KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 91-22

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

For illustration and discussion of PSA concepts

Mid-Continent Meeting of Predictive Stratigraphic Analysis (PSA)
Workshop – C. Blaine Cecil and N. Terence Edgar, Program Planners

prepared and compiled by

Lynn Watney
Ronald West
Chris Maples
Pauline Denham

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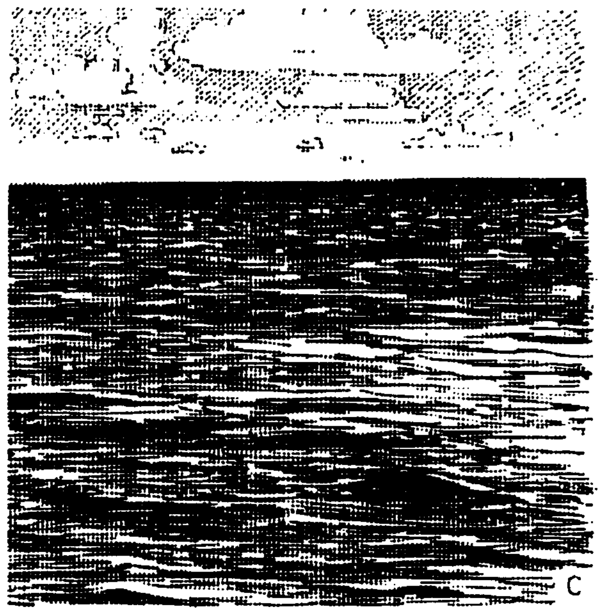

UPPER PENNSYLVANIAN (VIRGILIAN AND MISSOURIAN) CYCLOTHEMS IN THE LAWRENCE, KANSAS AREA

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Mid-Continent Meeting of Predictive Stratigraphic Analysis (PSA) Workshop -- C. Blaine Cecil and N. Terence Edgar, Program Planners

June 25, 1991

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Introduction to field trip

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Acknowledgements

Much of the introduction and stops 1 thorough 4 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.

The cross section used in stop 5 depicting biostratigraphically confirmed stratal correlations of the lower Virgilian Douglas Group comes from a field trip led by Phil Heckel and Allan Bennison this past May for the Mid-Continent Pennsylvanian Stratigraphic Working Group.

Most figures dispersed through stops 6 through 13 are taken from the guidebook prepared by R.C. Moore and D.F. Merriam, 1959, Kansas field conference: Association of State Geologists Annual Meeting, April 13-16, 55 p.

Description, interpretation, and measured sections of Stops 8, 9, and 10 originate from the guidebook stops of Heckel, P.H., 1979, in Heckel, P.H., Brady, L.L., Ebanks, Jr., W.J., and Pabian, R.K.: Field Guide to Pennsylvanian Cyclic Deposits in Kansas and Nebraska, Ninth International Congress of Carboniferous Stratigraphy and Geology (IX-ICC), Field Trip No. 10: Pennsylvanian Cyclic Platform Deposits of Kansas and Nebraska: Kansas Geological Survey, Guidebook Series 4, 79 p.

The discussion and illustrations used in Stop 13 originate from a stop described by R.R. West and R. Matsumoto in the guidebook compiled by Roger K. Pabian and R.F. Diffendal, 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.

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 second Predictive Stratigraphic Analysis (PSA) Workshop planned by C. Blaine Cecil and N. Terence Edgar with the U.S. Geological Survey and hosted by the Kansas Geological Survey. An objective of the field trip is to provide an opportunity to examine cyclothemic strata of the Upper Pennsylvanian and to discuss causal mechanisms of Pennsylvanian cyclothemic sedimentation including evidence for climatic control. 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. Strata from the Missourian Lansing Group are seen in stops 1 through 4. Virgilian strata of the from the Douglas, Shawnee, and Wabaunsee Groups are the focus of stops 5 thorough 13. 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 1 through 4 using standard symbols. A profile of natural gamma radiation is provided in stops 1 through 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 are taken 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).

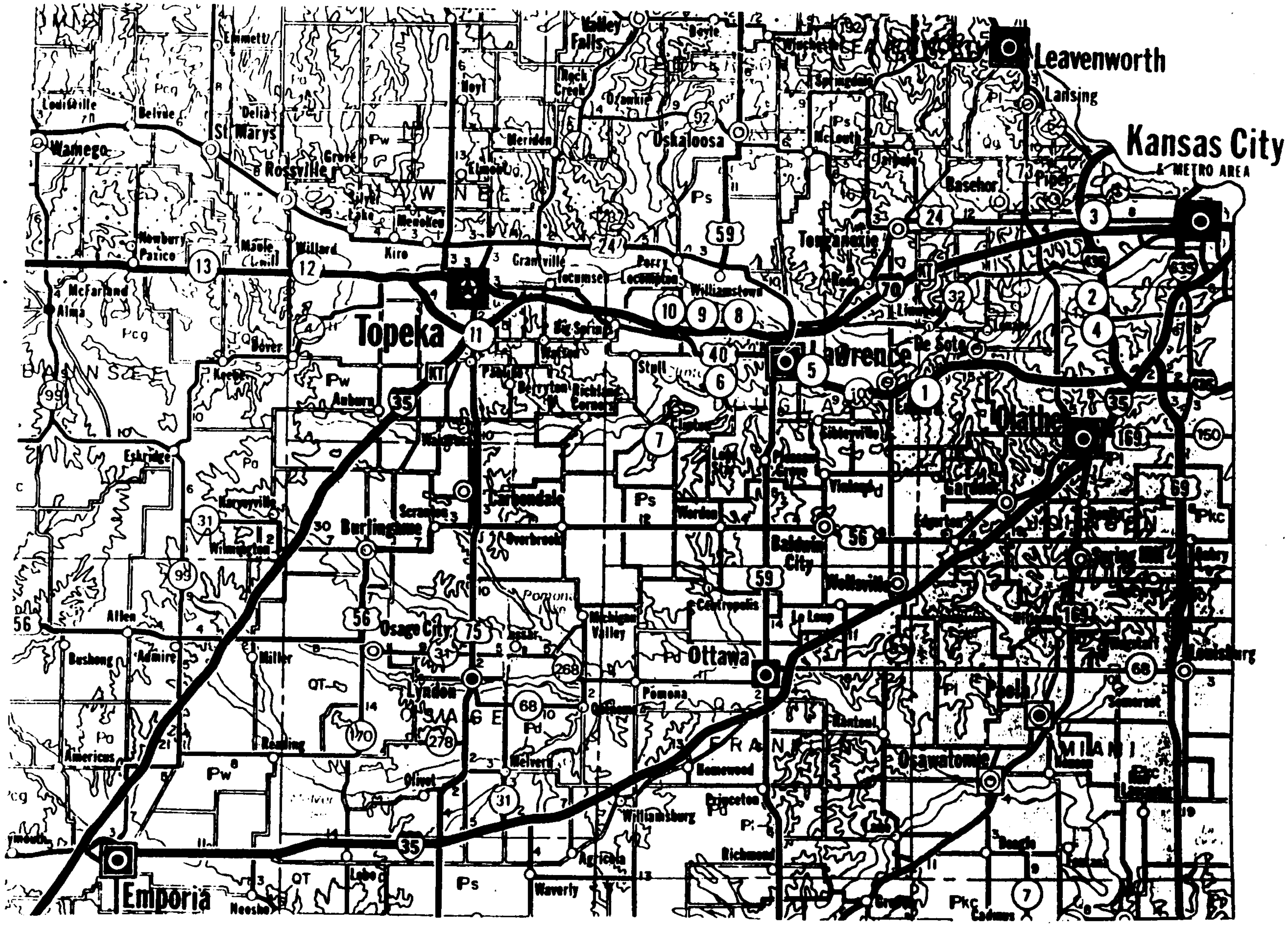


FIGURE 1—Index map of eastern Kansas showing stops on field trip (numbers and triangles), index of well locations (letters) used to make regional cross section found in fig. 4, and hatchured area in southeastern Kansas delimiting area mapped in figs. 5–13.

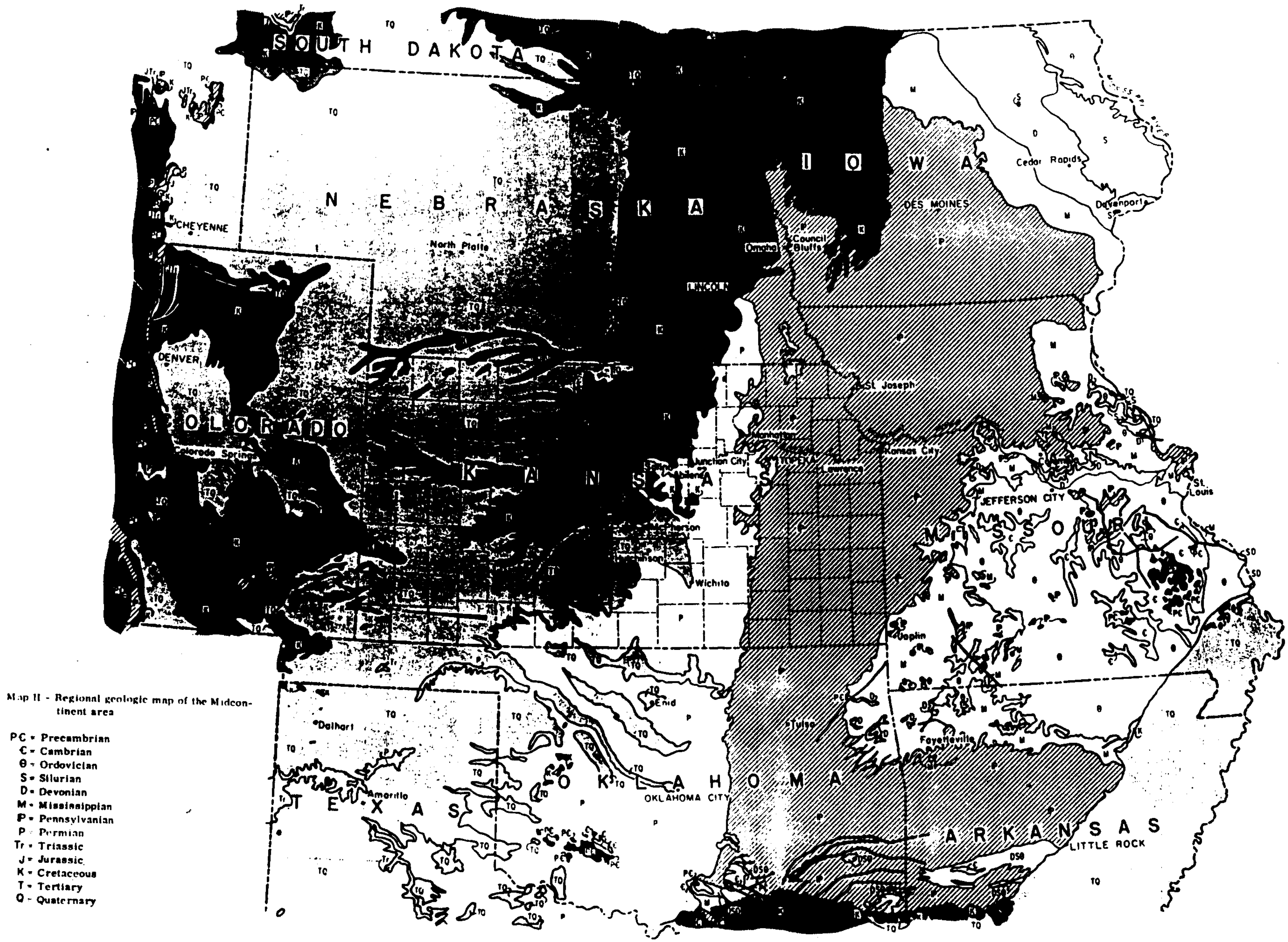


FIGURE 2-Bedrock geologic map of Mid-Continent region (Moore and Merriam, 1959).

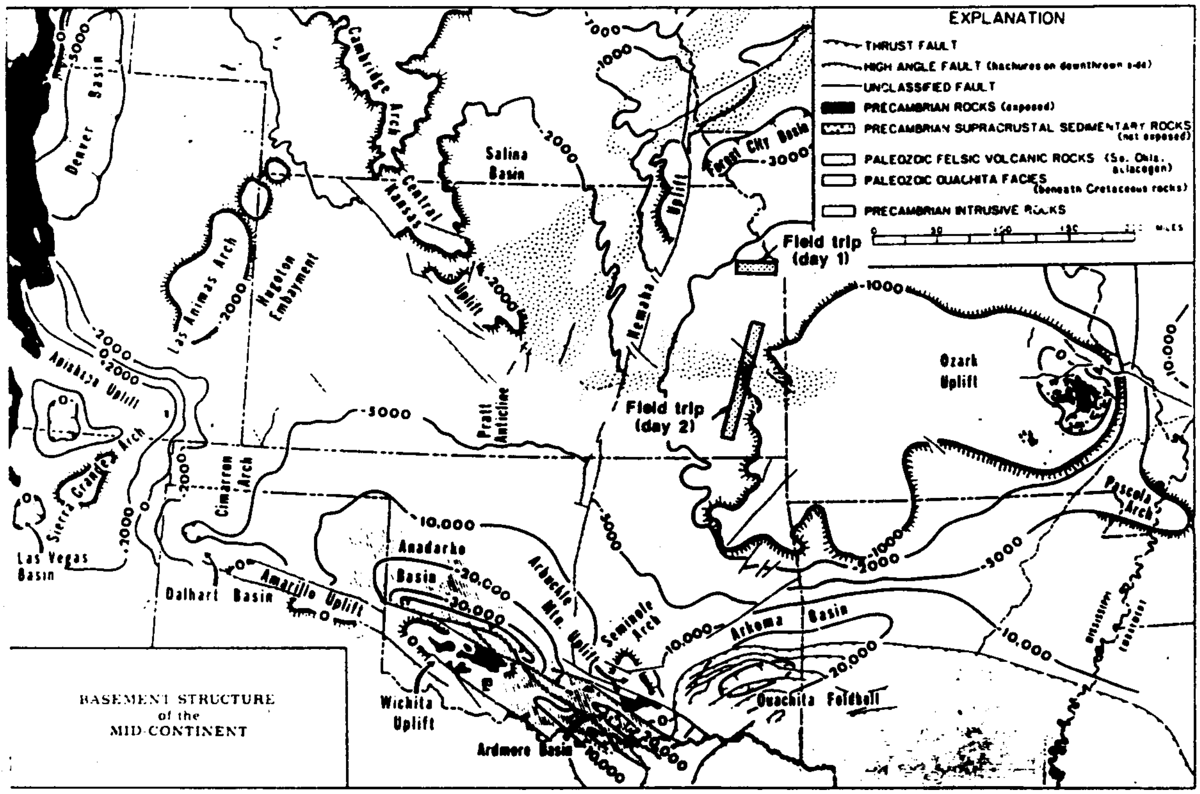


FIGURE 3—Configuration of the Precambrian basement in southern midcontinent (from Rascoe and Adler, 1983), annotated with location of field-trip traverse. Note that while southeastern Kansas is 200 mi (358 km) from the deep Arkoma basin, subsidence of the Arkoma basin during Missourian time significantly affected southeastern Kansas to form a depositional basin.

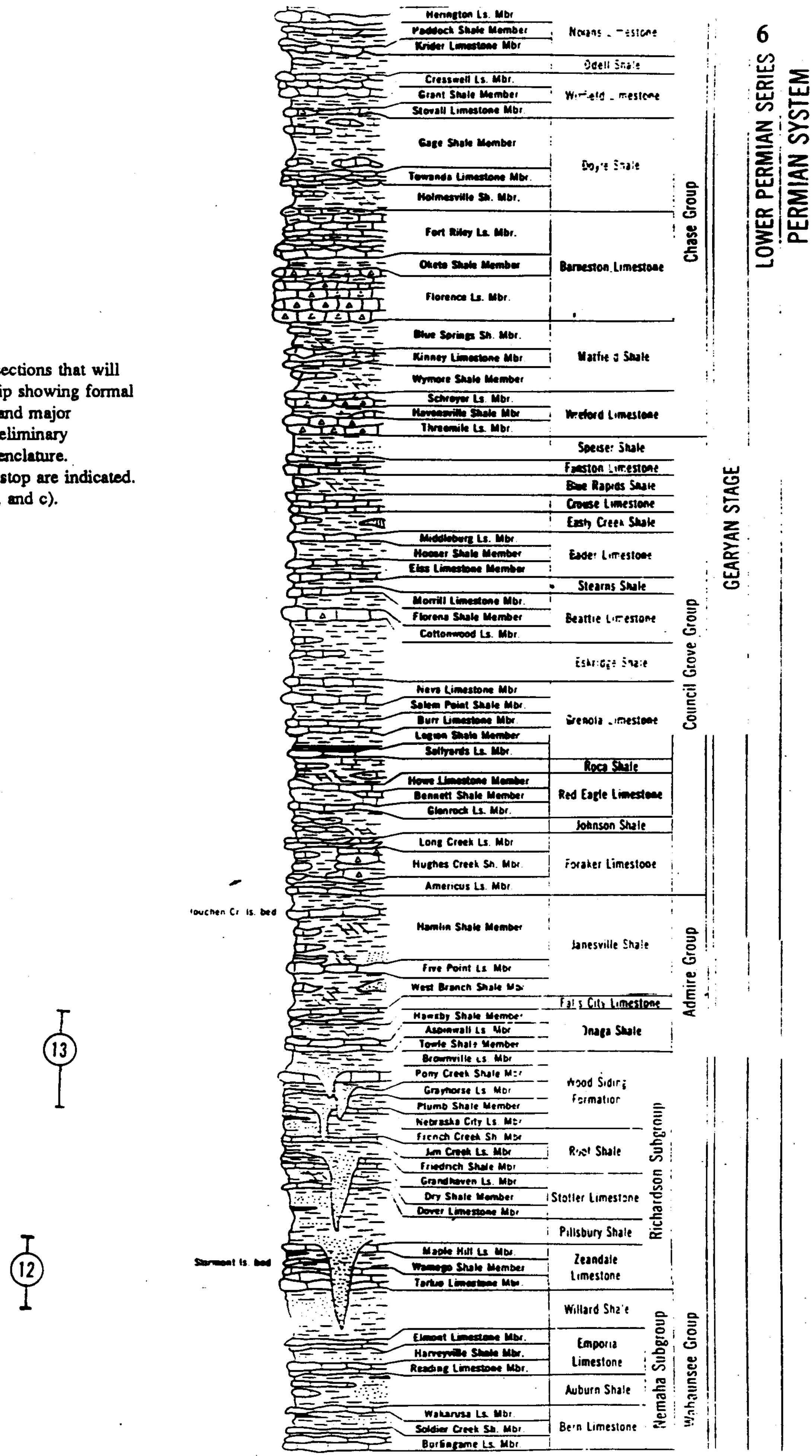
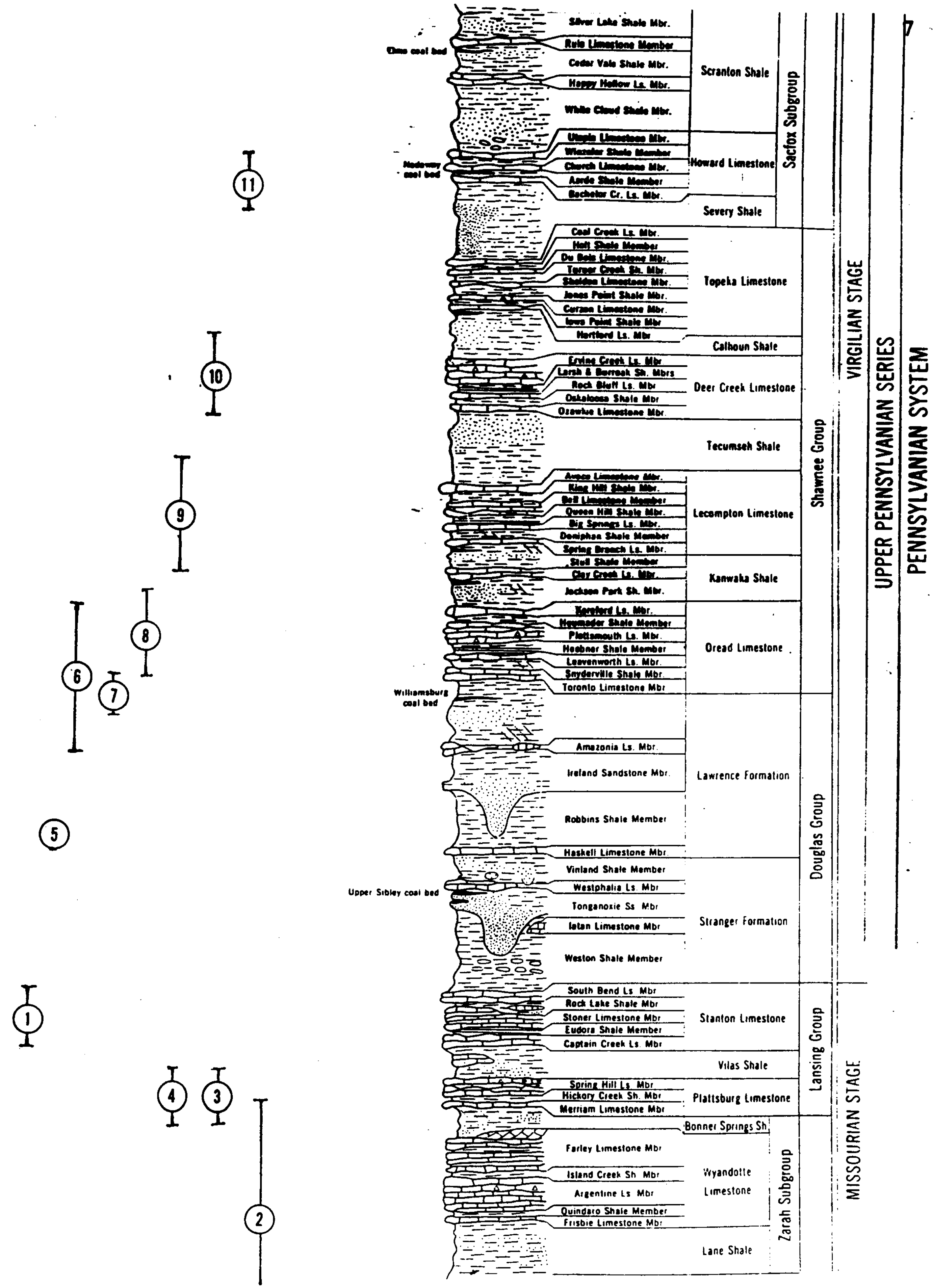


FIGURE 4—Stratigraphic sections that will be examined on the field trip showing formal stratigraphic nomenclature and major lithologies, and informal preliminary sequence stratigraphic nomenclature. Intervals examined at each stop are indicated. Figure has three parts (a, b, and c).


Silver Lake Shale Mbr.
Rulo Limestone Member
Dover coal bed
Cedar Vale Shale Mbr.
Scranton Shale
Happy Hollow Ls. Mbr.
White Cloud Shale Mbr.
Utopia Limestone Mbr.
Winzeler Shale Member
Nodaway coal bed
Church Limestone Mbr.
Howard Limestone
Aarde Shale Member
Bachelor Cr. Ls. Mbr.
Sacfox Subgroup
Severy Shale
Coal Creek Ls. Mbr.
Holt Shale Member
Du Bois Limestone Mbr.
Turner Creek Sh. Mbr.
Sheldon Limestone Mbr.
Topeka Limestone
Jones Point Shale Mbr.
Curzon Limestone Mbr.
Iowa Point Shale Mbr
Hartford Ls. Mbr
Calhoun Shale
Ervine Creek Ls. Mbr
Larsh & Burroak Sh. Mbrs
Rock Bluff Ls. Mbr
Deer Creek Limestone
Oskaloosa Shale Mbr
Ozawkie Limestone Mbr.
Tecumseh Shale
Avoca Limestone Mbr.
King Hill Shale Mbr.
Beil Limestone Member
Queen Hill Shale Mbr.
Lecompton Limestone
Big Springs Ls. Mbr.
Doniphan Shale Member
Spring Branch Ls. Mbr.
Stull Shale Member
Clay Creek Ls. Mbr.
Kanwaka Shale
Jackson Park Sh. Mbr.
Kereford Ls. Mbr.
Heumader Shale Member
Plattsmouth Ls. Mbr.
Heebner Shale Member
Oread Limestone
Leavenworth Ls. Mbr.
Snyderville Shale Mbr.
Toronto Limestone Mbr
Shawnee Group
Williamsburg coal bed
Amazonia Ls. Mbr.
Ireland Sandstone Mbr.
Lawrence Formation
Robbins Shale Member
Haskell Limestone Mbr.
Vinland Shale Member
Westphalia Ls. Mbr
Upper Sibley coal bed
Tonganoxie Ss Mbr
Stranger Formation
Iatan Limestone Mbr
Weston Shale Member
Douglas Group
VIRGILIAN STAGE
South Bend Ls Mbr
Rock Lake Shale Mbr
Stoner Limestone Mbr
Stanton Limestone
Eudora Shale Member
Captain Creek Ls. Mbr
Vilas Shale
Spring Hill Ls Mbr
Hickory Creek Sh. Mbr
Plattsburg Limestone
Merriam Limestone Mbr
Lansing Group
Bonner Springs Sh
Farley Limestone Mbr
Island Creek Sh Mbr
Wyandotte Limestone
Argentine Ls Mbr
Quindaro Shale Member
Frisbie Limestone Mbr
Lane Shale
Zarah Subgroup
MISSOURIAN STAGE
UPPER PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM
1
2
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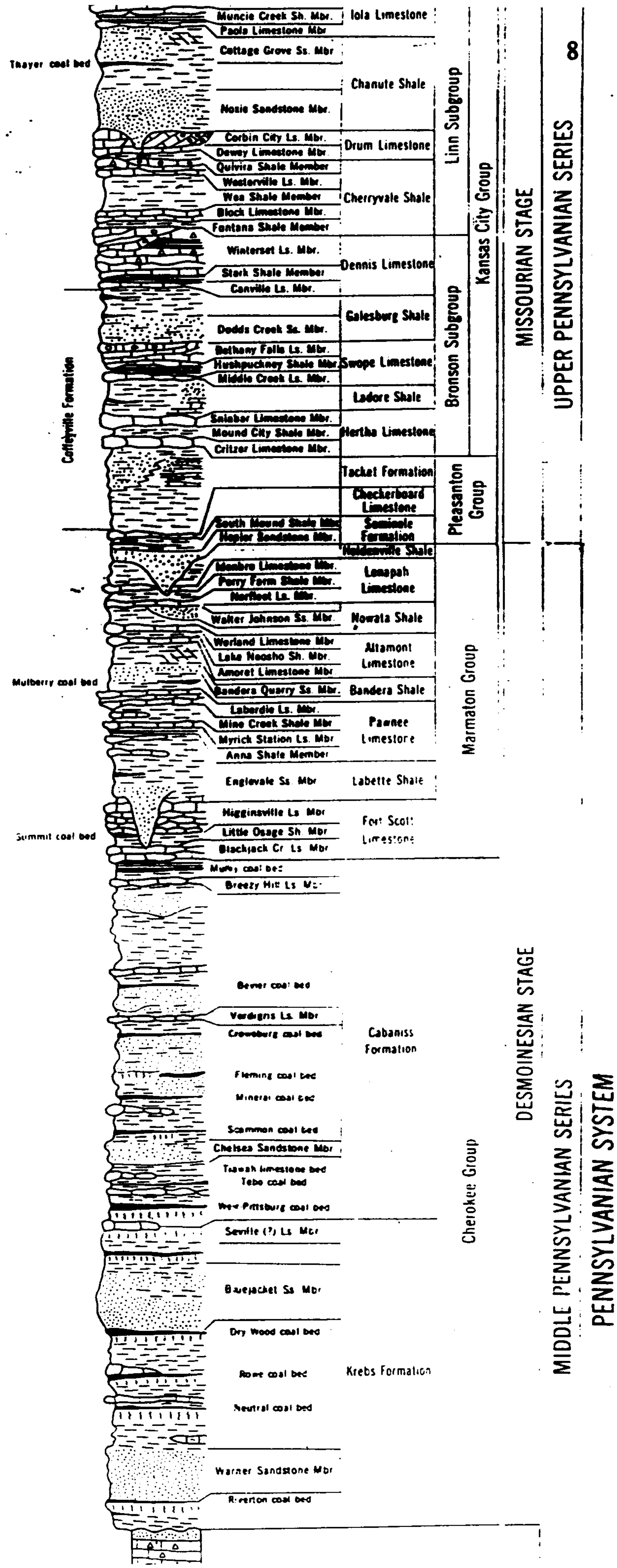
11



Muncie Creek Sh. Mbr.
Iola Limestone
Paola Limestone Mbr
Cottage Grove Ss. Mbr
Thayer coal bed
Chanute Shale
Nosie Sandstone Mbr.
Corbin City Ls. Mbr.
Dewey Limestone Mbr
Drum Limestone
Quivira Shale Member
Westerville Ls. Mbr.
Wea Shale Member
Cherryvale Shale
Block Limestone Mbr.
Fontana Shale Member
Winterset Ls. Mbr.
Dennis Limestone
Stark Shale Member
Canville Ls. Mbr.
Galesburg Shale
Dodds Creek Ss. Mbr.
Bethany Falls Ls. Mbr.
Hushpuckney Shale Mbr.
Swope Limestone
Middle Creek Ls. Mbr.
Ladore Shale
Sniabar Limestone Mbr.
Mound City Shale Mbr.
Hertha Limestone
Critzer Limestone Mbr.
Coffeyville Formation
Tacket Formation
Checkerboard Limestone
South Mound Shale Mbr.
Hepler Sandstone Mbr.
Seminole Formation
Holdenville Shale
Idenbro Limestone Mbr.
Perry Farm Shale Mbr.
Norfleet Ls. Mbr.
Lenapah Limestone
Walter Johnson Ss. Mbr.
Nowata Shale
Worland Limestone Mbr
Lake Neosho Sh. Mbr.
Amoret Limestone Mbr
Altamont Limestone
Mulberry coal bed
Bandera Quarry Ss. Mbr.
Bandera Shale
Laberdie Ls. Mbr.
Mine Creek Shale Mbr
Myrick Station Ls. Mbr
Anna Shale Member
Pawnee Limestone
Englevale Ss. Mbr
Labette Shale
Higginsville Ls. Mbr
Little Osage Sh. Mbr
Blackjack Cr. Ls. Mbr
Fort Scott Limestone
Summit coal bed
Mulky coal bed
Breezy Hill Ls. Mbr
Bevier coal bed
Verdigris Ls. Mbr
Croweburg coal bed
Cabaniss Formation
Fleming coal bed
Mineral coal bed
Scammon coal bed
Chelsea Sandstone Mbr
Tiawah limestone bed
Tebo coal bed
Weir-Pittsburg coal bed
Seville (?) Ls. Mbr
Bluejacket Ss. Mbr
Dry Wood coal bed
Rowe coal bed
Krebs Formation
Neutral coal bed
Warner Sandstone Mbr
Riverton coal bed
Linn Subgroup
Bronson Subgroup
Kansas City Group
Pleasanton Group
Marmaton Group
Cherokee Group
MISSOURIAN STAGE
DESMOINESIAN STAGE
UPPER PENNSYLVANIAN SERIES
MIDDLE PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM

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 ft^3. 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; Watney and Stephens, in press).

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

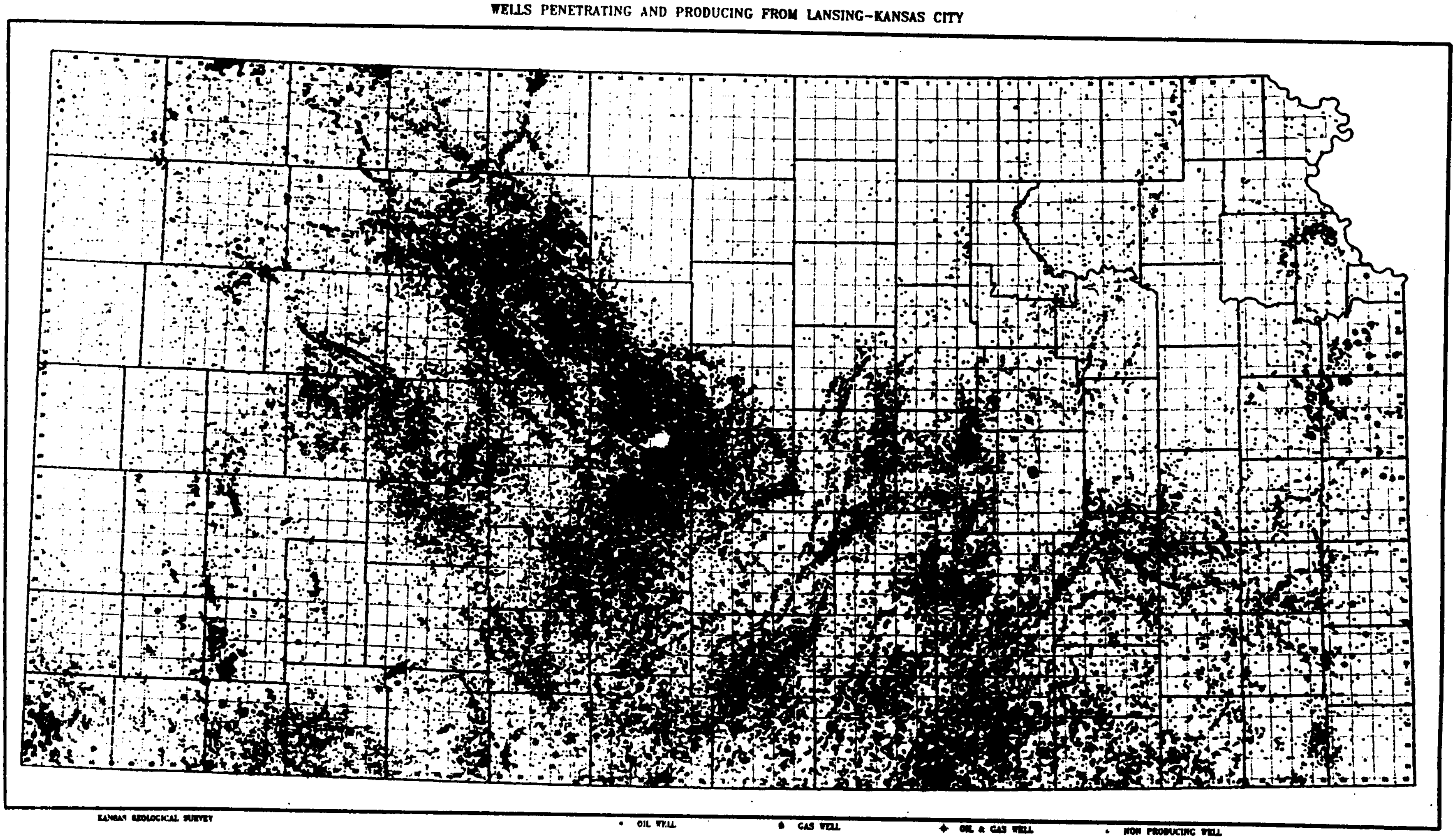


FIGURE 5-Wells penetrating and producing from Lansing and Kansas City Groups in Kansas.

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

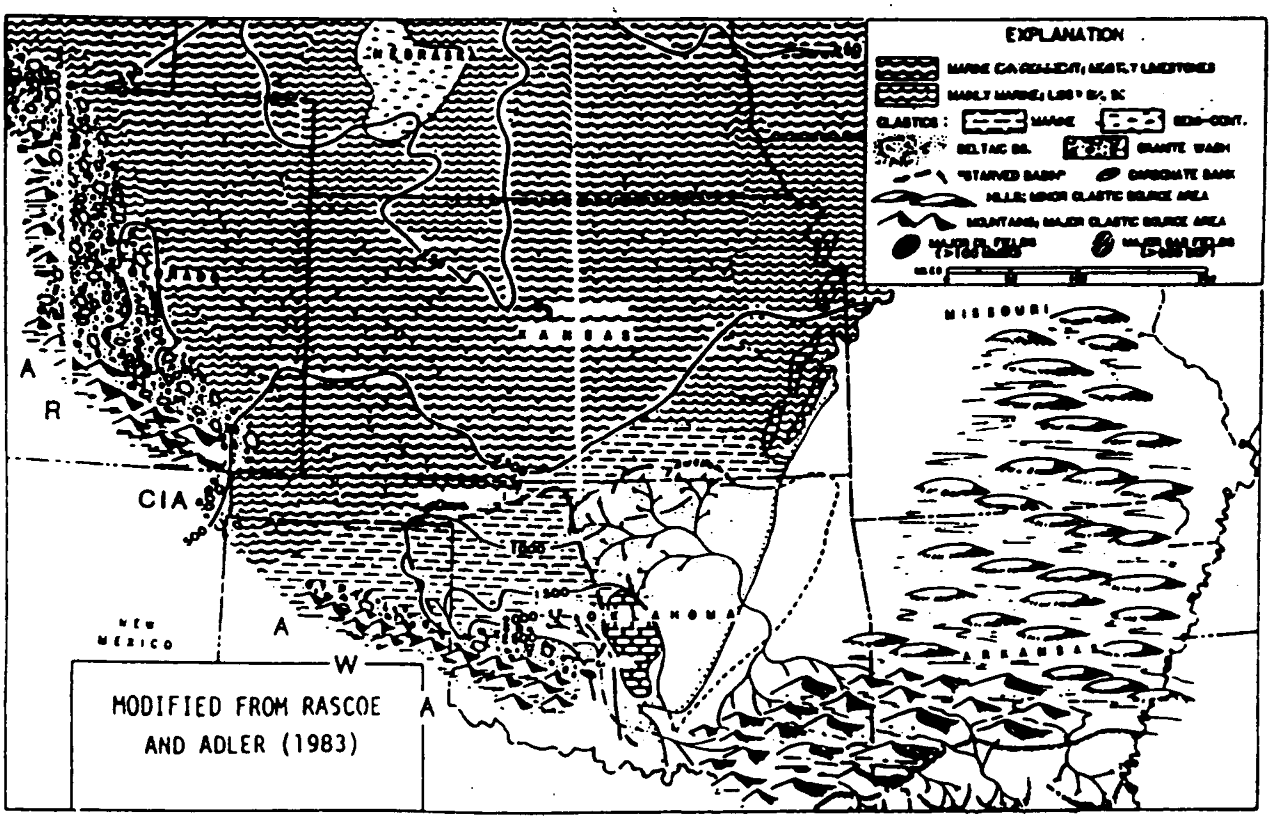


FIGURE 7—Lithofacies, paleogeography, and isopach map of strata deposited during Missourian (Pennsylvanian) in southern mid-continent (Rascoe and Adler, 1983).

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. 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,

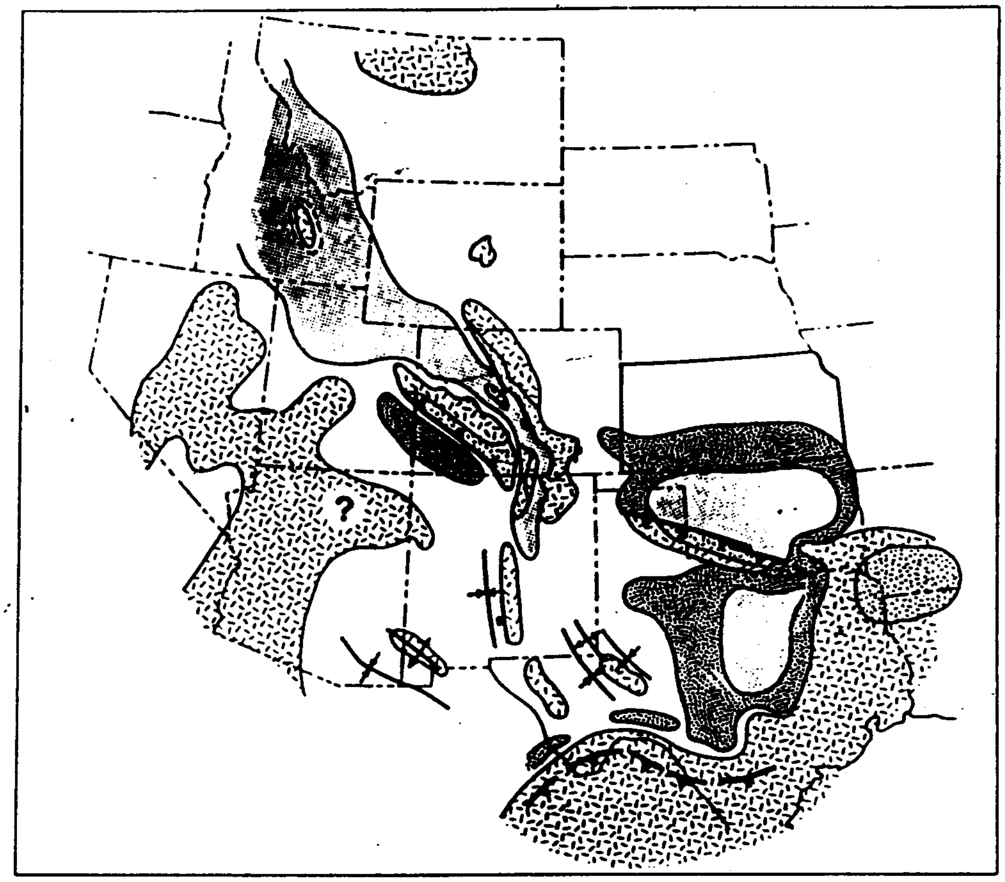


FIGURE 8—Missourian tectonic features with average subsidence rates for Missourian time: white areas = < 0.05 to 0.2 m/ka; dark stippled pattern = > 0.05 to 0.2 m/ka; and lighter stipple = > 0.2 to 0.3 m/ka. Subsidence in Arkoma basin in waning stages during the Missourian (Kluth, 1986).

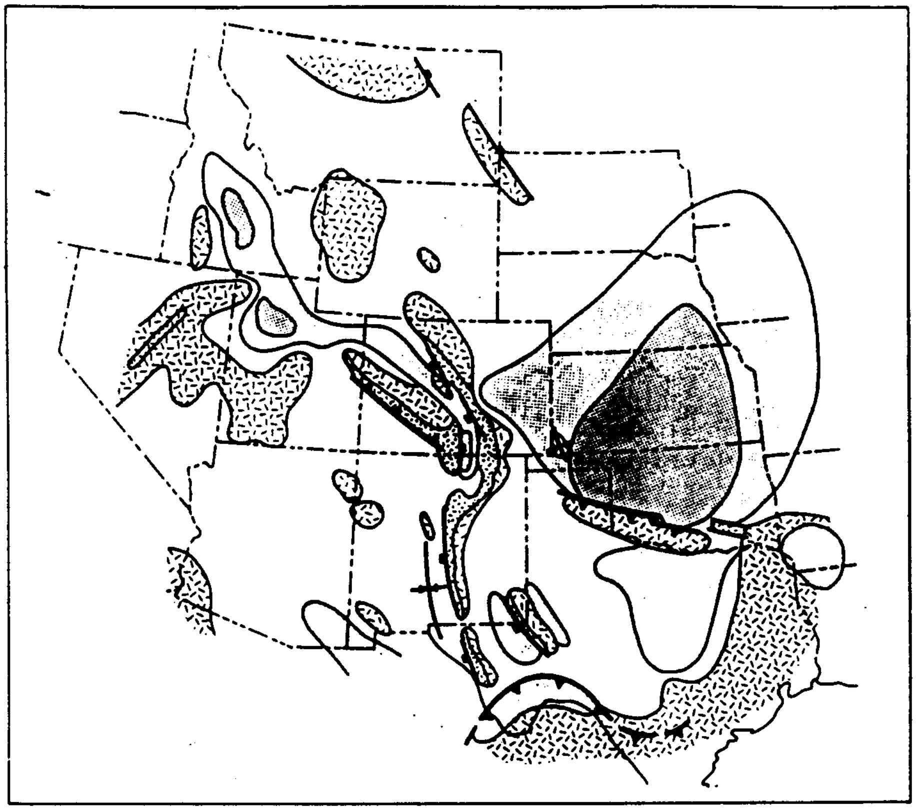


FIGURE 9-Virgilian tectonic features with average subsidence rates for Virgilian time (as fig. 8) (Kluth, 1986).

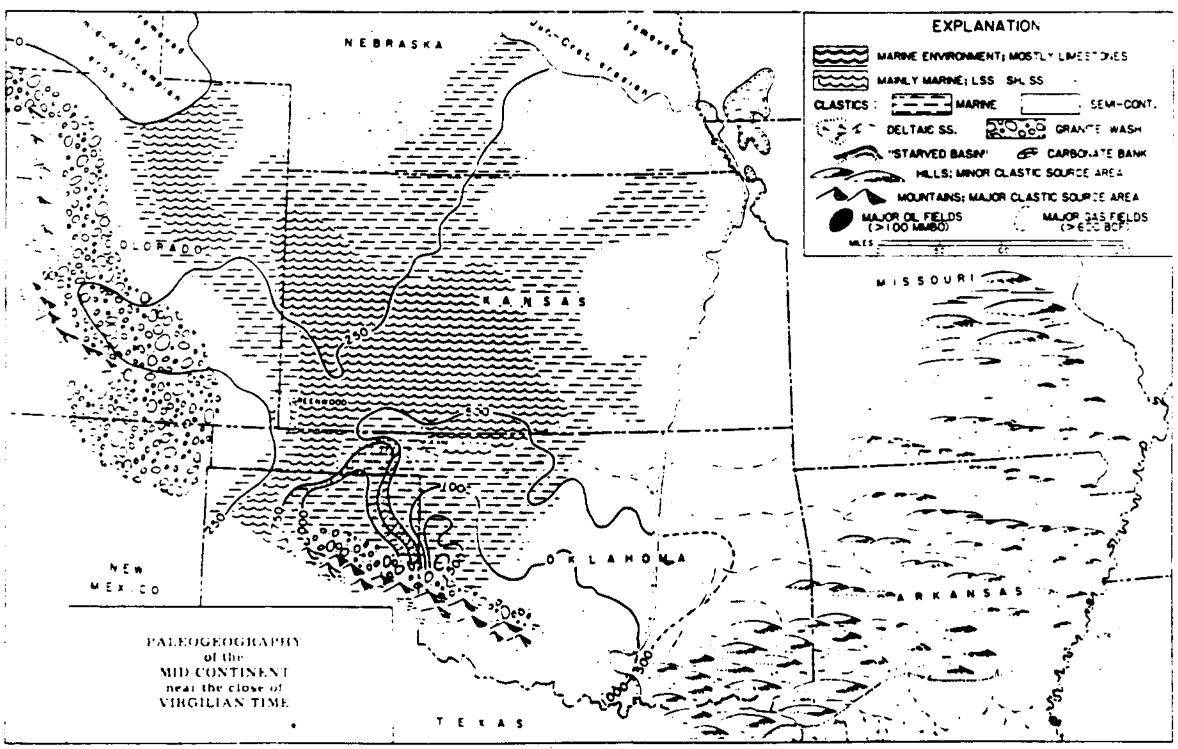


FIGURE 10-Lithofacies, paleogeography, and isopach map of strata deposited during Virgilian in southern mid-continent (Rascoe and Adler, 1983).

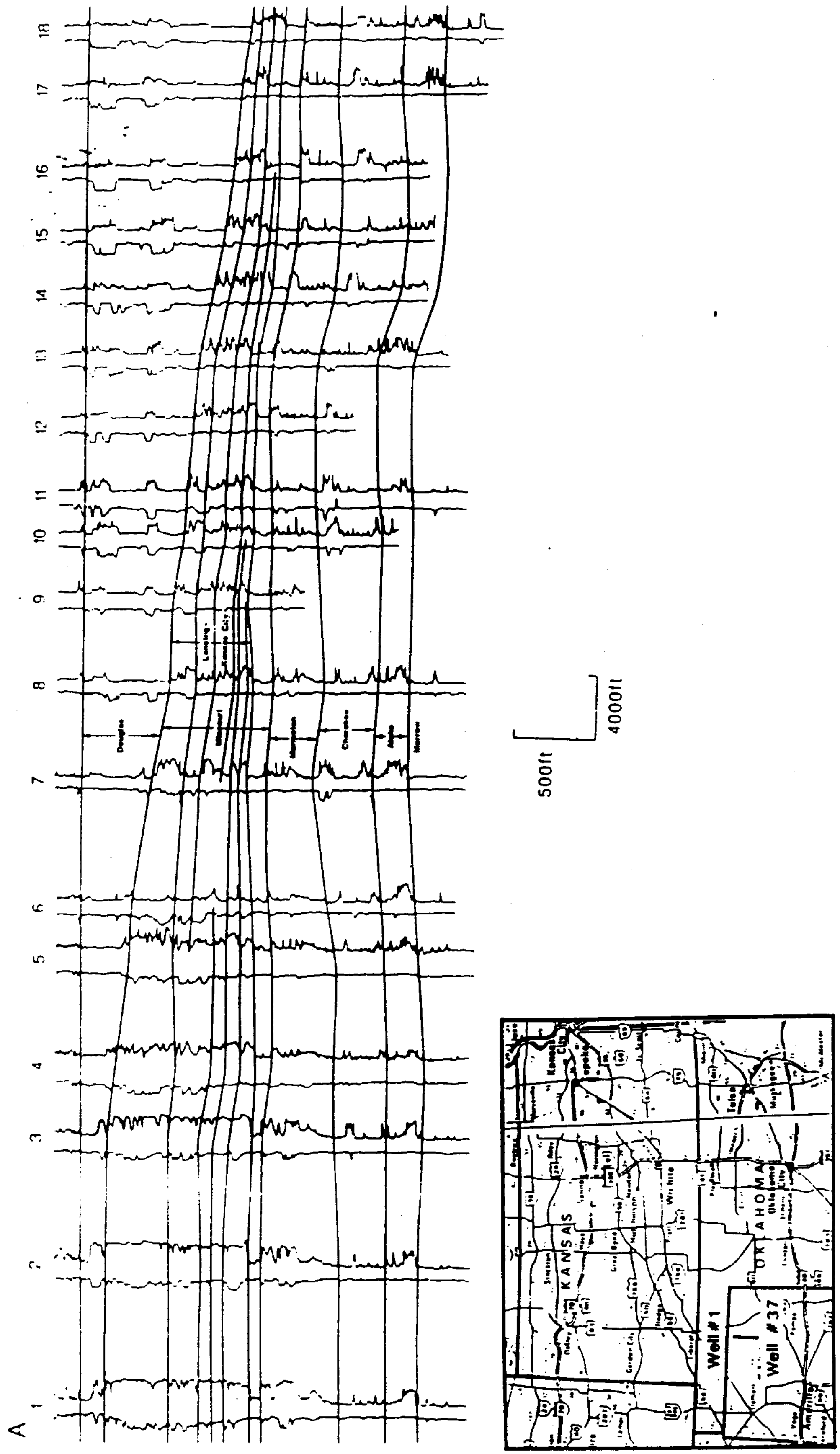
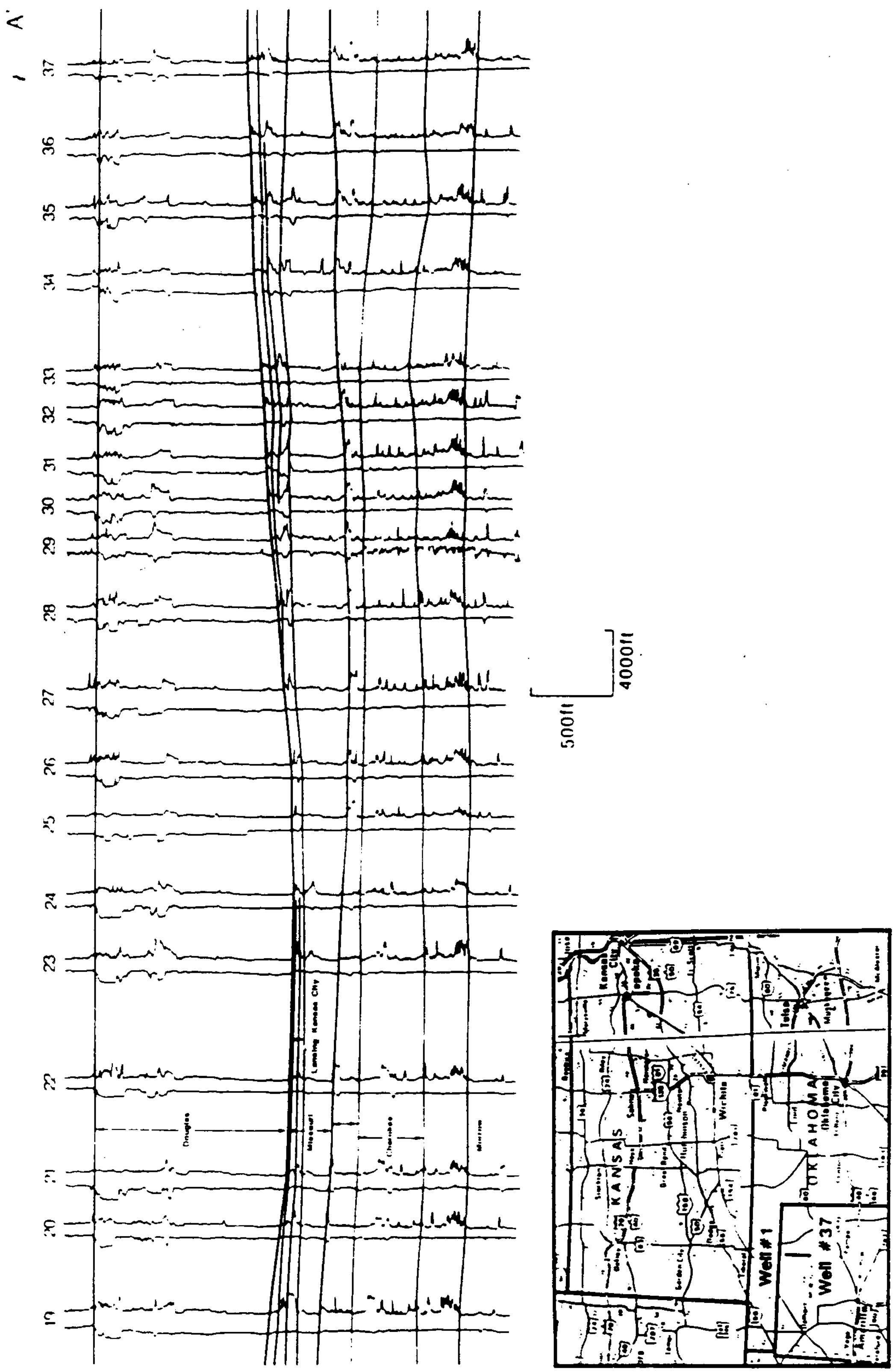


FIGURE 11—Stratigraphic wireline-log cross section across shelf edge of northwestern Anadarko basin in Hansford County, Texas. Datum is Virgilian Heebner Shale (from George Moore, circa 1974).


A'
500ft
4000ft
Lansing Kansas City
KANSAS
Wichita
Well #1
Well #37

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 "cyclothems" 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 cyclothems 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 subcyclothemic sequences are commonly imbedded within many cyclothemic 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.

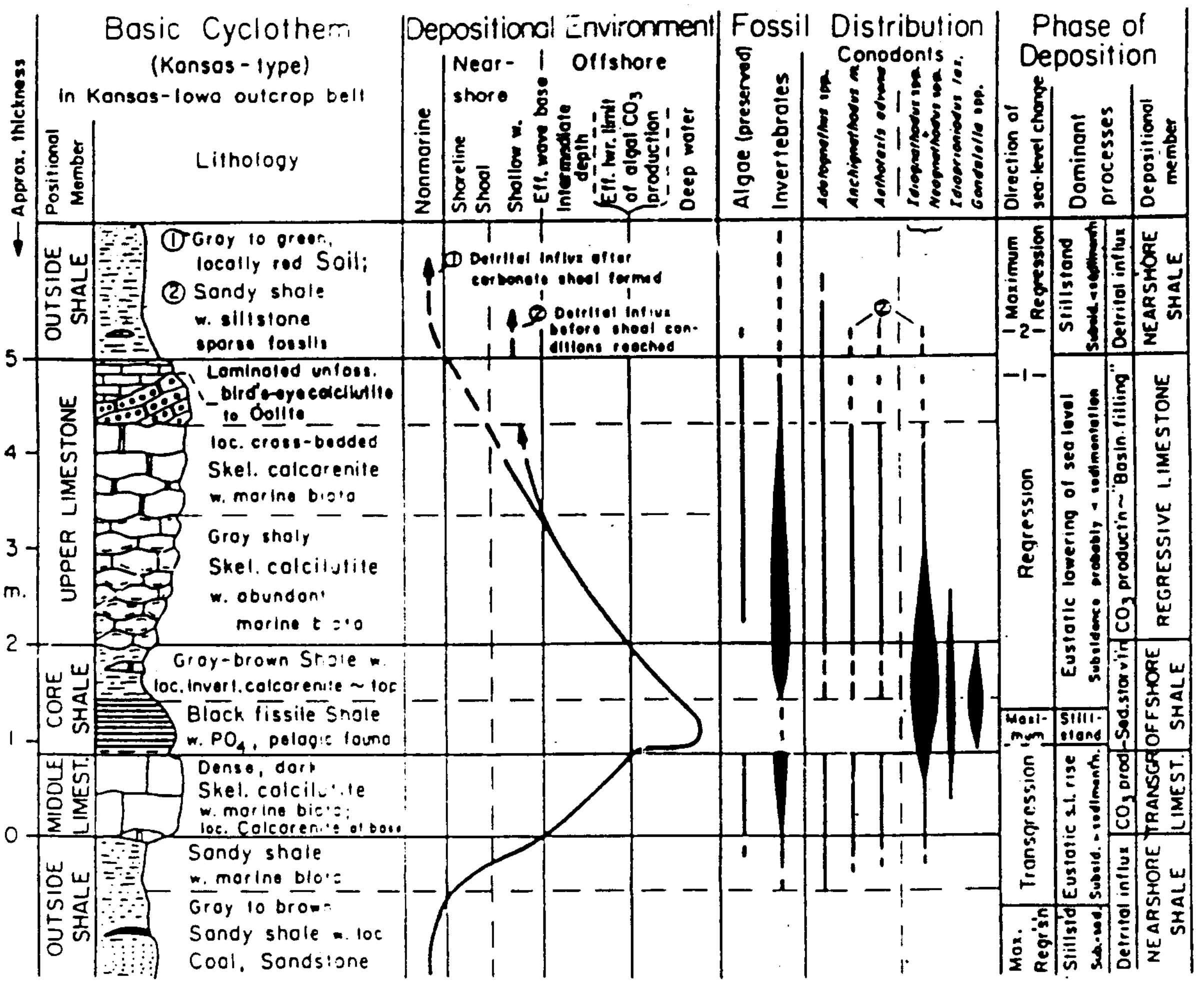


FIGURE 12—Basic Kansas cyclothem characterizing carbonate-dominated strata in the northern midcontinent shelf (Heckel, 1977, 1989).

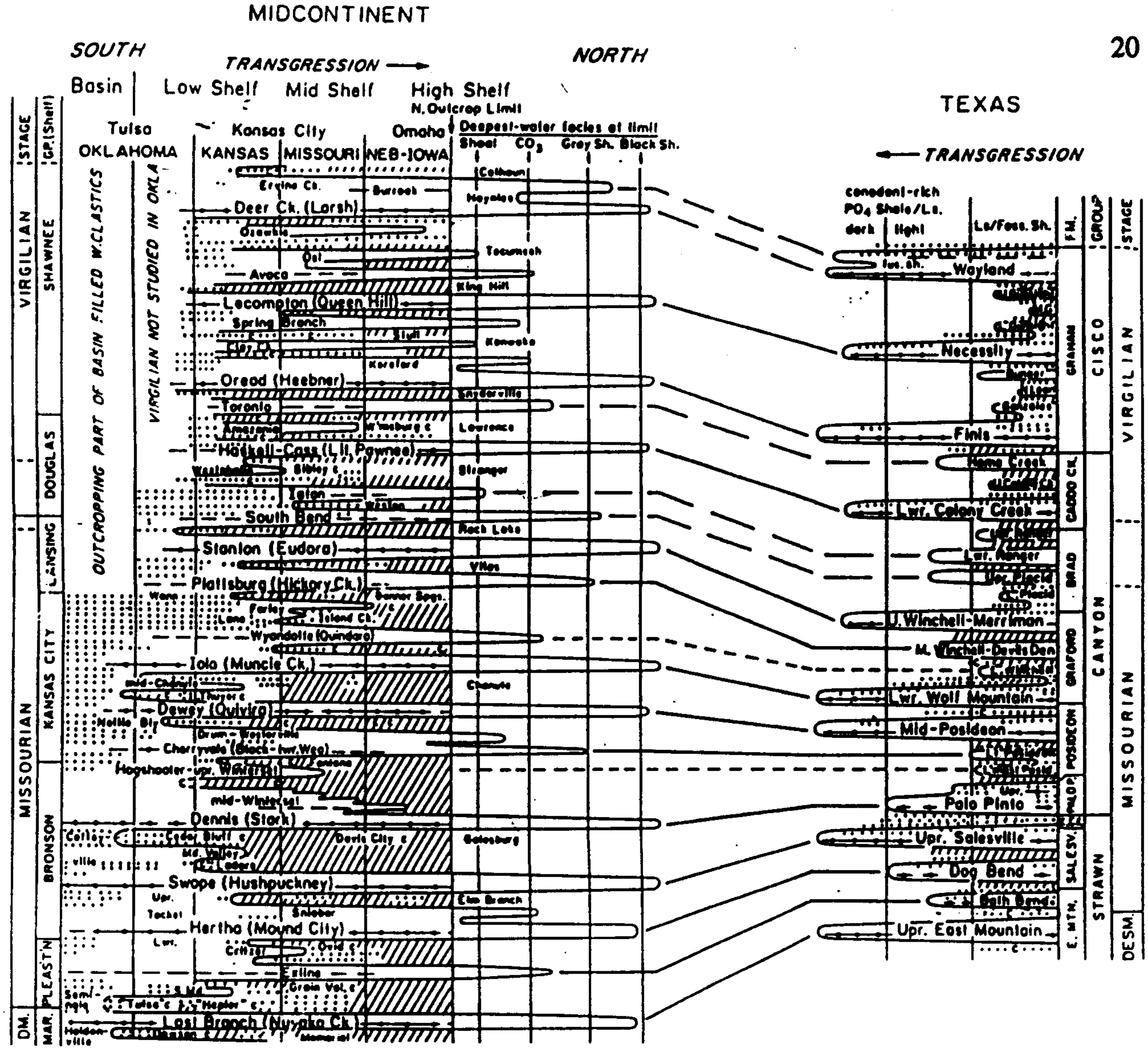


FIGURE 13—Glacial-eustatic sea-level curves for early Upper Pennsylvanian succession in north-central Texas and midcontinent correlated using biostratigraphy. Curves depict maximum inundations based on occurrence of black shale and low stand based on extent of subaerial exposure (Boardman and Heckel, 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	Sloss cratonic sequences plate movement-tectonic synthems 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 cyclothems
6th order	50–130 ka	PAC (punctuated aggradational cycles)—Goodwin and Anderson (1985); Pleistocene glacial-interglacial (rates 2–10 m/ka)

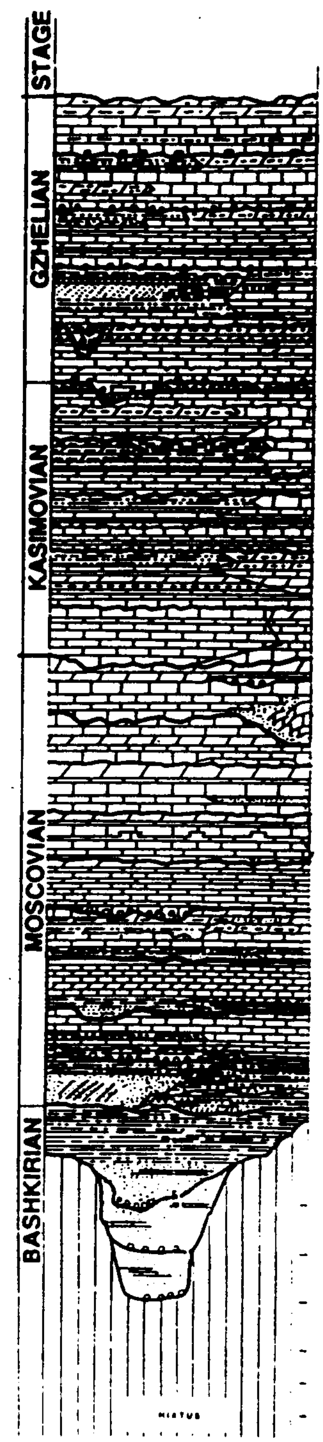


FIGURE 14—Stratigraphic section of carbonate-dominated Middle and Upper Carboniferous shelf cyclothems on Russian platform. Kasimovian is equivalent to Missourian and earliest Virgilian (Ross and Ross, 1988).

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 cyclothems 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 cyclothems (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 cyclothemic 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 eustacy 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.

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 clinoforms.

- 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.

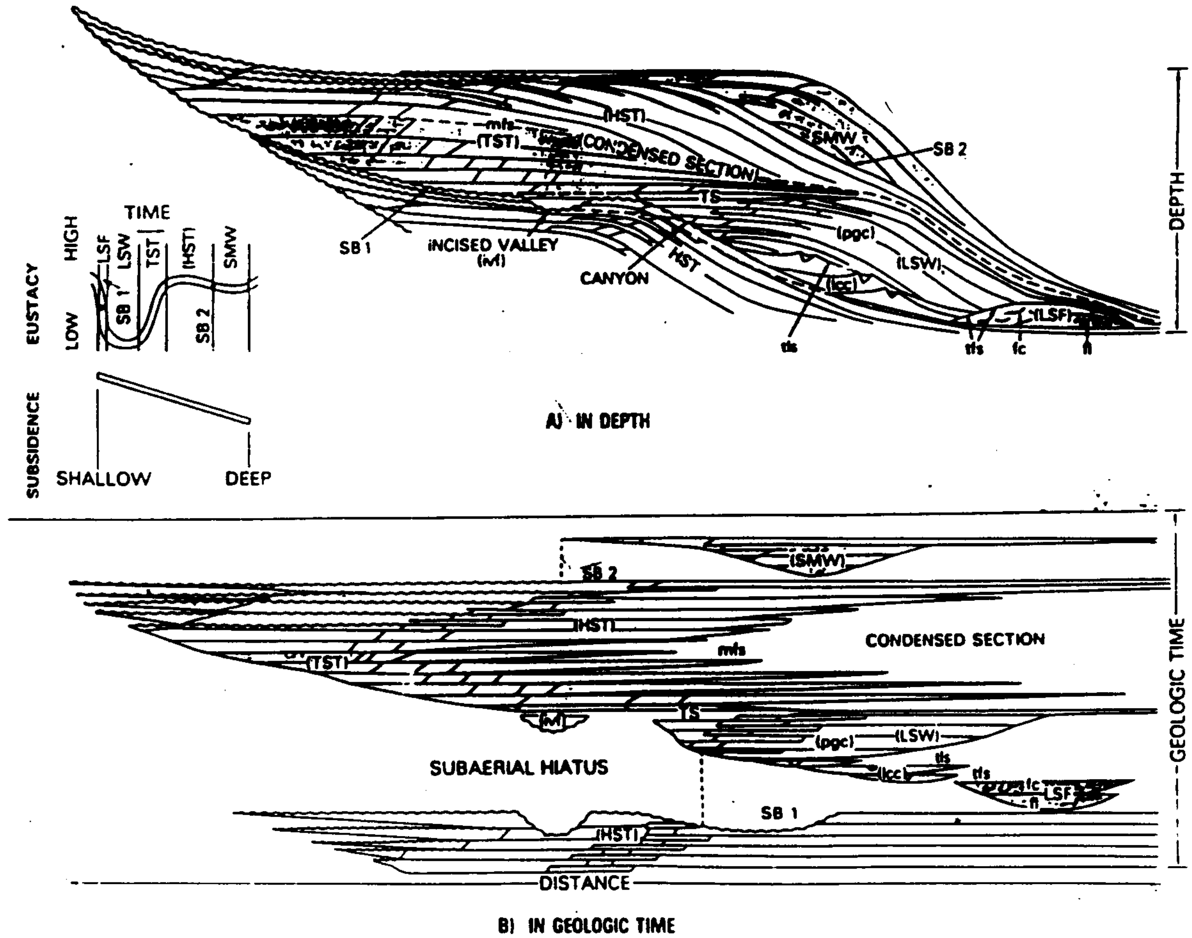
Expected stratal geometries on the shelf include: subtle onlap and offlap, local wedges of fluvial deposits and buildup of carbonate deposits, and subtle changes in sediment-surface elevation due to concurrent structural deformation.

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)



SURFACES	SYSTEMS TRACTS
(SB) SEQUENCE BOUNDARIES	HST = HIGHSTAND SYSTEMS TRACT
(SB 1) = TYPE 1	TST = TRANSGRESSIVE SYSTEMS TRACT
(SB 2) = TYPE 2	LSW = LOWSTAND WEDGE SYSTEMS TRACT
(DLS) DOWNLAP SURFACES	ivf = incised valley fill
(mfs) = maximum flooding surface	pgc = prograding complex
(tfs) = top fan surface	lcc = leveed channel complex
(tls) = top leveed channel surface	LSF = LOWSTAND FAN SYSTEMS TRACT
(TS) TRANSGRESSIVE SURFACE	fc = fan channels
(First flooding surface above maximum	fl = fan lobes
regression)	SMW = SHELF MARGIN WEDGE SYSTEMS TRACT

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.

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

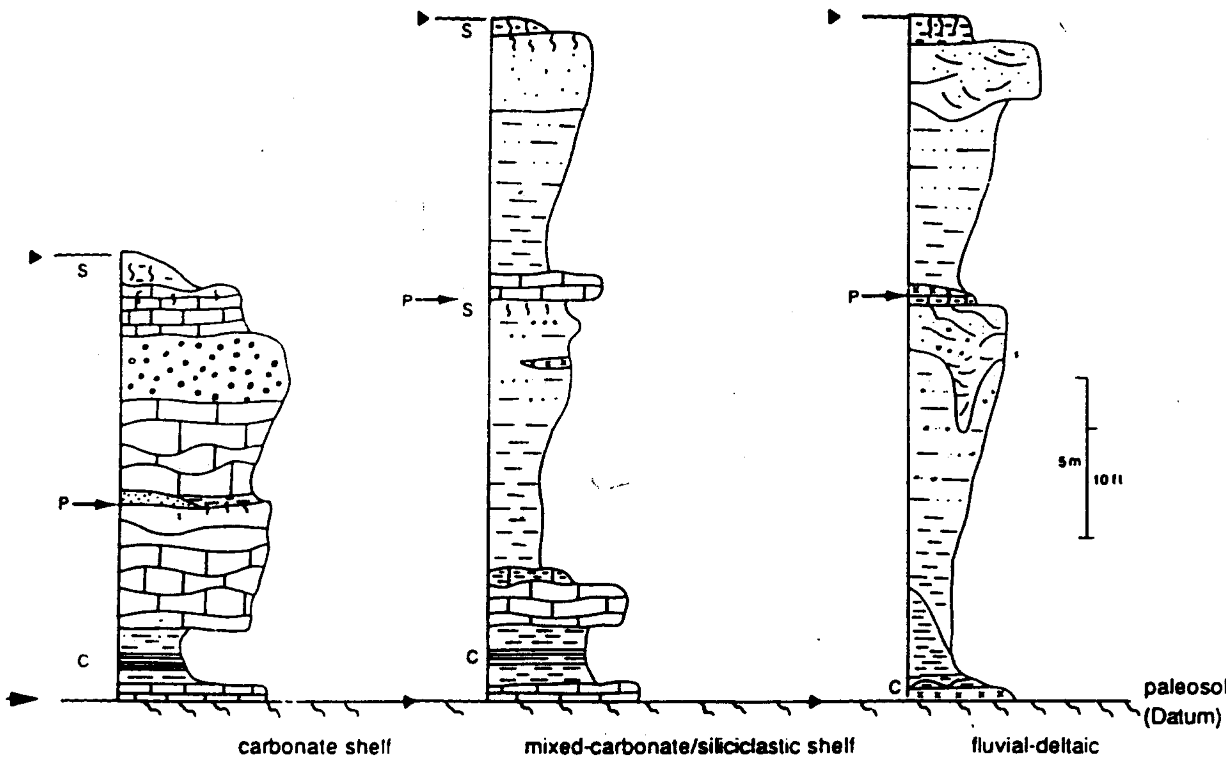


FIGURE 16—Vertical profiles of selected types of depositional sequences observed in Pennsylvanian strata of the midcontinent. Simple shallowing-upward sections shown.

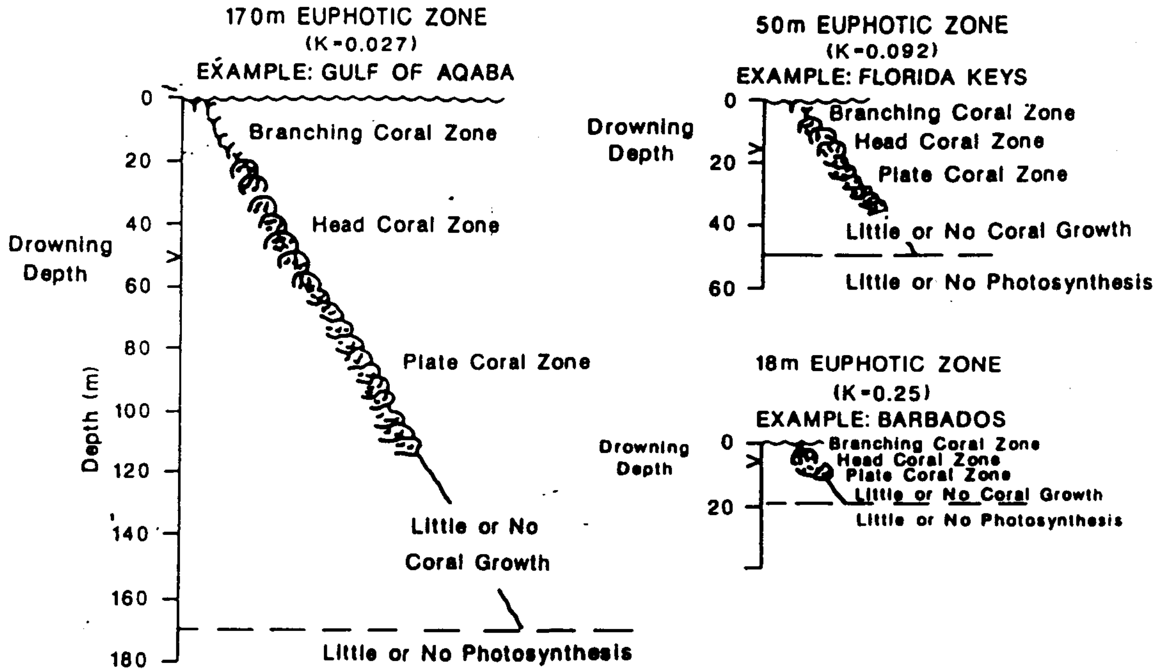


FIGURE 17—Illustrations showing influence of water clarity on zooxanthellae [sic] (zoochlorellate) corals. "K" is the extinction coefficient of light. Drowning depth shown is approximate submergence depth required to physically drown that reef (Hallock and Schlager, 1986).

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 zooxathellate 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 $CaCO_3$ 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 km^2); 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).

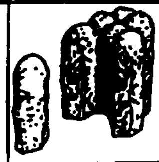
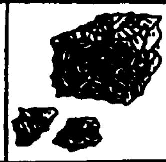
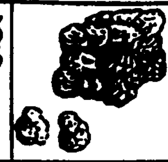
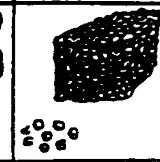
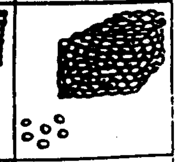
TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking 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

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.

Paleosols rich in calcium carbonate are referred to as *caliche*, defined as a strataform to irregular deposit, formed primarily of calcium carbonate, with concretional, 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

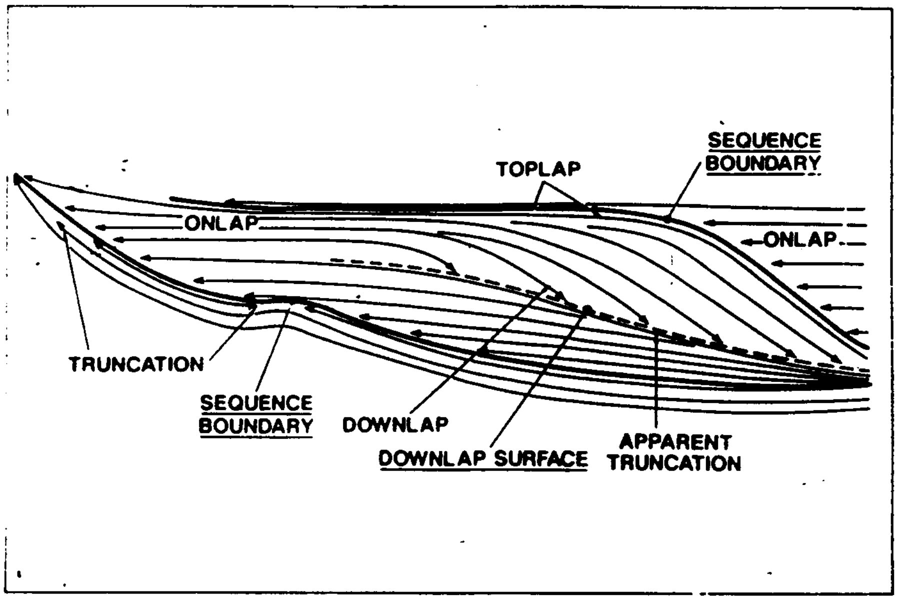


FIGURE 19-Types of discontinuities in a depositional sequence (from Vail, 1987).

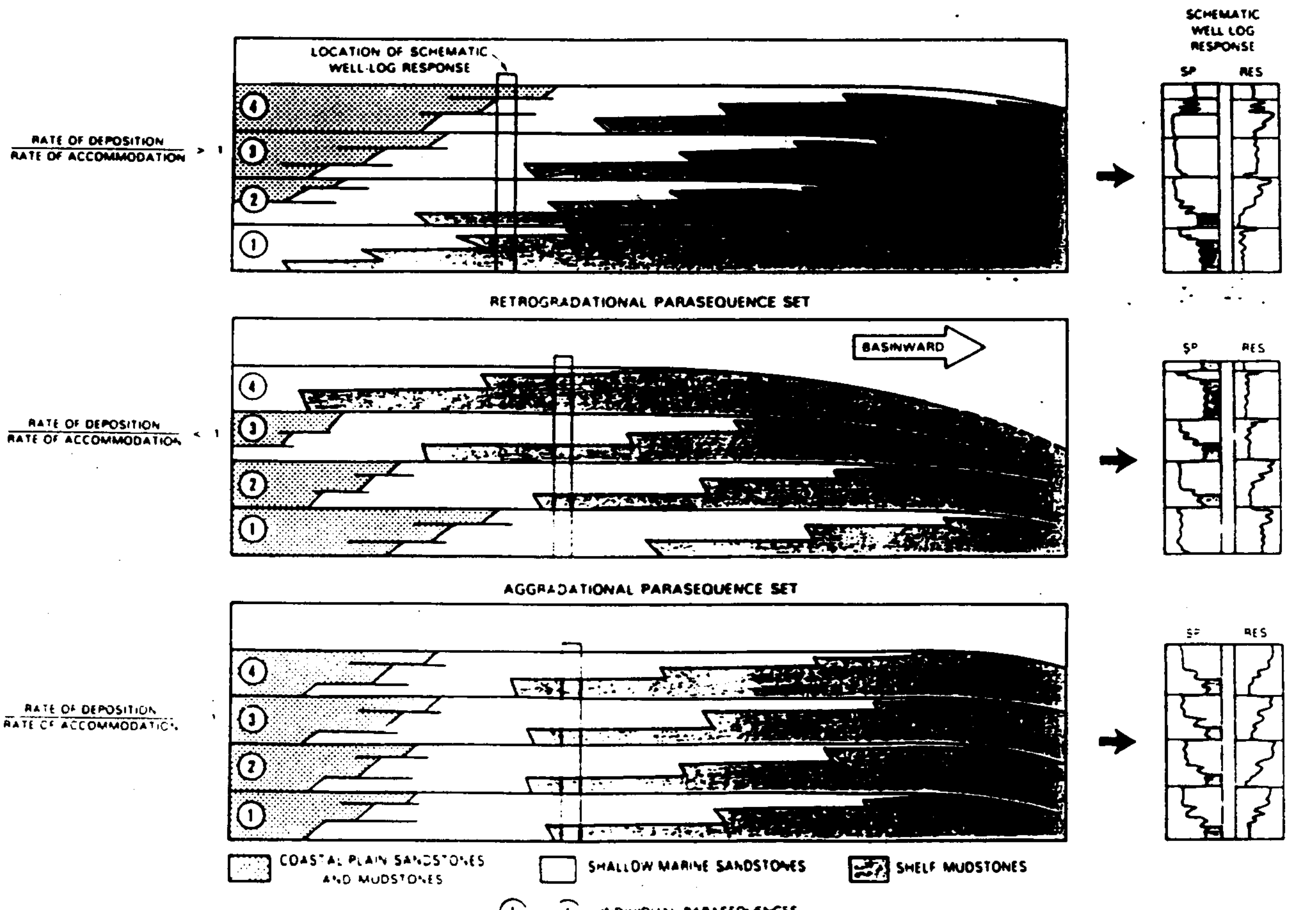


FIGURE 20—Examples of progradational, retrogradational, and aggradational parasequence sets for shelf with schematic well-log response (from Van Wagoner et al., 1987).

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.

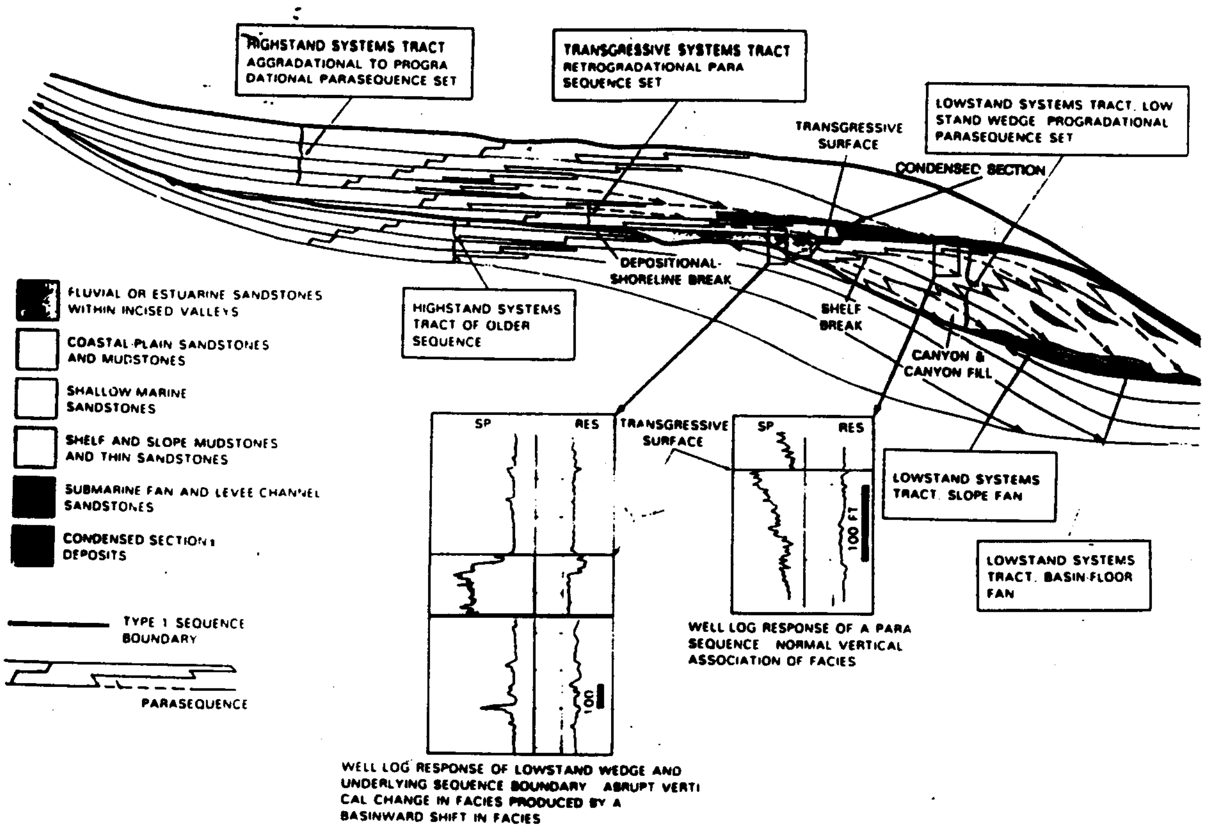


FIGURE 21-Example of parasequence geometries in context of crossing a type 1 sequence boundary (from Van Wagoner et al., 1987).

ROADLOG

miles	cum. miles	
0.0	0.0	Begin in parking lot of Travel Lodge motel in Lawrence Kansas. Leave parking lot heading south on Iowa St. **[depart at 7:20]**
1.0	1.0	Plattsmouth Limestone Member of Oread Limestone on both sides of road.
0.3	1.3	Corner of 19th and Iowa; KGS on right.
0.6	1.9	Turn left (east) on Kansas highway 10 (Clinton Parkway).
0.8	2.7	Dunkin Donuts on the right.
0.6	3.3	Haskell Indiana Junior College (founded 1884) on the right.
1.3	4.9	Fertilizer plant on north side of road.
0.6	5.5	The Haskell Limestone Member of the Lawrence Formation holds up the ridges in this area, and the Vinland Shale Member of the Stranger Formation is the valley former.
2.5	8.0	Douglas Co. 1057.
0.9	8.9	Wakarusa River.
2.0	10.9	Douglas Co. 1061 to Eudora.
1.2	12.1	Douglas Co. 442.
0.5	12.6	Stanton Limestone outcrop on left (north) of K10.
0.2	12.8	Vilas Shale on both sides of road.
0.4	13.2	Captain Creek Limestone Member of Stanton Limestone on both sides of road.
0.1	13.3	Douglas/Johnson Co. Line.
1.0	14.3	Road to Sunflower Ordinance plant.
1.2	15.5	**STOP 1**—Stanton Limestone on both sides of road. **[depart at 8:00]**
0.4	15.9	Vilas Shale–Captain Creek Limestone Member exposed on both sides of road.
0.2	16.1	Eudora Shale Member of Stanton Limestone on right overlain by Stoner Limestone Member. Note the black, platy nature of the Eudora Shale Member as we drive by.
1.2	17.3	Captain Creek Limestone Member of Stanton Limestone on left.
0.2	17.5	Road to DeSoto (Hwy 285).
1.0	18.5	Kill Creek section. Note that the Eudora Shale Member (on left side of road) is thicker and more gray than 2.4 miles farther west.
1.1	19.6	Stoner Limestone Member of Stanton Limestone on both sides of road.
0.7	20.3	Captain Creek and Stoner Limestone Members of Stanton Limestone on both sides of road.
0.4	20.7	Farley and Argentine Limestone Members of Wyandotte Limestone.
0.3	21.0	Camp Creek.
0.4	21.4	Cedar Creek.
0.1	21.5	Argentine and Farley Limestone Members of Wyandotte Limestone and Merriam Limestone Member of Plattsburg Limestone (in ascending order).
1.3	22.8	Plattsburg Limestone on both sides of road.
0.5	23.2	Spring Hill Limestone Member of Plattsburg Limestone on Cedar Creek Parkway south of K10.
0.4	23.6	Stanton Limestone on both sides of road.
0.5	24.1	Captain Creek Limestone Member of Stanton Limestone on both sides of road.

1.0	25.1	Kansas Highway 7.
1.7	26.8	Stoner and Captain Creek Limestone Members of Stanton Limestone on both sides of road.
0.3	27.0	Vilas Shale on left.
0.8	27.8	Spring Hill Limestone Member of Plattsburg Limestone overlain by Vilas Shale on both sides of road.
0.3	28.1	Captain Creek Limestone Member overlain by Eudora Shale Member and Stoner Stoner Limestone Member (all Stanton Limestone).
0.5	28.6	Quarry in Stanton Limestone on left (north) of K10.
0.4	29.0	Spring Hill Limestone Member of Plattsburg Limestone on right.Bear right to I-435 north. Bonner Springs Shale and PlattsburgLimestone on entrance ramp to I-435.
0.6	29.6	Bonner Springs Shale and Plattsburg Limestone on left sandstone in Vilas Shale above Plattsburg Limestone.
0.8	30.4	Captain Creek Limestone Member,Eudora Shale Member (black), and Stoner Limestone Member (all Stanton Limestone) on both sides of road.
0.7	31.1	Stoner Limestone Member of Stanton Limestone.
0.2	31.3	87th St.; exit 3.
1.1	32.4	Stanton Limestone.
0.4	32.8	Plattsburg Limestone and Bonner Springs Shale.
0.2	33.0	Two limestones (separated by shale) in the Farley Limestone Member of the Wyandotte Limestone.
0.2	33.2	Argentine Limestone Member of the Wyandotte Limestone on left.
0.8	34.0	Bonner Springs Shale and Plattsburg Limestone at exit 6A.
0.8	34.8	Top of Plattsburg Limestone.
0.2	35.0	Top of Plattsburg Limestone.
0.2	35.2	Vilas Shale overlain by Stanton Limestone.
0.3	35.5	Top of Plattsburg Limestone.
0.5	36.0	Bonner Springs Shale overlain by Plattsburg Limestone.
0.2	36.2	Bear right on Exit 8A Holiday Drive; upper Farley Limestone Member on right.
0.5	36.7	Turn left (west) on Holiday Drive.
0.3	37.0	Make U-turn at I-435 south; **STOP 2**—Holiday Drive Section. **[depart at 9:20]**
0.2	37.2	Turn right back onto I-435 north.
0.5	37.7	Kansas River; Johnson/Wyandotte Co. line.
1.4	39.1	Kansas City, Kansas, city limits.
1.5	40.6	Kansas Avenue exit.
1.3	41.9	Plattsburg Limestone overlying Bonner Springs Shale in cuts onleft.
0.5	42.4	Bear right on Exit 12B; Plattsburg Limestone on both sides of road;**STOP 3**—Sandstone in Bonner Springs Shale below PlattsburgLimestone. **[depart at 10:20]**
0.4	42.8	Circle under I-435 overpass; bear right onto Exit 441A back to I-435 South.
0.2	43.0	Plattsburg Limestone on left.
0.3	43.3	Bonner Springs Shale on right; note the paleosol developmenthere as we drive by and compare this exposure with the one wejust examined at Stop 3.
4.2	47.5	Kansas River; quarry in Wyandotte Limestone to right; this was Stop 2 from earlier in the

		morning.
1.0	48.5	STOP 4—Paleosol in the Bonner Springs Shale. [depart at 10:50]
5.8	54.3	Bear right onto Kansas Hwy 10, west to Lawrence.
11.2	65.5	Kill Creek section; gray Eudora Shale Member of StantonLimestone on right; conglomerate in Captain Creek LimestoneMember of Stanton Limestone at west end of exposure.
5.7	77.7	Turn right on Douglas Co. 442.
0.3	78.0	Stop sign; turn left onto 15th Street.
0.5	78.5	Railroad crossing.
2.2	80.7	STOP 5—Type locality of the Haskell Limestone Member, Lawrence Formation. [depart at 11:40]
0.8	81.5	Stop sign at Haskell Ave./15th St.; turn left (south) on Haskell Ave.
1.0	82.5	Intersection of Haskell Ave./23rd St.; turn right (west) on 23rd St.
2.0	84.5	Intersection of 23rd St. (aka, Clinton Parkway) with Iowa St.
2.3	86.8	Toronto Limestone Member of Oread Limestone on right.
0.4	87.2	Toronto Limestone Member of Oread Limestone.
0.5	87.7	Toronto Limestone Member of Oread Limestone.
0.6	88.3	STOP 6—Clinton Spillway section. [depart at 12:20]
0.3	88.6	Stop sign; turn left and cross dam of Clinton Reservoir.
2.4	91.0	Oread Limestone.
0.2	91.2	Upper part of Lawrence Formation overlain by Toronto LimestoneMember of Oread Limestone.
0.5	91.7	Stop sign; turn right on 1000E.
3.9	95.6	Turn left onto Douglas Co. 1039 to Lone Star Lake.
0.8	96.4	Lone Star, Kansas. Stop sign; turn right onto Douglas Co. 1.
2.6	99.0	Stop sign; turn right onto Douglas Co. 1-W; cross dam.
0.3	99.3	STOP 7—Lone Star dam spillway on right; lunch. [depart at 1:30]
0.2	99.5	Toronto Limestone Member of Oread Limestone on right.
1.1	100.6	Stop sign; turn left onto Douglas Co. 460.
0.7	101.3	Bear right at junction with 650E.
1.0	102.3	Stop sign; left turn onto 500N.
1.4	103.7	Stop sign; continue east on 500 N.
1.0	104.7	Junction of Douglas Co. 460 and 1039; continue east on 460.
4.9	109.6	Junction of Douglas Co. 460 and US 59 south; left turn (north) ontoUS 59 toward Lawrence.
1.8	111.4	Toronto Limestone Member of Oread Limestone on left.
5.9	117.3	Intersection of Iowa St and Clinton Parkway (aka, K10, 23rd St.);continue north on Iowa St.
0.5	117.8	KGS on left (19th and Iowa).
1.4	119.2	Bear right; stay on US 59 north to I-70 (aka, Kansas Turnpike, if east of Topeka).
1.2	120.4	Stop to get tollbooth ticket; continue west on I-70 towards Topeka.
0.7	121.2	Iowa street overpass; bridge number 201.751 (bridges along theturnpike are numbered to the nearest 1/1000th of a mile from the Oklahoma border, which is where the turnpike begins)
2.8	123.0	Mile marker 199
0.1	123.1	STOP 8—(=stop 1 of Moore and Merriam, 1959). [depart at 2:25]
2.9	126.0	Mile post 196; STOP 9—(=stop 2 of Moore and Merriam, 1959).[depart at 2:45]

2.0	128.0	Mile post 198; STOP 10—(=stop 3 of Moore and Merriam, 1959). **[depart at 3:20]**
5.5	133.5	Douglas/Shawnee Co. line.
5.5	139.0	Topeka Limestone on right (across from Hardee's).
0.9	139.7	Topeka city limits.
0.5	140.2	East Topeka Interchange; continue west, now on I-470 (still onKansas Turnpike).
3.8	144.0	Mile post 178; Aarde Shale Member of Howard Limestone on bothsides of road. The Nodaway coal bed occurs in the Aarde ShaleMember. R.C. Moore named the Aarde Shale Member forexposures on Aarde Farm, and picked the name so it would be thefirst one in the USGS Lexicon of geologic names (yes, it still is).
0.8	144.8	South Topeka exchange; bear right onto exit 127.
0.3	145.1	Stop, pay toll (thank you; have a nice day); continue west on I-470.
0.7	145.8	Bear right at Exit 5, Burlingame Road.
0.2	146.0	Stop sign; cross over to entrance ramp of I-470 west.
0.1	146.1	STOP 11—Aarde Shale Member and Church Limestone Memberof Howard Limestone. **[depart at 4:10]**
3.7	149.8	Mile post 2.
0.6	150.4	Follow detour signs around bridge construction at Hypermart.
0.8	151.2	Intersection of SW Wanamaker Road and SW 10th St.; followdetour to west I-70.
0.2	151.4	Entrance ramp for west I-70 at Wanamaker Road.
1.3	152.7	Mile post 355.
1.8	154.5	Outer Limits of Topeka.
4.1	158.6	STOP 12—Tarkio Limestone Member (overlain by Wamego Shale Member, mostly covered, and Maple Hill Limestone Member) of Zeandale Limestone. **[depart at 4:35]**
1.1	159.7	Mile post 348.
2.0	161.7	Shawnee/Wabaunsee Co. line.
0.9	162.6	Maple Hill exit; continue west.
0.7	163.3	STOP 13—Current Pennsylvanian-Permian boundary in Kansas. **[depart at 5:20]**
1.4	164.7	Mile post 339.
0.8	165.5	Bear right at Exit 338 onto Vera Road.
0.2	165.7	Turn left; cross under I-70.
0.1	165.8	Turn left onto entrance ramp for East I-70; return to Travel Lodge,Lawrence.
49.8	215.6	Travel Lodge, Lawrence. **[arrive 6:20]**

END OF FIELDTRIP

Stop 1 Edgerton Road: Vilas Shale and Stanton Limestone, (Captain Creek Limestone, Eudora Shale, Stoner Limestone)

Location: SE SE SE sec. 2, T. 13 S., R. 21 E., Johnson County, Kansas

Departure: 8:00

Contributors: *Lynn Watney, John French,* and *Evan Franseen*

Introduction

Stop 1 is located 12 mi (19 km) east of Lawrence at the Edgerton Road exit off Highway 10 (fig. 1-1). The Lansing Group, here represented by the Stanton Limestone, is composed of cyclical mixed-carbonate and siliciclastic deposits in eastern Kansas. The stratal succession seen here is a typical example of a Kansas cyclothem presented by Heckel (1977). A Kansas cyclothem contains four lithologic components; in ascending order these are the middle (or transgressive) limestone, the core (offshore) shale, the upper (or regressive) limestone, and the outside shale. This classification was previously discussed in the Introduction in the section on cyclothem concepts and illustrated in fig. 12.

A complete Kansas cyclothem represents a major marine inundation in a shelf setting. Carbonate-dominated cyclothems of equivalent age in other areas of the world are similarly developed, e.g. on the Russian platform and in the Paradox basin. Glacial eustasy is strongly supported as the cause of these relatively short-term (250 to 400 ka) but high-amplitude (perhaps 300+/- ft, 90+/- m) fluctuations in sea level. Evidence for eustatic change includes the ability to correlate individual marine inundations among basins and continents (Ross and Ross, 1987; Boardman and Heckel, 1989). Subsequent sea- level falls have been documented to extend in most cases to the shelf margin in the midcontinent (Heckel, 1980, 1986; Watney, 1984).

The Pleistocene analogue to late Paleozoic glacial eustasy suggests considerable variability in the shape of the eustatic curve from one inundation to another (also discussed in the Introduction). Pleistocene sea-level changes varied from symmetric to asymmetric and, in terms of other mechanisms of sea-level change, were potentially very rapid (2 to 10 m/ka [7–33 ft/ka]). Sea-level falls varied from uniform to very erratic.

Although the typical cyclothemic lithologic succession discussed above occurs repeatedly in Missourian strata in the midcontinent, in some cycles or in some shelf positions additional limestones and shales may occur, or some units may be missing. This variability makes modifications to this four-component format necessary.

An alternative methodology that we are using to describe these shelfwide marine inundations and withdrawals is sequence stratigraphy. Sequence-stratigraphic principles center on the recognition of temporally distinct stratal units and stratal geometries that are related to cycles of relative base-level change. It is almost universally agreed that such cycles were the major cause of midcontinent cyclic successions.

The procedures and nomenclature related to sequence stratigraphy are described in section V and appendix A of the Introduction. The measured sections of the stops are annotated with stratigraphic units (e.g., paleosols and condensed sections) and surfaces (such as flooding surfaces, erosion surfaces, and sequence boundaries) that are essential to sequence-stratigraphic analysis (fig. 1-2).

Stratigraphy at Stop 1

The *Vilas Shale* is an outside shale that caps the underlying Plattsburg cyclothem. The Vilas Shale is well exposed to our east at the southeast corner of this intersection and is included in the measured section (fig. 1-3). It is a silty gray shale that contains lenses and beds of fine-grained, rippled and in places cross-stratified quartz sandstone. Brachiopods, crinoids, and trace fossils are present in the sandstones, especially at the top of the Vilas Shale immediately below the overlying Captain Creek Limestone. No evidence of subaerial exposure is present in this exposure of the Vilas, making the placement of the sequence boundary problematic. The top of the underlying regressive carbonate unit underwent subaerial exposure north of this location but apparently did not this far south. The turnaround from falling to rising relative sea level probably occurred at some point during deposition of the Vilas.

Outside shales of the upper Kansas City and Lansing groups are of variable thickness but generally consist of several meters of shallow-marine shelf and deltaic siliciclastics.

The *Captain Creek Limestone* overlies the Vilas Shale and is the lower member of the Stanton Limestone. The Captain Creek Limestone is the middle (transgressive) limestone of the Stanton cyclothem and the flooding unit of the Stanton sequence. The unit is much thicker than other middle limestones in this shelf setting. It represents the initiation of carbonate sedimentation during inferred eustatic rise. Initial marine flooding begins in the upper Vilas Shale and is marked by a fossiliferous horizon at the top of the unit. The recognition and correlation of the initial flooding surface becomes relatively subtle when this surface diverges from the marine-flooding unit.

The Captain Creek Limestone is predominately a normal-marine phylloid-algal wackestone. Its homogeneity is also indicated by the gamma-ray profile. The unit thins markedly and contains mud-pebble conglomerates a few miles east of this locality. Farther east of this anomalous setting the Captain Creek Limestone is again the more resistant limestone ledge that is so prominently exposed along K–10.

This unit contains numerous shale partings and microstylolites, which are more typical of regressive limestones than transgressive limestones such as the Captain Creek. There are no apparent facies changes across most of these partings, and evidence of dissolution along them indicates that they most likely represent nonsutured seam solution analogous to that described by Wanless (1979). Some seams in certain regressive units have been traced for 10's of kilometers; a depositional signal probably exists for such continuous seams.

The Eudora Shale at this location is a typical core shale (of the Stanton cyclothem) that contains a platy, black, phosphatic facies. This unit is continuous over a wide area and is classified in sequence-stratigraphic nomenclature as a condensed section that originated during maximum rate of eustatic rise and/or in the deepest water associated with the Stanton sequence. The black facies grades between Stops 1 and 2 to soft-gray shale containing abundant benthic fauna. East of Stop 2 the shale is very similar to that at Stop 1 (fig. 1-4). The black shale is associated with elevated gamma radiation. Although the gamma radiation is higher than in the gray shale, the magnitude is considerably less than the Hushpuckney and Stark shales seen later at Stop 7. The radiation is primarily attributed to uranium content (see fig. 34 from the introduction) that is in turn related to the amount of organic matter and phosphate content (Coveney et al., 1991).

A minimum of 4% total organic carbon is needed to make a shale black (J. Hatch, personal communication, 1984). Other features of the black- shale facies include an abundance of conodonts usually at the exclusion of benthic fauna, suggesting anoxic bottom waters. Conodonts are sufficiently abundant on bedding surfaces of the black shale to be seen with a hand lens. Phosphate is present as light brown laminae or nodules. Remains of fish and scattered woody-plant material is also present.

Dark-gray shale overlies and underlies the black-shale facies at this location. This succession is typical for the Eudora Shale and common for other black shales. These shales commonly exhibit a diverse and taxonomically distinctive fauna that has been interpreted to represent dysoxic environments (Boardman et al., 1984).

The *Stoner Limestone* at this location is a typical upper limestone of a Missourian cyclothem. It consists of wavy-bedded skeletal/phylloid-algal wackestone, and with a host of other normal- marine organisms. It is a shallowing-upward unit and includes cryptic fenestral voids near the top; about 10 mi (16 km) to the northeast, near Stop 3, the Stoner Limestone is capped by an abraded skeletal grainstone. The Stoner Limestone most likely represents carbonate aggradation during relative sea-level stillstand and fall. There is no apparent evidence for subaerial exposure here, although it has been noted in other locations on the northern shelf (Heckel, 1989). The Stoner is usually capped by the Rock Lake Shale, which in places contains a mollusk-dominated fauna and a thin coal.

Common macrofossils that occur in these strata are included in figs. 1-5 and 1-6

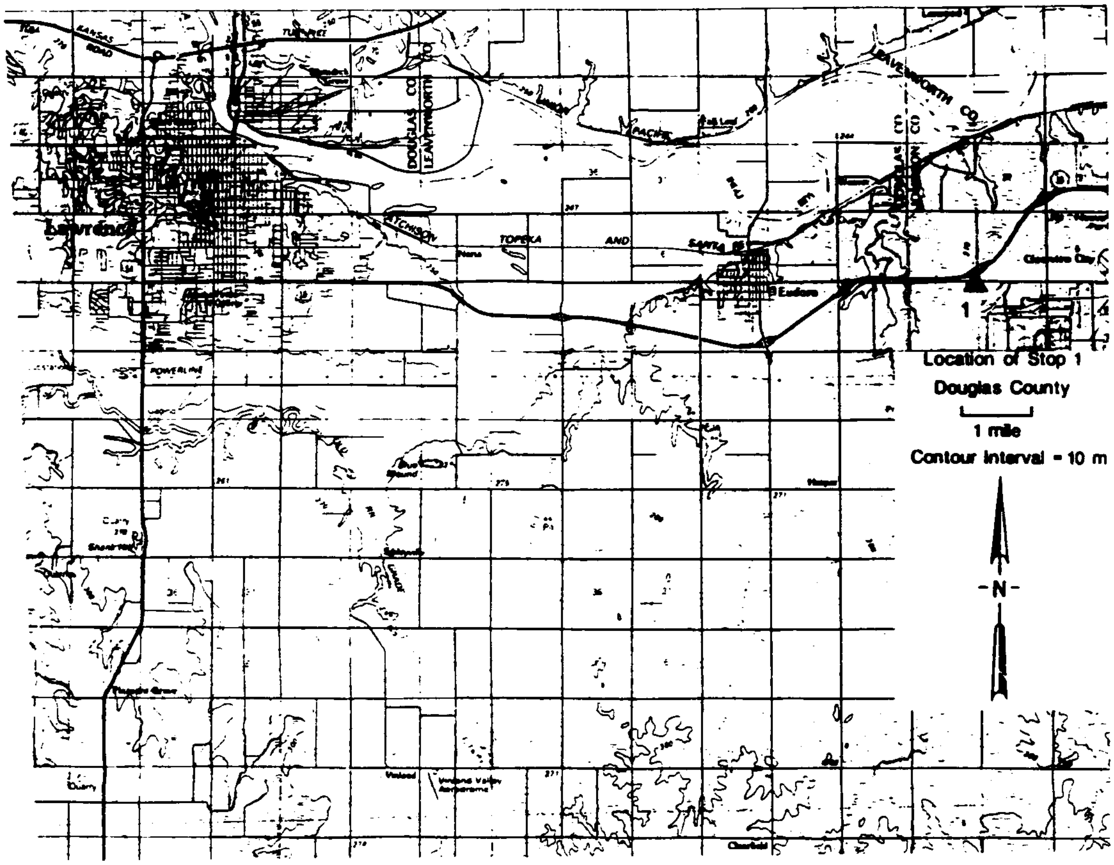


FIGURE 1-1—Location map for Stop 1, Edgerton exit on Highway 10 east of Lawrence.

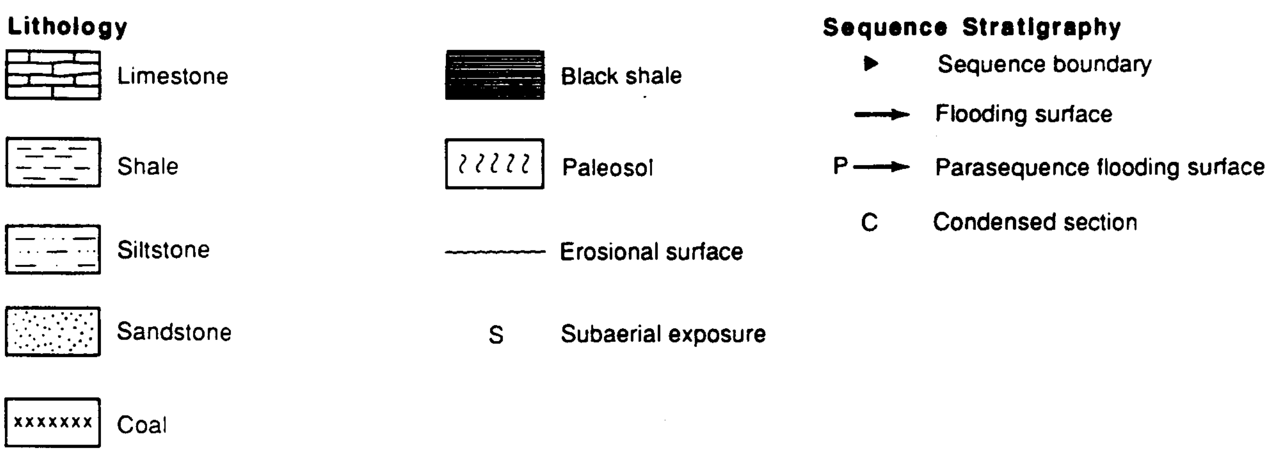


FIGURE 1-2—Legend with major lithologies, surfaces, and sequence-stratigraphic terms.

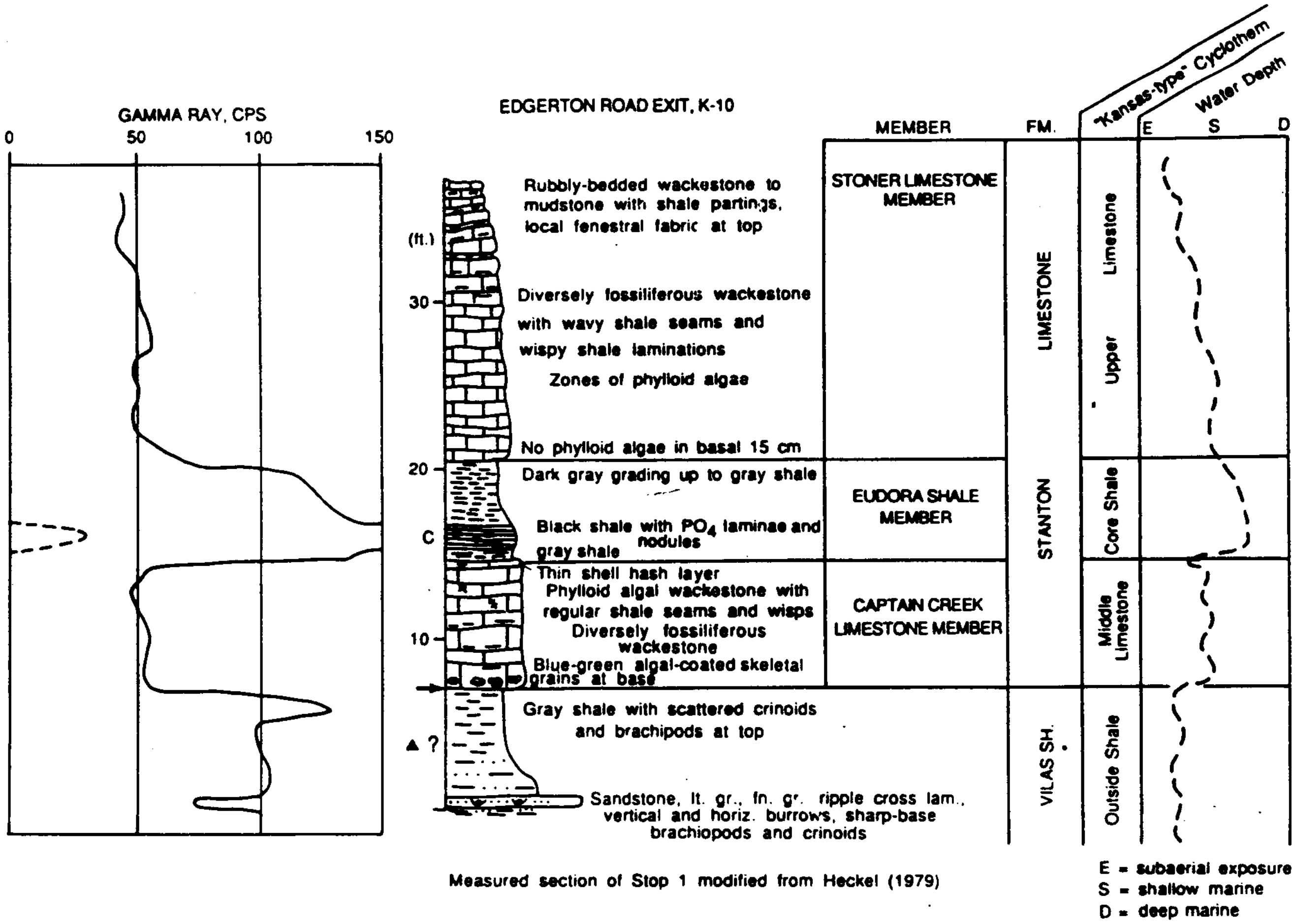


FIGURE 1-3—MEASURED SECTION OF STANTON LIMESTONE AT STOP 1. Natural gamma-ray profile obtained with hand-held gamma scintillation counter. Symbols used in graphic columns are shown in fig. 1-2.

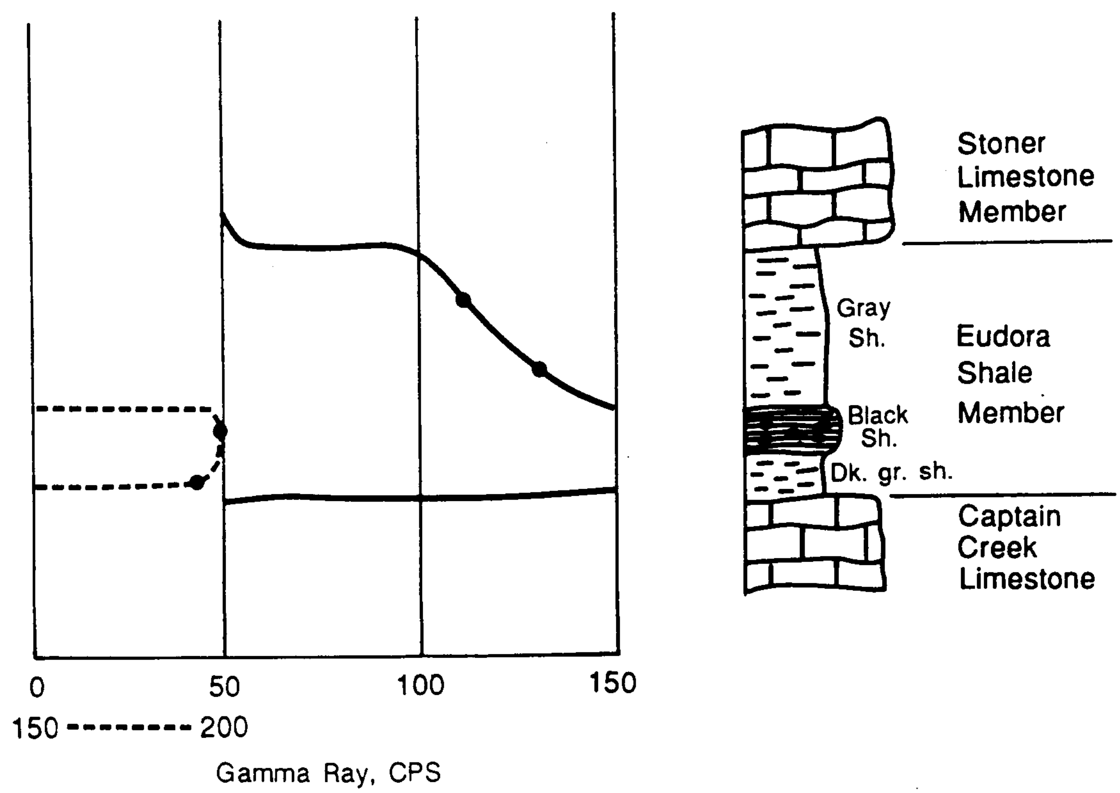


FIGURE 1-4—FOUR-FOOT (1.2-M)-THICK SECTION OF EUDORA SHALE EXPOSED ALONG I-435, 14 mi (23 km) east of Stop 1. Section is very similar to that seen at Stop 1.

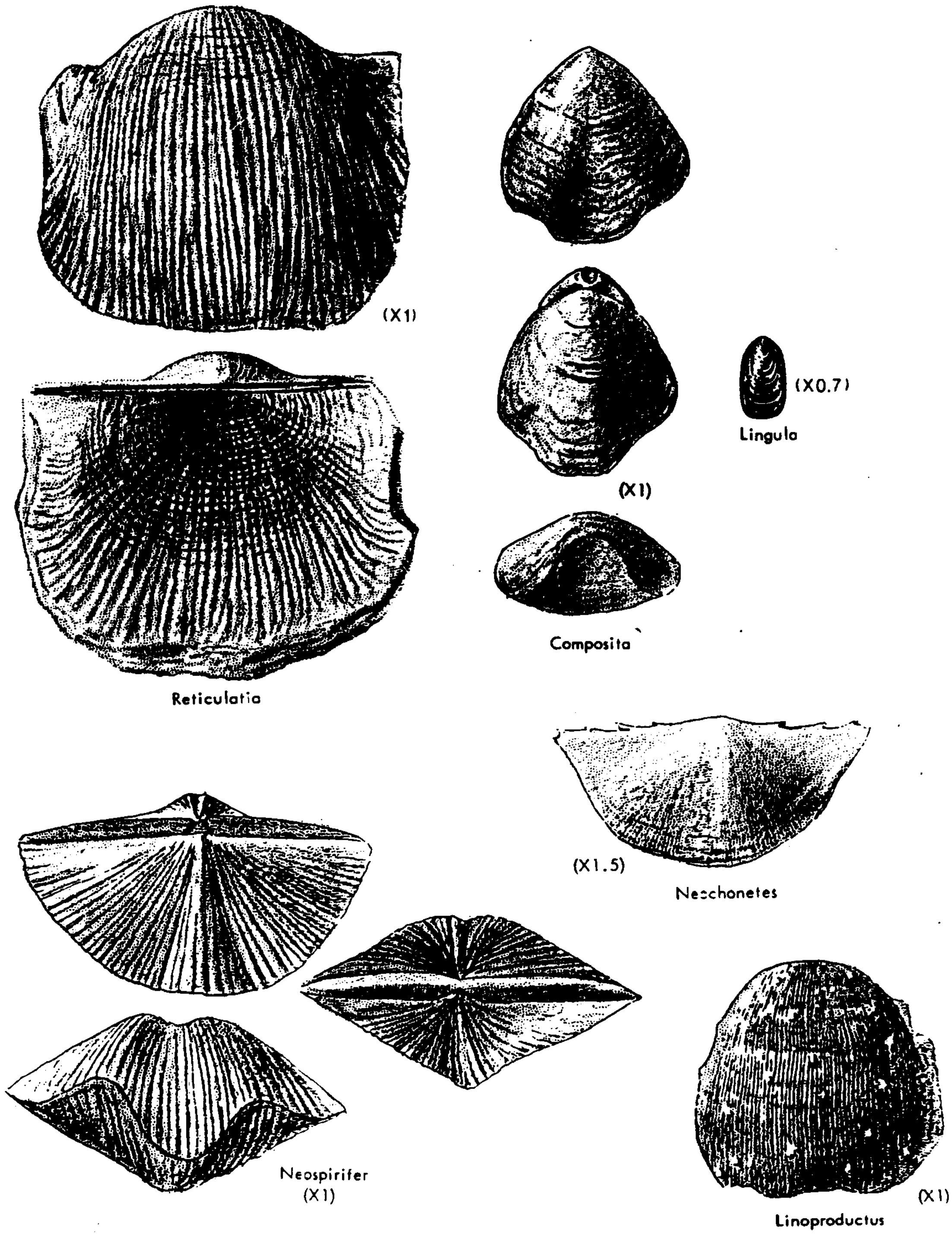


FIGURE 1-5—Common macrofossils occurring in Upper Pennsylvanian strata (from Moore, 1964).

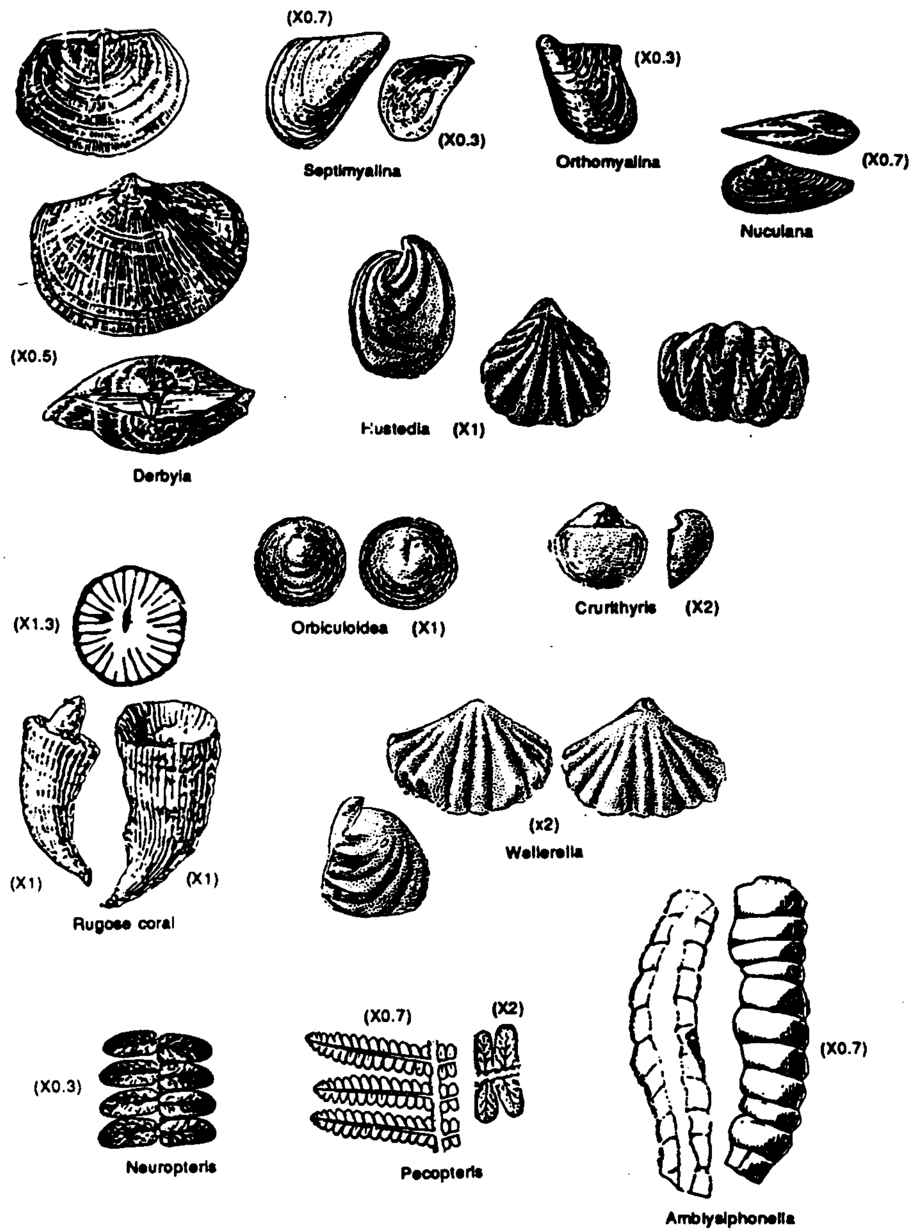


FIGURE 1-6—COMMON MACROFOSSILS OCCURRING IN UPPER PENNSYLVANIAN STRATA (from Moore, 1964).

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.)

Depart: 9:20

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. Ensuing 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.

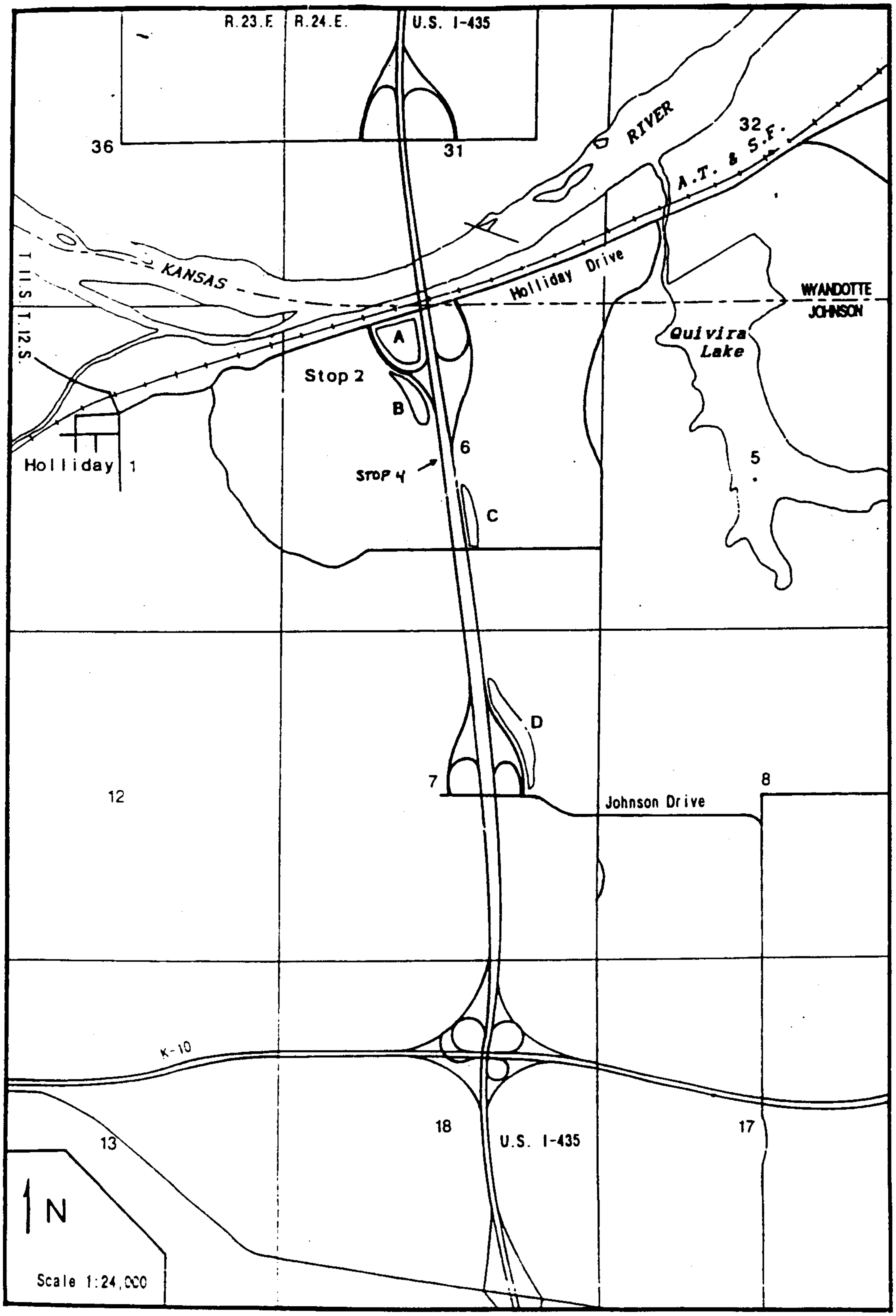


FIGURE 2-1–Location map of Stop 2 and sites A, B, C, and D used in preparing measured section provided with Stop 2 (fig. 2-2), from Johnsgard, 1984).

a

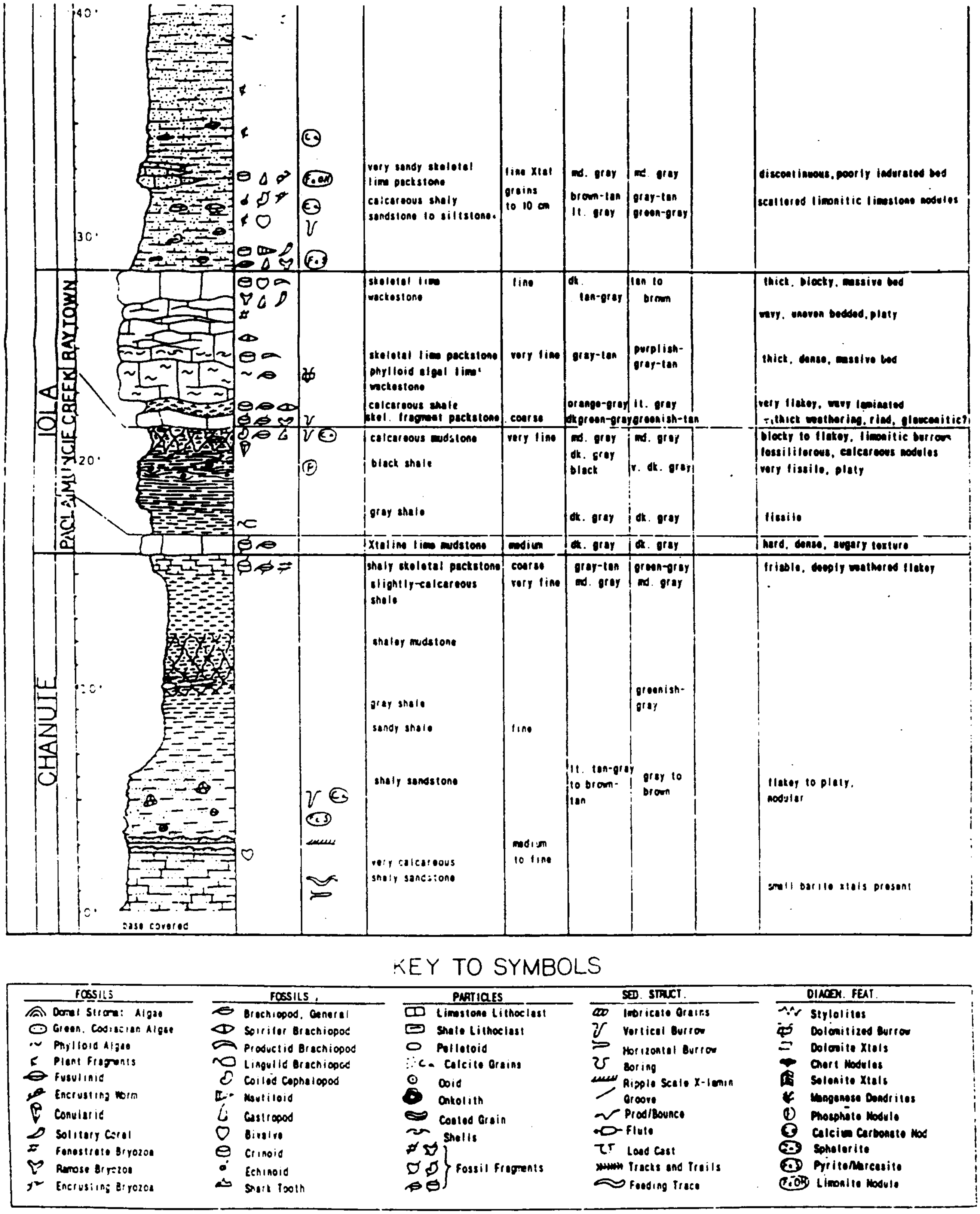
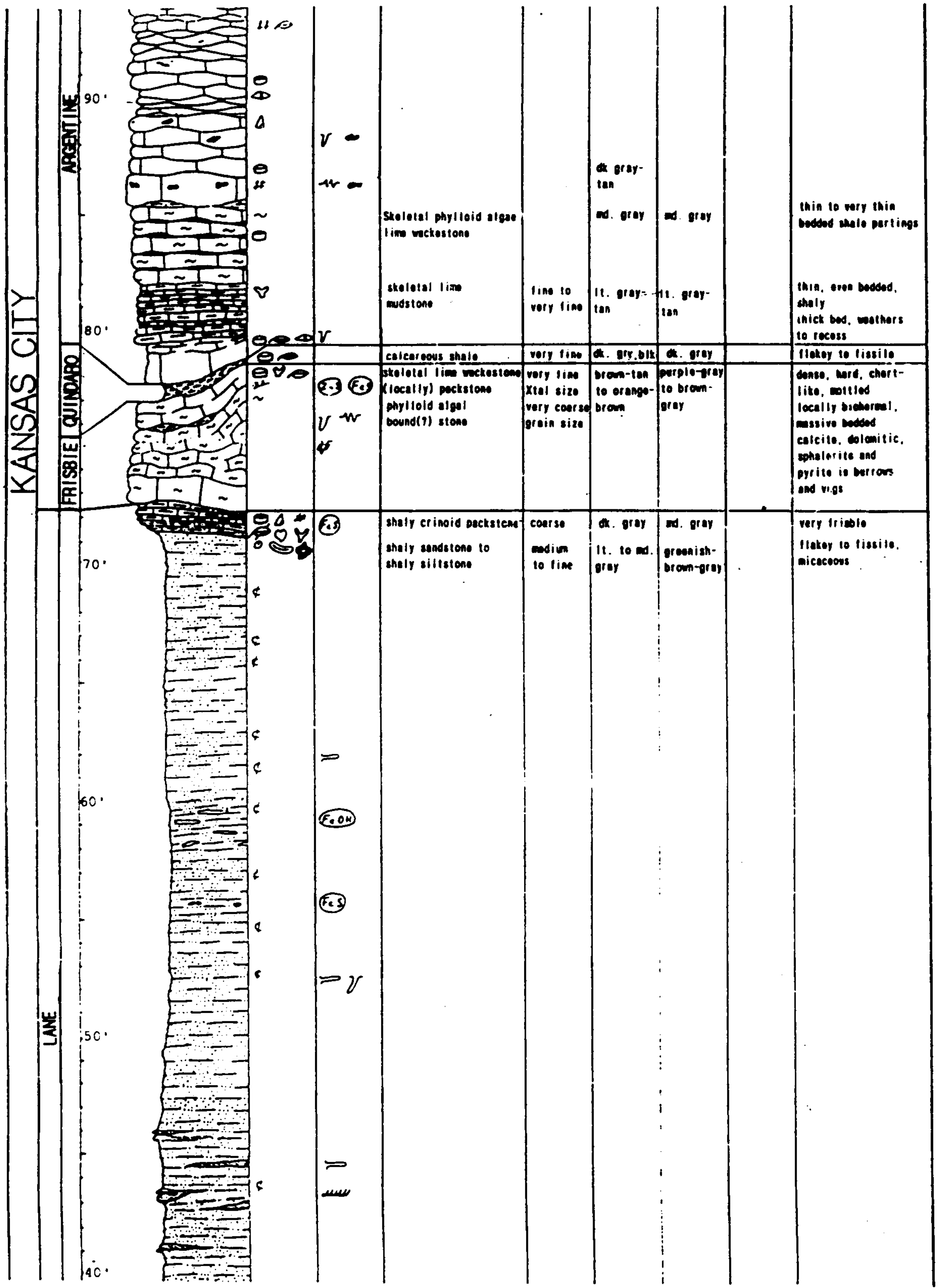
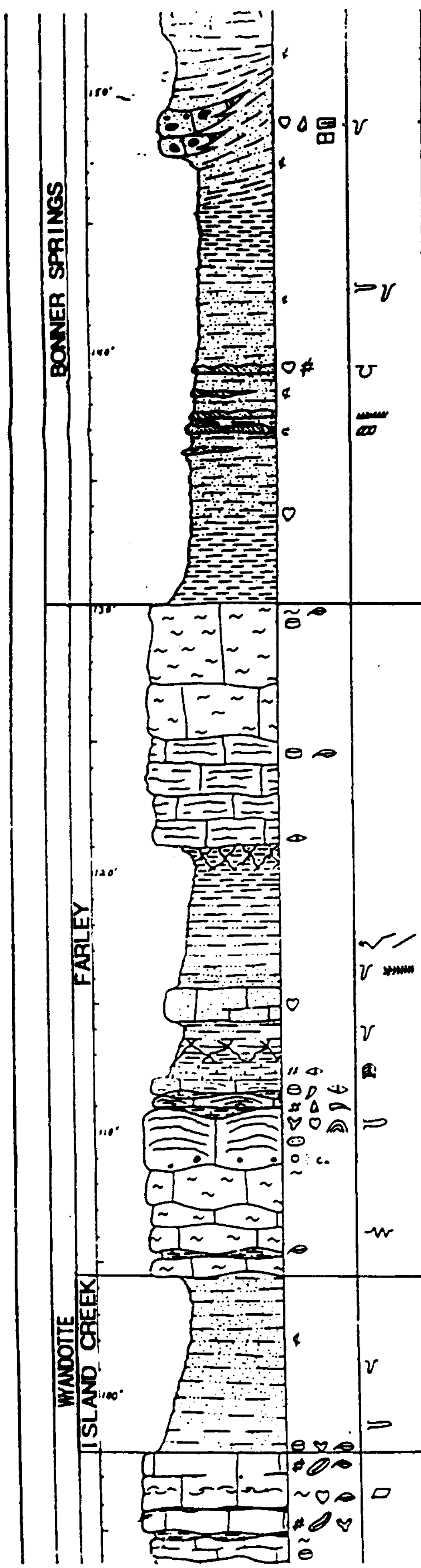


FIGURE 2-2 (A, B, C, D)–Measured section of Lansing and upper Kansas City Groups at Johnson Drive and Holliday Drive interchanges prepared by Johnsgard (1984).

b

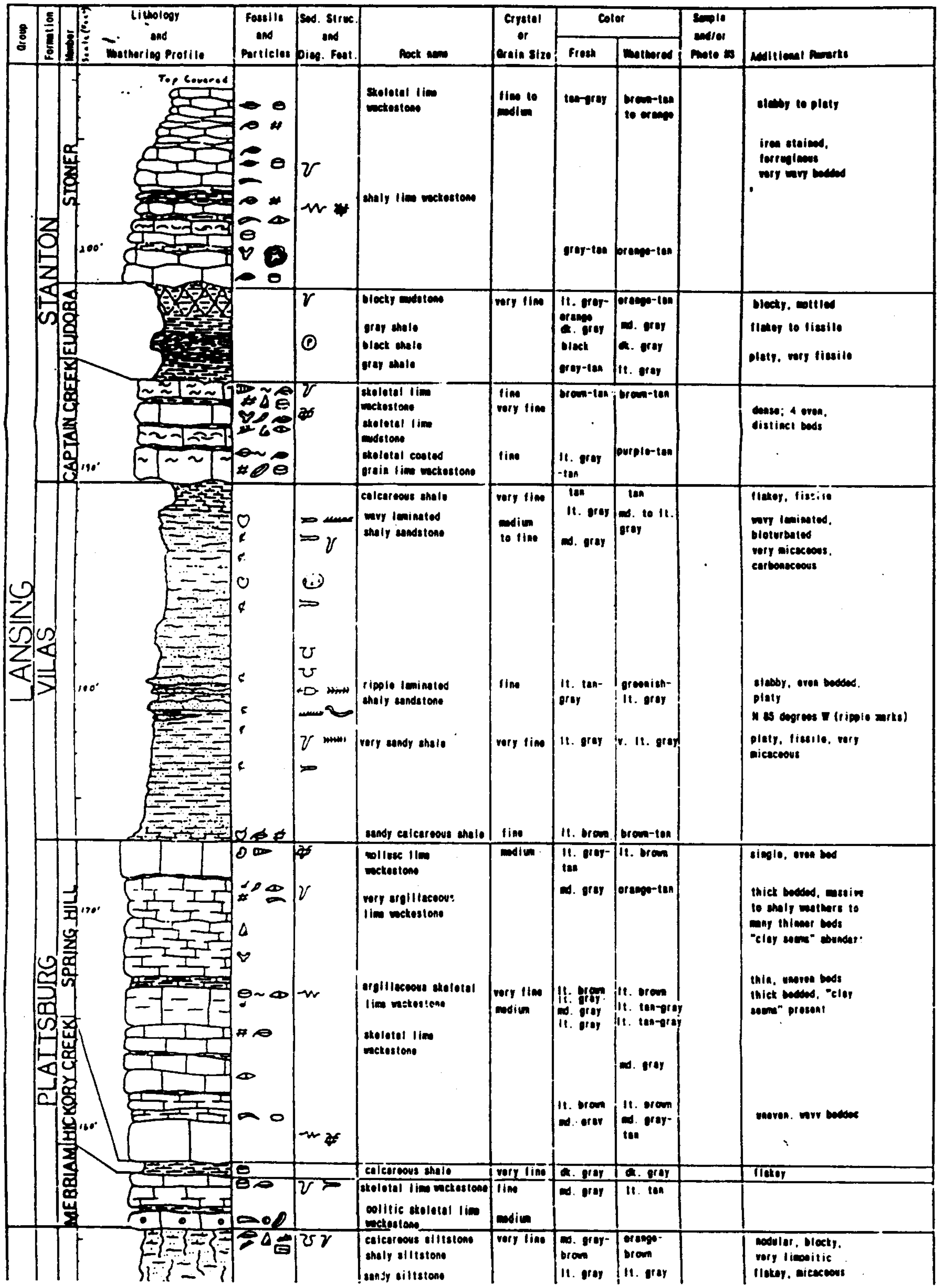

KANSAS CITY
ARGENTINE
QUINDARO
FRISBIE
LANE
90'
80'
70'
60'
50'
40'
Skeletal phylloid algae lime wackestone
dk gray-tan
md. gray
md. gray
thin to very thin bedded shale partings
skeletal lime mudstone
fine to very fine
lt. gray-tan
lt. gray-tan
thin, even bedded, shaly
thick bed, weathers to recess
calcareous shale
very fine
dk. gry,blk
dk. gray
flakey to fissile
skeletal lime wackestone (locally) packstone phylloid algal bound(?) stone
very fine Xtal size very coarse grain size
brown-tan to orange-brown
purple-gray to brown-gray
dense, hard, chert-like, mottled locally biohermal, massive bedded calcite, dolomitic, sphalerite and pyrite in berrows and vugs
shaly crinoid packstone
coarse
dk. gray
md. gray
very friable
shaly sandstone to shaly siltstone
medium to fine
lt. to md. gray
greenish-brown-gray
flakey to fissile, micaceous

C



shaly sandstone	fine	md. gray	pink-gray	platy to fissile
sandy lithoclastic mollusc lime 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
skeletal phylloid algae lime wackestone to packstone	very fine	gray-tan	pale pink-tan	thick bedded massive
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	fine			
lime mudstone	medium	gray-brown	pinkish-brown	single, persistent bed
shaly sandstone	fine	md. gray	lt. gray	flakey to fissile
shaly mudstone	very fine			
calcareous shale	fine	dk. brown	lt. brown	wavy to nodular bedded, domal stromatolitic(?) laminae
stromatolitic skeletal lime wackestone	medium	orange to tan-gray	orange-tan	
phylloid algal lime mudstone	fine	pink-tan to gray	pale pink-gray	sparse ooids & calcite grains
shaly sandstone	very fine	lt. gray	lt. gray	flakey
coated grain packstone	very fine Xtal size	tan-gray	brown-tan	3 even, distinct beds
skeletal wackestone	very coarse grain size			shells w/calcite, dolomite Xtals
coated grain packstone				wavy bedded, "clay seams" present
skeletal lime mudstone	very fine		gray-tan	

d


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

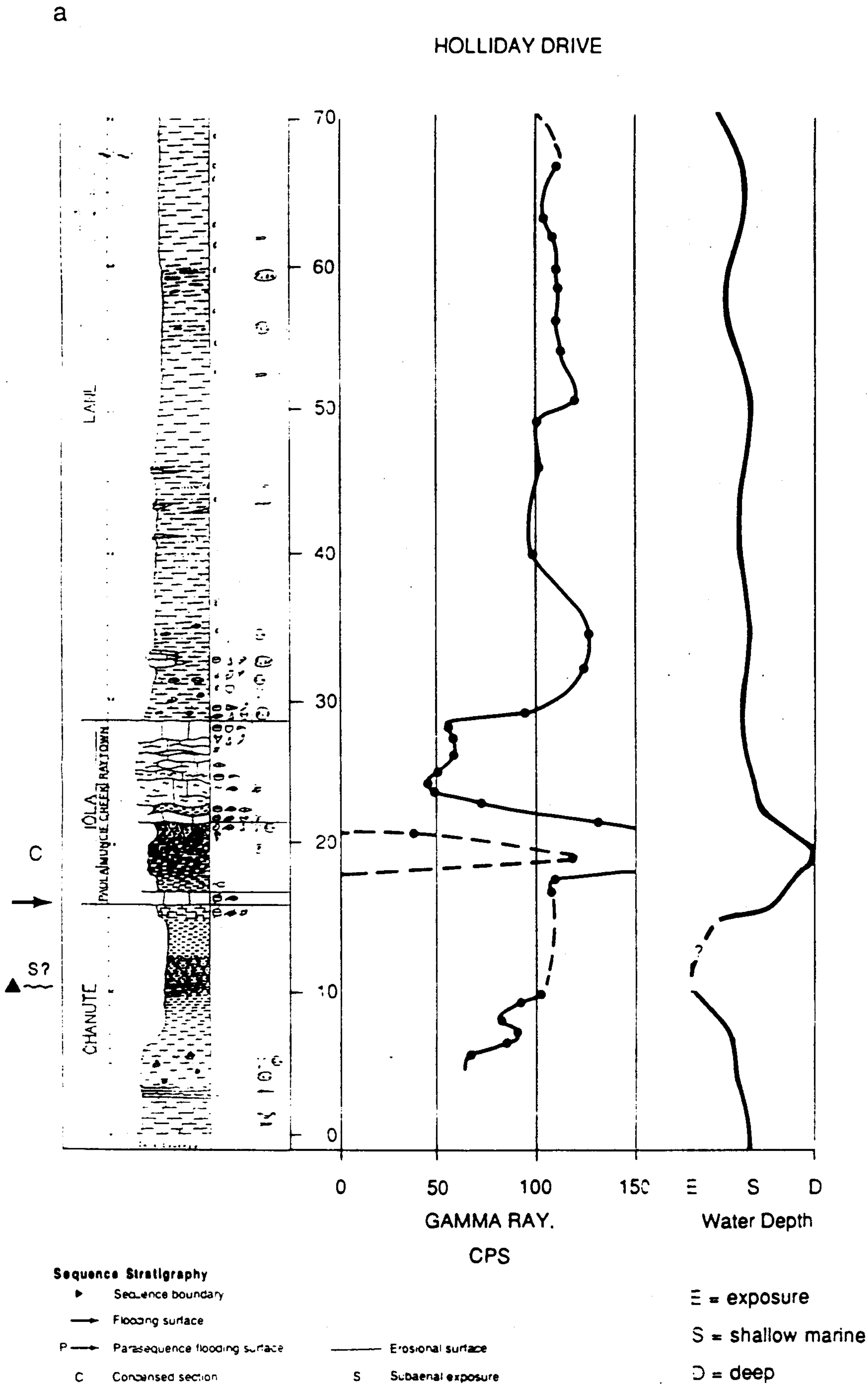
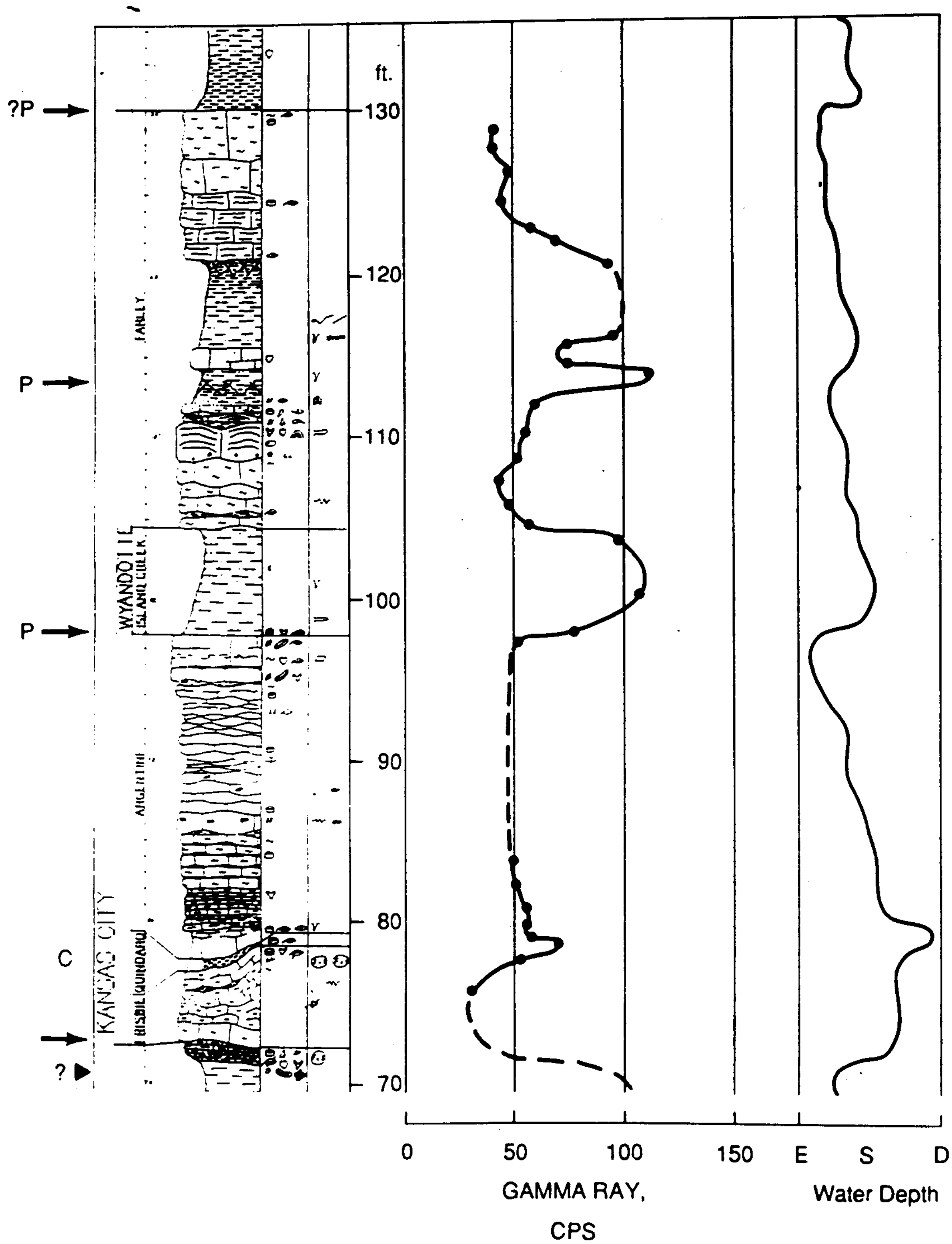


FIGURE 2-3 (A and B)–Stratigraphic section, natural gamma-radiation profile, water-depth curve, and sequence classification (extreme left) for lower portion of measured section if fig. 2-2.

b

HOLLIDAY DRIVE



E = exposure

S = shallow marine

D = deep

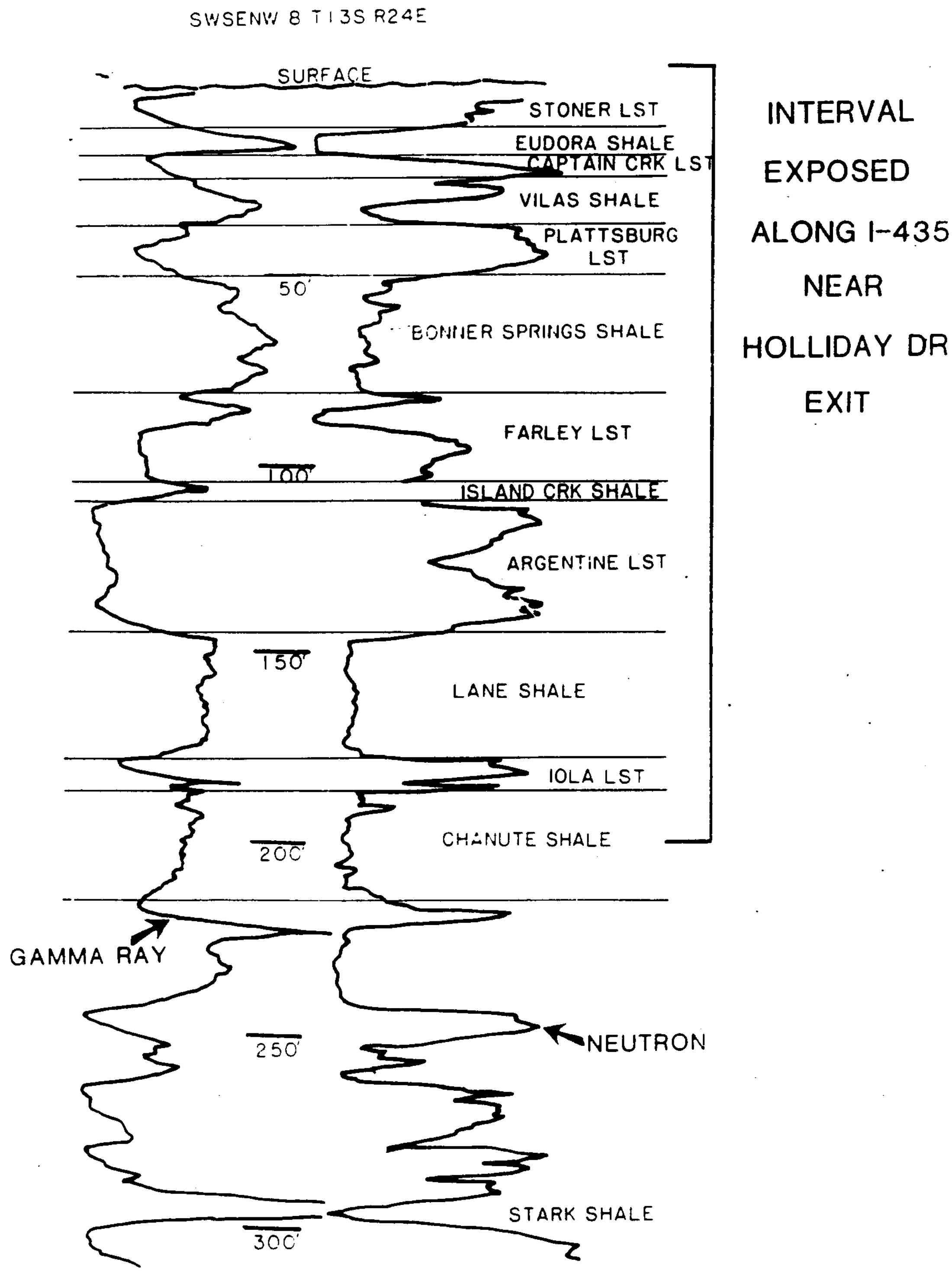


FIGURE 2-4--Correlation of formations in Lansing and Kansas City Groups based on gamma ray-neutron log of well located near Stop 2.


AR
QU
FR
LA
RT
MC

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

Departure: 10:20

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 this boundary is the focus of Stop 3 and 4. 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. In the succeeding stop (#4), we will briefly examine 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 m ± 2.36 m (26.2±7.8 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 spirifid 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 ± 0.33 m (0.9 ± 1.1 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 oncoid 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 ± 5.7 cm (7.2 ± 2.3 inches); the range is from 7 to 27 cm (3–11 inches). Although the Hickory Creek is reported to contain a black, platey, 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-spired 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-spired 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, Echinochoncus*, 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, platey to flakey, calcareous shale. A low-diversity fauna of low-spired gastropods (*Trepospira* and, rarely, bellerophontids), 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 toplap 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 toplap 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 pectins and high-spired gastropods (sect IX, fig. 3-2). The overlying sand-shale sequence (sections X, IX, and VIII) contains Myalina clams, pectins, 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 by 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 cyclothemic 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 *Trepospirid–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 cyclothems. 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."

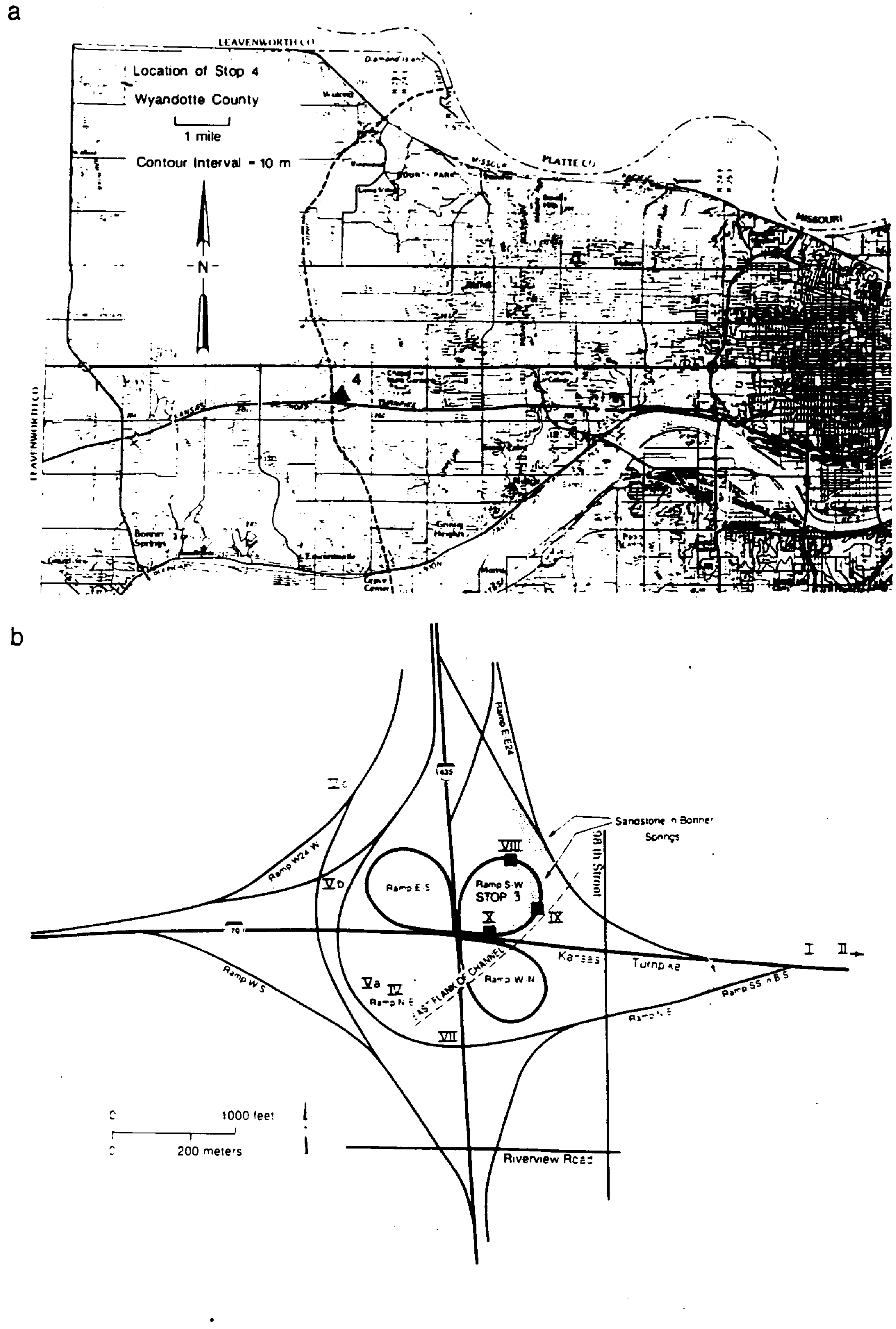


FIGURE 3-1(A and B)—Location map for Stop 3 in Wyandotte County (A) and index map showing intersection with location of Stop 3 along northeastern cloverleaf of interchange of I-70 and I-435 and location of measured sections used in cross section (fig. 3-2a and b) identified with Roman numerals. Stippled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

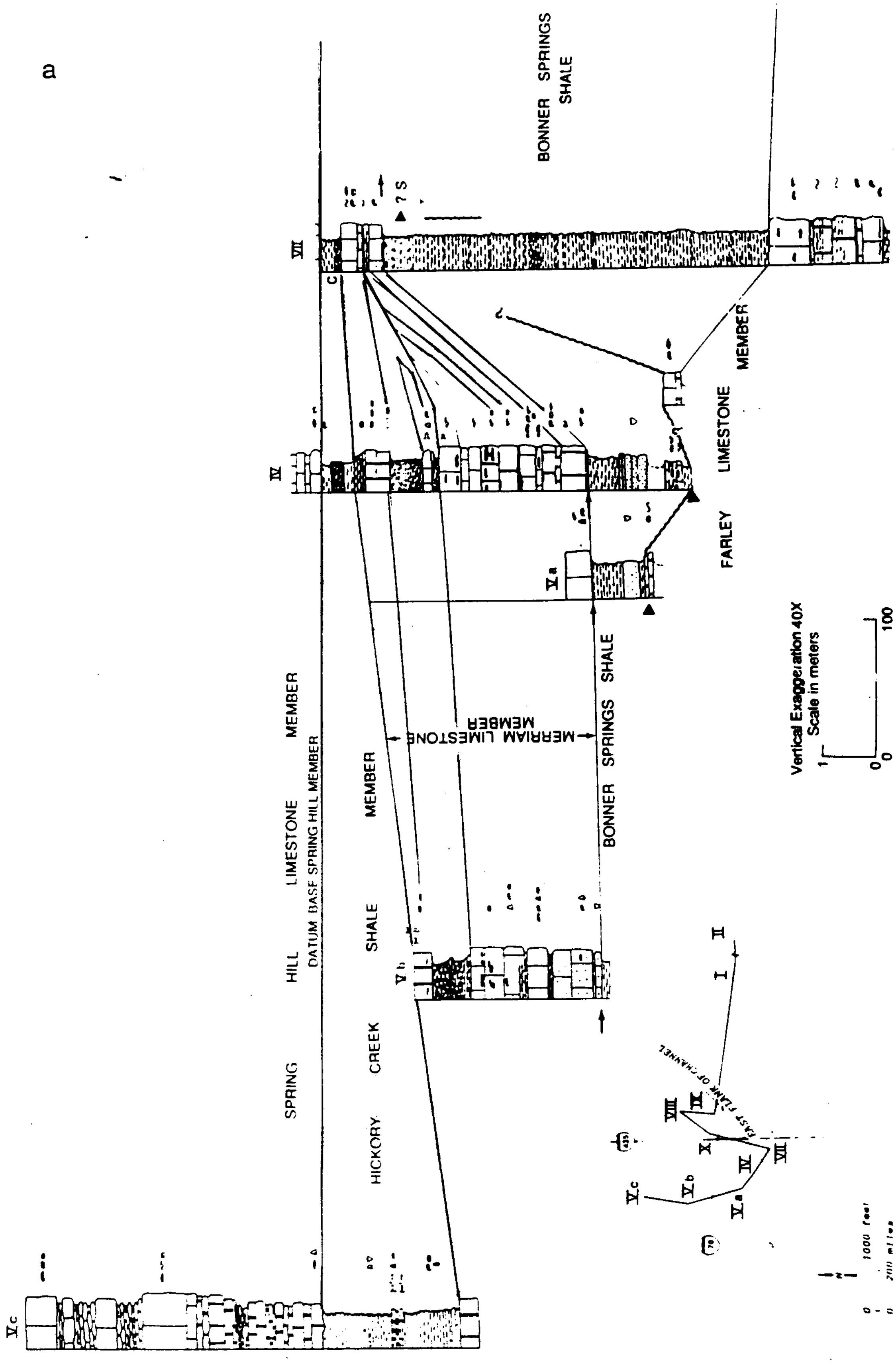
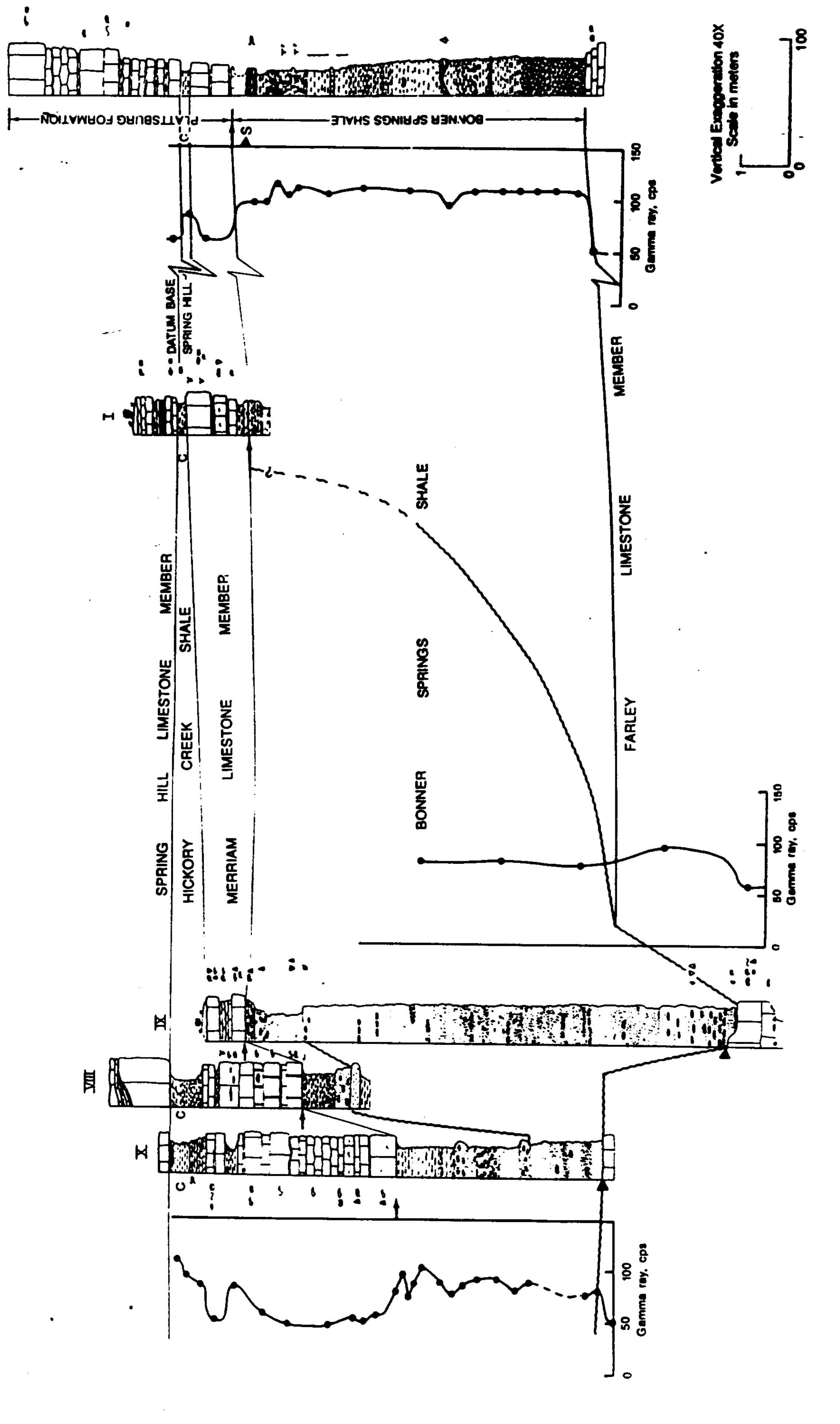
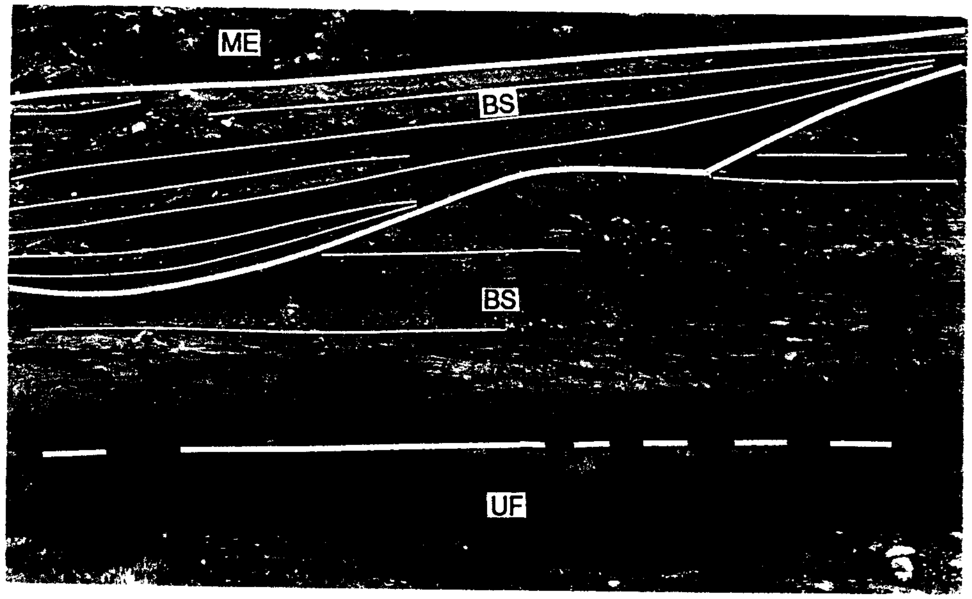


FIGURE 3-2(a and b)—Northwest-to-east stratigraphic cross section through I-70/I-435 interchange area based on measured sections and interpretations (less sequence interpretations) by Enos and Herman, in ms. Datum for the cross section is the base of the Spring Hill Limestone. Uppermost Farley Limestone,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


SPRING HILL LIMESTONE MEMBER
HICKORY CREEK SHALE
MERRIAM LIMESTONE MEMBER
BONNER SPRINGS SHALE
FARLEY LIMESTONE MEMBER
DATUM BASE SPRING HILL
PLATTSBURG FORMATION
BONNER SPRINGS SHALE
Gamma ray, cps
Vertical Exaggeration 40X
Scale in meters
X
VIII
IX
I
II

b



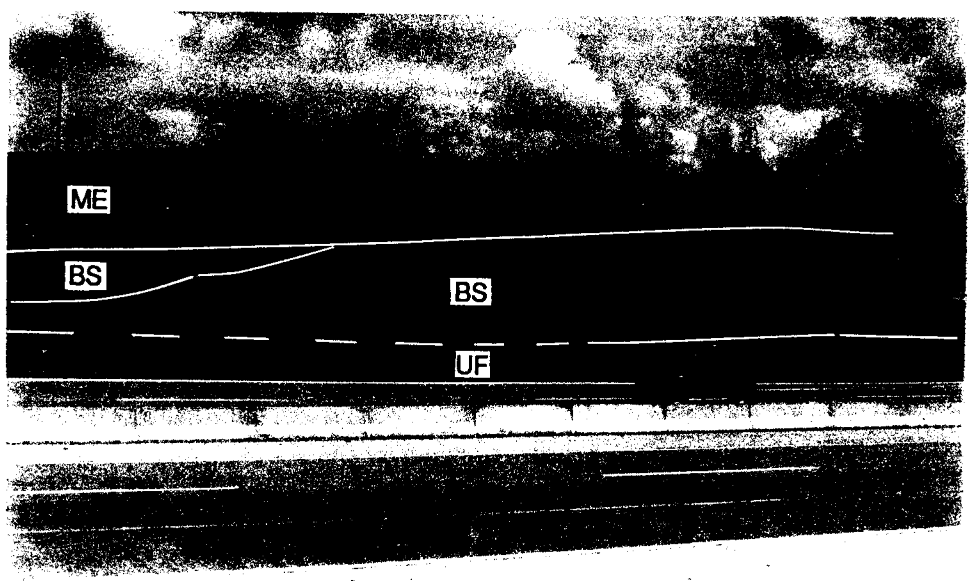
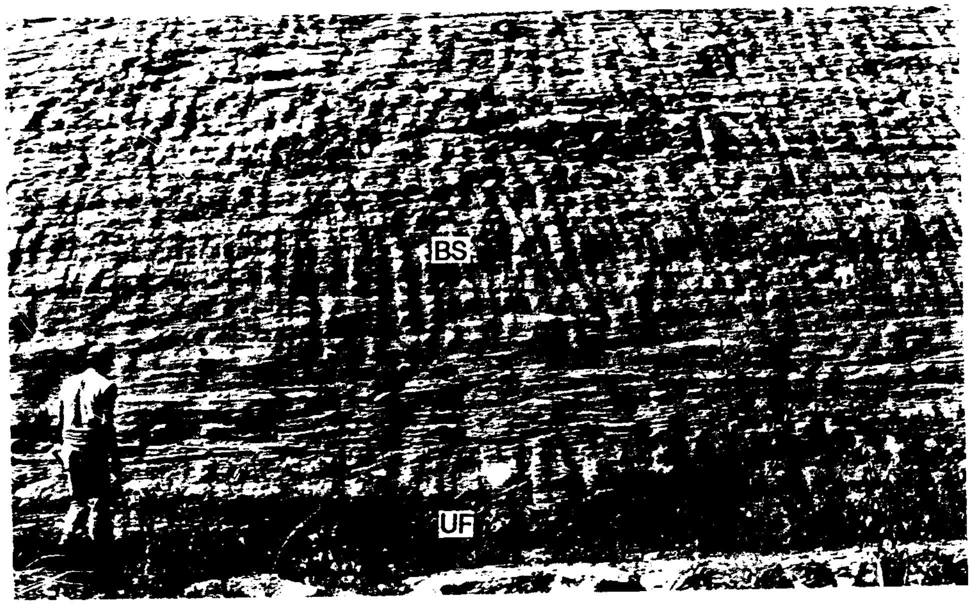


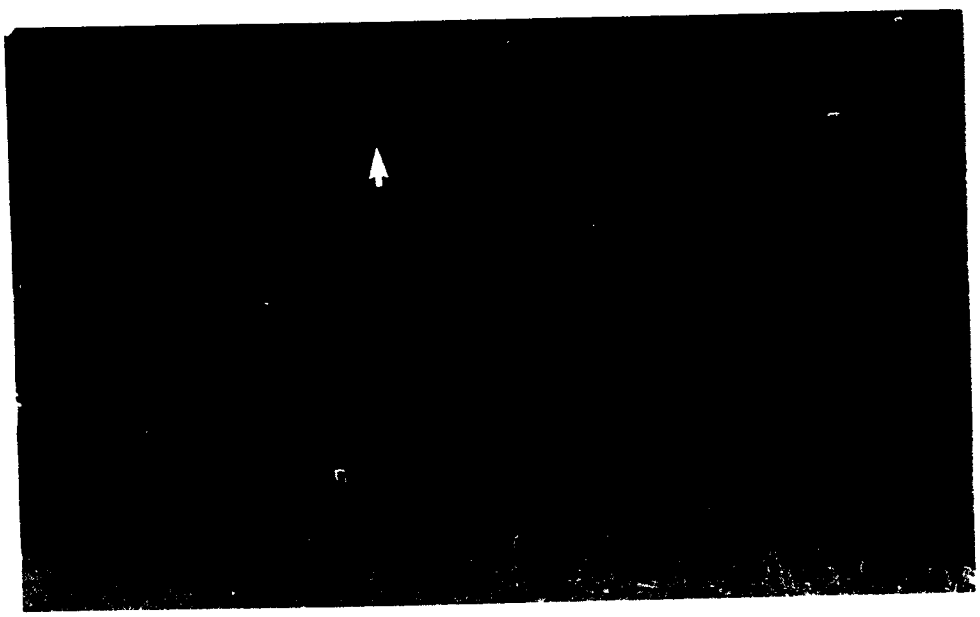
fig. 3–3 (A) ·Bonner Springs Shale at Stop 4 showing sandstone of Bonner Springs (BS) resting on locally eroded upper Farley Limestone (UF) near section X. Sandstone is cut by erosional surface beneath a hemi-channel form which extends up to near the base of the Merriam Limestone (ME). Hemi-channel is filled with Photos are close-up of left portion of fig. 4-3(C and D). Note hammer left of center for scale (1 ft [0.32 m]).

fig. 3–3 (B) —South side of Stop 4, 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.

fig. 3–3 (C) Close-up of east face of sandstone in Bonner Springs Shale at Stop 4 (section IX). The sandstone includes a few festoon cross sets up to 30 cm thick and herringbone cross-bedding near the base.

fig. 3–3 (D) –Typical Bonner Springs Shale (section II) shown in fig. 4-2(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.


BS
UF



Stop 4 I–435 south of Holiday Road exit

Location: Center sec. 6, T. 12 S., R. 24 E., Johnson County, Kansas

Departure: 10:50

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

Introduction

Stop 4 is located on fig. 2-1. The measured section of the interval seen was obtained on the east roadcut near Stop 4 (fig. 2-2c and d). Fig. 4-1 provides three photos illustrating the paleosol developed at the top of the Bonner Springs Shale, the focus of Stop 4.

The Bonner Springs Shale and Plattsburg Limestone are typically developed along this roadcut. The Bonner Springs Shale is 25.3 ft (7.7 m) thick. The Plattsburg Limestone consists of the 2.3-ft (0.71-m)-thick Merriam Limestone Member, the 20-cm (8-inch)-thick Hickory Creek Shale Member, and the 14.6-ft (4.44-m)-thick Spring Hill Limestone Member. A series of channel forms near the top of the Bonner Springs Shale at and near this stop may be related to processes that led to the atypical Bonner Springs observed at the previous stop. Maximum dimensions of sandstone lenses within the channels are 1 to 2 m (3.3–10 ft) thick and about 100 m (330 ft) in apparent width.

An objective of this stop is to examine a calcareous paleosol developed at the top of the Bonner Springs Shale. This interval was eroded at the previous stop by local channeling. The paleosol, although sporadic, is widespread above the maroon zone. Its surface is the boundary between the Plattsburg sequence (above) and the Wyandotte sequence (below).

The paleosol has been described as a characteristic argillaceous, nodular, yellow-weathering limestone within the top meter of the Bonner Springs Shale. This limestone unit, which overlies the maroon shale, was described in part as "marlite" by Newell (1935, p. 68). It is nodular and locally conglomeratic in appearance, with fragments of calcareous mudstone or argillaceous limestone. Vertical prismatic fractures are scattered near the top of this limy interval. The calcareous zone grades down into nodular calcareous mudstone that locally contains large woody fragments, including *Calymites*, root casts, and U-tubes with poorly developed spreiten.
At several localities, the yellow-weathering carbonate unit extends down vertical fractures, interpreted as syndepositional desiccation cracks (Harris, 1985). The general V-shaped downward extension of the filled cracks and their irregular surface traces indicate large polygons resembling desiccation cracks, rather than a joint set. The best evidence that they are penecontemporaneous with deposition is at another location, where a V-shaped fracture fill of skeletal wackestone 10 cm (4 inches) deep is nested in a V-shaped zone of yellow-weathering carbonate that extends downward more than a meter. The skeletal wackestone was evidently deposited during marine flooding associated with Merriam Limestone deposition.

The nodular and brecciated appearance of the yellow-weathering carbonate is probably due to displacive crystal growth, enhanced compaction of the shale around semi-lithified carbonate, and growth of plant roots. Thin sections of the carbonate zone indicate microcrystalline calcite with scattered fragments of dense brown micritic calcite that are surrounded by circumgranular cracking. This texture is common in caliche. Rhizoliths (downward branching, clay-filled tubules) are also scattered through the unit. Prismatic fractures are probably ped surfaces, common in soils (fig. 4-1). Types of peds are illustrated in fig. 4-2.

Caliche, rhizoliths, vertical prismatic ped surfaces, oxidation, and a gleyed (reduced, clay-rich) soil horizon define a well-developed paleosol. The complexity of the paleosol reflects changes in moisture level that probably resulted from changes in climate during falling sea level.

A typical section of Merriam Limestone, Hickory Creek Shale, and Spring Hill Limestone overlies the Bonner Springs Shale at Stop 4. This interval contrasts with the section examined at Stop 3. In some places the Bonner Springs Shale does not contain this paleosol due to local erosion. The thick preservation here may be related to a topographic low formed as the underlying sandstone channel subsided. Further description and interpretation of the paleosol is planned in subsequent studies.

FIGURE 4-1 (A)—West-facing exposure at Stop 4 (on highway median) showing BS, Bonner Springs Shale; ME, Merriam Limestone; HC, Hickory Creek Shale; SP, Spring Hill Limestone. Bonner Springs Shale here is a typical section as opposed to that seen at Stop 2. Paleosol is unusually thick in association with a lenticular sandstone located at the position of the letters, BS. Derek Herman provides a scale.

FIGURE 4-1(B and C)—Paleosol developed near top of Bonner Springs Shale from west-facing slope in the highway median at Stop 4. Evan Franseen is taking a close-up photo of the paleosol shown in (C). Photo (C) shows ped surfaces, one of the diagnostic features of a soil.

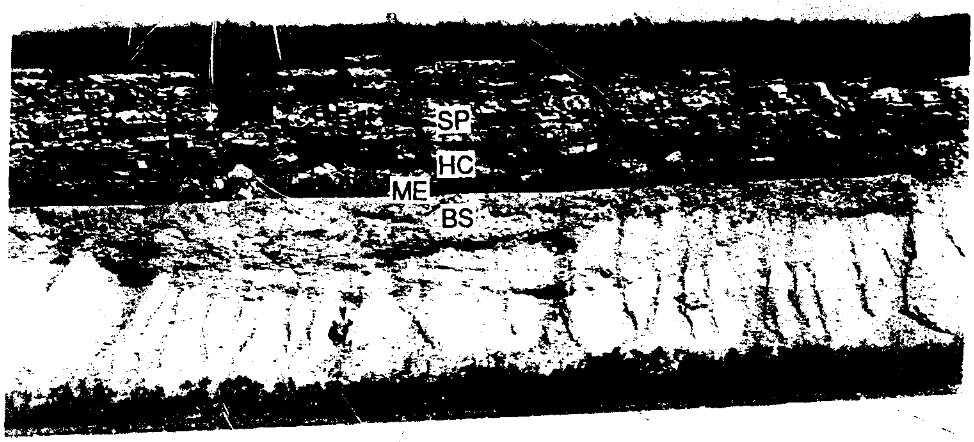


fig. 4-1 (A)

fig. 4-1 (B)

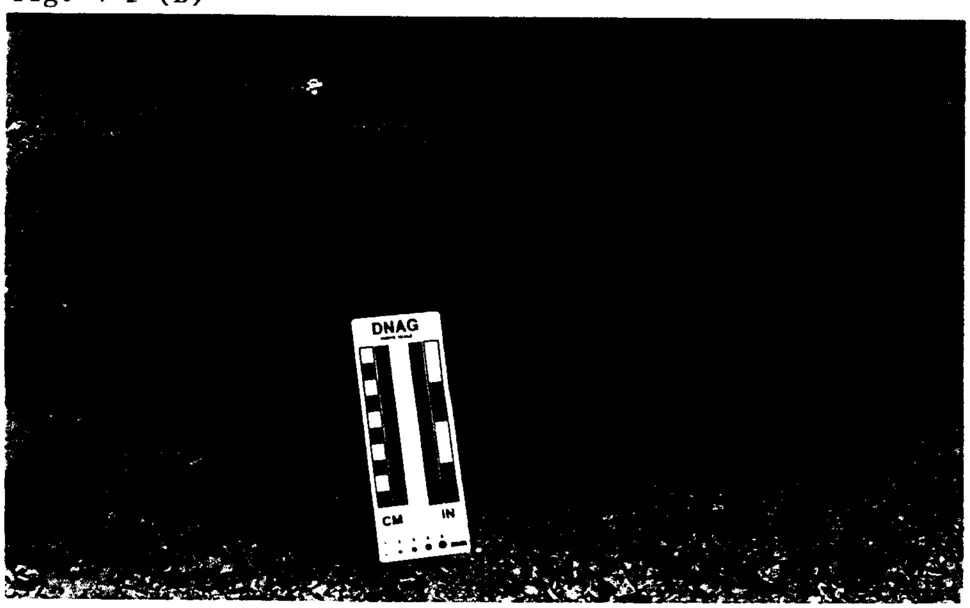


fig. 4-1 (C)

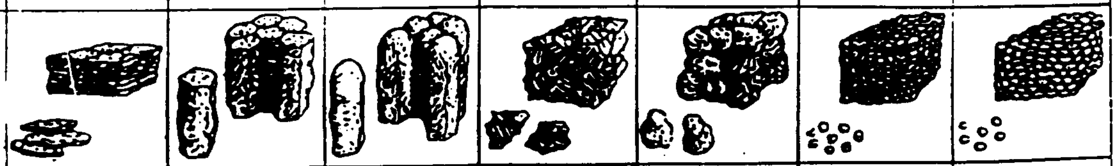
TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking 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

FIGURE 4-2—Classification of soil peds (from Retallack, 1988).

Stop 5 East 15th Street, Lawrence: Type Section of Haskell Limestone

Location: (ctr N line NE 1/4 sec 5, T13S, R20E)

Departure: 11:40

Contributors: *Philip Heckel and Lynn Watney*

Introduction and General Discussion

Currently the Missourian-Virgilian boundary is recognized at the top of the South Bend Limestone in Kansas, Nebraska, and Iowa, and at the base of the Tonganoxie Sandstone in Missouri, some distance above the South Bend Limestone. In Oklahoma the boundary is placed at the top of the Tallant Formation, some distance below the Bowring Limestone at an indeterminate horizon (but one that may be close to the position recognized in Missouri). It has now been recognized that the top of the South Bend Limestone is younger in Nebraska where it is a regressive limestone, than in Kansas where the top is placed on a transgressive limestone. This is exemplified in this stop where the Haskell only contains the transgressive limestone.

Conodont and ammonoid information reveal that the only faunal change in the interval between the Eudora Shale (Stanton Limestone) and the Heebner Shale (Oread Limestone) that can be recognized throughout the Mid-Continent, Texas, and Illinois is the thin dark shale above the Haskell Limestone, which is named the Little Pawnee Shale. The Little Pawnee Shale is a member of the Cass Limestone in Nebraska. This shale contains the first appearance of the distinctive idiognathodid conodont Streptognathodus zethus in Nebraska, Kansas, and Oklahoma, and of distinctive ammonoids in Kansas and in equivalent strata in Texas. Therefore, Boardman et al. (1989) proposed that the base of the Virgilian Stage be placed at the base of the Haskell Limestone.

The stratigraphic change from the carbonate-dominated Lansing Group into what is presently called the Douglas Group is substantial. However, the outside shales in the Lansing Group and upper Kansas City Group suggest a trend toward increasing competence of a siliciclastic system that began to affect this area of the shelf late during deposition of the Kansas City Group. Outside shales in the lower Kansas City Group are essentially paleosols characterized by gray shale horizons with possibly a thin coal smut and rhizoliths overlying calcrete and autoclastic breccias of the underlying carbonate unit, e.g., top of Bethany Falls and Sniabar Limestones exposed in the Kansas City area. This trend toward an increasing siliciclastic component may reflect a climate change from drier to fluctuating wet and dry conditions encouraging increased erosion from nearby positive areas (Cecil, 1990).

Stratigraphy at Stop 5

The Haskell Limestone here at the type locality is four feet thick with a sandy limestone at the base overlain by an oolite and grading upward into skeletal calcilutite, forming a deepening-upward sequence characteristic of a transgressive limestone. The Haskell Limestone was named by Moore (1936) from exposures near the Haskell Indian Institute in Lawrence, and the type locality was designated by Moore (1936). The proposed stratigraphic revision of Heckel places the Haskell Limestone above the Vinland Shale Member of the Stranger Formation and beneath the Little Pawnee Shale Member of the Cass (fig. 5-1).

Fig. 5-2 is a diagrammatic section of the siliciclastic dominated interval that surrounds the Haskell Limestone (Moore, 1949). Although the nomenclature is in the process of being modified, the illustration gives a good impression of the complex geometries of the strata in this siliciclastic dominated interval. Paralic sedimentation dominates including many occurrences of thin coals. The

Ireland and Tonganoxie sandstones are actually aggregates of many lenticular sandstone bodies, some downcutting into underlying strata. The Ireland refers to those sandstones occurring above the Haskell and the Tonganoxie is named for sandstones that are found below the Haskell. The sandstones referred to as the Tonganoxie occasionally cut down into the Lansing Group. A southwestward-trending valley filled by Tonganoxie sandstone averages about 20 miles wide can be traced through northeastern Kansas (Lins, 1950). The sandstones in the Tonganoxie can be up to 75 feet thick.

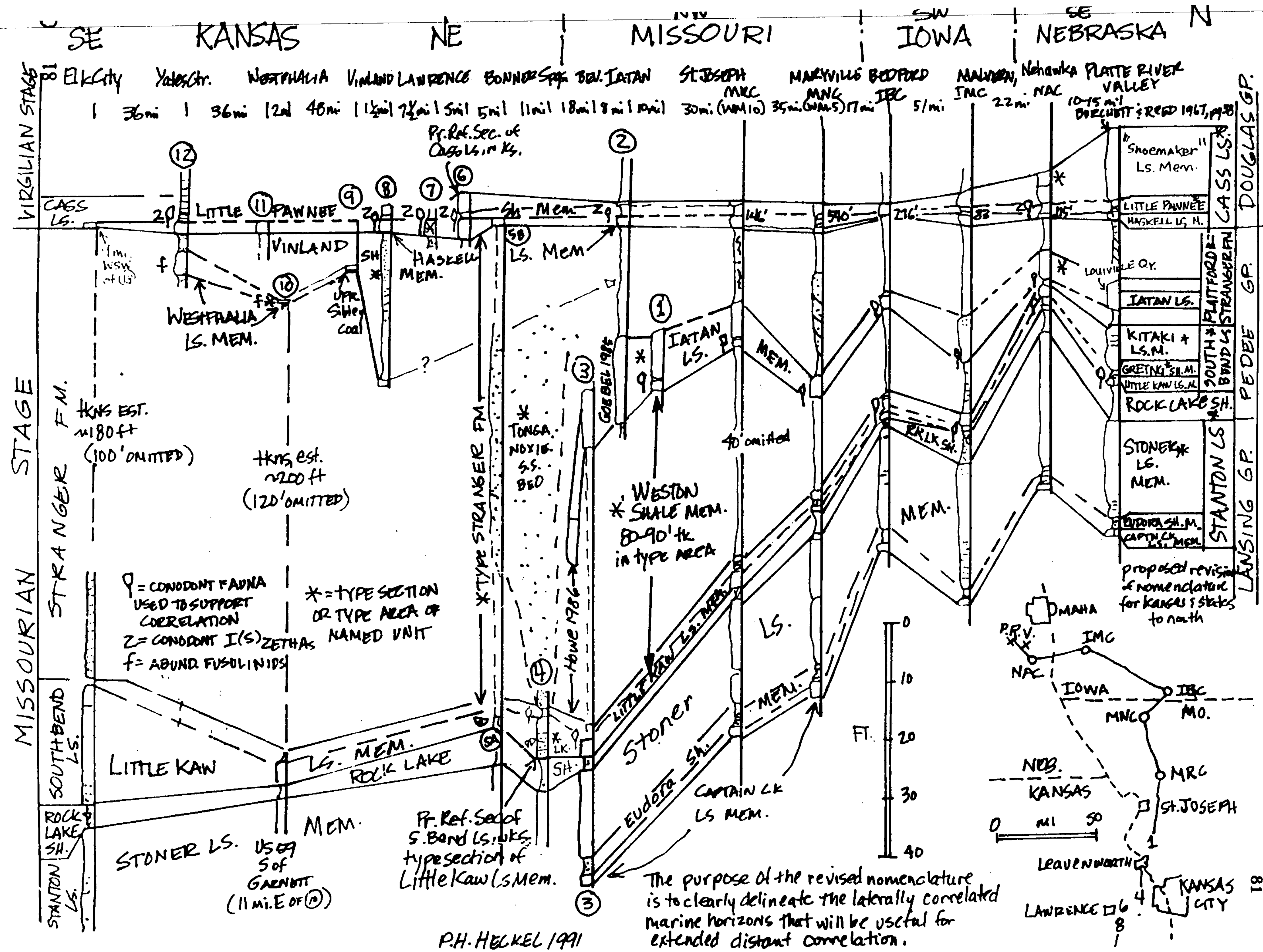


FIGURE 5-1--Stratigraphic cross section obtained from surface exposures of uppermost Missourian and lowermost Virgilian. Datum is Haskell Limestone. Proposed revisions to the stratigraphic nomenclature are included (presented at Midcontinent Stratigraphic Working Group field trip, Heckel, 1991)

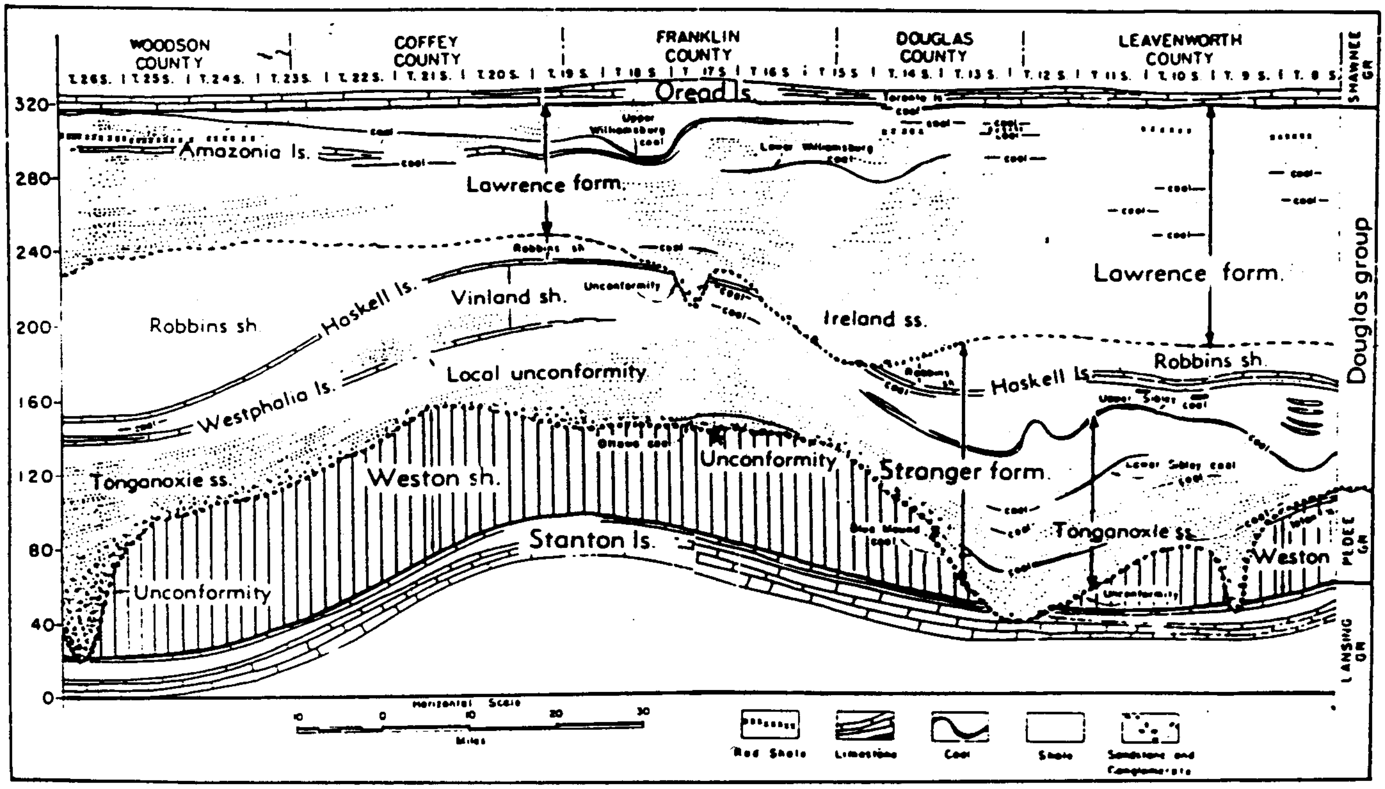


FIGURE 5-2--Diagrammatic cross section of uppermost Missourian and lowermost Virgilian (Moore, 1949).

Stop 6 Clinton Lake Spillway: upper Lawrence Shale and Oread Limestone

Departure: 12:20

Contributors: *Bryan Stephens and Lynn Watney*

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. 6-1). The interval from the Plattsmouth Limestone down to the Amazonia Limestone Member of the Lawrence Shale is well exposed on the spillway wall (fig. 6-2). The measured section at this locality is provided in Fig. 6-3.

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 ddPlattsmouth Limestone, Heeumader 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 Tornoto, 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 6-4). 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 eustacy.

The presence and the extent of subaerial exposure due to relative sea level fall is also a key issue relating to the mechanism responsible for sedimentation. We saw evidence of channel downcutting in the Bonner Springs Shale at stop 3. Channels 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 that cut down as deep as 110 feet into upper Virgilian strata. These can be considered lowstand incised valleys and when combined with the marine inundation together reflect considerable fluctuations in relative sea level.

The measured section (fig. 6-3) 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 below the Williamsburg Coal above the Amazonia and additional evidence of oxidation in the shale above the coal.

The Williamsburg coal is one of several coals developed in the upper portion of the Lawrence Formation (fig. 5-2, from stop 5). This upper Williamsburg coal is the more laterally continuous. The Amazonia Limestone is lenticular in the area.

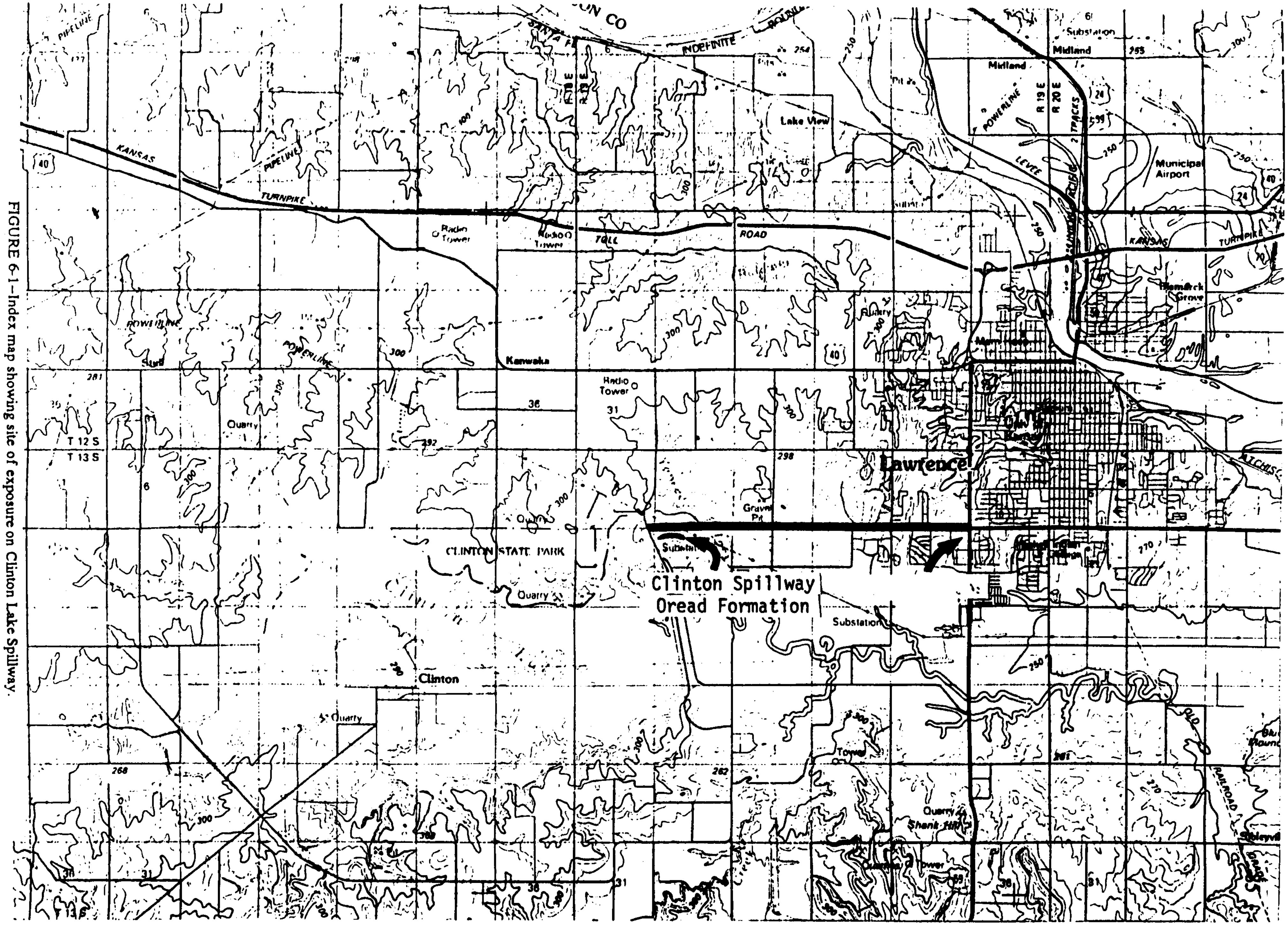


FIGURE 6-1–Index map showing site of exposure on Clinton Lake Spillway.

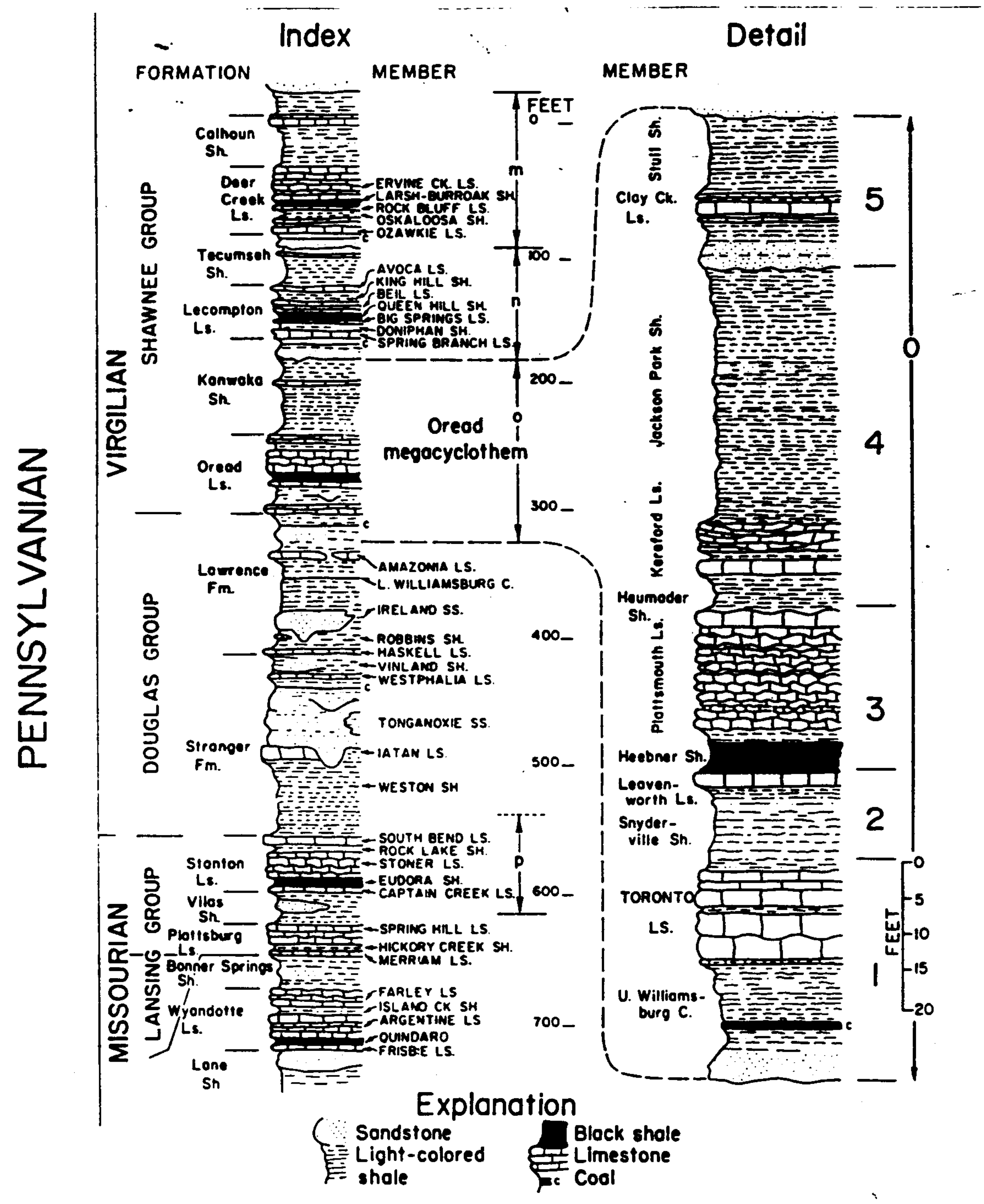


FIGURE 6-2--Stratigraphic position of the Oread Limestone and Oread megacyclothem (from Troell, 1969).

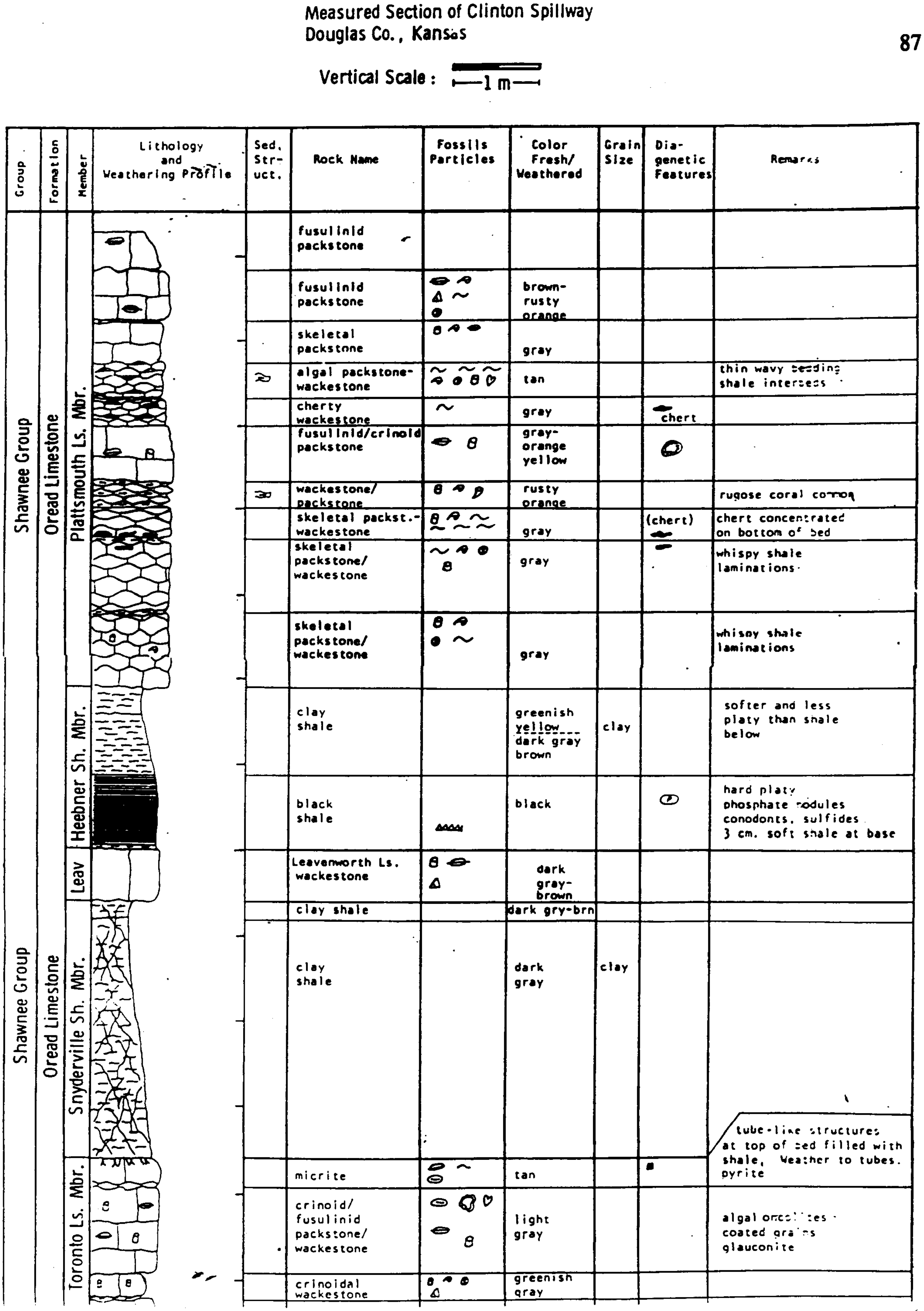
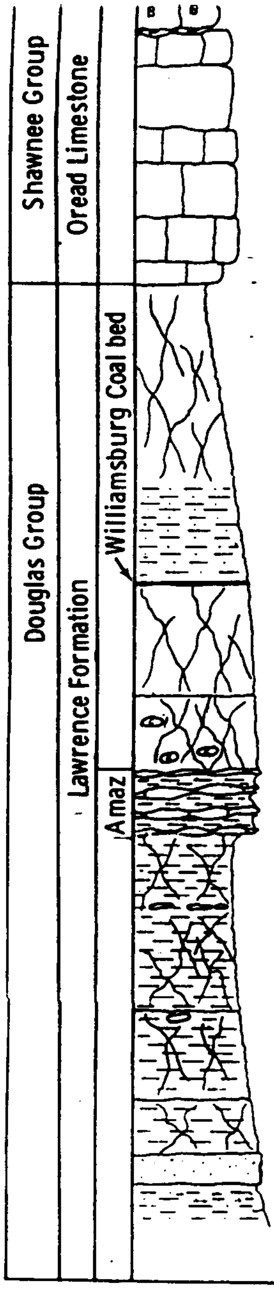


FIGURE 6-3–Measured section of upper Lawrence and Oread at Clinton Lake Spillway.



	crinoidal packstone/ wackestone	8 ~ 8 ~ ◆	light greenish gray			whispy shale laminations
	skeletal packstone	~ 8 ◆ ⬬	light gray -orange yellow			iron stains
	skeletal wackestone	8 ⬬ ◆ ∇	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
V ♭	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 7 Lonestar Lake Spillway, Upper Lawrence Shale

Location: (Center/south line Sec. 11, T.14S., R.18E.)

Departure: 1:30

Contributors: *Allen Archer and Ronald West*

Introduction

Within gray shales of the Lawrence Formation of Kansas, well developed tidal rhythmites occur locally above the Upper Williamsburg Coal. Stratigraphy and general depositional environments of this formation have been detailed by Rutan (1980) and Garbish et al (1991). The coal that underlies these tidalites includes some of the lowest sulfur coals in Kansas and is unusual because most Kansas coals have extremely high sulfur values (see Brady et al., 1976). In addition, these gray shales within the Lawrence Formation contain well-preserved plant fossils within sideritic concretions and thus share a geochemical/paleoecological similarity with other gray shales that occur above low-sulfur coals (see Baird et al., 1986). More detailed field-based analyses are needed in order to further delineate the similarities and differences among these various gray-shale lithofacies; however, the number of apparent similarities is quite striking.

Direct comparisons can be made between laminae thickness periodicities observed with shale of the Lawrence and synthetic rhythmites generated based upon tidal data recorded at Do Son, Vietnam (fig. 7-1, photo). Both the shales and the synthetic tidalites exhibit similar periodicities in laminae thicknesses and where the laminae are very thin, it becomes difficult to delineate individual tidal events. Thus based upon the similarities of the periodicities, one can make a reasonable environmental interpretation of tidal deposition within shales of the Lawrence Formation.

The association of gray shale roof and low sulfur coal has been long known from studies performed within the Illinois Basin (Gluskoter and Hopkins, 1970); however, the association of tidal rhythmites within gray shale and occurrences of low-sulfur coal has only been recently documented (Kvale and Archer, 1989, 1990; Archer and Kvale, in press). This association is common within Desmoinesian coals in the Illinois Basin and based upon preliminary observations may be common in the Oklahoma-Kansas Desmoinesian coals. Virgilian occurrence of this facies and lower sulfur coals in the Lawrence is relatively unique and suggests a brief return to Desmoinesian-type climato-depositional settings. This implies that coal/climate connection cannot be tied simply to paleolatitudinal setting but that other factors also affect the system.

Generally, deposition of the gray-shale facies can invoke either a muddy, tidally influenced delta or tidally influenced estuarine system (fig. 7-2). These depositional models rely on low-latitude tropical analogs; the systems are mud dominated because of the high degree of chemical weathering that occurs in such systems and the general lack of storm and wave energies that occur at such latitudes (C. B. Cecil, pers. comm., 1990). In this model, coastal peat swamps can be rapidly transgressed by muddy tidal facies; enhanced preservation of the underlying peat and protective mantling of the muds prevent marine sulfates to increase the sulfur content of the coals that ultimately develop in such settings (Archer and Kvale, in press).

Stratigraphic Section

Fig. 7-3 is the stratigraphic section of the Upper Lawrence Shale exposed in the spillway. The upper Williamsburg Coal is unit 14. Both overlying and underlying siltstones and sandstones contain flaser bedding and laminations diagnostic of tidal current activity.

FIGURE 7-1– Comparison of (a) simulated tidalite (based on diurnal, DO Son-type tidal system) and (b) polished slab of Lawrence Shale. Sample of shale taken from excavation made behind Kansas Geological Survey during construction of core-storage facility in February of 1990.

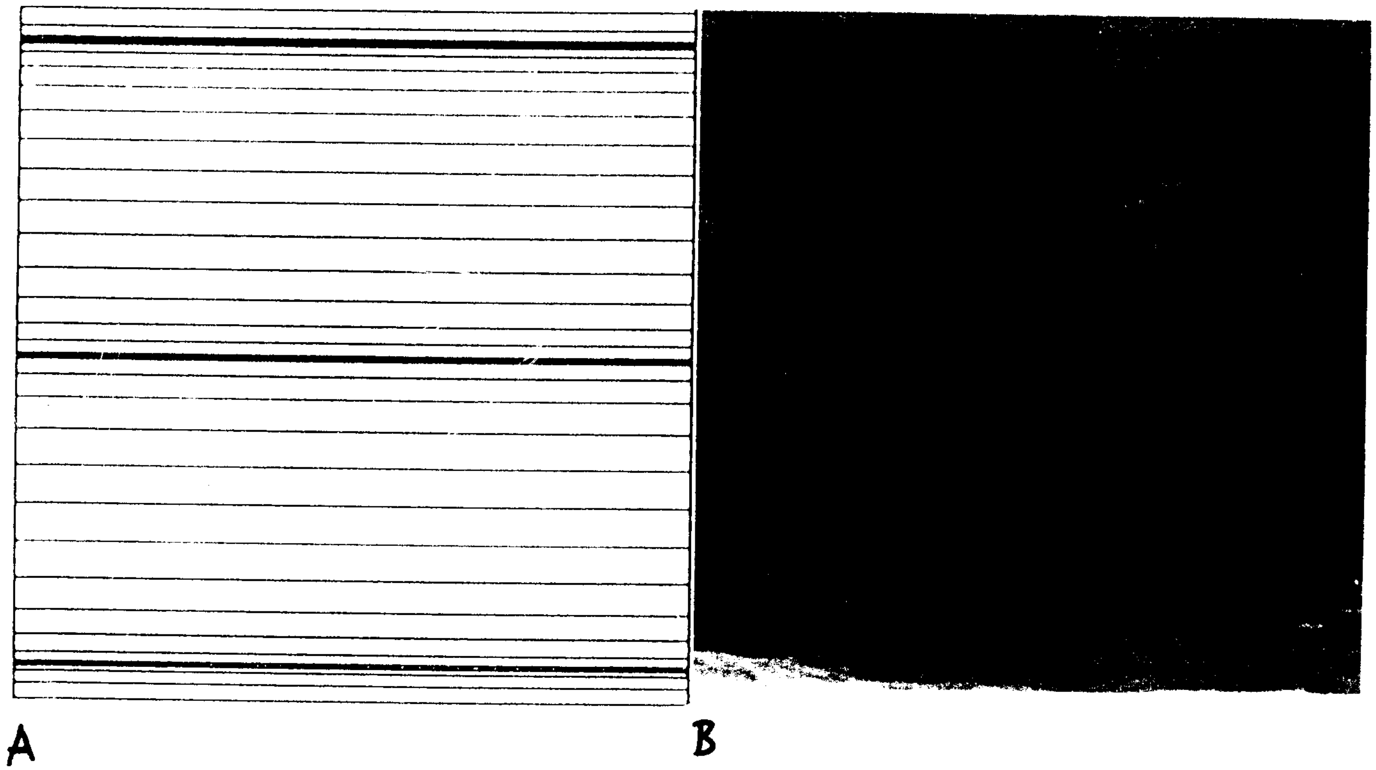


fig. 7-1

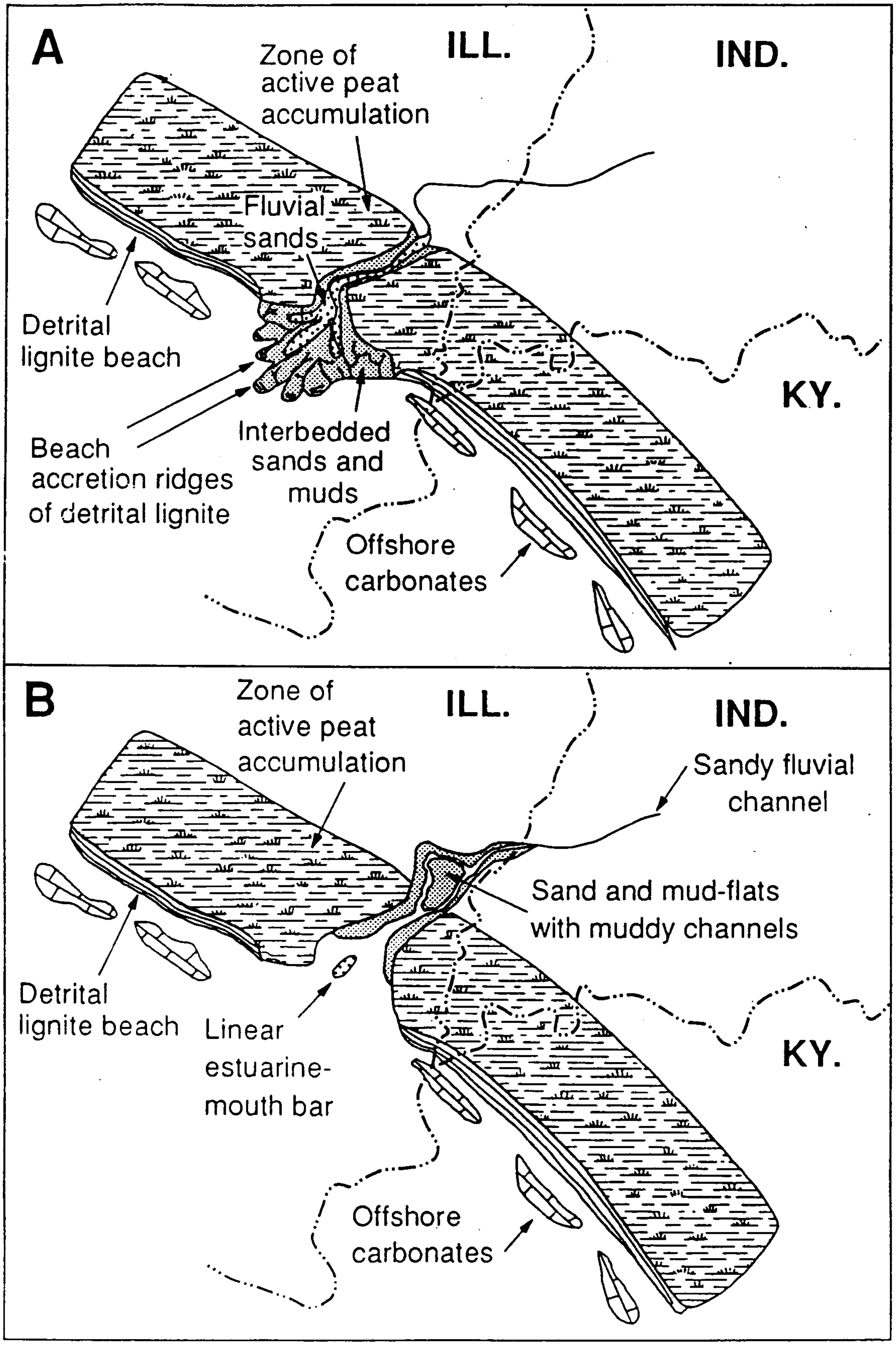
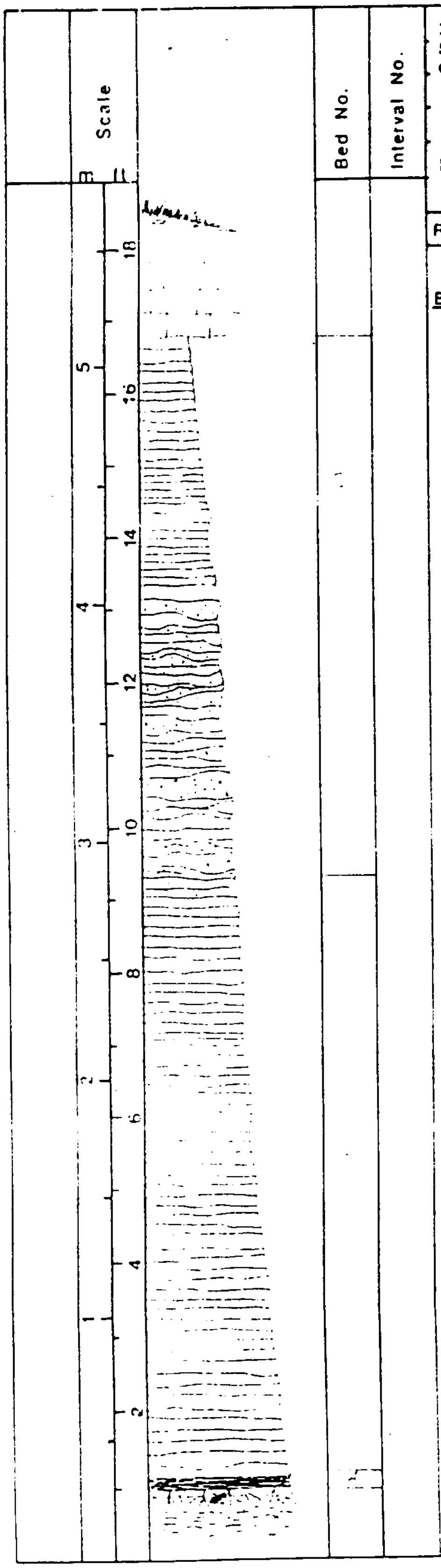


FIGURE 7-2–Gray-shale lithofacies depositional models based upon (a) muddy, tidally influenced delta and (b) estuarine system. In the deltaic system, potential lithofacies variations formed by transgression of a mixed fluvial and tidal delta formed immediately following deposition of the peats that were to form the Springfield Coal. In the estuarine model, these same lithofacies are produced within a localized estuarine sequence developed during transgression of a preexisting fluvial system. The locally thickened clastic interval may be related to subsidence caused by differential compaction or by deep-seated block faulting.



Locality Description: Center of South line of Sec. 11, T.14S., R.18E., Douglas Co., Kansas; Globe 7.5' Topographic Quadrangle, revised 1983.

Location: Lonestar Lake Spillway

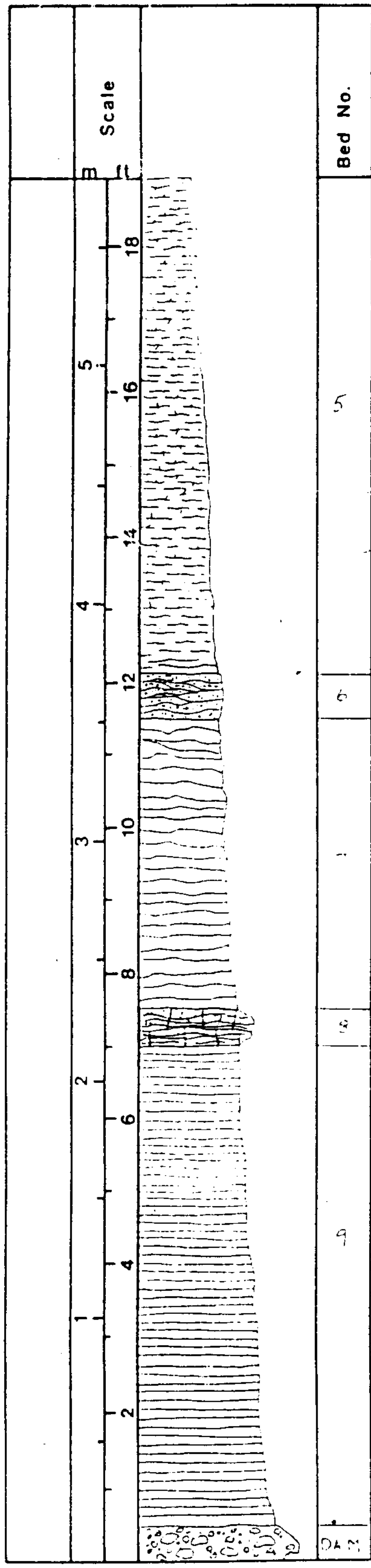
Measured By: B. Smith, B. Tilley, K. Ross, & K. Krogstad: Fall'90.

Remarks:

Description

Bed No.	
1	Slabby calcarenite (packstone to wackestone), moderate yellowish brown, fossiliferous; crinoid, bivalve, and brachiopod fragments, fusulinids, lower contact sharp. Basal Toronto limestone.
2	Thinly laminated siltstone, 228cm thick, gray-green, lower 122cm contains interbedded flaser micaceous sandstone lenses.
3	Finely laminated silty mudstone, 249cm thick, gray.
4	Thin blocky coal, 3cm thick.
5	Blocky mudstone, 218cm thick, purple brown gray.

FIGURE 7-3--Stratigraphic section of the Upper Lawrence Shale at the Lonestar Lake Spillway.



Locality Description: Center of South line of Sec. 11, T.14S., R.18E., Douglas Co., Kansas; Globe 7.5' Topographic Quadrangle, revised 1983.

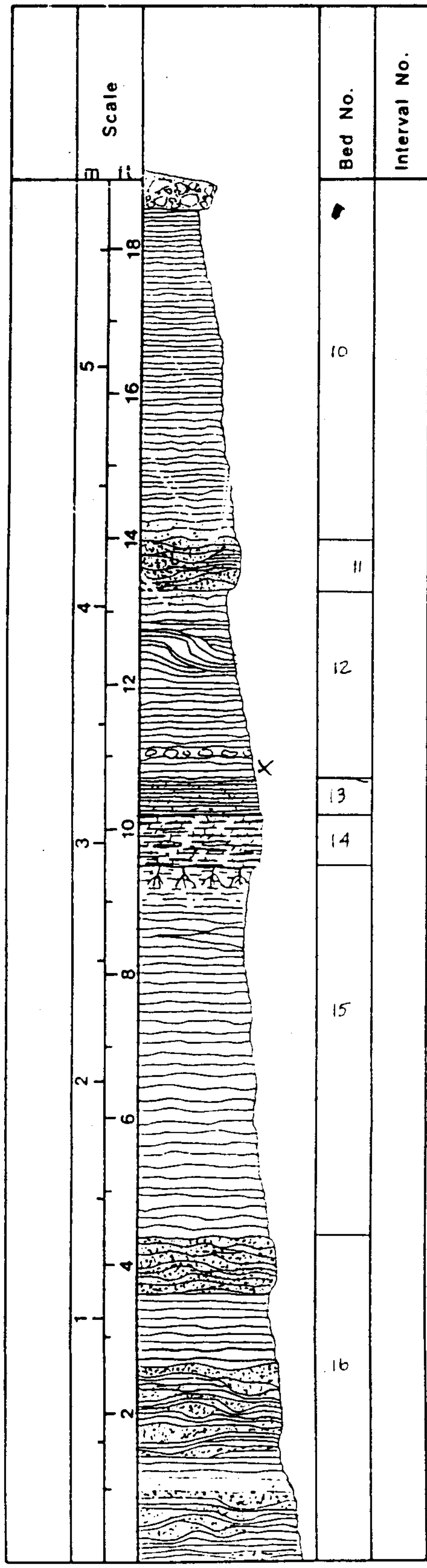
Location: Lonestar Lake Spillway

Measured By: B. Smith, B. Tilley, K. Ross, & K. Krogstad; Fall'90.

Remarks: 2 of 3

Description

Bed No.	Description
5	Blocky mudstone, 218cm thick, purple brown gray.
6	Flaser bedded sandstone, 20cm thick, *Asteriacites*.
7	Bioturbated gray mudstone, 120cm thick, horizontal laminations contain interbedded siderite deposits.
8	Cross-bedded calcarenite, 15cm thick, nodular, myalinids abundant..
9	Laminated to blocky mudstone, 200cm thick, gray, *Phestia* common.



Locality Description: Center of South line of Sec. 11, T.14S., R.18E., Douglas Co., Kansas; Globe 7.5' Topographic Quadrangle, revised 1983.

Location: Lonestar Lake Spillway

Measured By: B. Smith, B. Tilley, K. Ross, & K. Krogstad; Fall'90.

Remarks: 3 of 3

Description

B. no.

10 Sandy siltstone, 75cm thick, thin horizontal laminations with no fossils to highly bioturbated with Planolites, Lockeia Aulichnites and Isopodichnus?, medium light gray.

11 Flaser bedded sandstone, 20cm thick, Lockeia, Scalarituba, Scolichia? present and Planolites abundant.

12 Siltstone, 80cm thick, light gray, horizontal to flaser laminations, sandstone lenses (2-3cm thick), current direction, measured 30cm above coal, varies from N60W to N80W, prominant siderite bearing layer (5-10cm above coal), nuculoid bivalves, Myalina, Aviculopecten common. Probable Amazonia limestone equivalent.

13 Shaly coal, 15cm thick, very dark gray, horizontally laminated, friable, disarticulated Annularia, Calamites, Cordaites, Neuropteris, Spenopteris, abundant, articulated Asterophyllites common, disarticulated Pecopteris common, Myalina, Aviculopecten common, fusain present, spirorbids common, upper and lower contacts gradational.

14 Blocky coal, 18cm thick, abundant disarticulated plant fragments, pyrite dendrites along blocky edges, upper contact gradational, lower contact sharp.

15 Sandy siltstone, 1.5m thick, light gray, finely laminated horizontal to flaser laminations, sandstone lenses present, highly bioturbated, rhizoliths present.

16 Sandy siltstone,light brownish gray, finely laminated flaser bedforms dominant over horizontal laminations, contains more clay than overlying unit and grain size decreases upward, Planolites, Lockeia, and possible tool marks, contacts gradational, base convered.

Stop 8 Kansas Turnpike, 3 miles est of West Lawrence Exit: Virgilian Oread Limestone

Location: (NW Sec. 21, T.12 S., R. 19 E.)

Departure: 2:25

Contributors: *Philip Heckel (1979) and information from Moore and Merriam (1959) and Moore (1949)*

Introduction

This and the next to stops show three of R.C. Moore's megacyclothems, that of the Oread, Lecompton, and Deer Creek Limestones. The stops are all on the Kansas Turnpike (fig. 8-1).

Stop 8 is an exposure of the Oread Limestone that has been a mainstay since it was described by R.C. Moore. The outcrop has grown over since the turnpike was opened (compare to R.C. Moore's sketch in fig. 8-2). The measured section (fig. 8-3) is from Heckel (1979).

The outcrop includes the Toronto Limestone (lower limestone of the megacyclothem), the Leavenworth Limestone (middle limestone), and the Plattsmouth Limestone (upper limestone). At the highest position the Kereford Limestone (super limestone) is exposed.

Lithologic Character and Classification. The Shawnee group contains the following formations, named in upward order: Oread limestone, Kanwaka shale, Lecompton limestone, Tecumseh shale, Deer Creek limestone, Calhoun shale, and Topeka limestone.

According to Moore (1949),

The Shawnee group is especially distinguished by prominence of limestones. In this respect, the Shawnee part of the Virgilian Series is comparable with the Kansas City and Lansing groups of the Missourian Series. The mid-portion of Virgilian time was characterized in the Kansas region by maximum accumulation of clear-water calcareous sediments which seem to be mainly organic in origin. Clastic deposits are not lacking, for in total thickness they exceed the aggregate of all limestone beds, but they are much less prominent than the limestones.

Four formations assigned to the Shawnee group are largely, if not predominantly, made up of limestone. The three intervening formations consist mainly of shale and sandstone. These alternating calcareous and clastic deposits reflect major cyclic oscillations of sedimentation, which furnish evidence of important back and forth shifting of the strand lines of Virgilian seas. Sedimentation associated with retreat of the shallow seas consists of coal beds and nonmarine sandstone and shale, some of which contain well-preserved land plants. Marine sedimentation is represented by the limestones and by several types of shaly deposits; most of these strata contain marine invertebrates of various sorts. The arrangement of terrestrial and marine deposits indicates both a simple progression in cyclic sedimentation, in which as many as a dozen distinct environments are represented, and a repetition of sets of cycles in constant order. The compound cyclic arrangement of Shawnee deposits is expressed in units named megacyclothems (Moore, 1936, p. 29). Each Shawnee megacyclothem includes four or five simple cyclothems having individual peculiarities. The presence of cyclothems [lowermost limestone unit] characterized by prominent brown-weathering massive limestone, which contains abundant fusulinids in many places, distinguishes the Shawnee megacyclothems from those recognized in Missourian and Desmoinesian deposits of Kansas and Missouri [which do not have this lower limestone.

Fig. 8-4 shows diagrammatic sections of the Upper Pennsylvanian in Kansas (Moore and Merriam, 1959). The succession are shown as representative of megacyclothems. Fig. 8-5 shows Moore's interpretation of the water depth through the course of one megacyclothem.

Stratigraphy

As described by Heckel (1979)

Lawrence Shale here represents a delta-plain deposit with short-lived coal swamp developed followed by marginal marine detrital influx (Hakes, 1977) before delta abandonment at the top.

Toronto Limestone is the "lower" limestone of the Oread "megacyclothem." Detailed study by Troell (1965, 1969) suggests that it represents a single transgressive-regressive fluctuation of sea level. In this exposure, transgression is recorded by passage upward from the thin basal shell concentration into skeletal calcilutite deposited between effective wave base and base of the photic zone. The thin fossiliferous shale near the middle is widespread enough to have been used as the major stratigraphic datum by Troell (1965), who interpreted it as a product of very slow offshore clay deposition in view of its fauna of filter feeders (bryozoans, corals, crinoids), which would not have developed in a rapid turbid nearshore detrital pulse. It is possible that scarcity of carbonate mud at this horizon reflects lack of algae near the base of the photic zone, and in view of the relative abundance of conodonts (about 100/kg, mostly idiognathodids), this shale represents the core shale deposited at maximum transgression of the Toronto cyclothem. Regression is recorded by passage from the overlying skeletal calcilutite into the capping argillaceous calcilutite with low-diversity fauna of euryhaline groups, which may represent a restricted lagoonal environment.

Snyderville Shale records spread of detritus in an alluvial environment followed by initial inundation of the succeeding transgression.

Leavenworth Limestone is the "middle" limestone of the Oread megacyclothem and the transgressive limestone of the Oread cyclothem. Detailed study by Toomey (1969) documents the lateral persistence of its nearly uniform nature 500 km from Iowa to Oklahoma. It records a blanket of algal mud production during transgression between effective wave base and the base of the photic zone.

Heebner Shale is the core shale of the Oread cyclothem. Detailed study by Evans (1967) was among the first to strongly propose interpretation of this type of black shale as the deepest-water phase of the megacyclothem. It records depths great enough to establish quasi-estuarine circulation and upwelling, followed by enough shallowing to cause the quasi-estuarine cell to break up and allow some bottom reoxygenation below the effective base of algal mud production.

Plattsmouth Limestone is the "upper" limestone of the Oread megacyclothem and early regressive limestone of the Oread cyclothem. It records enough shallowing to thoroughly reoxygenate the sea bottom and reestablish algal mud production. Calcilutite with diverse biota throughout indicates deposition entirely below wave base.

Heumader Shale records a rapid detrital pulse in view of its sparse fauna.

Kereford Limestone is the "super" limestone of the Oread megacyclothem and probably the late regressive limestone of the Oread cyclothem separated from the early regressive limestone by a fortuitous detrital wedge. Here, its base records resumption of algal mud production below wave base, but laterally, oolites and molluscan biotas record shoaling above wave base and perhaps lagoon formation.

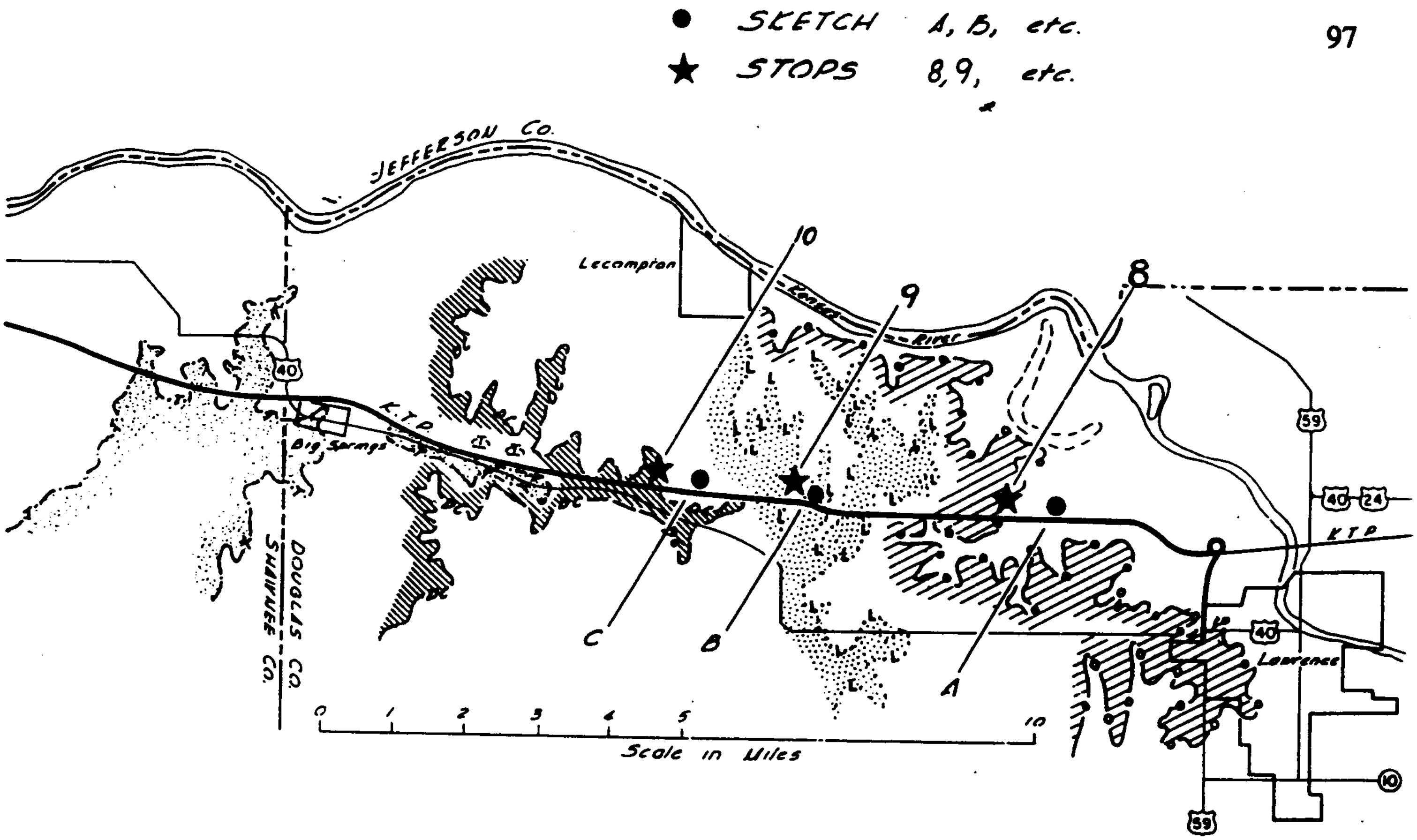


FIGURE 8-1--Map showing locations of stops 8, 9, and 10.

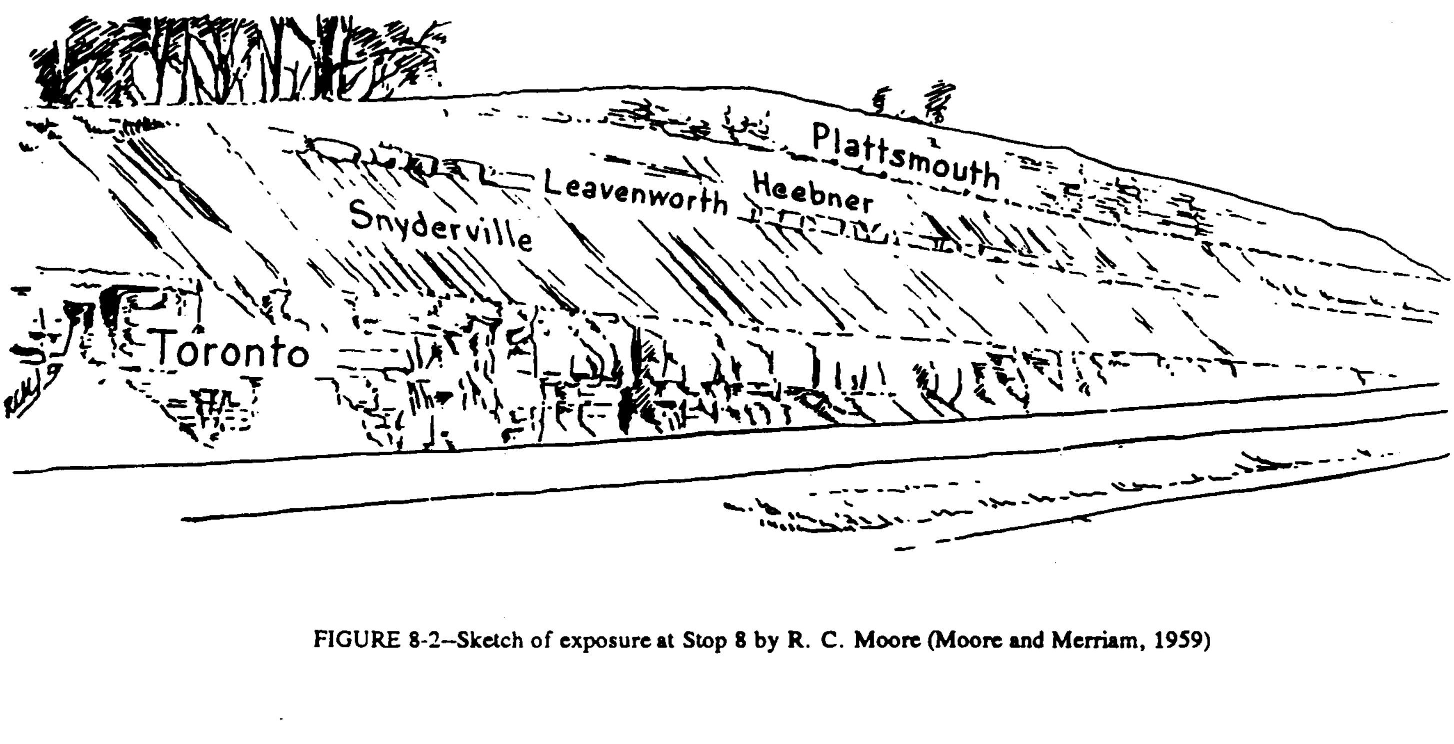


FIGURE 8-2--Sketch of exposure at Stop 8 by R. C. Moore (Moore and Merriam, 1959)

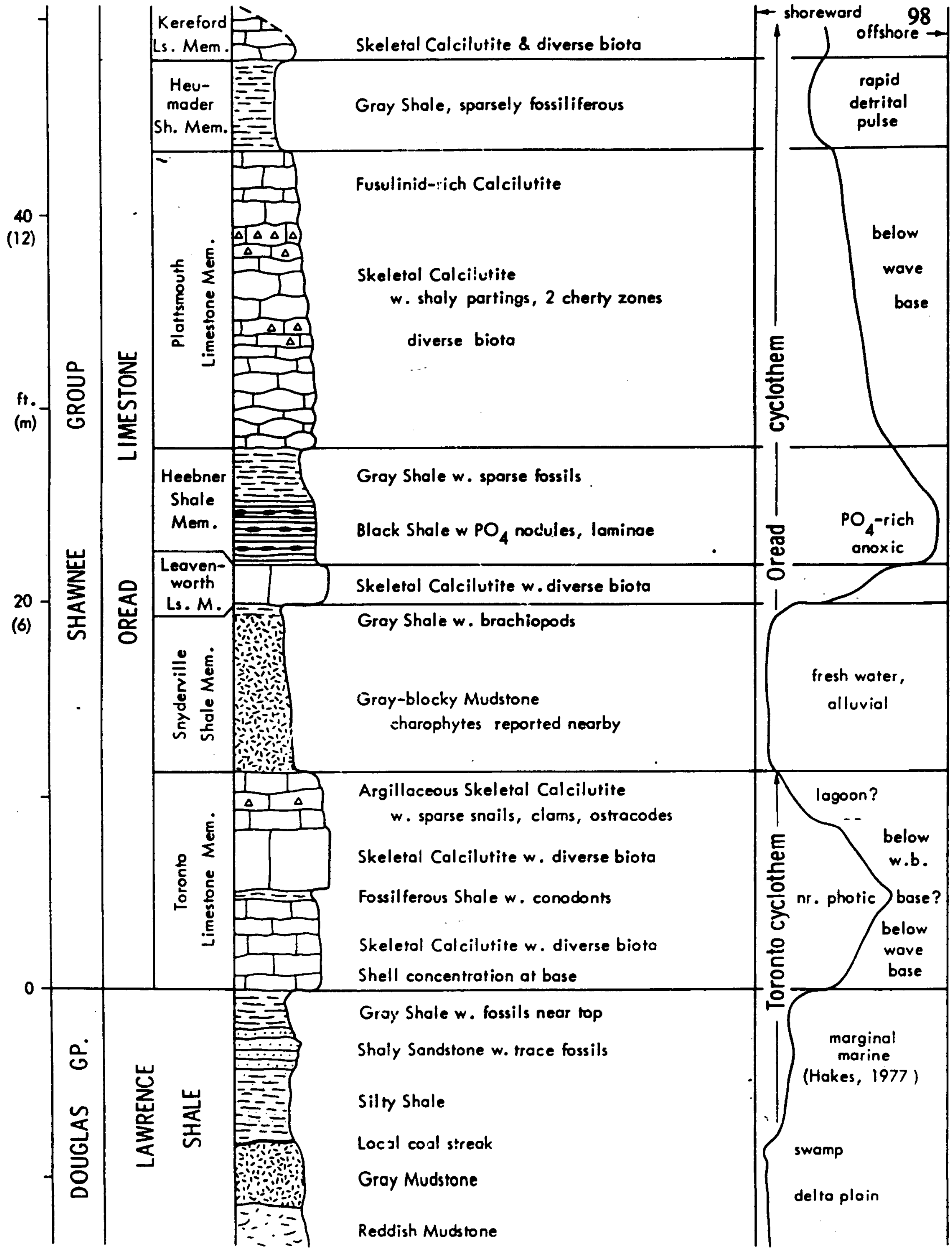


FIGURE 8-3–Measured section of Oread Limestone at Stop 8 (Heckel, 1979).

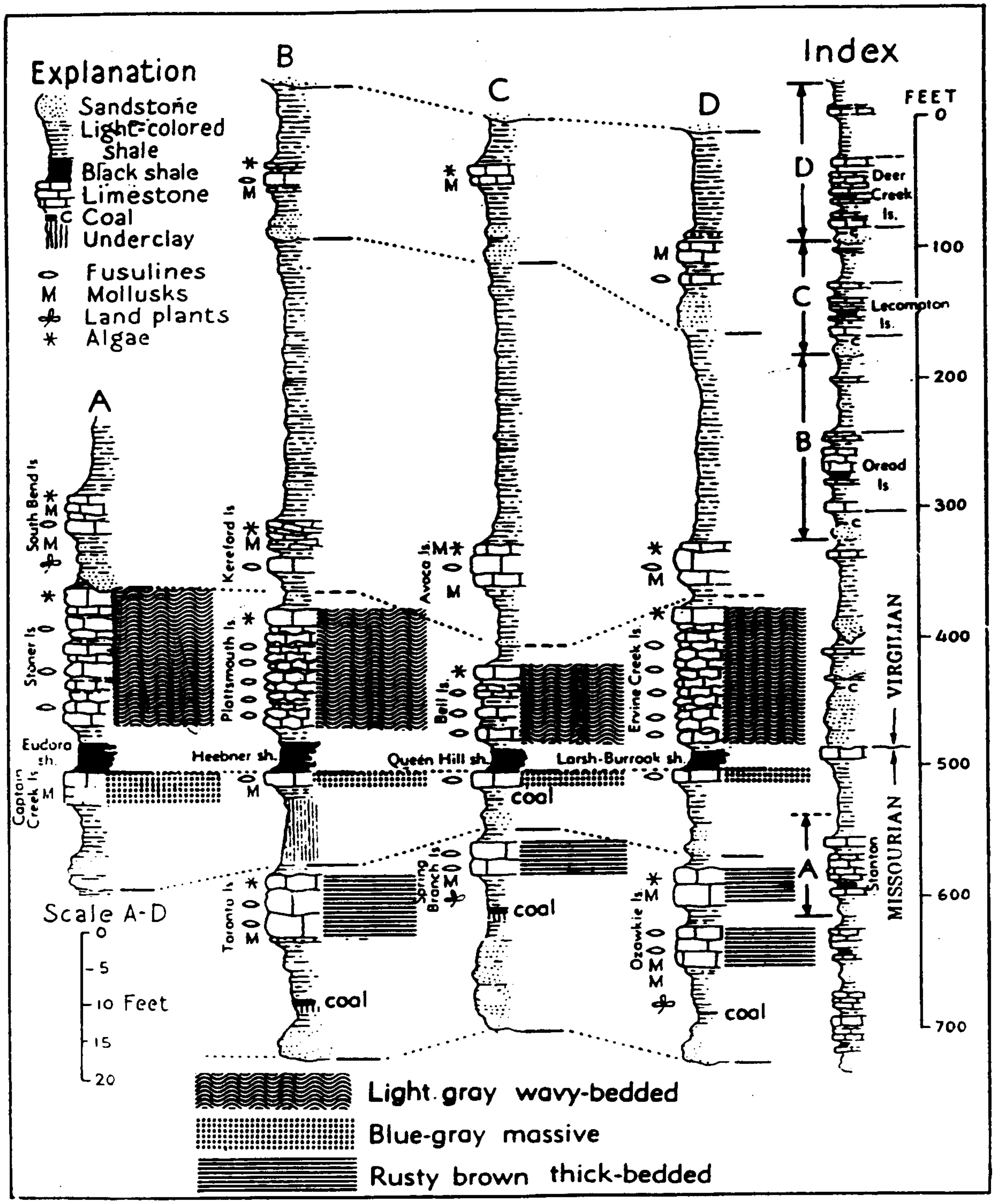


FIGURE 8-4—Diagrammatic stratigraphic sections of the Upper Pennsylvanian in Kansas (Moore and Merriam, 1959).

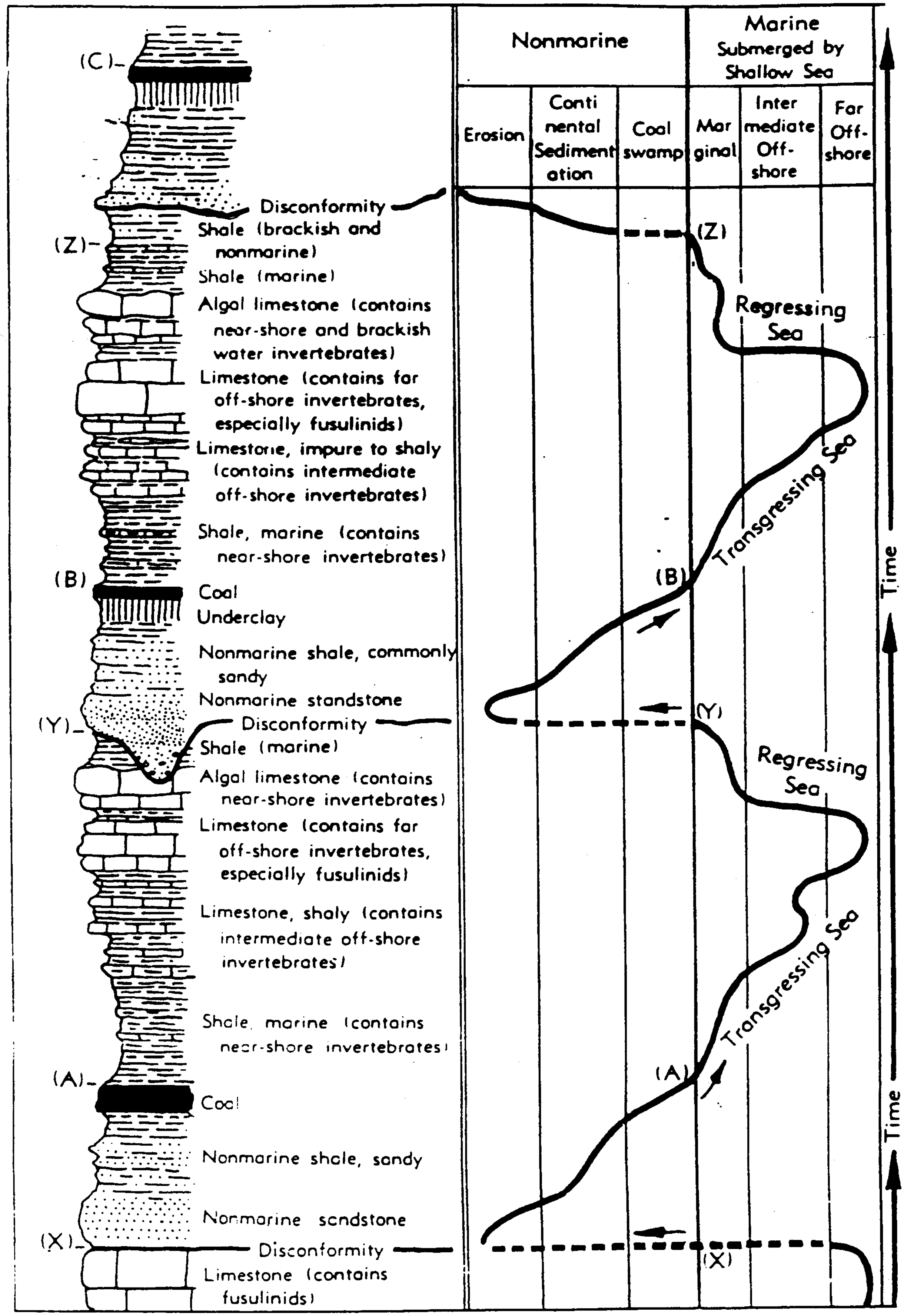


FIGURE 8-5–Water depth interpretation of R.C. Moore (Moore and Merriam, 1959).

Stop 9 Kansas Turnpike, 6 miles west of West Lawrence Exit: Lecompton Limestone and Kanwaka Shale

Location: (NW NW Sec. 24, T. 12 S., R. 18 E.)

Departure: 2:45

Contributors: *Philip Heckel (from Heckel, 1979) and material from Moore and Merriam (1959)*

Introduction

The Lecompton Limestone is another example of Moore's Shawnee megacyclothems. This stop shows the middle of the Lecompton Limestone, the next higher "Shawnee megacyclothem," differing from the others in extreme shadiness of the regressive limestone, which affords excellent fossil collecting. His sketches of this turnpike exposure are again indicative of the fresh exposures of that time (fig. 9-1). The measured section is shown in fig. 9-2 is from Heckel 1979).

Stratigraphy

from Heckel (1979)

Spring Branch Limestone, the "lower" limestone, may record only reduced detrital influx in a nearshore marine environment during general regression.

Doniphan Shale records more overwhelming detrital influx into a marginal marine environment, followed by initiation of the succeeding major transgression.

Big Springs Limestone, the "middle" limestone of the Lecompton megacyclothem and transgressive limestone of the Lecompton cyclothem, records algal mud production and fusulinid proliferation between wave base and base of the photic zone.

Queen Hill Shale is the core shale of the Lecompton cyclothem, which records quasi-estuarine circulation at maximum transgression.

Beil Limestone is the "upper" limestone of the Lecompton megacyclothem and regressive limestone of the Lecompton cyclothem. It records algal mud production and invertebrate proliferation on a sea floor that was subject to more detrital influx from distant deltas than were most other regressive limestones. Fine calcarenite in the topmost bed records regression above effective wave base.

King Hill Shale records more overwhelming detrital influx from a closer delta as shoreline approached. Environment of the yellow carbonate is not clear.

"Super" limestone of the Lecompton megacyclothem (Avoca) is not exposed here.

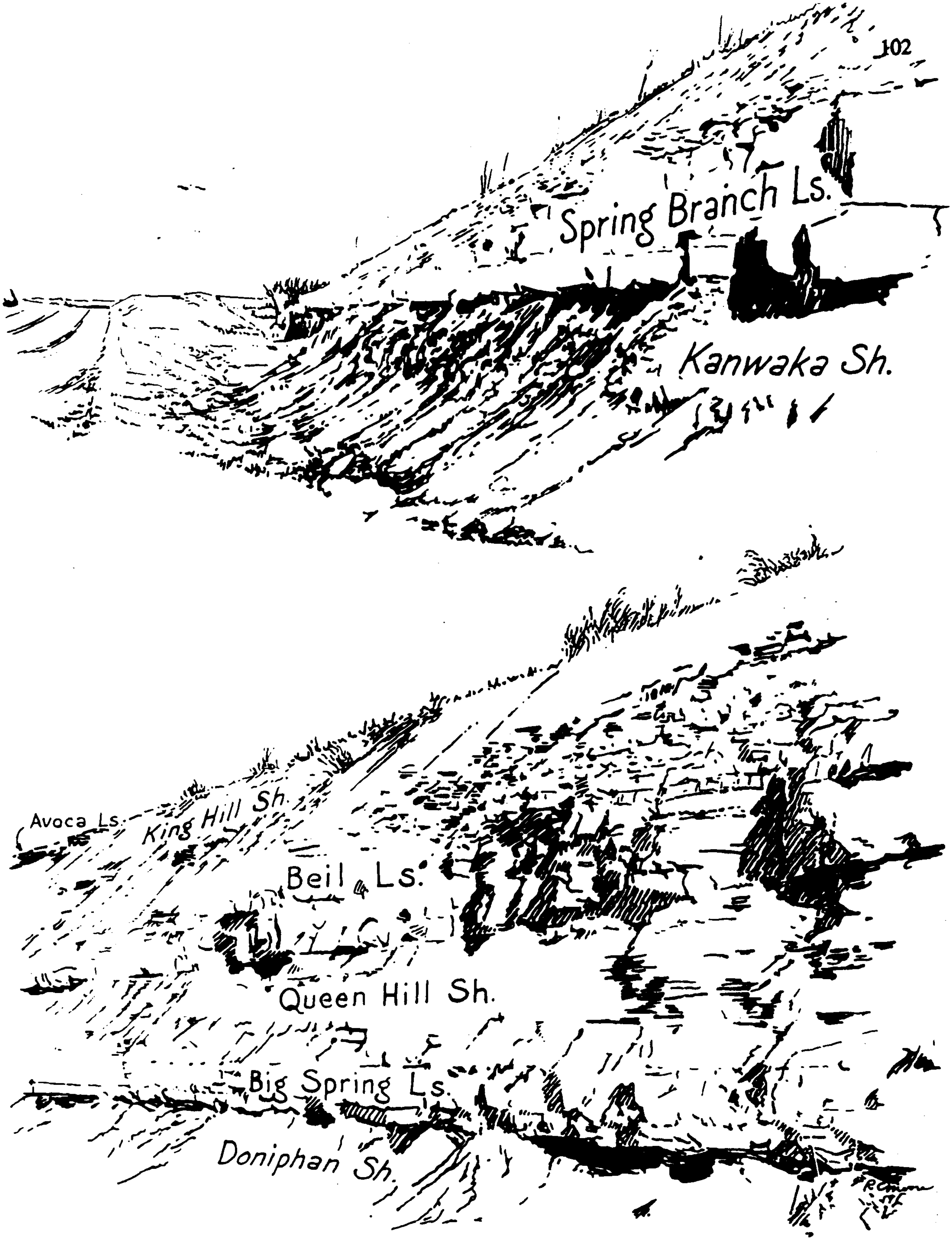


FIGURE 9-1–Sketch of exposure at Stop 9 by R.C. Moore (Moore and Merriam, 1959).

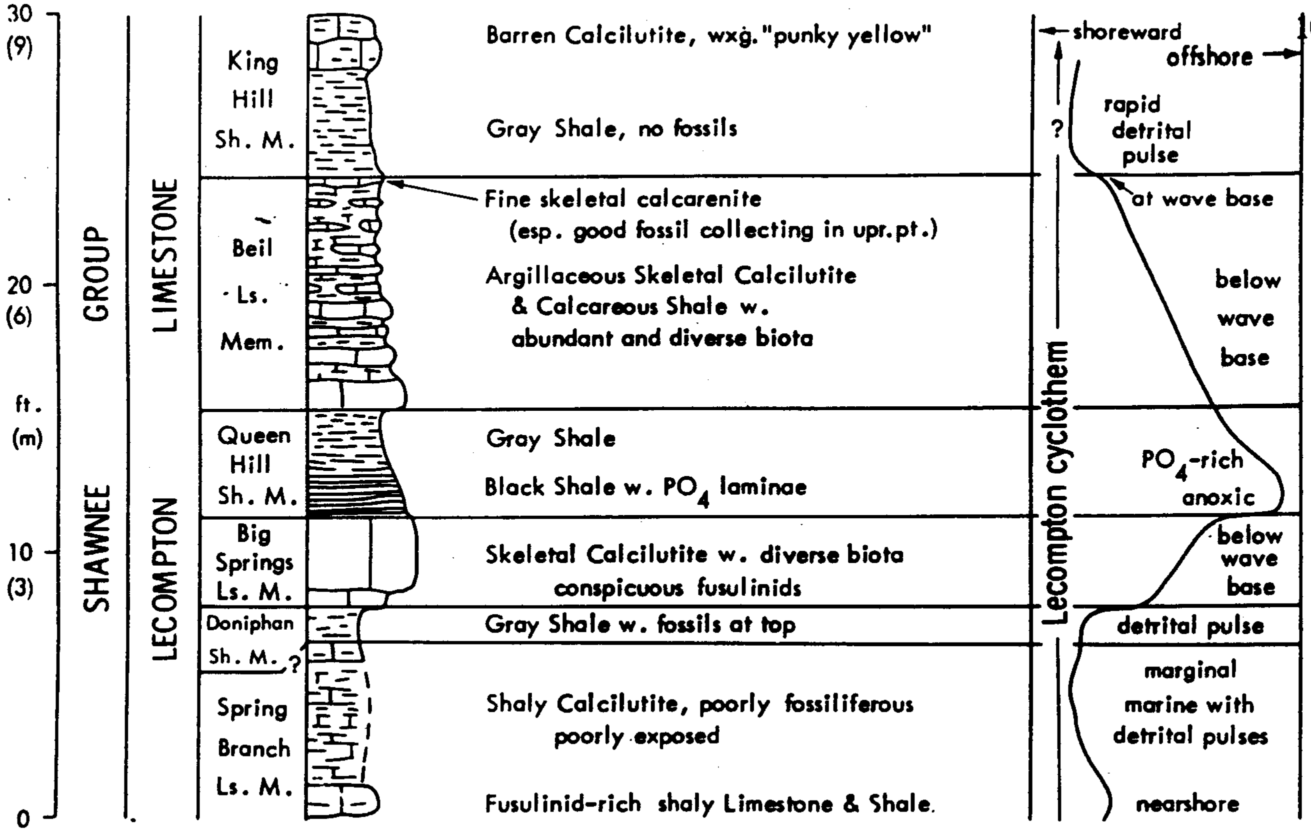


FIGURE 9-2–Measured section at Stop 9 (from Heckel, 1979).

Stop 10 Kansas Turnpike, 8 miles west of West Lawrence Exit: Deer Creek Limestone and Tecumseh Shale

Location: (NE NW Sec. 22, T. 12 S., R. 18 E.)

Departure: 3:20

Contributors: *Philip Heckel (from Heckel, 1979) and material from Moore and Merriam (1959) and Moore (1949)*

Introduction

The Deer Creek Limestone is the third and final example of the megacyclothems of the Virgilian Shawnee Group. The succession is recognizable from Iowa to Oklahoma (Heckel, 1979). R.C. Moore's sketch of the outcrop is shown in Fig. 10-1. The measured section is in fig. 10-2 (from Heckel, 1979) and a diagram comparing Moore's megacyclothem development in the Deer Creek and Topeka Limestones is shown in fig. 10-3.

Stratigraphy

from Heckel (1979)

Tecumseh Shale records detrital influx into a shallow nearshore environment, in which transgression initiating Deer Creek deposition can be detected by vertical sequence of trace fossils toward the top (Hakes, 1976).

Ozawkie Limestone is the "lower" limestone of the Deer Creek megacyclothem. Entirely oolitic here, it records an agitated carbonate shoal, which requires no significant change in sea level. Like the Spring Branch ("lower" limestone of the Lecompton) it is absent in Nebraska (Moore, 1949), thus supporting possible origin of both from delta shifting near the end of regression, rather than from widespread sea level change as suggested for the Toronto ("lower" limestone of the Oread), which is as well developed in Nebraska as in Kansas.

Oskaloosa Shale records the last detrital pulse before major transgression.

Rock Bluff Limestone is the "middle" limestone of the Deer Creek megacyclothem and transgressive limestone of the Deer Creek cyclothem, recording algal mud production between effective wave base and base of the photic zone.

Larsh-Burroak Shale is the core shale of the Deer Creek cyclothem, recording quasi-estuarine circulation at maximum transgression. It has been considered equivalent to two thin shales and an intervening limestone in Nebraska.

Ervine Creek Limestone is the "upper" limestone of the Deer Creek megacyclothem and regressive limestone of the Deer Creek cyclothem, recording reestablishment of algal mud production. Although not exposed here, the top is oolitic in places (Moore, 1949), recording shallowing above wave base.

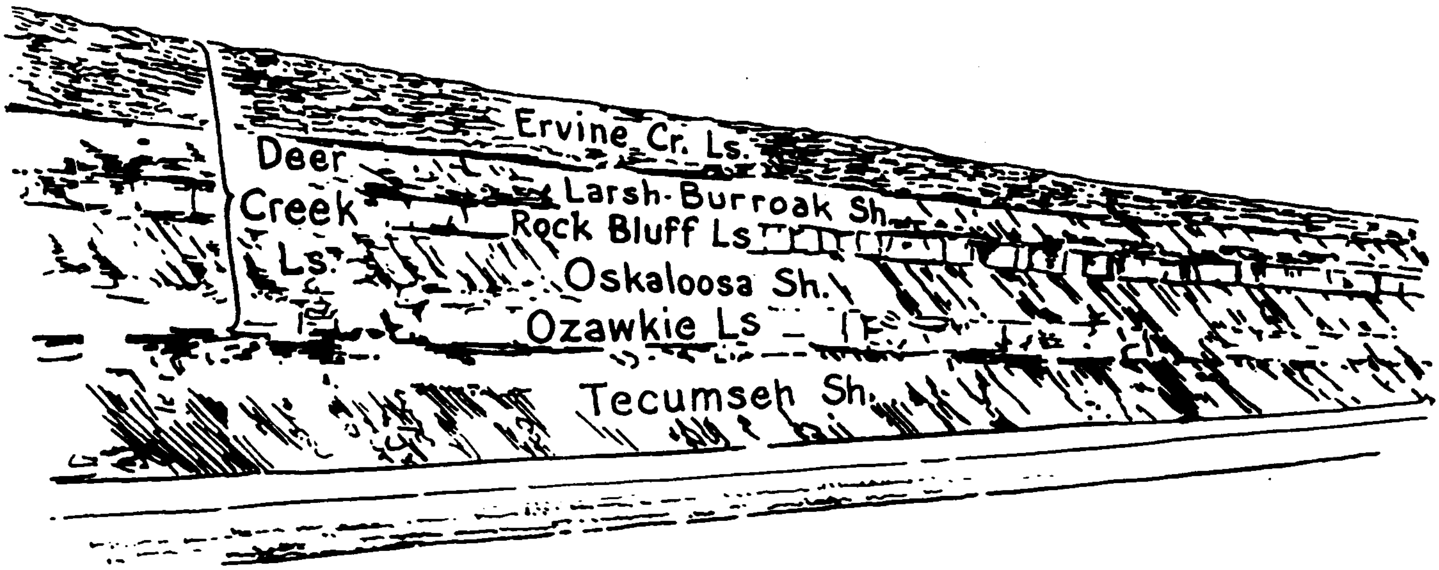
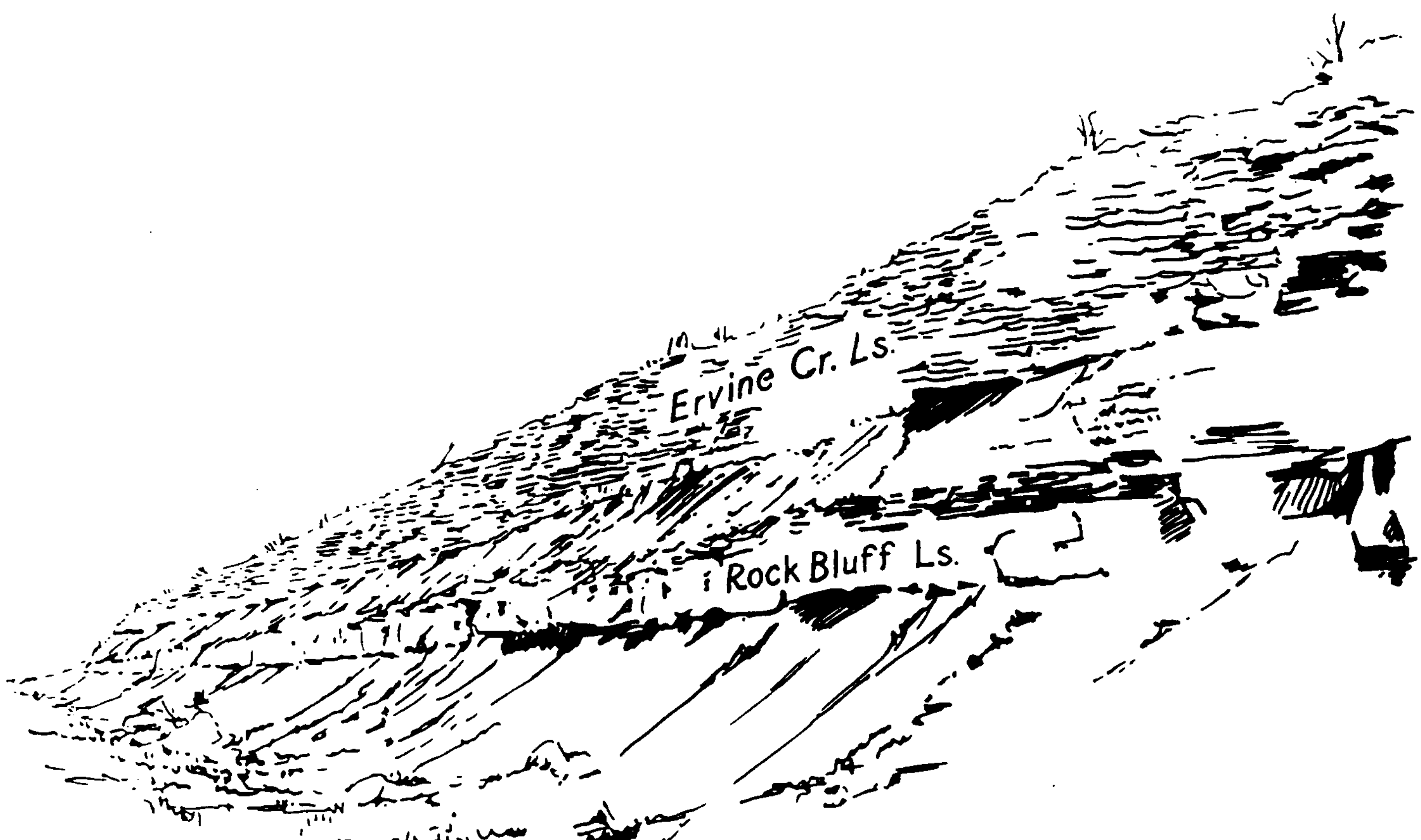


FIGURE 10-1–Sketch of exposure at Stop 10 by R.C. Moore (Moore and Merriam, 1959).



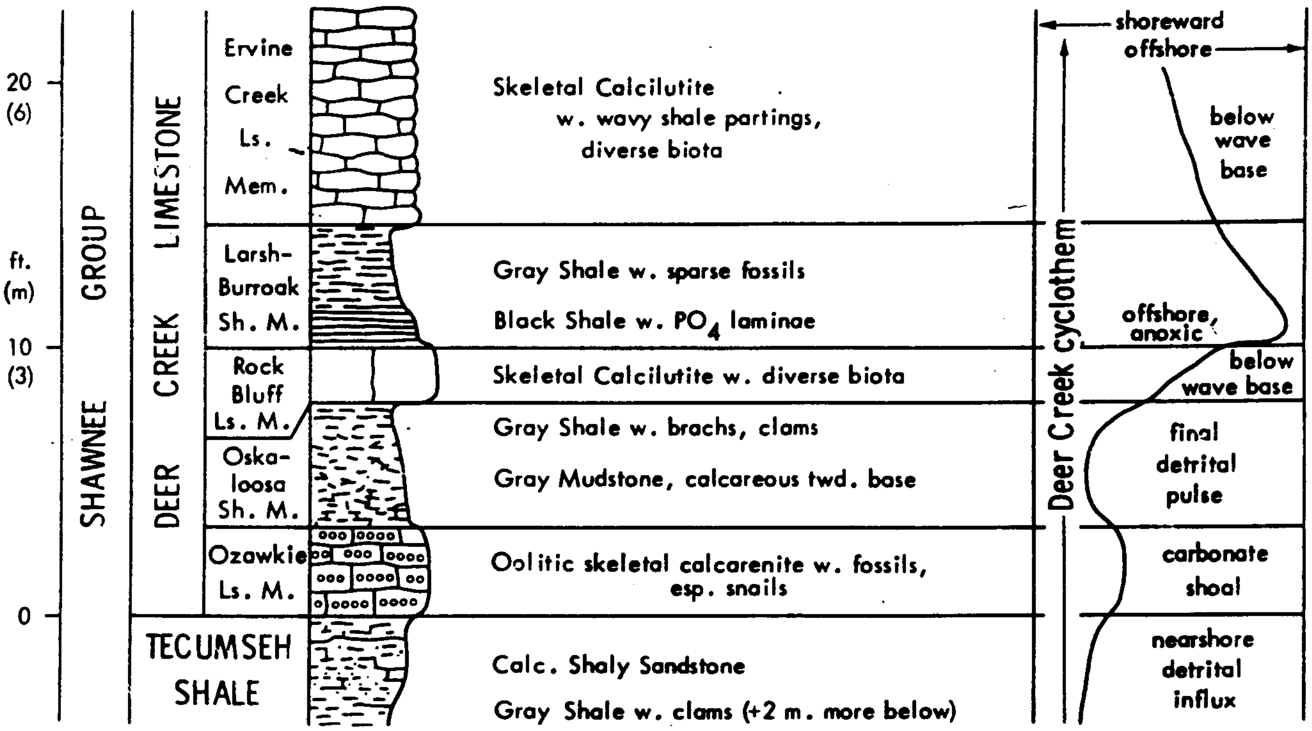


FIGURE 10-2–Measured section at Stop 10.

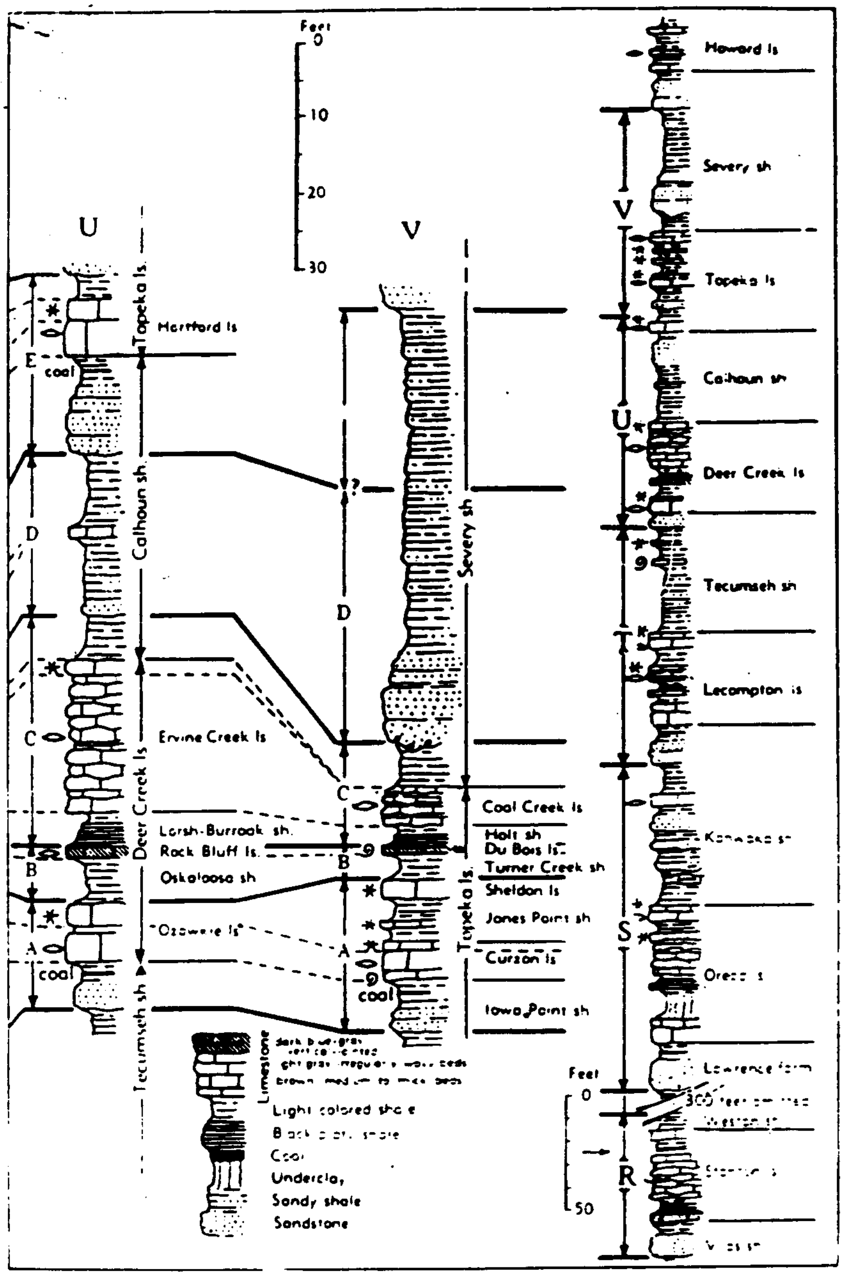


FIGURE 10-3--Diagram comparing megacyclothem development in Deer Creek and Topeka Limestones (from Moore, 1949).

Stop 11 Topeka south entrance to Kansas Turnpike: Howard Limestone including Nodaway Coal

Departure: 4:10

Contributors: *Pauline Denham, Lynn Watney, and Chris Maples*

Introduction

The uppermost major division of the Virgilian strata includes beds above the Topeka Limestone and below the Permian Admire Group. Shale is the chief rock type in this group. The shale is commonly sandy and at several horizons there are extensive sandstones. Limestones in this group are uniformly thin, but persistent. Thicknesses of individual members is only 2 or 3 feet. The thickness of the Wabaunsee Group commonly is about 500 feet.

The Wabaunsee group is distinguished chiefly by its general lithologic features and by the character of its cyclothems from the underlying Shawnee and the succeeding Lower Permian beds, but there are also some faunal peculiarities.

Moore (1949) states,

A distinctive feature of the Wabaunsee group is the character of the cyclic sedimentary succession, which shows regularly alternating nonmarine and marine units, in which (excepting beds at the base) a grouping of cyclothems in megacyclothems is not evident. This serves especially to set the Wabaunsee beds apart from those of the Shawnee group.

The Wabaunsee group is divided into alternating shale and limestone formations. The shales include shale, sandstone, coal, and some minor limestone beds which all together comprise the initial and terminal parts of adjoining cyclothems. The limestones contain limestones and intervening shales which represent the medial part of each cyclothem. This classification is applicable to all of the Wabaunsee beds except one or two seemingly rudimentary cyclothems, which are not separately indicated by the present defined formations.

The Howard Limestone is the lowest limestone formation in the Waubaunsee Group. It is comprised from its base of the Bachelor Creek Limestone, the Aarde Shale, Church Limestone, Shanghai Creek Shale, Waunetta Limestone, Winzeler Shale, and the Utopia Limestone. The complete sequence of Howard Limestone in Kansas is present only in the southern half of the state. Here, the Bachelor Creek Limestone (a "lower" limestone), Shanghai Creek Shale (core shale), and Waunetta Limestone ("upper" limestone) are absent. The Nodaway coal bed is located in the Aarde Shale. It is generally 0.1 foot to 2 feet in thickness. The shale underlying the coal is commonly laminated with plant debris.

The measured section is found in fig. 11-1.

Shale (Winzeler), tan-brown, weathers red-tan; highly fossiliferous-brachiopods,bryozoans..1.0 (.30m)

Limestone (Church), medium gray, weathers creamy-tan; wackestone to packstone; crinoid debris, brachiopods, bryozoans, oncolites.....................................1.6 (.46m)

Shale (Aarde), tan, weathers lt. tan, bottom 3 inches red-brown; chonetids, productids, *Composita*, gastropods,*Hustedia*.....................1.7(.48m)

Coal (Nodaway), black, weathers red-brown; bottom 3 inches coaly shale.........................1.1(.33m)

Shale (Aarde), dark gray with tan mottling, weathers lt. gray; clay rich.........................5.8(1.72m)

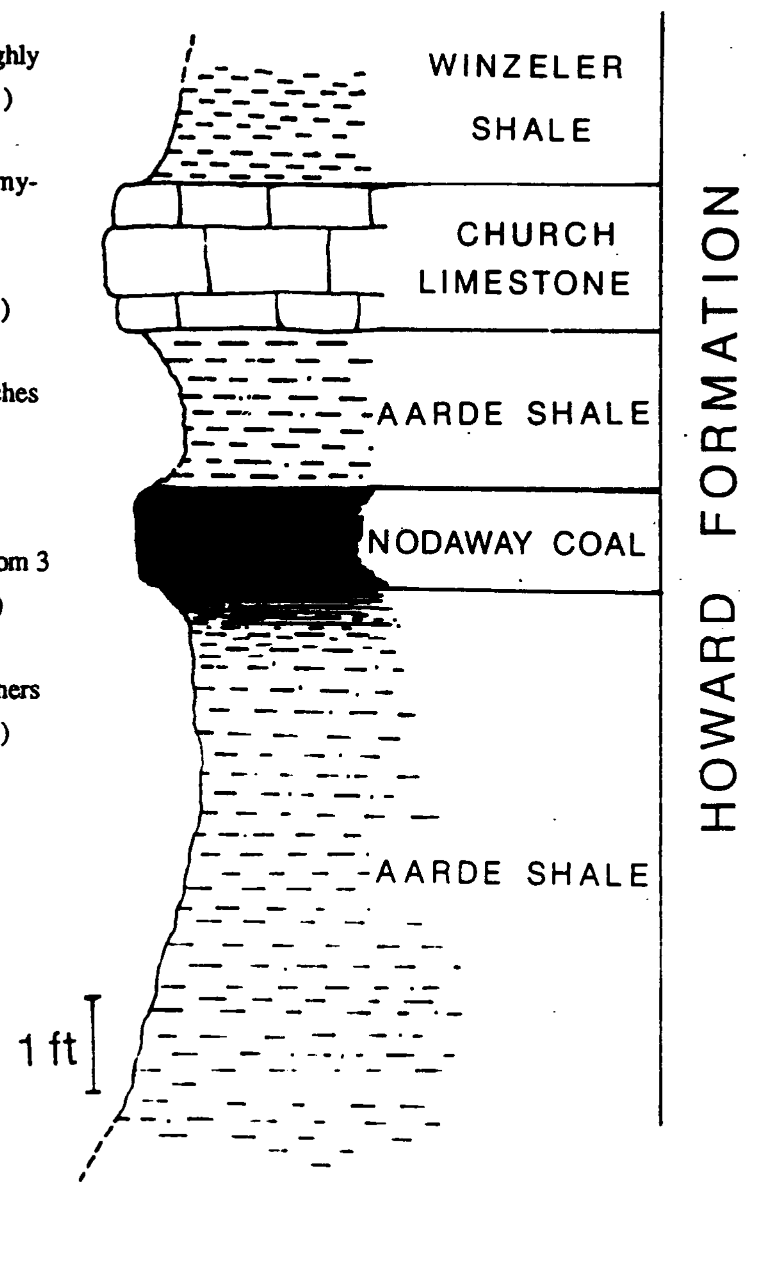


FIGURE 11-1--Measured section at Stop 11.

Stop 12 I-70, 8 miles west of Topeka: Zeandale Limestone

Departure: 4:35

Contributors: *Lynn Watney and material from Moore and Merriam (1959) and Moore (1949)*

Introduction

The exposure includes the Tarkio Limestone and Maple Hill Limestone Members of the Zeandale Limestone of the Virgilian Wabaunsee Group as indicated in a sketch from R.C. Moore in fig. 12-1. The Tarkio Limestone one of the most easily recognized units in the Wabaunsee Group. It is characterized by its brown color of weathered outcrops (it was originally known as the "Chocolate Limestone") and the abundance of large fusulinids (Triticites). Locally algae occur in the upper part. Thickness ranges from 0 to about 10 feet. The Maple Hill Limestone ranges from 1 to 5 feet thick.

The measured section is found in fig. 12-2 (Moore and Merriam, 1959). The cyclothems as identified by Moore (1949) in the Wabaunsee Group are identified in fig. 12-3.

General Discussion of Causes Leading to Change in Stratigraphic Pattern

The cycle of sedimentation seen here and at the next stop is considerably different than that observed down in the Missourian. The limestones are thinner and shales are thicker and more abundant. Environmental indicators suggest shallow-marine and nearshore or strandline conditions. The cycles are thin and fluctuation of marine and nonmarine environments is much more frequent and evident. Black shale is absent or very poorly developed in these upper Virgilian strata. Possible explanations for this change in style of sedimentation from the Missourian may reflect changes in climate. While semiarid conditions may have dominated during the Missourian Stage, the later Virgilian may have brought a change to fluctuating wet-dry conditions. The wet-dry conditions would promote greater influx of fine-grained terrigenous clastics (Cecil, 1990). This should be evident in the kind of paleosols and the types of coal deposits preserved in the upper Virgilian.

Alternatively, or in addition to climate change, the magnitude of sea-level fluctuations could have diminished leading to less significant rates and magnitudes of deepening, eliminating black shale accumulation and more paralic sedimentation. The lateral fluctuations in the shoreline may thus have been less, facilitating the quick (early) return of terrigenous clastic influx after each minor marine inundation of the shelf. The Virgilian lithofacies is predominately siliciclastics in eastern and northern Kansas and in adjoining areas (Rascoe and Adler, 1983).

Incised channels are especially evident in surface exposures in eastern Kansas in the interval from the Willard Shale into the lower Permian. The incisions up to 110 feet (Mudge, 1956) suggests that significant lowstands probably occurred. The record of this lowstand would be expected to have been poorly preserved in what would be the subaerially exposed upland surface. Thus, the magnitude of sea level fluctuation may have been similar to the Missourian, but the mean sea level may have been lower. This trend toward a fall in relative sea level in the Permian is supported by paleogeographic reconstructions, e.g., Hills (1942).

Finally, tectonics may have also contributed to the observed stratal assemblage. Differential subsidence was significant across Kansas during the Missourian due to continued orogenic activity in the Ouachita and Wichita mountains. During the Virgilian subsidence patterns were broader and rates were moderate compared to the Missourian. Orogenic activity moved southwestward with continued movement in the

Wichita Mountains and adjacent Anadarko basin accounting for the sustained moderate levels of subsidence (see fig. 9 in the introduction; Kluth, 1986). The Arkoma basin (foreland basin) was filled with sediment in late Missourian and siliciclastics were readily available from the remaining positive areas of this uplift (see fig. 10 in introduction; Rascoe and Adler, 1983). Additional siliciclastic sources were from the north and east, probably filling the depositional trough created by subsidence. Carbonate sedimentation was maintained during the Virgilian in southwest Kansas due to isolation from the silciclastic source (again see fig. 9 from introduction).

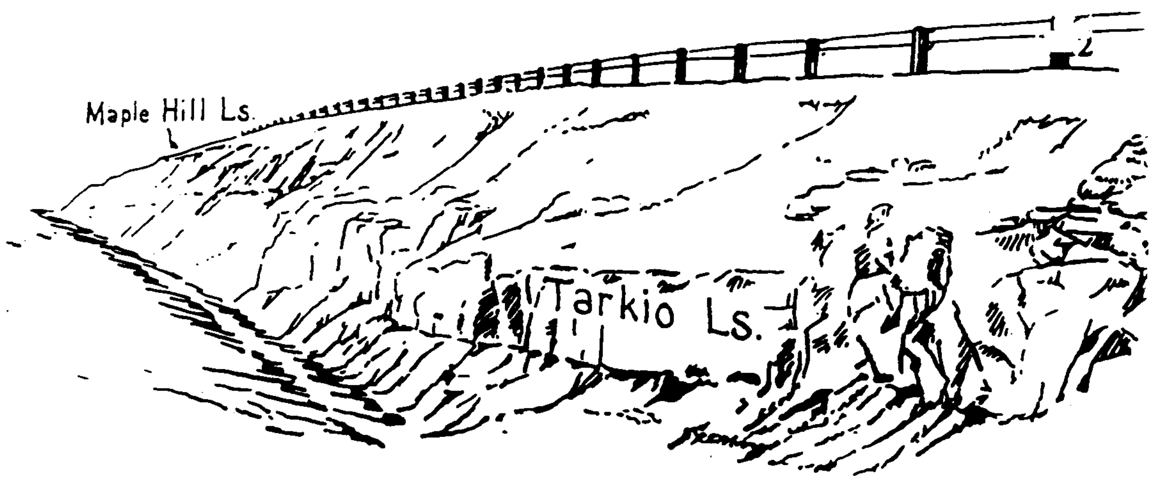
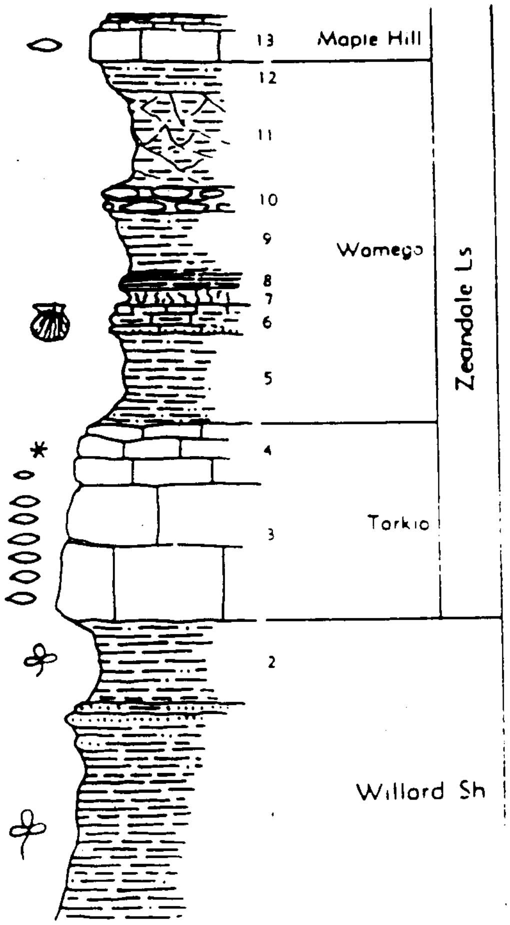


FIGURE 12-1--Sketch of exposure at Stop 12 by R.C. Moore (Moore and Merriam, 1959).



13. Limestone (Maple Hill), gray on fresh surface, weathers brown, massive, compact (medium-hard); slender fusulinids, crinoids, sparse mollusks, brachiopods 1.8
12. Siltstone (Wamego), yellow-brown, indistinct bedding 1
11. Clay (Wamego), gray; unfossiliferous 3
10. Ironstone (Wamego), limonitic concretion zone 1
9. Shale (Wamego), gray-green to tan, flaky bedding; clayey to silty upward 2
8. Shale (Wamego), dark gray to black, bedding indistinct; unfossiliferous 0.7
7. Clay (Wamego), gray-blue to gray-green 0.5
6. Limestone (Wamego), gray, very impure, shaly; molluscan fauna, crinoid remains, Linoproductus 1
5. Shale (Wamego), yellowish-brown, silty and micaceous; crinoidal float from above 3
4. Limestone (Tarkio), gray to tan on both fresh and weathered surfaces, massive, detrital texture, more compact than unit 3; algae (Osagia) with pelecypods, brachiopods, bryozoans, crinoid remains, and scattered fusulinids. 2
3. Limestone (Tarkio), brown on both fresh and weathered surfaces, massive, deep weathering results in a medium soft, almost earthy texture (dull thud when struck with hammer). abundant ventricose Triticites give rock a speckled character scattered crinoid remains, sparse brachiopods; scattered irregular tubes filled with celesite in lower 3 feet 5
2. Shale (Willard), gray to green on fresh surface, weathers gray bedding indistinct, silty, sparse plant remains, parts of crinoid stems and individual columnals (not indigenous to shale-weathering out of overlying limestone) 5
1. Siltstone (Willard), reddish brown on fresh surface, weathers tan to brown, bedding indistinct, abundant limonite stain seen in fresh trench; uppermost part more resistant; contains sparse, poorly preserved plant remains . . . . 6 -

(Section measured by S. M. Ball and M. M. Ball)

FIGURE 12-2--Measured section at Stop 12 (Moore and Merriam, 1959).

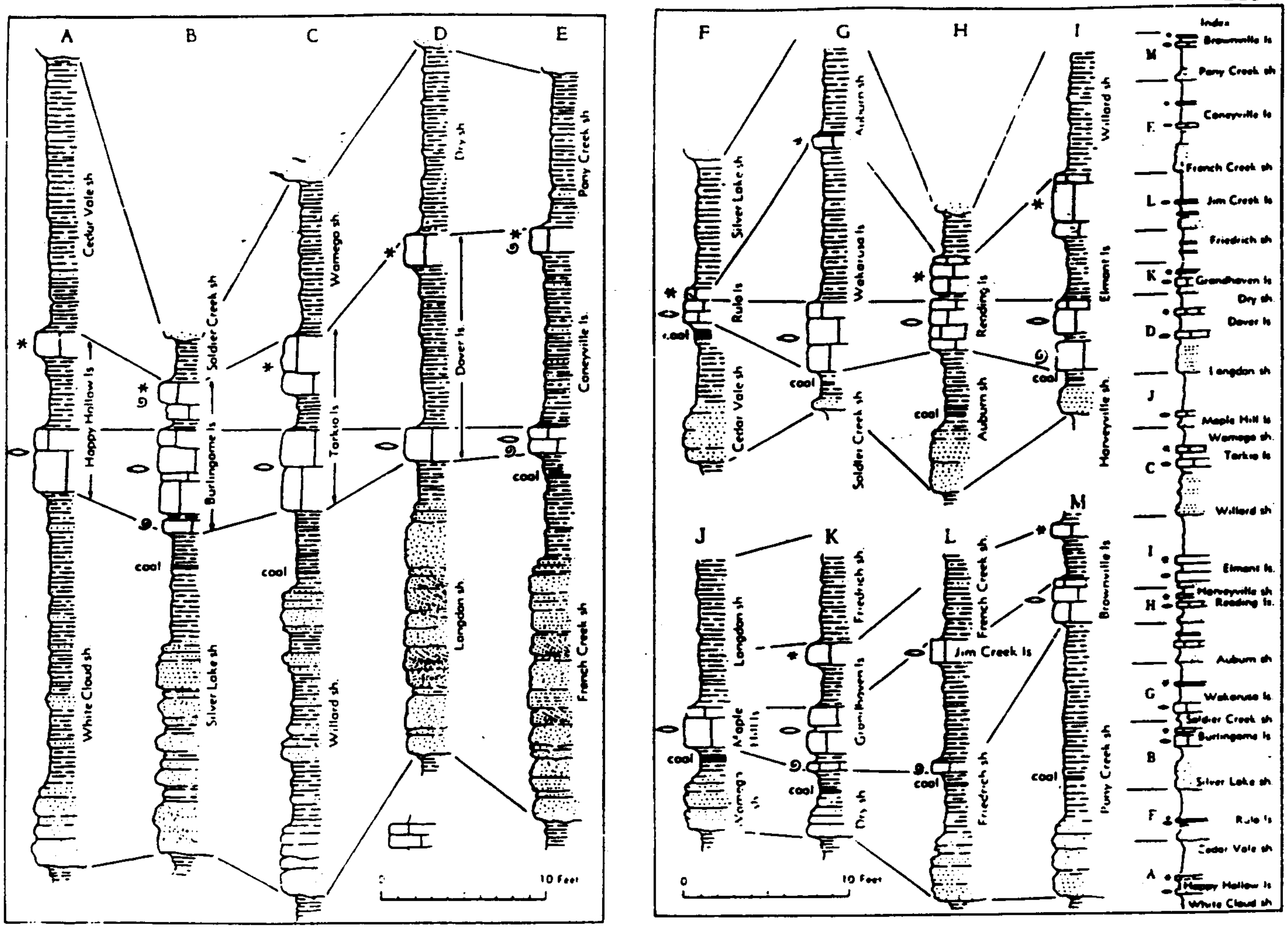


FIGURE 12-3–Comparison of cyclothems in the Waubansee Group (Moore, 1949).

Stop 13 I-70, 0.5 miles west of Maple Hill Exit, west of Topeka: Pony Creek, Brownsville Limestone, Towle Shale, and Aspinwall Limestone

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

Departure: 5:20

Contributors: *R.R. West and R. Matsumoto*

Things to see: Pennsylvanian-Permian boundary, lack of Kansas-type cyclothem, and facies mosaic in Pony Creek Shale.

The Pennsylvanian-Permian contact is exposed on both sides of I-70 at this locality. As shown in fig. 13-1 this exposure is located on the west flank of the Brownville Syncline, an asymmetrical structure in the Forest City Basin, and the east flank of the Nemaha Anticline. The depositional environment is marginal marine as determined by Bisby (1985) and shown in fig. 13-2. 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 (Pennsylvanian), which crops out low in the road ditch at the west end of the exposure, to the Aspinwall Limestone Member of the Onaga Shale (Permian) at the top of the outcrop (fig. 13-1C). 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.

The three important aspects of this stop are: 1) the current Pennsylvanian-Permian boundary is clearly visible, 2) the basic "Kansas" cyclothem seen in the Missourian earlier on this trip 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 systematic boundary between the Pennsylvanian and Permian is 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 is based on what have been considered major changes in the "aspects" of the fossil assemblages in the rocks below this position and compared to fossil assemblages in the rocks above 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). Recently, Baars et al. (1990) have suggested moving the Pennsylvanian-Permian boundary up to the Neva Limestone.

In this part of the stratigraphic sequence (upper Wabaunsee and lower Admire groups), the typical "Kansas" cyclothem of Heckel (1977) is difficult, if not impossible, to recognize, and may not exist. The basic lithologies of these Upper Pennsylvanian and Lower Permian rocks, in this area, 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 occurs in an 8-to-11 cm (3.14-4.33 in.) interval, about 3 m (9.8 ft) below the top of the Brownville Limestone Member in this roadcut. A total of 30 stratigraphic sections were measured and described along a 300-m (984 ft) transect (fig. 13-2A, secs. H to DD). From the base to the top of the 8-to-11 cm 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 higher intertidal to nonmarine environment. This uppermost depositional environment is represented by an interval of heavily oxidized ironstone nodules and crusts in a unfossiliferous mudstone (West and Matsumoto, 1986). The low intertidal to very shallow subtidal part of this thin sequence is represented by a 2-cm (0.78-in.) thick tempestite that overlies a 1-cm (0.39-in.) thick, clayey carbonate mudstone (West and 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 Glossifungites ichnofacies (sec. E, fig. 13-2B) to a Trypanites ichnofacies (secs. P and BB, fig. 13-2B). Across the valley to the west (sec. EE, fig. 13-2B), a nonmarine-to-marginal-marine quartz sandstone correlates with this ichnofacies mosaic. This interpretation is reasonable in terms of the paleotopography at the time of deposition of these units (Bisby, 1985, 1986). Essentially, 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 this storm deposit and its hiatus pebbles and cobbles is, in general, similar to genetic sequence Via described by Fursich (1979) for some Jurassic rocks and a pebbly to reworked morphological hardground described from the Ordovician of Ontario by Brett and Brookfield (1984). The lateral relationships described by Pemberton and Frey (1985) and West et al. (in press) between sands and Glossifungites and Trypanites ichnofacies along the offshore islands of the Georgia coast are a reasonable modern analog for this record within the Pony Creek Shale Member at this locality.

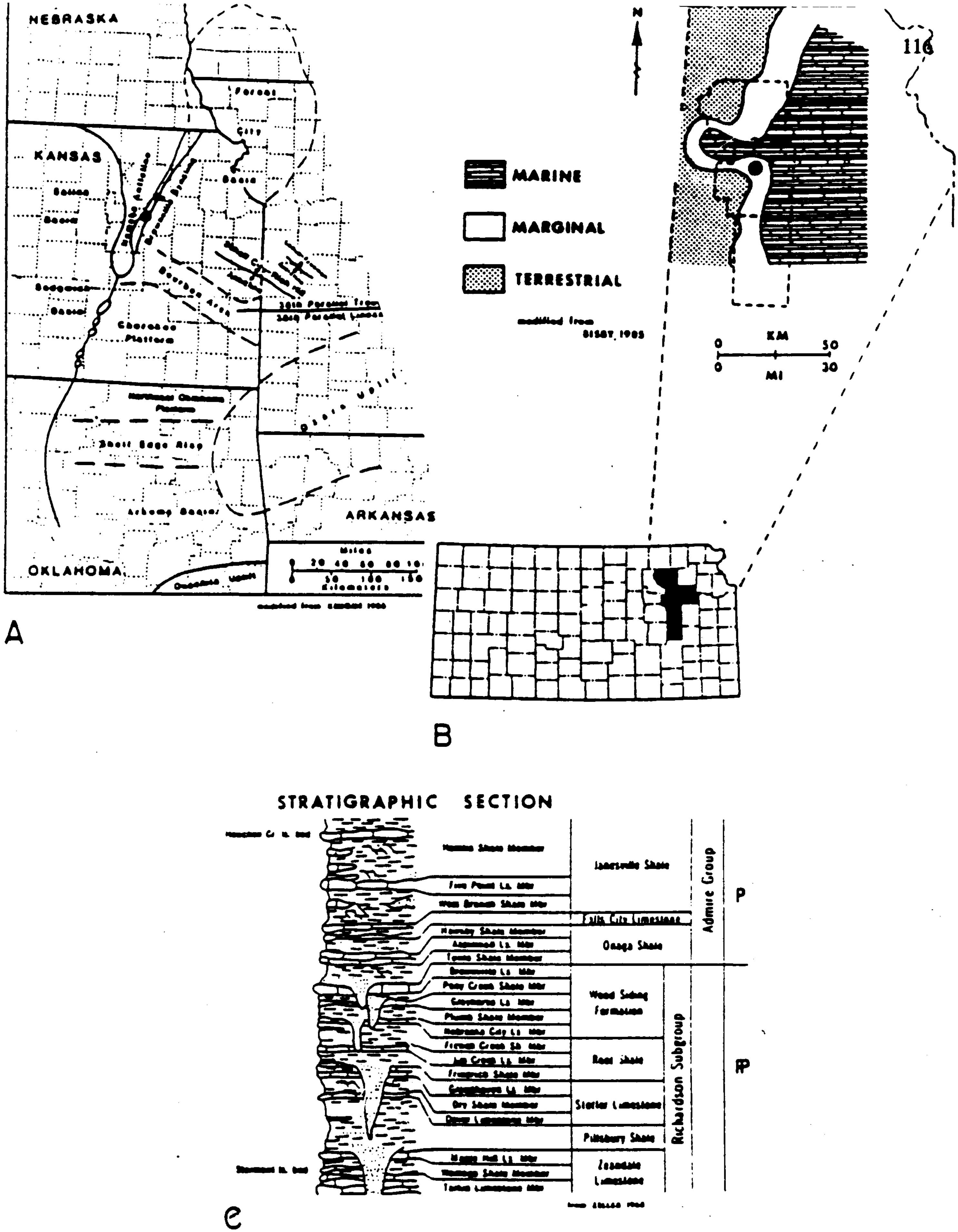


FIGURE 13-1--Maple Hill, Kansas, Stop 13; A) location of stop relative to structural features (modified from Knight, 1985); B) location of stop relative to inferred depositional environments (modified from Bisby, 1985); C) stratigraphic sequence (from Zeller, 1968).

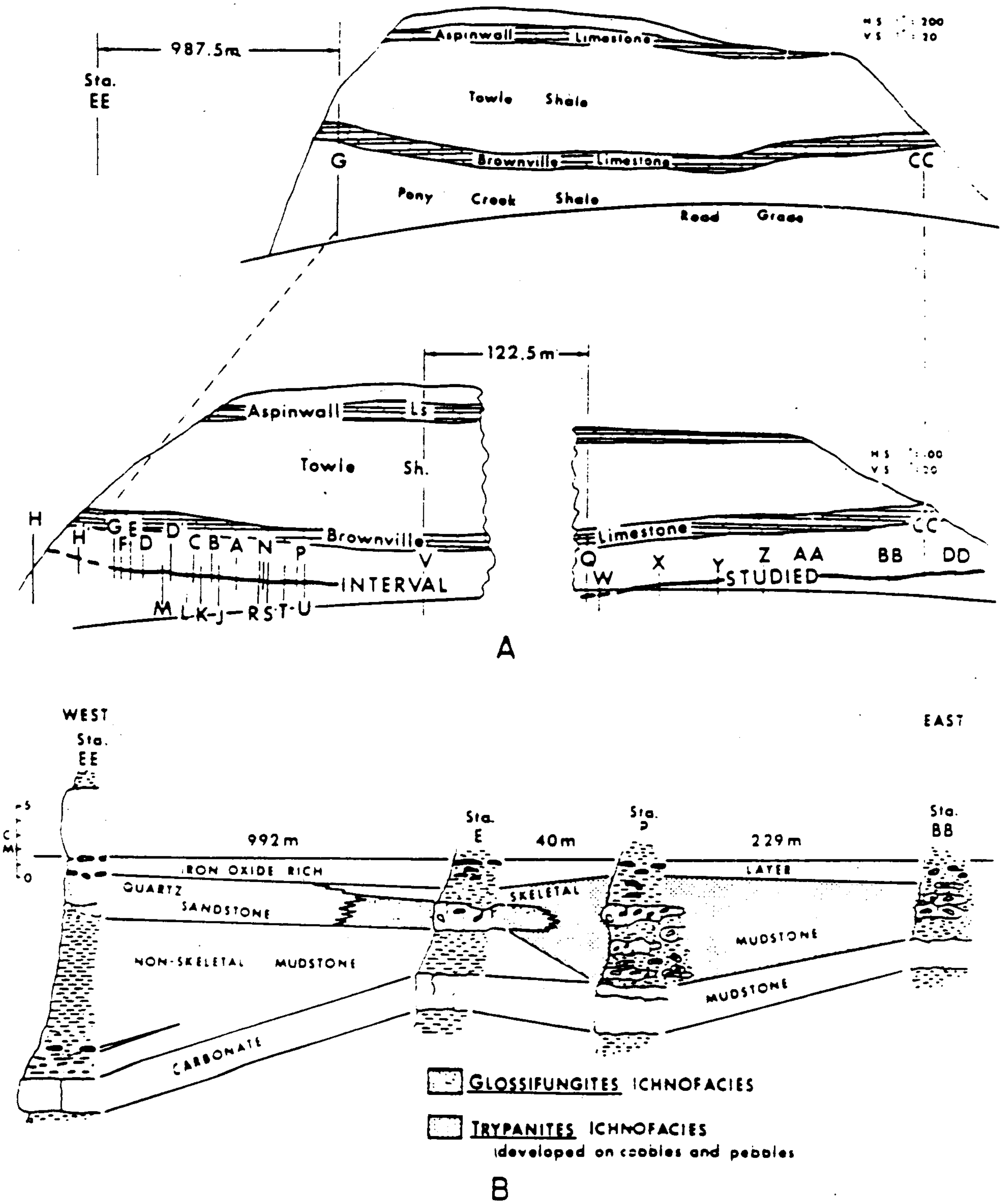


FIGURE 13-2—A) Vertical profile of exposure at Maple hill stop showing locations of stratigraphic sections; B) stratigraphic cross section at Maple Hill stop (west to east) showing facies mosaic.

R.C. Moore and D.F. Merriam ended their 1959 field trip with conclusions and suggestions relating to Pennslvanian-Permain cyclic sedimentation not generally accepted. This field trip concludes with these comments.

In this section of the paper belong the disagreements and unsolved problems of interpreting Pennsylvanian and Permian cyclic deposits. Special effort is needed to discuss subjects objectively and, in particular, to avoid over-great length. The latter aim will be served by omissions, both intentional and unintentional, and by restricting attention to a surely incomplete list of topics.

Boundaries of Cyclothems

An appropriate problem for initial notice in the "unaccepted" category is that of defining the boundaries of a cyclothem. Is there a natural beginning and natural ending of sedimentary deposition that progresses in circular manner through several distinguishable "phases"? If cyclothems very commonly succeed one another without interruption, in perfect conformity, we can answer this question in the negative, because several different points in the circle could be chosen on the basis of such considerations as priority of publication of proposed definition, practical utility (as by selecting the most easily recognizable and prevailingly represented boundary), interpretation based on inferred historical geology, or usage established by general agreement. The presence locally, or even regionally, of disconformities (signifying "negative sedimentation") and occurrence likewise of recognized paraconformities (Dunbar and Rodgers, 1957, p. 119); new term denoting breaks in sedimentation, with or without accompanying erosion, that coincide with a bedding plane and therefore lacking perceptible relief) do not suffice to define cyclothem boundaries more "natural" than others. On the other hand, they may be judged to qualify as natural if they fit an hypothesis of individual cyclothem development (or in zoological terminology, ontogeny) accepted by a geologist (Weller, 1931, 1934, 1956). British and other European geologists favor designation of the top of a coal bed as terminal boundary of the cyclic sedimentary deposits that contain the coal; strata next above the coal belong to a new cyclothem and therefore the top of the coal (or base of these strata) marks the lower limit of the next cyclothem.

Most American geologists working on Pennsylvanian cyclic deposits have accepted definition of cyclothem units as advocated by Weller (papers cited), beginning with a nonmarine sandstone that may or may not overlie a disconformity. Moore (1936, 1949, 1950), Moore, Frye, Jewett, Lee, and O'Connor (1951) and others of the Kansas Geological Survey have classified Kansas Pennsylvanian cyclothems in the Weller manner, but re-study led Moore (1953) to accept the top-of-coal-bed boundary as preferable for several reasons and this was adopted by Howe (1956) in a reclassification of Cherokee beds in southeastern Kansas. Discussion of this problem would require much more space than can be allowed, and therefore only two of the reasons for change to European procedure in boundary definitions are given. (1) Practical utility, accompanied by precision in ability to place boundaries in the field (coal horizons commonly being identifiable where coal beds are absent), favors the top-of-coal boundary. (2) the ending of coal swamp sedimentation (or, lacking coal, termination of nonmarine conditions) and change to marine environment furnish the most nearly universal "punctuation point" in cyclic successions of all regions. In addition, philosophical grounds (Moore, 1953) not here stated support this choice.

Contemporaneity of Individual Cyclothem "Phases" Within Single Province

Pennsylvanian and Permian cyclothems lack volcanic ash beds, so far as known, but if present such a bed, representing a single fallout from transporting winds, would be recognized as a synchronously formed deposit from any of its featheredges to others. Are thin limestone members ("phases") of the marine parts of cyclothems or coal beds belonging to the nonmarine parts comparable to an ash bed in having complete or near-complete age equivalence throughout the area of their distribution? This concept is viewed favorably or at least held to *be admissible by some geologists but denied by others who are unable to imagine a mechanism for coincident spreading of clastic sediment over many thousand square miles, followed by simultaneously introduced swamp conditions, let us say, throughout such territory, contemporaneous cessation of coal-forming plant accumulations with "overnight" appearance of black-mud- or limemud-depositing shallow sea, and so on. Instead of this picture of building successive time-equivalent layers, the hypothesis that terrestrial clastics accumulating in one area chronologically match coal formation in another and marine shale or limestone in still another part of a province seems much more plausible. A corollary of the just-stated interpretation is conclusion that each cyclothem "phase" obliquely transects time planes at a very low angle and any one "phase" may be partly or wholly younger in one locality than the same physically continuous unit in another.*

The problem of deciding between these conflicting concepts persists. In my view, stratigraphic evidence favors a modification of both postulates that brings them nearly together, that is, a crossing of time planes at an almost infinitely small oblique angle.

Contemporaneity of Individual Cyclothems in Widely Separated Regions

Does a cyclothem of the Kansas-Oklahoma region that includes record of temporary marine conditions exactly correspond in age to a similarly composed cyclothem in the same part of the rock succession but located 1,000 miles distant, as in Ohio? Alternatively, are the compared cyclothems actually offset in age to the extent that they correspond only partly, or to a degree that they do not match at all, one being wholly just a step younger than the other? These are important questions from the standpoint of understanding the regional stratigraphic relationships and correctly determining what are facts of the geologic record. As example, the limestone called Verdigris in northeastern Oklahoma is undoubtedly continuous with the unit named Ardmore in Kansas and Missouri, and with some confidence this is correlated with the Oak Grove Limestone of Illinois, which is traced into the Velpen Limestone of Indiana and Hamden Limestone of Ohio. If these variously named beds were laid down as a continuous sheet of carbonate rocks, the matter of age equivalence of all parts of the sheet is not settled, for obviously the sea could have invaded one district before it reached others. Yet, when the entire succession of cyclothemic deposits is compared step by step across country, very near, if not perfect, approach to contemporaneity of the several local units seems most probable.

For the present, precise age equivalence of individual cyclothems defined in widely separated regions can not be claimed reliably as fact.

Mechanism Providing for Transportation of Clastic Sediment

The manner in which sandstone bodies and extremely widespread thin sheets of shale of various sorts came to be spread over territory aggregating roughly a million square miles or more in the central United States during Pennsylvanian and Permian time is a major problem. If Permian deposits once were continuous from Kansas-Nebraska to Pennsylvania, erosion has removed them from all places between eastern Ohio and the present edge of Permian outcrops in the northern Midcontinent. For purposes of inquiry about the mode of clastic-sediment transportation, we do not need to consider the whole succession, but only some representative fraction or fractions. For example, let us choose clastics that form a sheet bounded by the Ardmore and Fort Scott Limestones, below and above, and by equivalent limestones elsewhere. This sheet can be delimited with reasonable precision throughout an area of at least several states, in which it shows some but not great variation in thickness and sand-shale ratios. It is about as good a sample as any.

Two importantly differing postulates to explain the dispersal of sand, silt, and clay in a body of clastic sediment such as we have chosen for inspection may be stated. (1) The clastics were spread by low-gradient subaerial running water (streams and possibly sheet-wash) that carried the sediment from source areas to places of deposition. Weller (1956, p. 45) has employed the conservative estimate of a gradient amounting to 1 foot per mile in trying to account for transportation of clastic sediment that in territory east of the Mississippi River he computes (op. cit., p. 35) averaged approximately 2,500 cubic miles per cyclothem. (2) The clastics were spread mostly at near-zero gradients throughout most of the area of sedimentation (all except a marginal belt of inconsiderable relative width in which subaerial transportation possibly predominated), transportation being *effected by generally slow back-and-forth shifting induced by waves and currents in shallow standing water. The water bodies are conceived as discontinuous, fluctuating ponds, extremely shallow lakes and lagoons of varying size, and semi-enclosed extensions of shallow seas, the plexus of water bodies ranging from fresh or slightly brackish to normally saline sea water. In such an environment clastic sediments would be sorted and re-sorted, deposited and re-deposited again and again as lateral movements carried them eventually throughout areas of many ten-thousand square miles. This hypothesis calls for minimum topographic relief in the area of sedimentation as a whole.*

Corollaries of the two postulated modes of clastic dispersal are (1) need for appreciable relative uplift of sediment source areas and basin margins as compared with central parts of sedimentary basins (Weller, 1956, p. 45, estimates a differential of 1,000 feet as average), and (2) lack of required differential uplift of sediment-source areas of appreciable amount (that is, a very few hundred feet at most). In any case, epeirogenic warping of some amount must be invoked, with the sum of results expressed by relative subsidence of sedimentary basins. The role of eustatic changes of mean sea level in the early, middle, and late parts of successive cycles enters the picture, and evidently this may be a subordinate factor (1st hypothesis, diastrophic control of transportation of clastics) or a dominant one (2nd hypothesis).

Disagreement exists in explaining the dispersal of clastic sediments that form important units of nearly all Pennsylvanian and Permian cyclothems, but ultimately this question seems to be resolvable by completion of well-planned studies that take account of many yet unstudied lines of evidence.

Significance of Knife-Sharp Lithologic Boundaries

A prevailing attribute of the discriminated subdivisions of Pennsylvanian and Permian cyclothems is abruptness of change from one kind of sedimentary deposit to another. This gives rise to knife-sharp lithologic boundaries, as contrasted with gradational ones. What rational explanation can be offered for lithologic punctuations of such character, especially in view of the unbroken nature of circularity and the reasonable presumption that cyclic sedimentation should at any one place yield a succession of deposits grading upward from one rock type to another as environments slowly changed? The sharp lithologic boundaries seem to deny inferred slow change. The question here raised has received almost no attention from geologists and therefore judgments are not yet ready for consideration as accepted or unaccepted. It is a curious fact that most geologists, including myself as one, take for granted that a sharply bounded layer of rock seen in the field simply belongs where found as part of the local section; it is described and measured in the geologist's notebook and that is the lend of it. No special consideration generally is given to the significance of sharp lithologic changes, whereas each of them calls for notice. They bear on understanding of cyclic sedimentation.

Dunbar and Rodgers (1957, p. 126) discuss the subject of abrupt lithologic changes in stratigraphic sections, citing several good examples. In examining each of the contacts referred to, evidence is found that nearly all denote existence of a hiatus, either disconformities or paraconformities (see definition under "Boundaries of Cyclothems"). These authors subsequently (p. 129-134) give a lucid discussion of diastems, which mostly also are defined by abrupt boundaries of rock layers, pointing out that relationship of surfaces of sedimentation to locally and temporarily existing baselevels of aggradation controls the production of a diastem (nondeposition) or its absence. Evidently, Pennsylvanian and Permian cyclothems contain numerous diastems, signifying that frequently during accumulation of different kinds of sediment, temporary baselevels of aggradation were encountered. In water bodies, the chief factors controlling the depth of such baselevel are currents, waves, and the nature of bottom sedimentary load. Eustatic changes of sea level, even very slight in amount, may shift the sea floor above or below the baselevel of aggradation, with resulting subelevation of already accumulated sediment or resumption of sedimentation. During time when depth of the baselevel is relatively constant, equilibrium conditions on the sea floor exist and incoming sediment is bypassed to possibly distant places.

Actuality of Megacyclic Successions

Various parts of the Kansas Pennsylvanian and Lower Permian column are composed of cyclothems that are themselves classifiable as units of orderly sequences of cyclothems of differing characters. These have been *called megacyclothems (Moore, 1936). They are most completely developed in the Shawnee Group, where the megacyclic sequences comprise five individual cyclothems, but (with equivalent of the lowermost Shawnee cyclothem missing) they are well displayed also in the Missourian and upper Desmoinesian (Marmaton) parts of the section. Megacycles exist in the Lower Permian but are differently expressed and have not yet been described. Previously unpublished graphic representation of what seem to be rather clearly expressed repetitions of a megacyclic nature is given beneath the generalized section of Lower Permian strata with interpretative marine oscillations prepared by Elias (1937) (page 28 of this guidebook).*

No geologist who has studied typical examples of the megacyclothems in Kansas can entertain doubts as to their existence, because distinguishing characters can hardly be overlooked (Moore, 1949, 1950). Question arises only with respect to identification of the component distinguished cyclothems as severally independent cyclic successions, because some of them are decidedly atypical in one way or another and not all "phases" of the ideal cyclothem are developed.

Possibility exists that Kansas megacyclothems correspond to subdivisions of the Illinois Pennsylvanian that have been classed as cyclothems, or that different parts of the grouped Kansas cyclothems represented in a megacyclothem are equivalent to unit "phases" of Illinois cyclothems, others being absent. These relationships remain to be determined and when known they should throw light on the interpretations of both. Meanwhile, there is no reason to question the validity of megacyclic concepts.

No hypothesis yet has been formulated to account for the observed peculiarities of the different cyclothems in typical megacyclothems. Indeed, this is one of the most puzzling of all unsolved problems relating to Pennsylvanian and Permian sedimentation in the northern Midcontinent area.

<u>Debated Subjects Omitted from Present Discussion</u>

Mainly because of space limitation, several debated aspects of cyclic sedimentation in late Paleozoic time are merely enumerated, cognizance being taken of the fact that the list of subjects could be considerably expanded. In my opinion the following are most noteworthy problems: (1) Ultimate causes of Pennsylvanian-Permian cyclic sedimentation as observed in various parts of the world, generally with regularly alternating widespread transgressions and regressions of shallow seas; (2) "Direct" geologic causes of marine invasions and retreats in continental platform areas, that is, whether primarily controlled by local to regional epeirogeny or by eustatic changes of world sea level; (3) Relations of cyclothems and megacyclothems to known Pennsylvanian and Permian localized orogenies; (4) Quantitative and qualitative aspects of Pennsylvanian-Permian clastic sediments in relation to rocks of inferred source areas, account being taken especially of the prevailingly many-times-reworked nature of the clastics and adequacy of the needed kinds of source rocks (mostly not igneous or metamorphic crystallines).

CONCLUSION

As concluding statement, it seems sufficient to say that great advances surely have been made during the last two or three decades toward an understanding of the conditions of sedimentation and historical geology that are recorded by Pennsylvanian and Permian cyclothems in the northern Midcontinent region. At the same time, it is evident that as much or more remains to be learned before comprehension of geologists may be considered to be adequate.

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