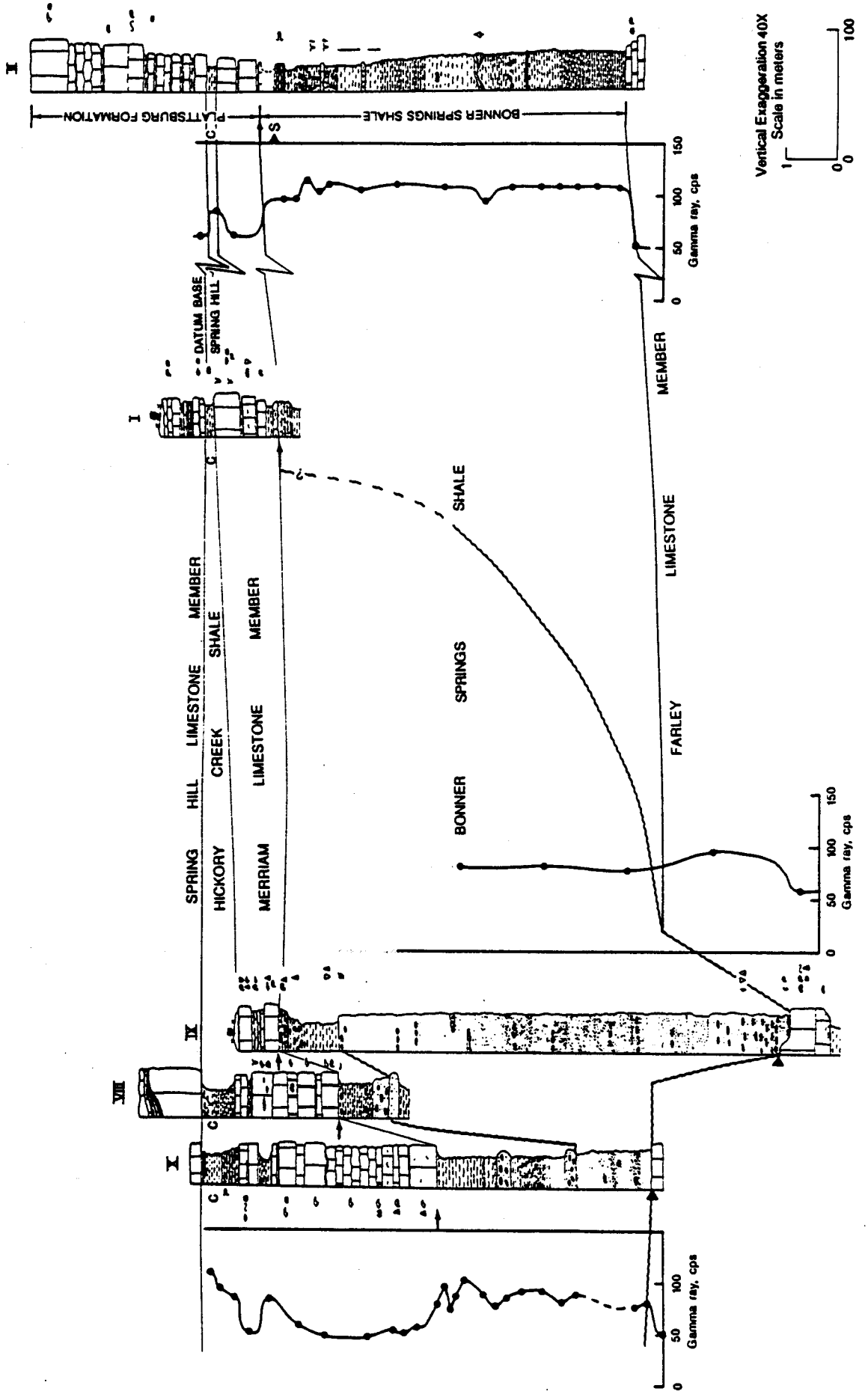


FIGURE 3-2 (A and B)--Northwest-to-east stratigraphic cross section through I-70/I-435 interchange area based on measured sections and interpretations (less sequence interpretations) by Enos and Herman, in ms. Datum for the cross section is the base of the Spring Hill Limestone. Uppermost Farley Limestone, Bonner Springs Shale, Merriam Limestone, Hickory Creek Shale, and Spring Hill Limestone are included in section.

II - 2

b



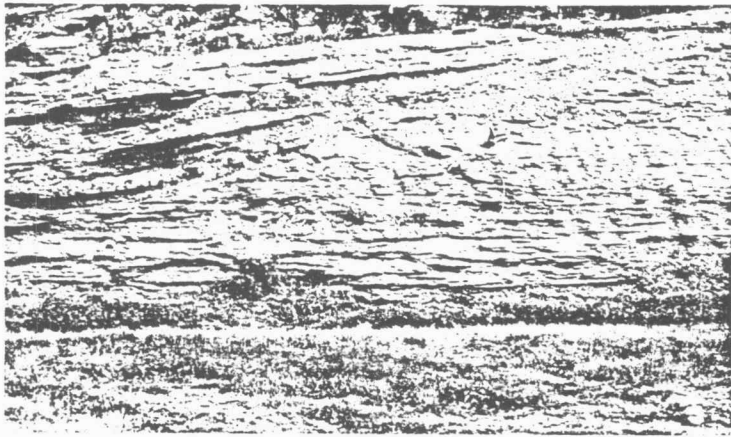
II-73

Figure 3-3 (A and B)--Bonner Springs Shale at Stop 3 showing sandstone of Bonner Springs (BS) resting on locally eroded upper Farley Limestone (UF) near section X. Sandstone is cut by erosional surface beneath a hemi-channel form which extends up to near the base of the Merriam Limestone (ME). Hemi-channel is filled with shale, siltstone, and thin beds of sandstone. Photos are close-up of left portion of fig. 3-3 (C and D). Note hammer left of center for scale (1 ft [0.32 m]).

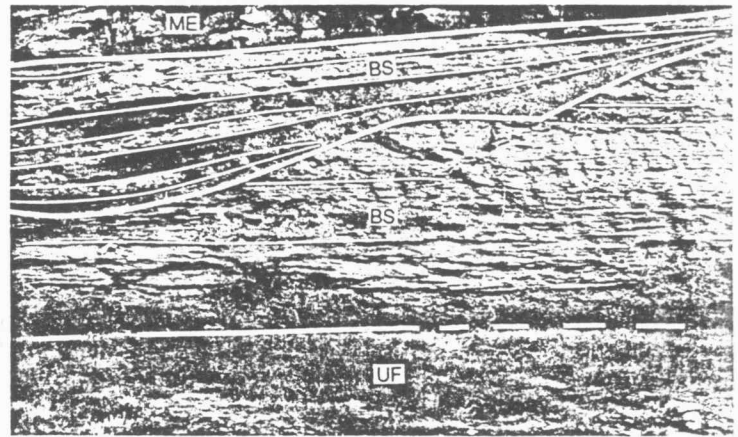
Figure 3-3 (C and D)--South side of Stop 3, northeast clover-leaf of intersection of I-70/435, between sections X and IX. Large channel-form sandstone in Bonner Springs Shale passes diagonally (northeast-to-southwest) through this exposure. Sandstone is cut by deep erosional surfaces beneath hemi-channel forms. Merriam Limestone, ME, thickens to left into hemi-channel form seen on opposite side of this clover-leaf. UF, upper Farley Limestone, resides at the base of the Bonner Springs Shale. It is locally eroded beneath the sandstone, losing elevation quickly to the lower right of this photo.

FIGURE 3-3 (E)--Close-up of east face of sandstone in Bonner Springs Shale at Stop 3 (section IX). The sandstone includes a few festoon cross sets up to 30 cm thick and herringbone cross-bedding near the base.

FIGURE 3-3 (F)--Typical Bonner Springs Shale (section II) shown in fig. 3-2(b). Upper portion commonly contains maroon interval (beneath base of arrow) that is overlain by a calcareous paleosol horizon (point of arrow). The maroon interval is clearly truncated near section VII, on the southwest side of I-70/435 intersection.



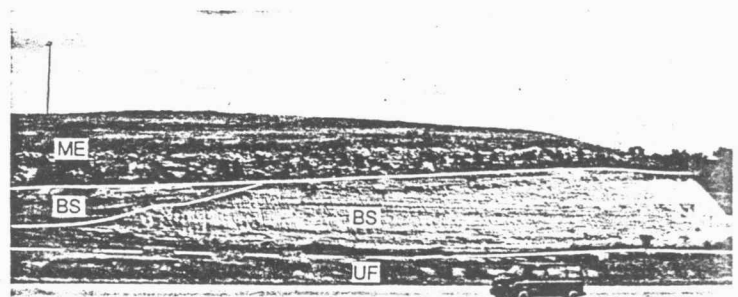
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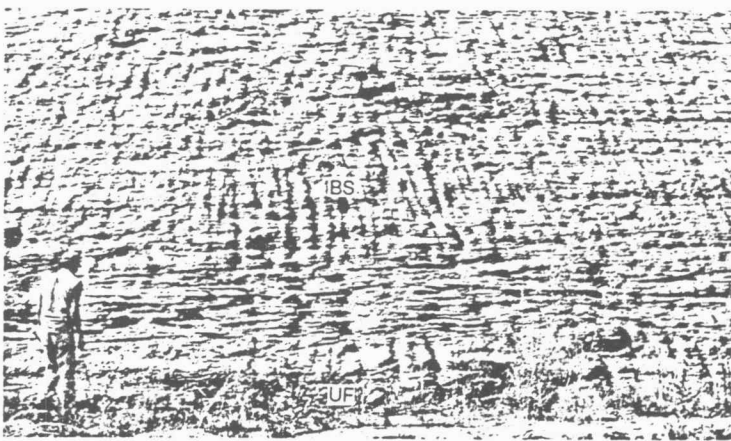
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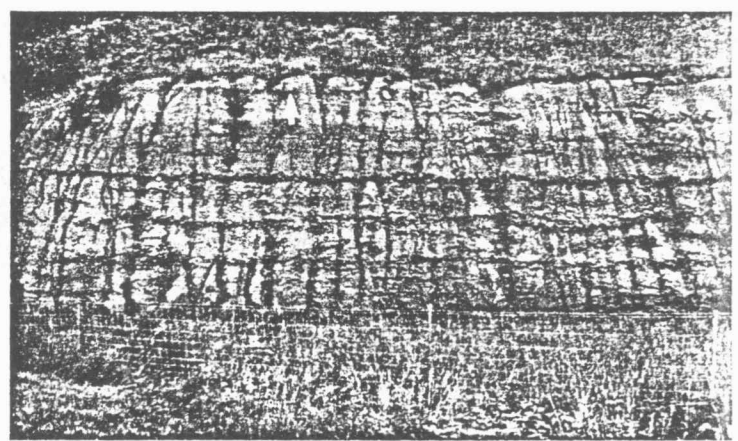
C



D



E



F

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