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OF  
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Kansas Geological Society  
41st Annual Field Trip

SEQUENCE STRATIGRAPHIC INTERPRETATIONS AND  
MODELING OF CYCLOTHEMS  
in the Upper Pennsylvanian (Missourian) Lansing and Kansas City  
groups in eastern Kansas

by *W. Lynn Watney, John French, and Evan K. Franseen*  
Kansas Geological Survey

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# Introduction to field trip

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## Forward

This two-day field trip is held in conjunction with a pre-trip, one-day conference and workshop on sedimentary modeling featuring nine speakers and 24 poster papers by authors from across the United States in celebration of the centennial year of the Kansas Geological Survey. This trip also represents the 41st annual field conference of the Kansas Geological Society of Wichita, Kansas. The conference and field trip are co-sponsored and partially funded by the Kansas Geological Society, Kansas Geological Foundation, ARCO Oil and Gas Company, the Division of Academic Affairs and Division of Continuing Education at The University of Kansas, and the Kansas Geological Survey. An objective of the conference and field trip is to provide a working forum for sedimentary computer modeling, a rapidly developing and promising discipline. Another objective is to permit interac-

tion of model developers with academic and industry geologists from around the country who are acquiring data from the rocks and whose interpretations could be assisted by computer simulation and vice versa. We will also examine approaches to describing and analyzing geologic data that will be helpful in constraining geologic interpretations and increasing accuracy and precision of geological predictions. Modeling is a tool, the model being only as good or useful as the input data.

The focus of the field trip is to examine current approaches to deciphering the history of cyclothem deposition of the Upper Pennsylvanian (Missourian) Lansing and Kansas City groups and to evaluate the applicability of sequence-stratigraphic concepts to these strata.

## Logistics and organization of field trip

### Field stops

Fig. 1 identifies the field stops for the two-day field trip. Fig. 2 shows the regional structural setting for the field trip using the present-day configuration of the Precambrian surface. Additional maps are provided for each stop to orient readers to the local surroundings. Table 1 lists the schedule and itinerary for the field stops. The stratigraphic section seen during the course of the field trip is illustrated in fig. 3 (a, b, and c). These sections are annotated with the stratal interval seen on each stop. Formation nomenclature and an informal sequence-stratigraphic nomenclature is also included. Stops 1 through 7 seen on the first day of the trip will be made in the Lawrence and Kansas City area. Driving time is short between stops on the first day, permitting close examination of the outcrops and hopefully providing sufficient time for questions. All of these surface exposures are relatively new and fresh.

The second day of the trip includes Stops 8 through 13. These stops will illustrate changes in stratigraphy associated with the transition from shelf to shelf margin to the depositional basin developed shelfward of the deep Arkoma basin (fig. 2). The longer driving time between stops during the second day will provide time to assimilate commentary about nearby surface exposures and the subsurface data base, which will help to clarify interpretations. Fig. 4 is a regional north-south stratigraphic cross section composed of wireline

logs that will be useful for orientation along the shelf-to-basin transition. The cross section extends from south of Kansas City to the Oklahoma line immediately west of Coffeyville, Kansas. The index map for this cross section is shown in fig. 1. Wells used for this cross section are very shallow and located in proximity to the stops. The cross section is annotated with the projected locations of the field stops for orientation.

Figs. 5 through 14 are isopach maps useful in understanding the regional shelf-to-basin transition. These computer-generated maps include data points (wireline logs), wells present on the regional cross section (fig. 4), and locations of field stops for both days. The area covered by this series of maps is provided in the road map (fig. 1).

The first part of this guidebook is an introduction to the regional geologic setting, the cyclothem concept, and application of sequence stratigraphy. Appendix A follows the introduction providing definitions used in sequence stratigraphy. Two papers follow the appendix before the field stops, one on the status of computer modeling of midcontinent cyclothem by Watney, French, and Wong and the other on application of high-resolution reflection seismology to eastern Kansas cyclothem by Knapp.

Stop descriptions include orientation information and an introduction to the regional and local perspectives of the stop. Commentary on stratigraphy with graphic sections

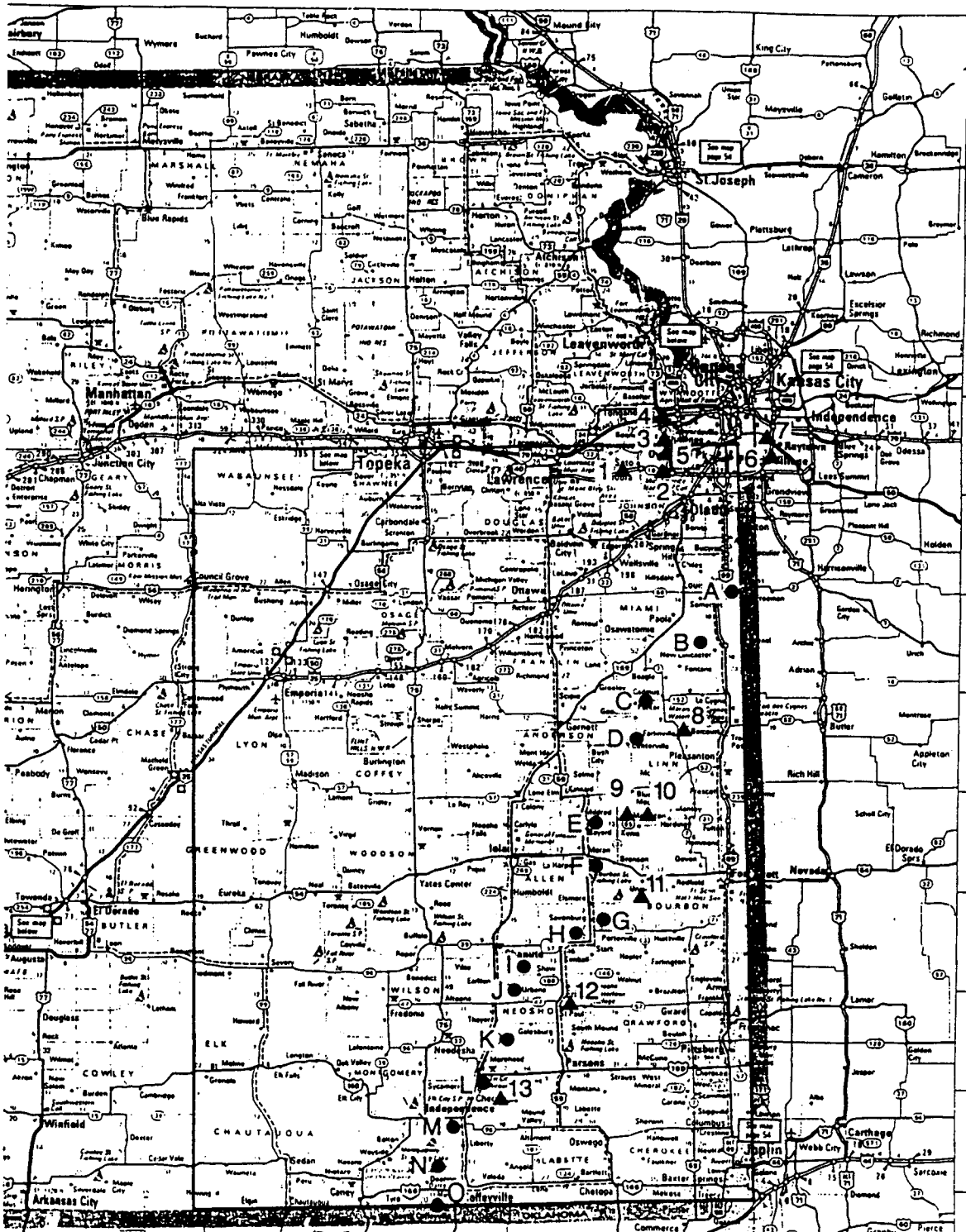


FIGURE 1—INDEX MAP OF EASTERN KANSAS SHOWING STOPS ON FIELD TRIP (numbers and triangles), index of well locations (letters) used to make regional cross section found in fig. 4, and hatched area in southeastern Kansas delimiting area mapped in figs. 5-13.

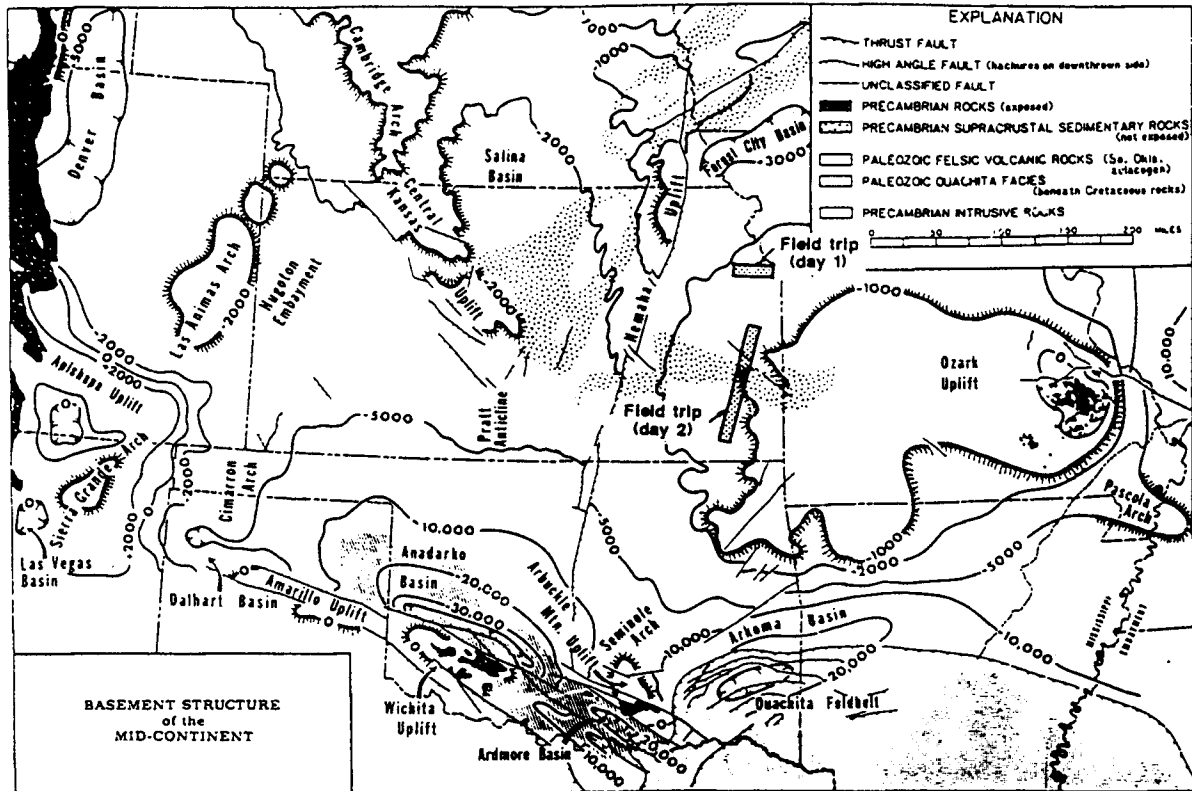


FIGURE 2—CONFIGURATION OF THE PRECAMBRIAN BASEMENT IN SOUTHERN MIDCONTINENT (from Rascoe and Adler, 1983), annotated with location of field-trip traverse. Note that while southeastern Kansas is 200 mi (358 km) from the deep Arkoma basin, subsidence of the Arkoma basin during Missourian time significantly affected southeastern Kansas to form a depositional basin.

and photos describe each stop. Lithology, formation nomenclature, and cyclothem and sequence-stratigraphic nomenclature are indicated in the graphic sections. Dunham's carbonate classification is used. Significant surfaces useful in sequence-stratigraphic interpretation are annotated on each measured section using standard symbols. A profile of natural gamma radiation is provided on most sections 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 are correlated in some stops 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 descriptions are not exhaustive but provide sufficient information to convey the principles of sequence stratigraphy. This is a progress report and the object of continued interdisciplinary study. Ancillary measured sections from nearby localities, maps, and cross sections are included at some stops to assist in establishing their interpretation.

Several individuals will contribute at the various stops. Their participation illustrates different approaches that are important to improve understanding of these rocks and to constrain interpretations. Collaborative efforts should continue to help reach the goal of establishing accurate and precise quantitative process-response relationships and detailed correlations that will facilitate development of more sophisticated models of these rocks.

This field trip is a sampling of our approach to re-examine outcrops of the Lansing and Kansas City groups in eastern Kansas in order to develop quantitative process-response sedimentary models. These studies are being conducted in concert with reservoir studies to assist industry in optimizing exploration and development strategies as applied to similar reservoirs.

## Petroleum-reservoir analogue development

We believe that southeastern Kansas will serve as an excellent near surface analogue where depositional models

for petroleum reservoirs contained in similar rocks in the subsurface can be refined and tested. Additional funds that are currently pending should accelerate these efforts of the Kansas Geological Survey in better constraining petroleum-reservoir description, analysis, and prediction. Advantages of this area for improved reservoir modeling include: 1) significant stacking geometries over short distances resulting from significant depositional topography; 2) large carbonate buildups constrained in three dimensions; 3) equivalent siliclastic- and basinal-facies sequences 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.

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. 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 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<sup>3</sup>. 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. 15). 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 review).

Stacked pay zones are common on larger structures. Also, lateral porosity variations in individual zones are common within a field, e.g., the 80-well Cahoj field in Rawlins County, Kansas, is compartmentalized into elements ranging from one to 10 wells (Watney and Stephens, in review). In addition to continued exploration, the prediction of porosity and permeability development at an interwell scale will be a major future challenge as improved recovery strategies are applied. Kansas harbors a multitude of opportunities for petroleum companies.

Primary recovery of original-oil-in-place in Lansing and Kansas City reservoirs in northern and central Kansas is typically low due to solution-gas-drive reservoirs.

Applications of secondary-recovery methods typically double primary production and can increase production five-fold. New drilling and completion technology, such as horizontal drilling and permeability modification in producing and injection wells (to reduce fracture and vug permeability), should offer substantial rewards.

We believe the optimum approach to reservoir analysis involves an interdisciplinary approach coupled with quantitative process modeling of stratigraphic units associated with the reservoirs. A goal of modeling is to simulate stratigraphic architecture and associated reservoir compartmentalization to assist in defining constraints for porosity occurrence. For example, late-stage cementation may be a very important component in porosity loss in some areas (Anderson, 1989). Southeastern Kansas will serve as a near-surface and surface analogue for more deeply buried reservoirs. Here data can be acquired economically at critical sites to build and test models.

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).

## Stratigraphic framework

Stratigraphic nomenclature in Kansas is based on the carbonate-dominated strata of Missourian age, typified by shelf sequences on the northern midcontinent (fig. 3). The formations examined in this field trip extend from the Stanton Limestone of the Kansas City Group (Missourian, Upper Pennsylvanian) down to the Pleasanton Group of lowest Missourian age (fig. 3a and b). The "Coffeyville Formation" is an informal classification of the basinward siliciclastic-dominated succession found in southeastern Kansas (fig. 3c). Equivalent shelf-based strata composing the "Coffeyville Formation" include the Swope and Hertha formations and Pleasanton Group identified on the regional cross section across the Kansas shelf to basin (fig. 4).

Thirteen stops on the two-day trip reveal the nature of the Missourian cyclothem stratigraphic succession and include a plethora of rock names and attendant rock-classification schemes (fig. 3a, b, and c). These names are confusing to those unfamiliar with midcontinent geology. So, keep the stratigraphic charts handy! We will observe, however, that certain thin stratal units are correlative over widespread areas and important in overall interpretation. Stratal and lithologic variability exist; this variability will be illustrated on the trip. We will demonstrate what we believe to be temporally distinct, surface-bounded depositional sequences (fig. 3) that provide an efficient means to establish correlations, and which can be used to develop process interpretations suitable for modeling.

ACKNOWLEDGMENTS—Extensive funding needed for systematic interdisciplinary studies have been sought by the Kansas Geological Survey, e.g., an NSF Center for Quantitative Genetic Stratigraphy. These efforts continue. The Survey has encouraged and nominally supported interdisciplinary efforts with very encouraging results. The information conveyed on this field trip constitutes, in part, the results of some of these workers as cited, many of whom are in attendance. Deepest appreciation is extended to them; their efforts and contributions make a trip like this possible. Contributors to stops on this trip include Donald Baars, Allan Bennison, Paul Enos, Howard Feldman, Evan Franseen, John French, Philip Heckel, Derek Herman, Ralph Knapp, Chris Maples, Lenore Tedesco, Harold Wanless, Jr., and Lynn Watney. Appreciation is extended to Lea Ann Davidson for word processing and to Renate Hensiek for preparing technical illustrations; to Rob Fillmore, Kevin Cunningham, Brian Forgey, and Mike Lambert for assistance provided with technical illustrations; and to Donald Baars, Paul Enos, Philip Heckel, and Chris Maples for review of the manuscript. Thanks is given to Rob Fillmore, Steven Roth, Kevin Cunningham, and John Youle for help with field logistics.

A stratigraphic cross section (fig. 16) links the upper Desmoinesian and lower Missourian "Coffeyville formation" in southern Kansas with the siliciclastic-dominated section in Oklahoma. The section extends southward from the Kansas cross section shown in fig. 4. The regional correlation of cyclothem has posed considerable problems over the years due to the abrupt change from carbonate-dominated strata in Kansas to siliciclastic-dominated strata in Oklahoma. Bennison (1984, 1985) has developed lithostratigraphic evidence to establish detailed basin-to-shelf correlations along the Arkoma basin of Desmoinesian and Missourian siliciclastic strata using black shales and associated marine-flooding episodes. He depicts a depositional model characterized by progradation of clastic wedges derived from the Ouachita Mountains which eventually filled the Arkoma basin (Bennison, 1985; fig. 16).

Episodes of both siliciclastic and carbonate sedimentation in Oklahoma and Kansas are punctuated by widely correlative black shales, thin limestones, and coals. The black shales, and to a lesser degree the thin limestones, persist across both the southern siliciclastic belt and the northern carbonate-dominated shelf. In contrast, intervening shallowing-upward strata change notably in thickness and composition from south to north (fig. 16). Bennison (1985) identifies three thick, siliciclastic intervals, the Ladore and Galesburg shale equivalents and the Nellie Bly. These are informal names in Oklahoma. The Ladore and Galesburg Shale

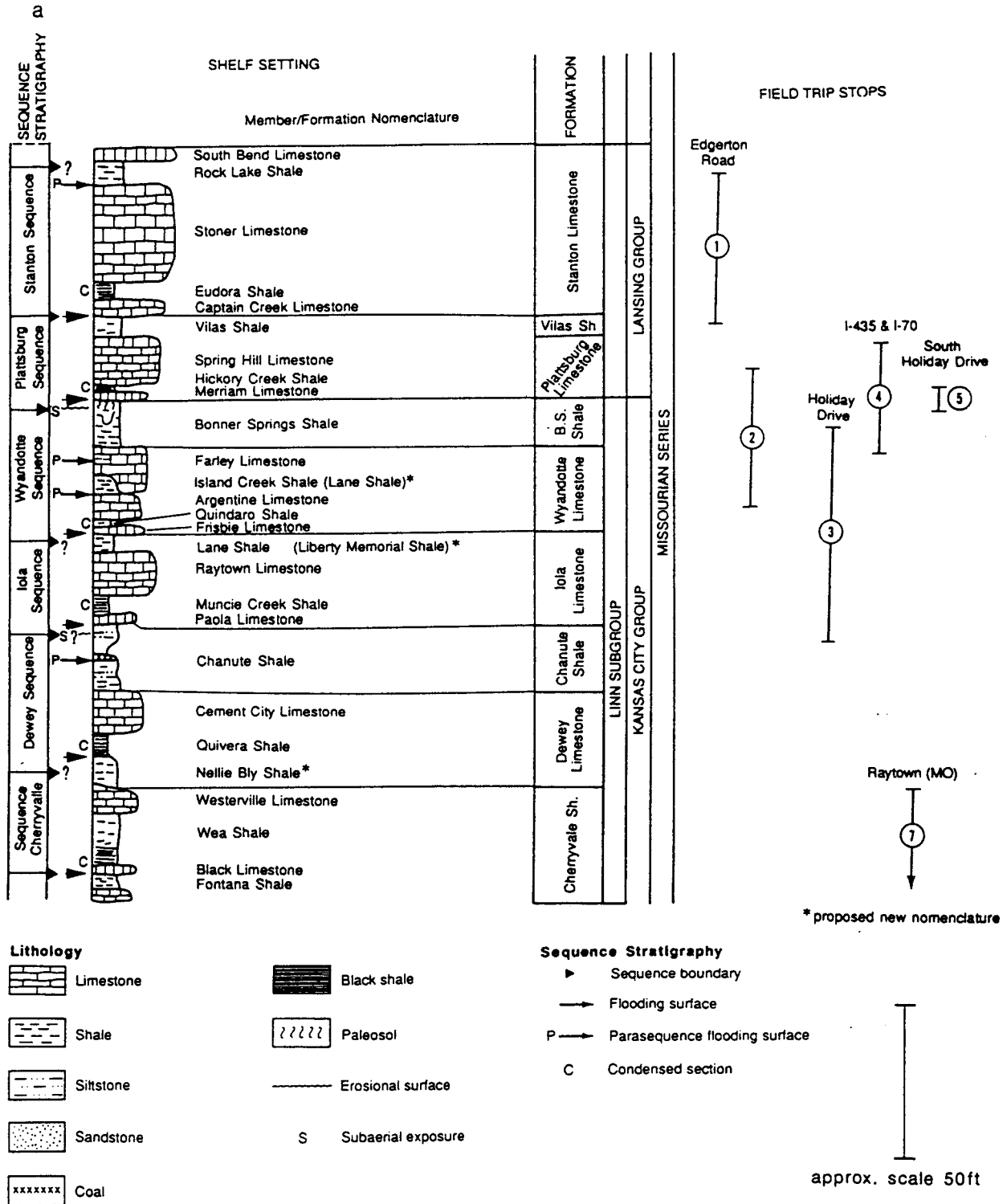
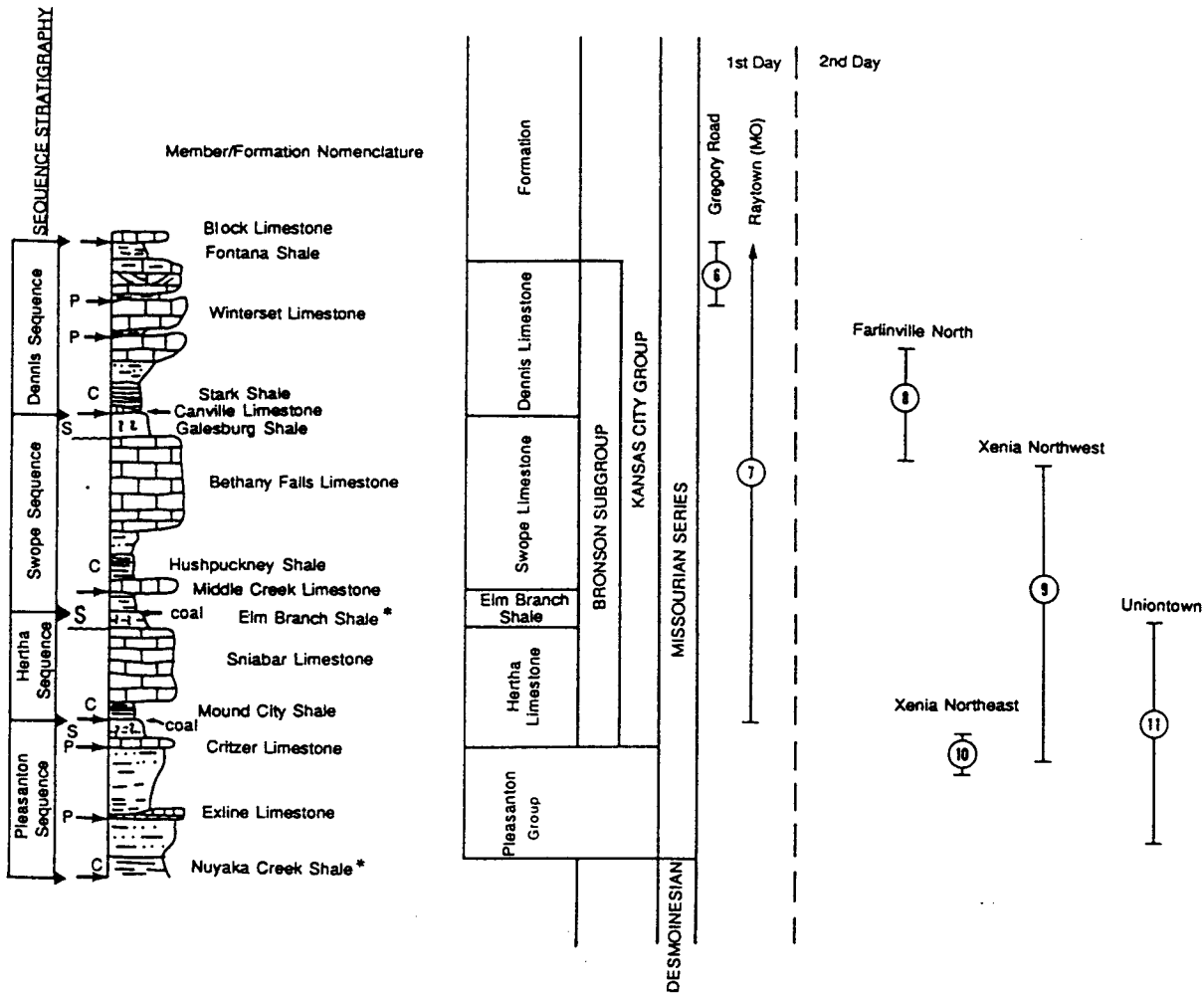


FIGURE 3—STRATIGRAPHIC SECTION THAT WILL BE EXAMINED ON THE FIELD TRIP SHOWING formal stratigraphic nomenclature and major lithologies, and informal preliminary sequence stratigraphic nomenclature. Intervals examined at each stop are indicated. Figure has three parts (a, b, and c), plus a legend.

b

SHELF-SHELF MARGIN SETTING

FIELD TRIP STOPS



Lithology

- Limestone
- Shale
- Siltstone
- Sandstone
- Coal

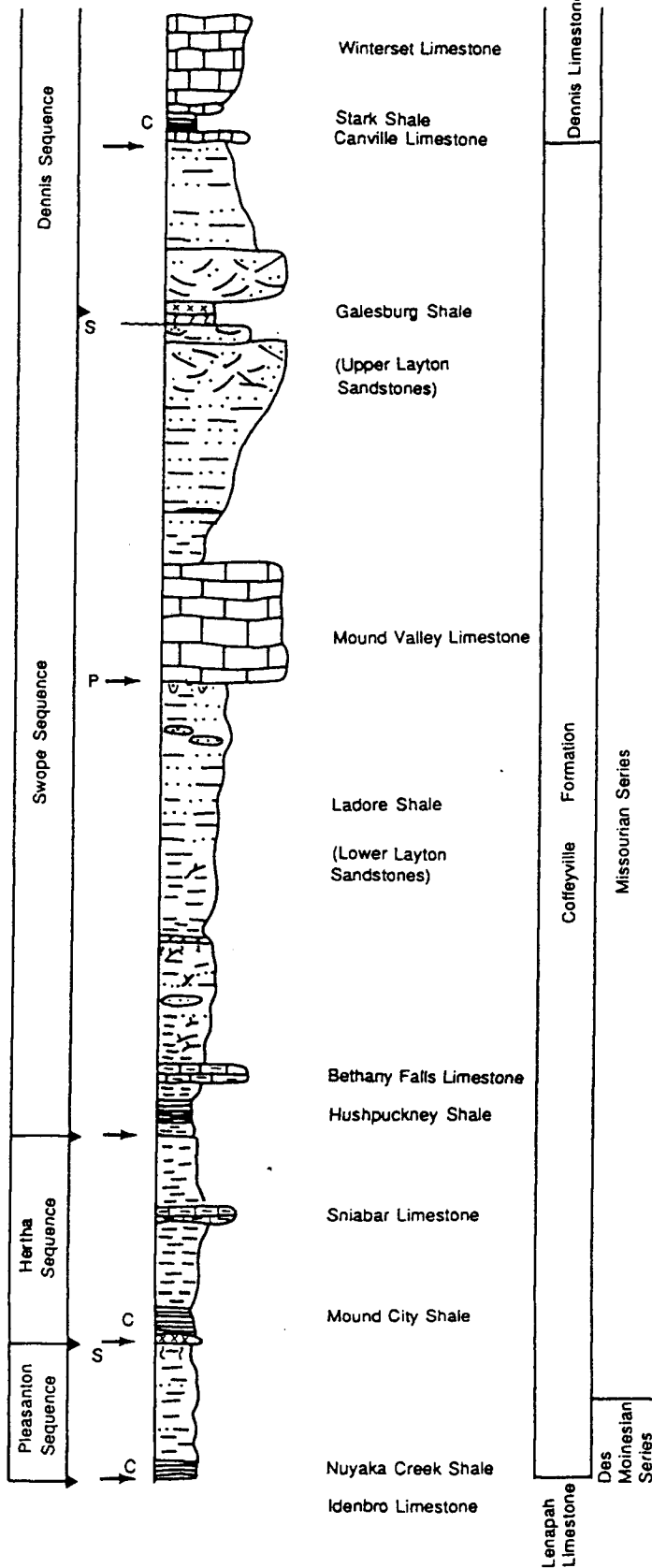
- Black shale
- Paleosol
- Erosional surface
- S Subaerial exposure

Sequence Stratigraphy

- Sequence boundary
- Flooding surface
- P Parasequence flooding surface
- C Condensed section

C

BASINAL SETTING



FIELD TRIP STOPS

Ogeese Creek

I 12

Lithology

- Limestone
- Shale
- Siltstone
- Sandstone
- Coal
- Black shale
- Paleosol
- Erosional surface
- S Subaerial exposure

Sequence Stratigraphy

- Sequence boundary
- Flooding surface
- Parasequence flooding surface
- C Condensed section

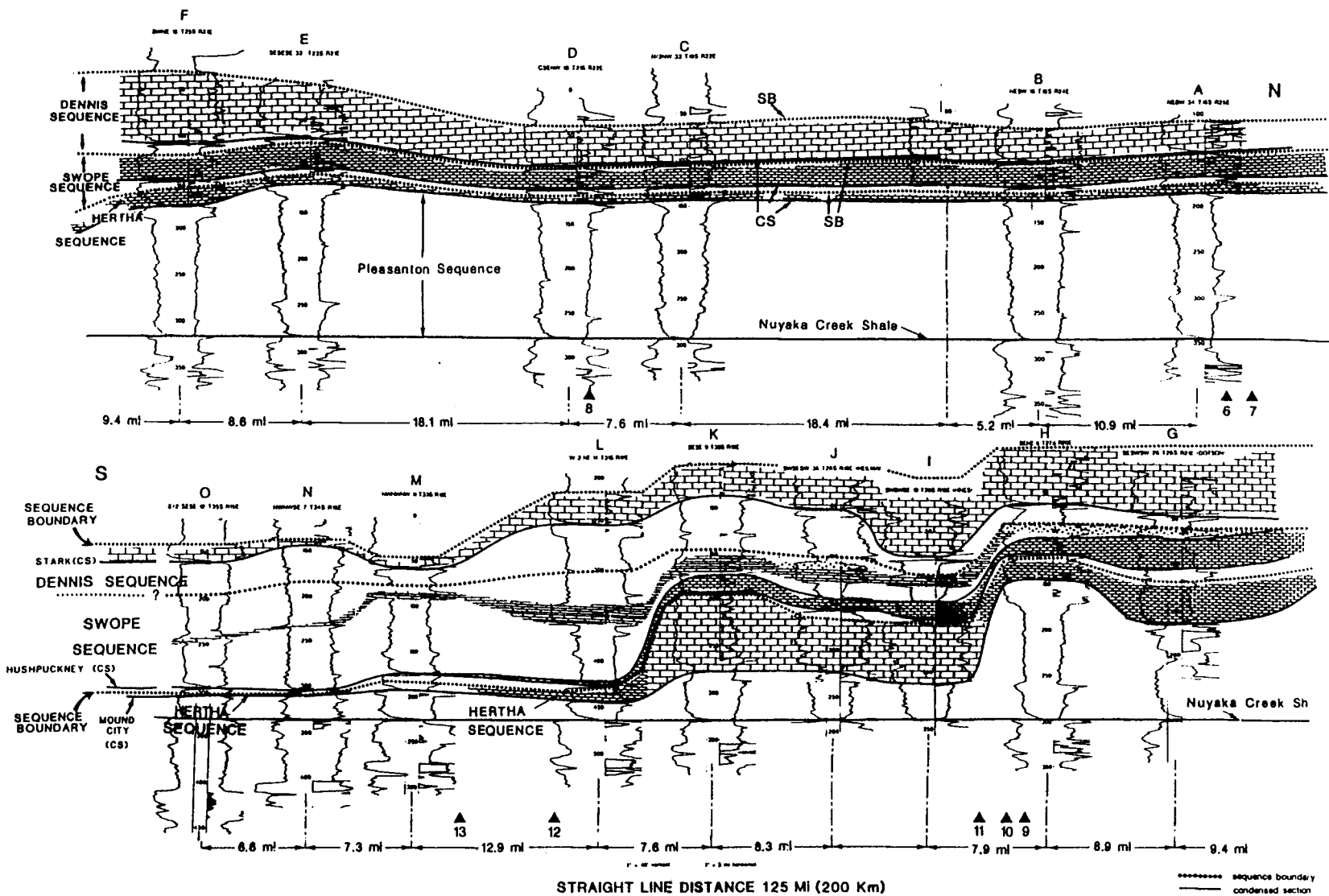


FIGURE 4—REGIONAL NORTH-SOUTH WIRELINE LOG STRATIGRAPHIC SECTION EXTENDING FROM SOUTH OF KANSAS CITY TO IMMEDIATELY WEST OF COPPERVILLE, KANSAS. Damm is base of Nuyaka Creek Shale, a regional radioactive black shale. Stratigraphic interval included in section extends from below the Pleasanton Group, up to the mid-portion of the Dennis Limestone in the Kansas City Group. Sequence-stratigraphic nomenclature is provided.

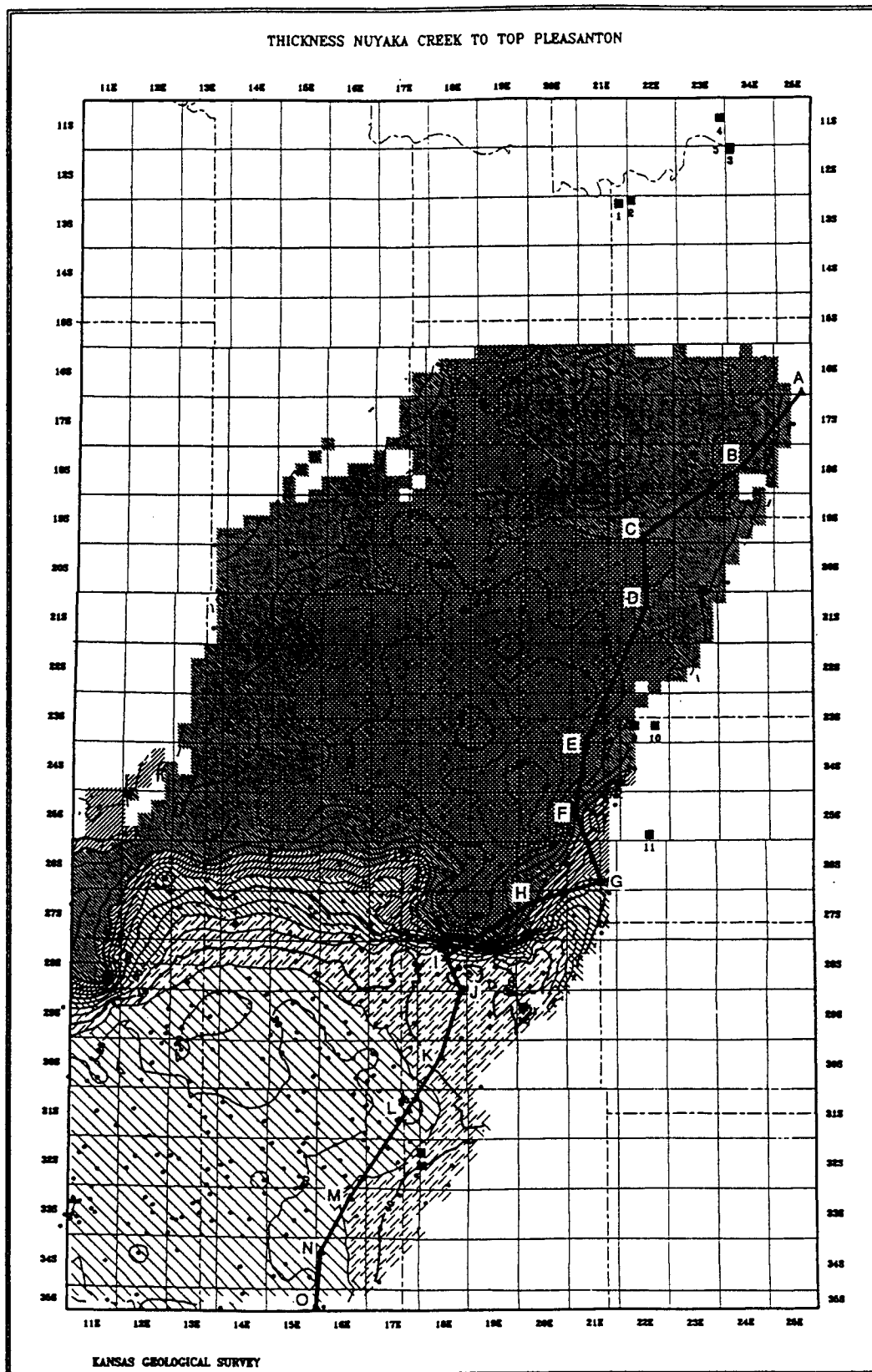


FIGURE 5—ISOPACH MAP OF INTERVAL FROM NUYAKA CREEK SHALE TO TOP OF PLEASANTON GROUP, PICKED HERE AS BASE OF RADIOACTIVE MOUND CITY SHALE. The Pleasanton Group is composed of predominately fluvial-deltaic siliciclastics. Contours in feet. Each square on the map is a township, 6 mi (9.7 km) on a side. Dashed lines are county lines. Southern border is Kansas-Oklahoma border. East line is Kansas-Missouri border. Numbered squares represent field stops. Lettered triangles represent locations of wells used to construct regional cross section shown in fig. 4.

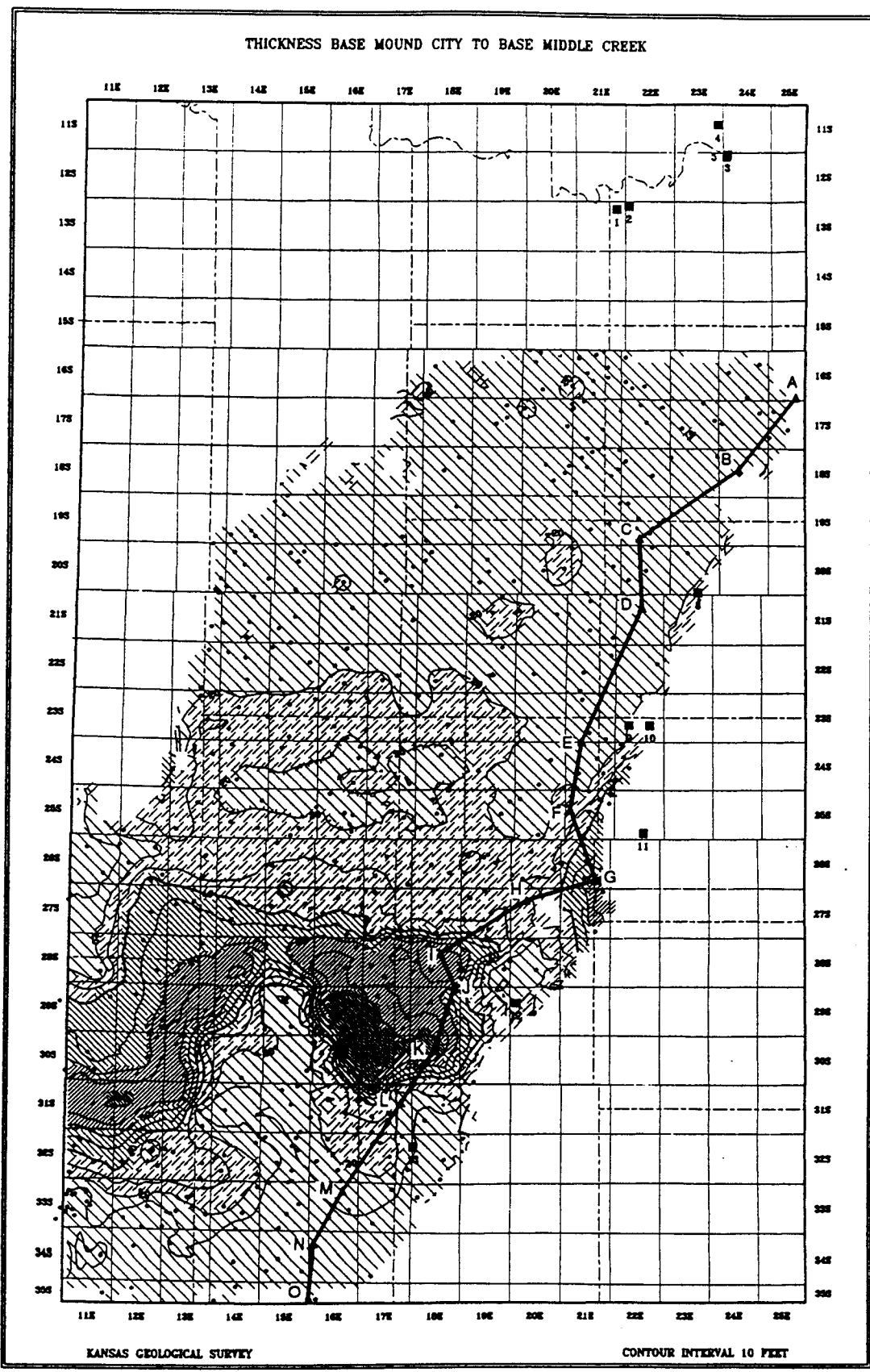


FIGURE 6—ISOPACH MAP OF BASE OF MOUND CITY SHALE TO BASE OF MIDDLE CREEK LIMESTONE, HERTHA SEQUENCE. Interval represents Hertha depositional sequence, a carbonate-dominated package thickened to become a phylloid-algal mound complex along the southern margin of the "Pleasanton delta."

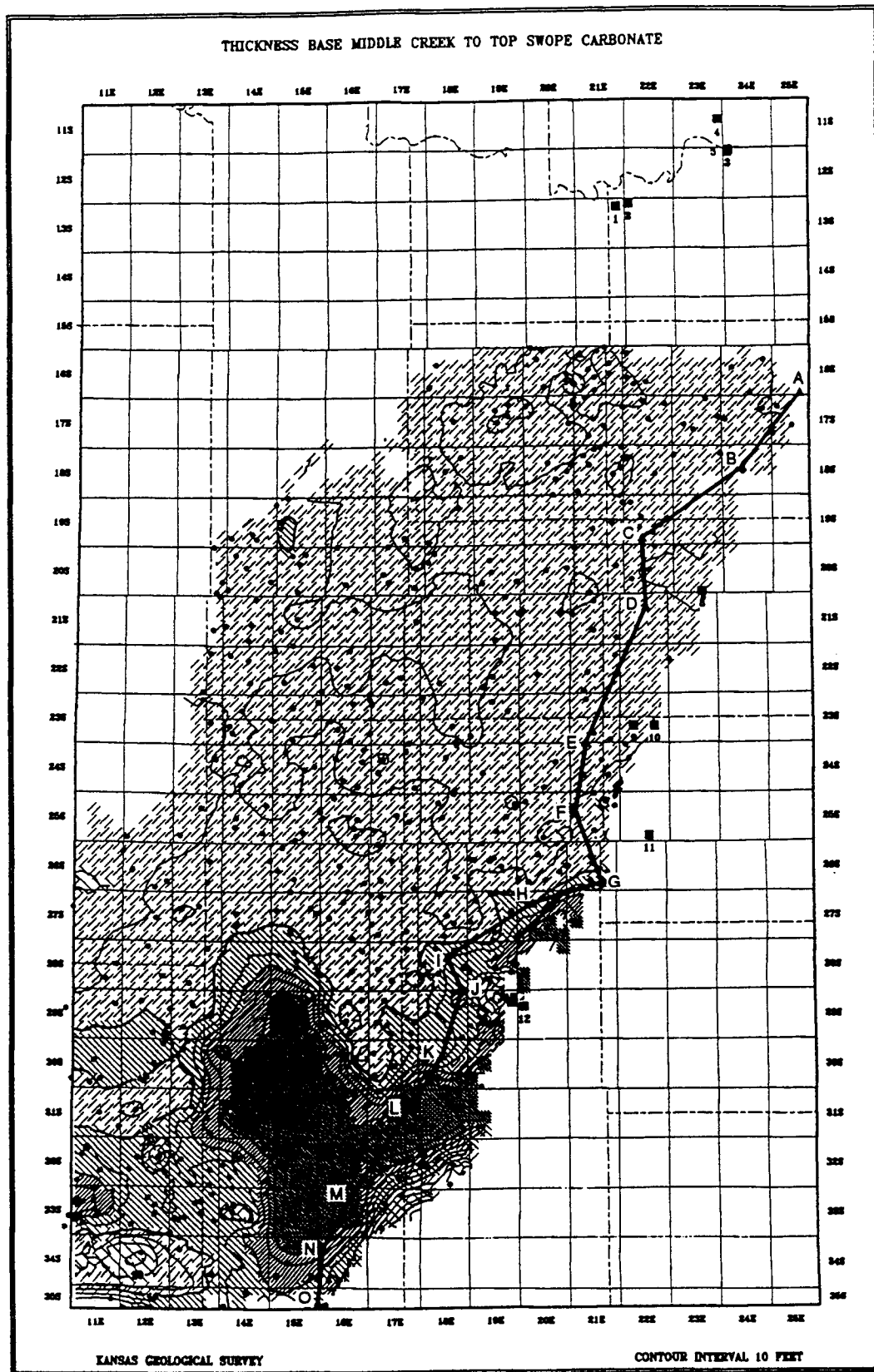


FIGURE 7—ISOPACH MAP OF THE BASE MIDDLE CREEK LIMESTONE TO TOP SWOPE LIMESTONE INTERVAL INCLUDING BETHANY FALLS LIMESTONE, LADORE SHALE, AND THE MOUND VALLEY LIMESTONE. The Swope sequence includes this interval and part of the overlying Galesburg Shale. The latter is only developed in southern Kansas and therefore not seen on the shelf stratigraphic section. Area of thickening coincides with southern (basinward) margin of thick Hertha sequence.

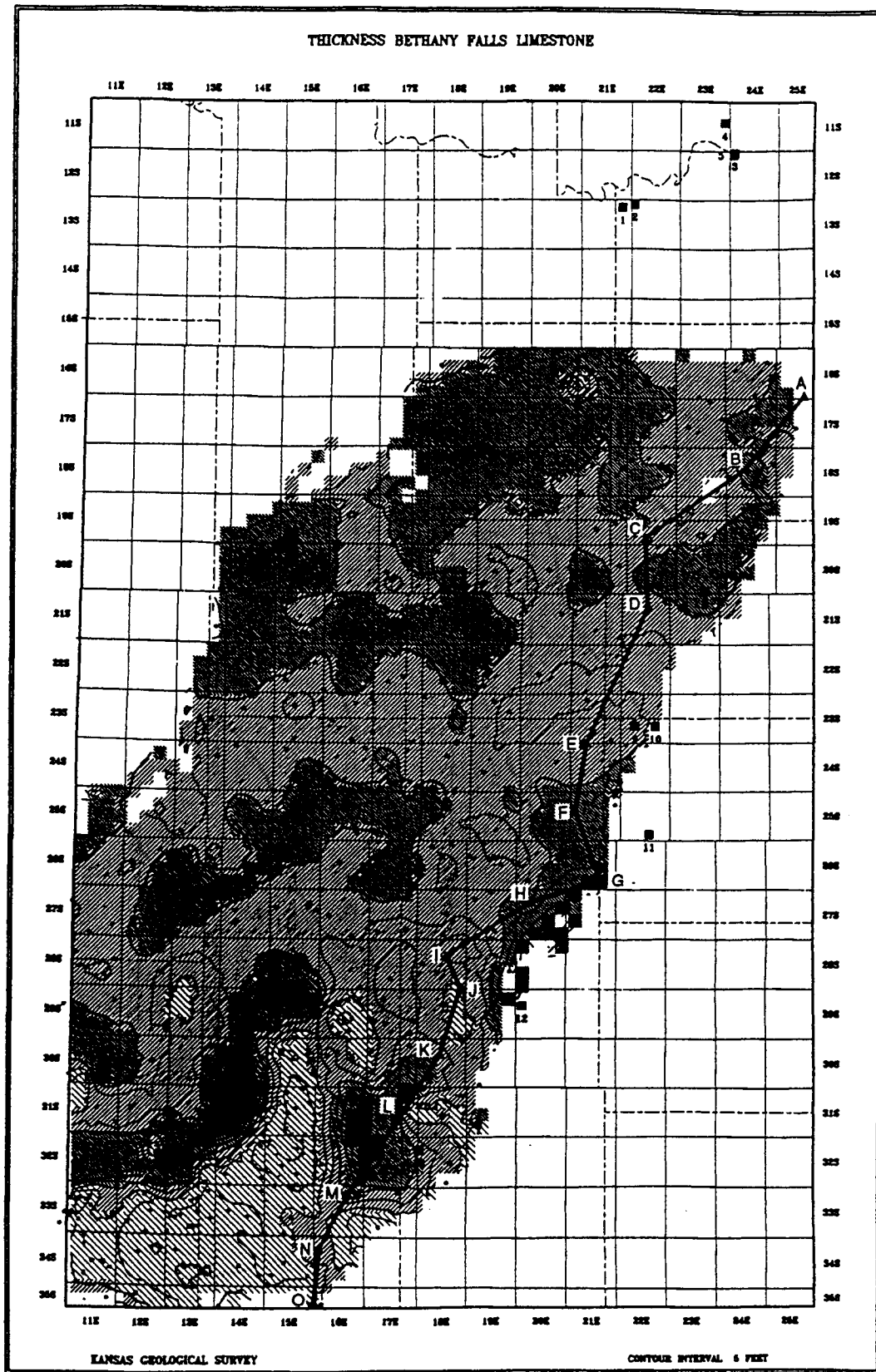


FIGURE 8—ISOPACH MAP OF BETHANY FALLS LIMESTONE, a shallowing- upward carbonate unit of the Swope sequence included in fig. 7.

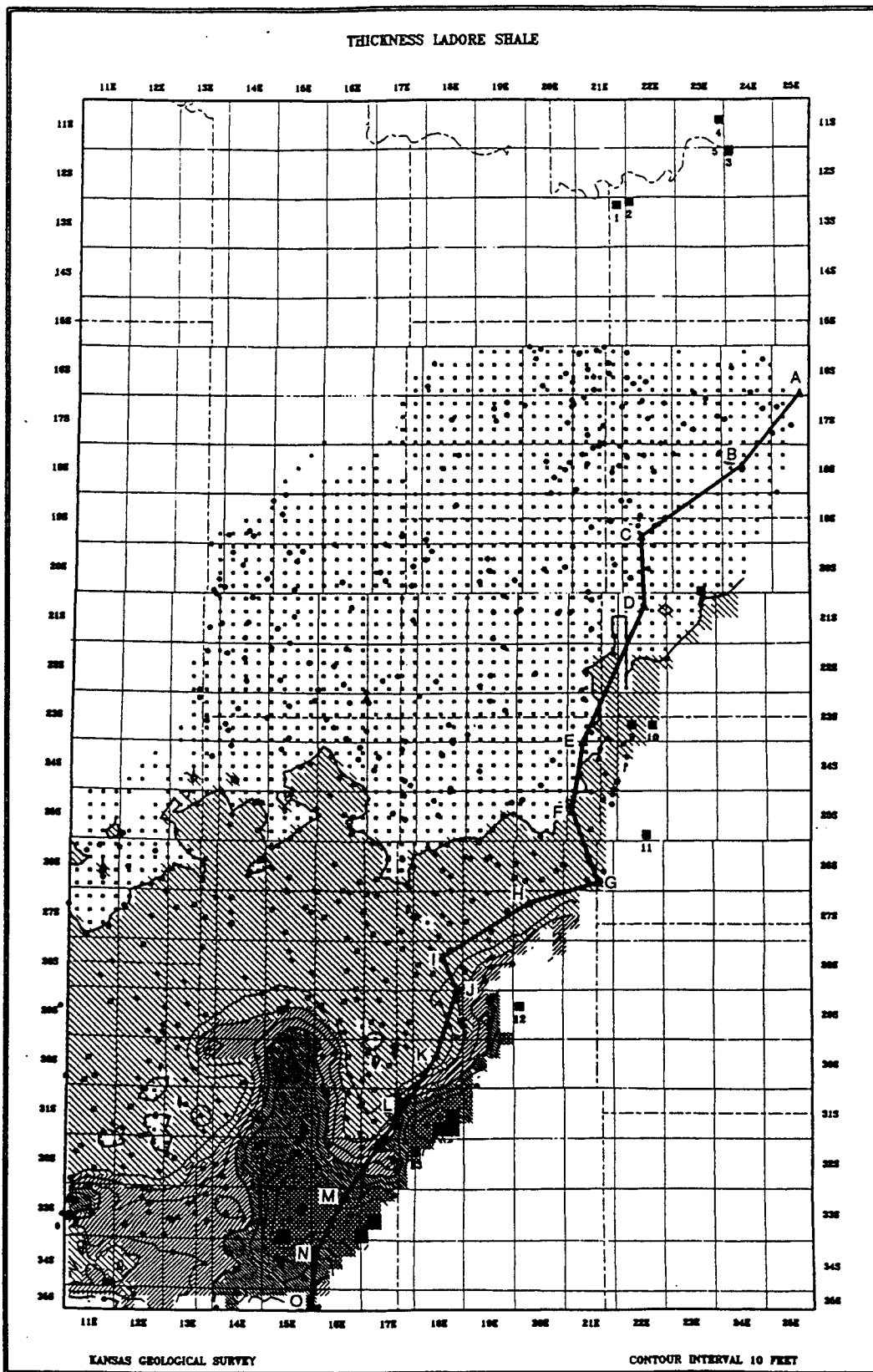


FIGURE 9—ISOPACH MAP OF LADORE SHALE, also referred to as the “lower Layton sandstone,” a predominately fine-grained siliciclastic unit only present in southern Kansas. Note zero line.

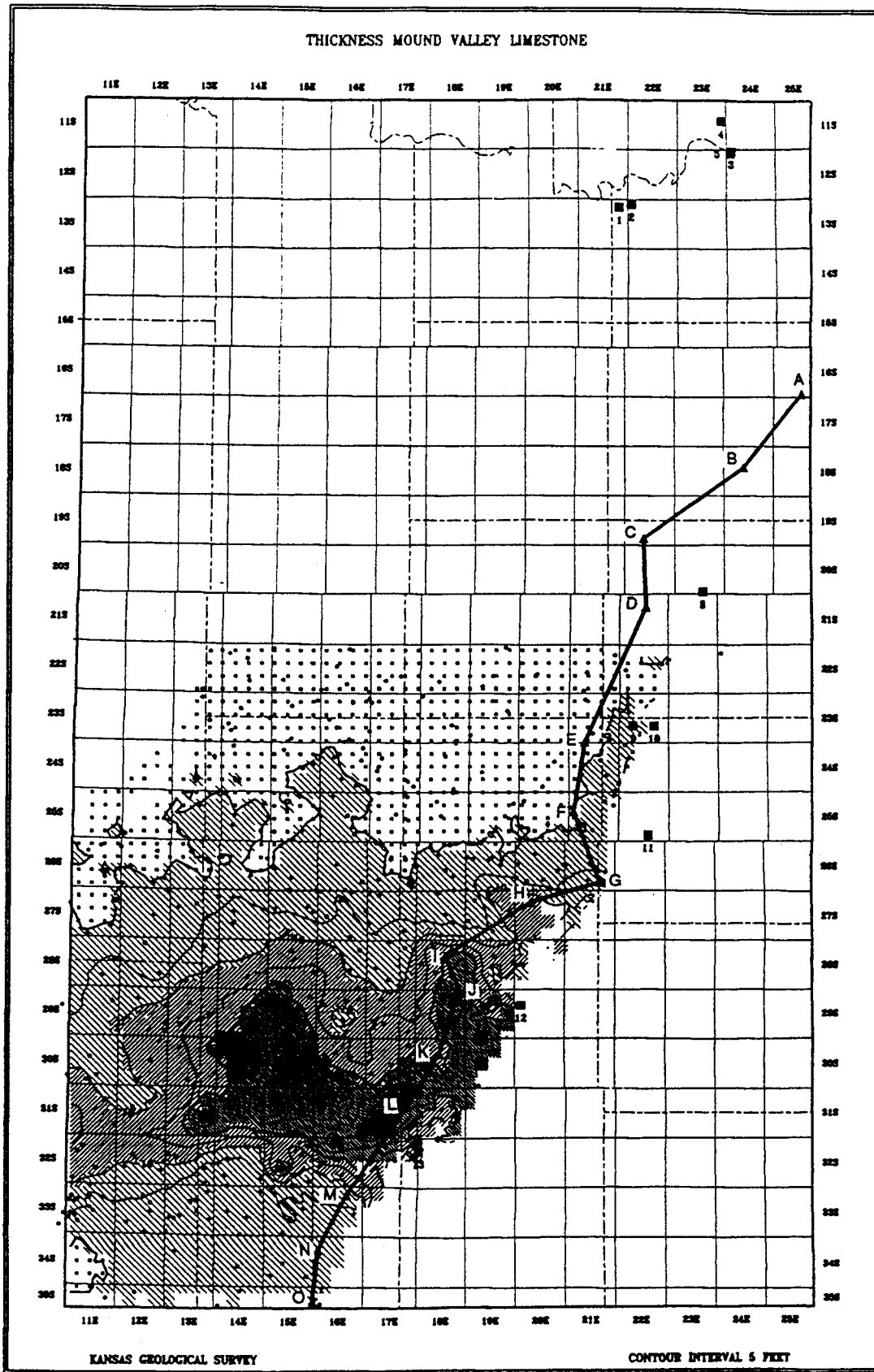


FIGURE 10—ISOPACH MAP OF MOUND VALLEY LIMESTONE, the upper carbonate of the Swope sequence only developed on the southern shelf margin and basin. This unit is also included in interval-isopach map of fig. 7.

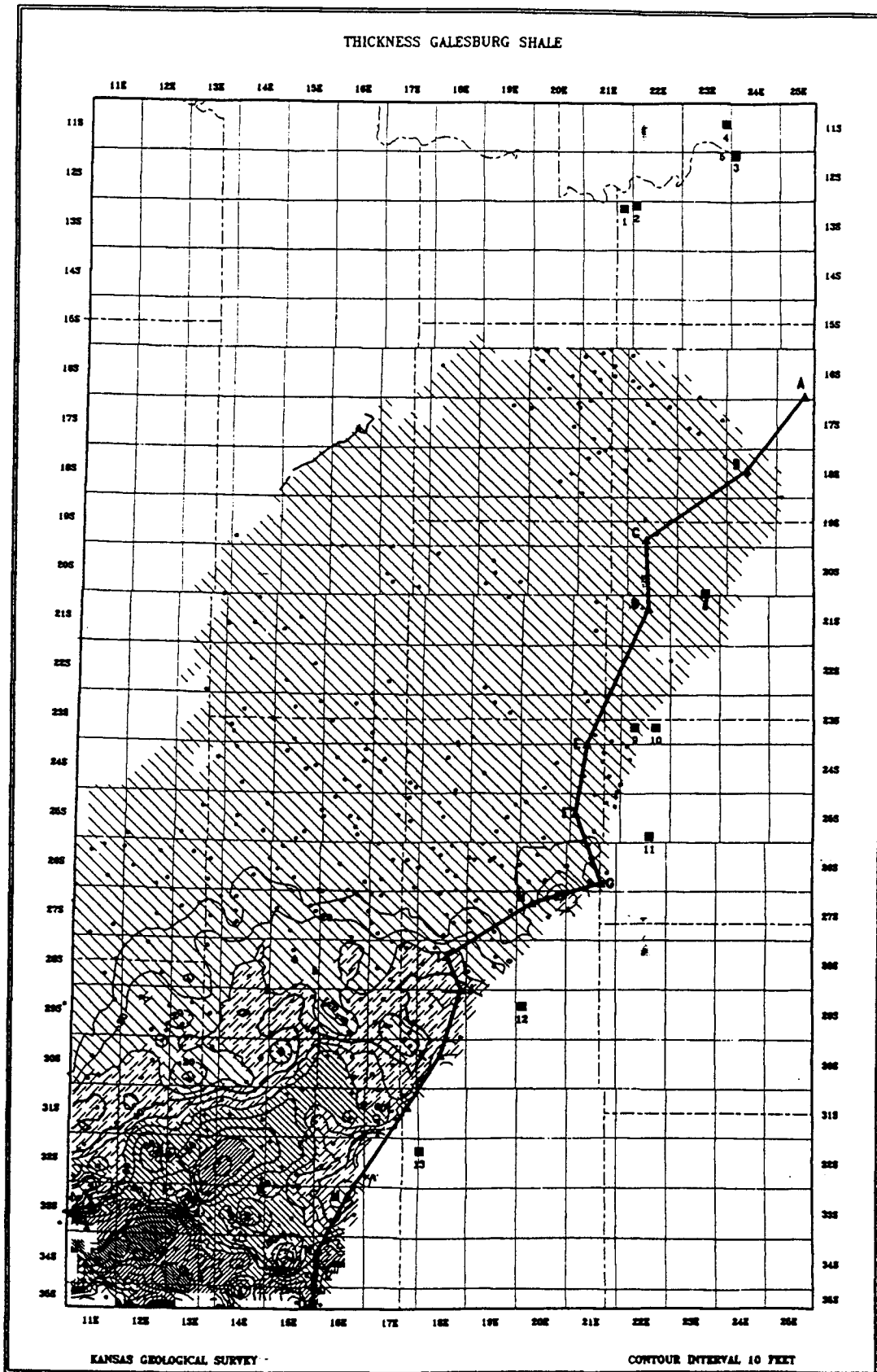


FIGURE 11—ISOPACH MAP OF GALESBURG SHALE. It is very thin on the northern two-thirds of the shelf where developed as paleosol. It becomes very thick basinward where it is composed of increasingly coarser siliciclastics southward. The boundary between Swope and Dennis sequences is tentatively placed in this package. It is referred to as the "upper Layton sandstone" in the subsurface where the interval produces oil and gas.

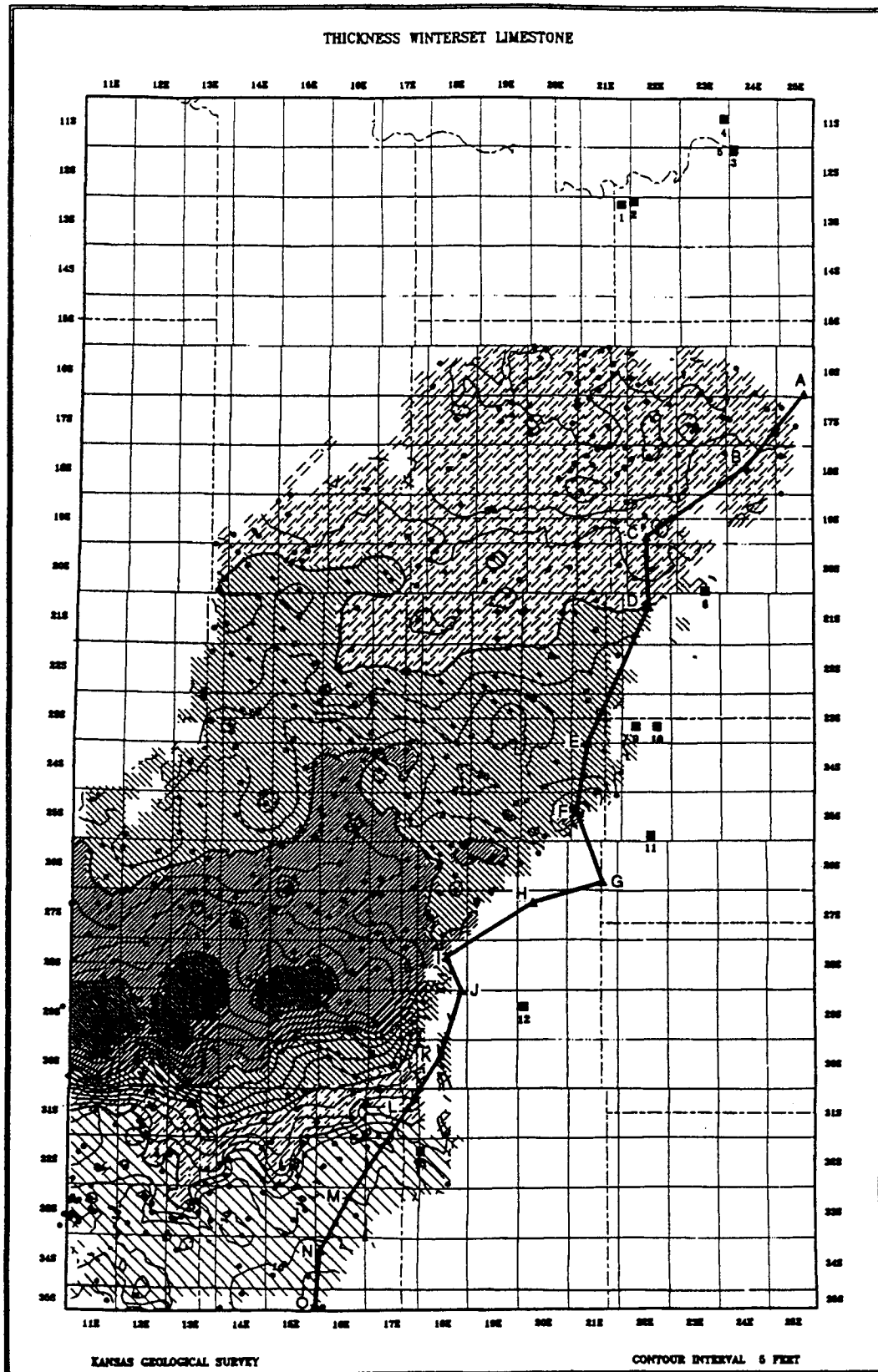


FIGURE 12—ISOPACH MAP OF WINTERSET LIMESTONE, a shallowing-upward limestone unit of the Dennis sequence. The phylloid-algal mound and oolitic grainstone complex form a thickened east-west band in southern Kansas, north of the location of thick Swope sequence, but overlying location of thick Hertha sequence.

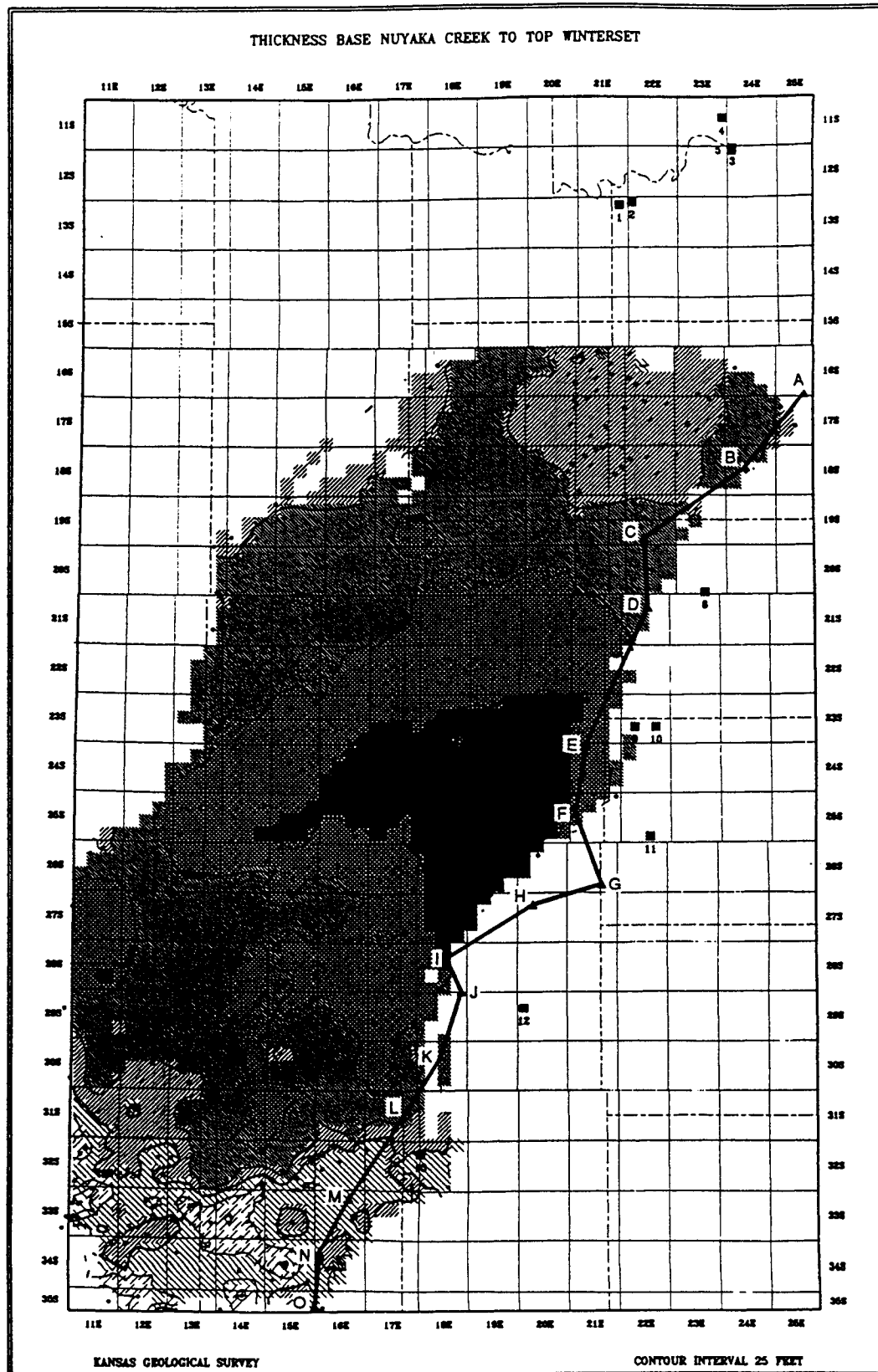


FIGURE 13—INTERVAL-ISOPACH MAP FROM BASE OF NUYAKA CREEK SHALE TO TOP WINTERSET LIMESTONE. The unit represents the combined thickness of Pleasanton Group, Hertha and Swope sequences, and major portion of Dennis sequence. Thickness is quite uniform over the shelf.

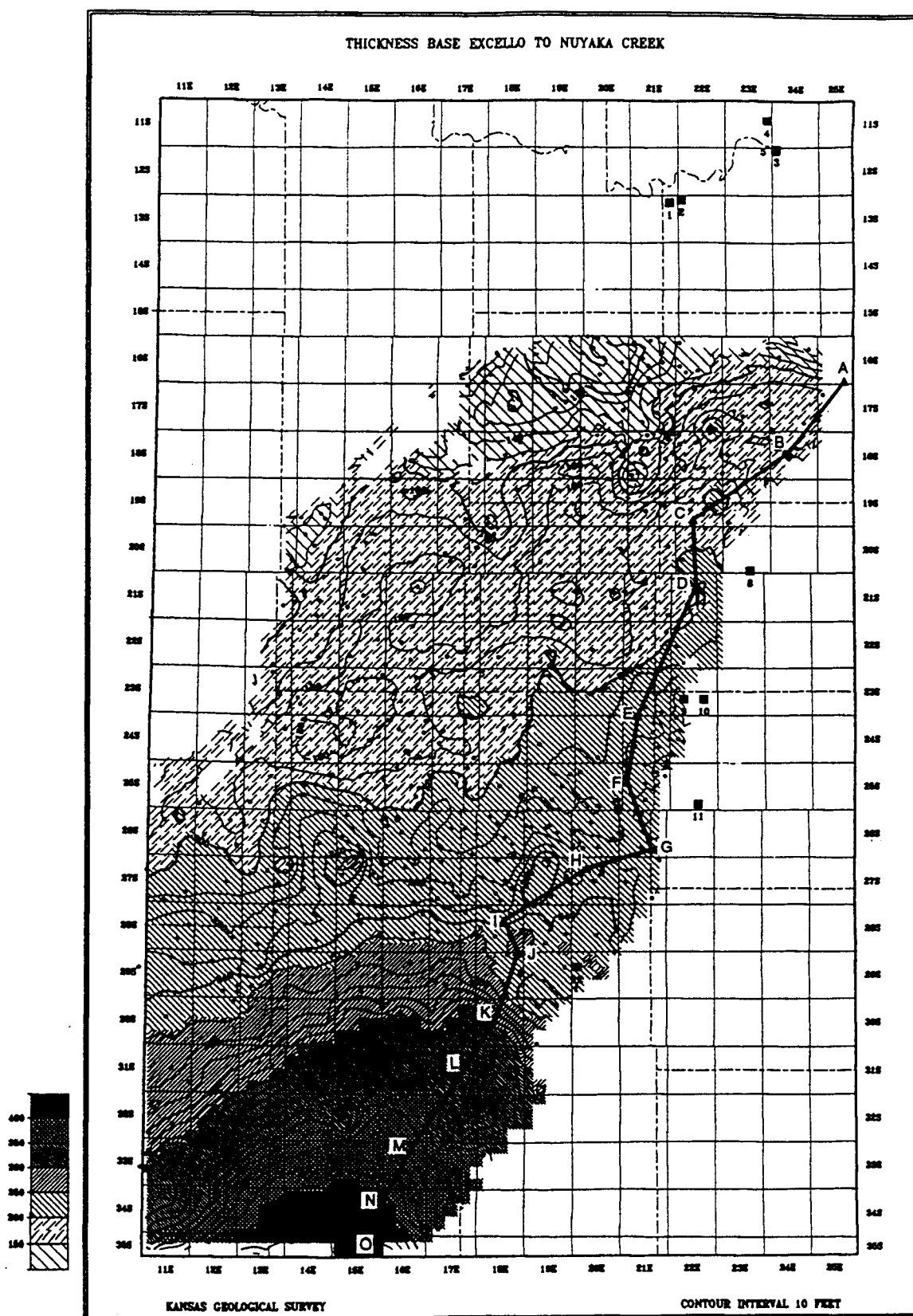


FIGURE 14—INTERVAL-ISOPACH MAP OF EXCELLO SHALE (black shale at top of Desmoinesian Cherokee Group) to Nuyaka Creek Shale, located just above the Marmaton Group at the top of the Desmoinesian. More rapid thickening of the interval toward the Arkoma basin along east-west "hinge" at T. 29 S. is similar to locations of younger phylloid-algal-mound complexes in Hertha and Dennis sequences.

equivalents are referred to as the lower and upper Layton sands, respectively, when encountered in the subsurface.

The black Hushpuckney and Stark shales are examples of the regionally correlative lithostratigraphic units (fig. 16). Lithostratigraphic correlations in other basins are substantiated by conodont and ammonoid biostratigraphy (Boardman and Heckel, 1989). Both shales emit elevated gamma radiation and provide very distinctive "kicks" on the natural gamma-ray log (fig. 4). The black shales maintain a remarkable homogeneity across extensive areas of the shelf and basin. The Hushpuckney and Stark shales are part of major marine inundations referred to as the Swope and Dennis depositional sequences in Kansas (fig. 3).

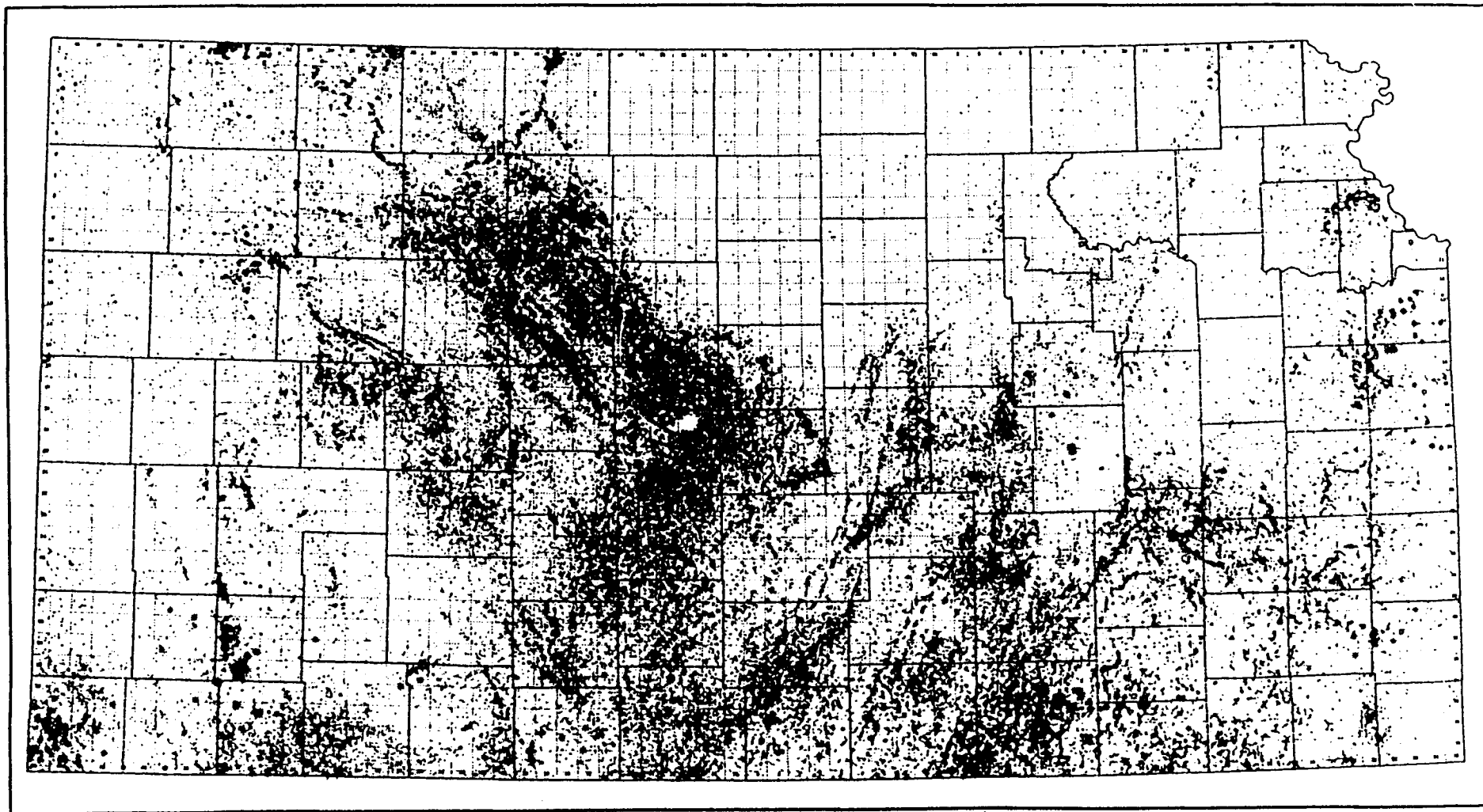
Other lithologically, biostratigraphically, and petrophysically (natural gamma-ray maxima) distinctive marine shales are persistent over large areas of eastern Kansas and eastern Oklahoma and therefore provide good surface and subsurface correlation. These shales include the Nuyaka Creek Shale found in the uppermost Desmoinesian of Kansas, overlain by the Mound City Shale of the Hertha Formation. Other widespread, stratigraphically higher black shales that serve as good markers include the Quivira Shale Member of the Dewey Limestone, the Muncie Creek Shale Member of the Iola Limestone, and the Eudora Shale Member of the Stanton Limestone (fig. 3). These markers are continuous between areas that represent significant changes in depositional environments.

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. 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. 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, it is the deciphering of these stratal packages in areas of varying levels of stratigraphic and sedimentologic resolution and composition that will ultimately provide the means to identify and quantify the controlling processes.

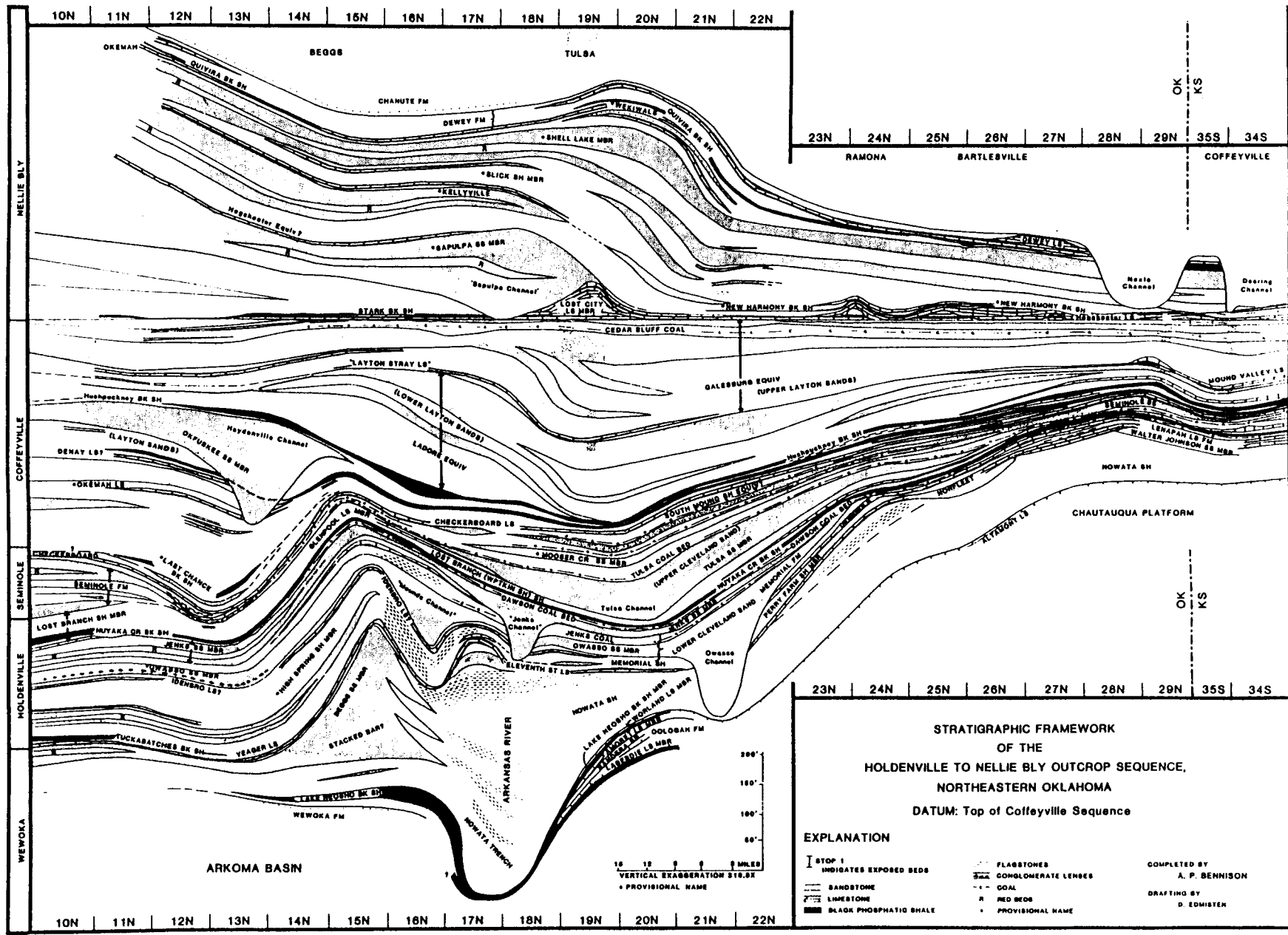
FIGURE 15—MAP ILLUSTRATING WELLS PENETRATING THE UPPER PENNSYLVANIAN-AGE LANSING AND KANSAS CITY GROUPS IN KANSAS: nonproductive wells (lighter shaded spots) and producing wells (black spots).

WELLS PENETRATING AND PRODUCING FROM LANSING-KANSAS CITY



KANSAS GEOLOGICAL SURVEY

○ OIL WELL      ⊙ GAS WELL      ⊕ OIL & GAS WELL      ◻ NON PRODUCING WELL



## Regional geologic setting

During Missourian time the large supercontinent Pangea was in the final stages of formation (fig. 17). The Ouachita Mountains bordering the midcontinent on the south-east formed along the suture zone created by the collision of Laurasia with Gondwana (fig. 18, 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. Clastic progradation from the Ouachitas episodically filled the Arkoma basin and occasionally reached onto the carbonate platform to the north into southern Kansas (fig. 18). The Arkoma basin was nearly filled with detrital sediments by Missourian time due to diminished subsidence, as compared to peak subsidence during climactic orogenic activity during Atokan time (Houseknecht and Kacena, 1983). In contrast, the southern margin of the western shelf along the Anadarko basin was never affected by similar clastic 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. 19; 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 parallelism 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.

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. 20, prepared by George Moore (unpublished, circa 1974), provides an excellent depiction of this

FIGURE 16 (opposite)—NORTH-SOUTH STRATIGRAPHIC CROSS SECTION OF THE UPPERMOST DESMOINESIAN AND LOWER MISSOURIAN siliclastic-dominated strata along the traverse from towns and cities of Okemah, Beggs, Tulsa, and Bartlesville in eastern Oklahoma extending into extreme southern Kansas (prepared by Allen Bennison).



FIGURE 17—HEMISPHERE OF GLOBE SHOWING EURAMERICA AND LOCATION OF MIDCONTINENT DURING PENNSYLVANIAN (Ross and Ross, 1987).

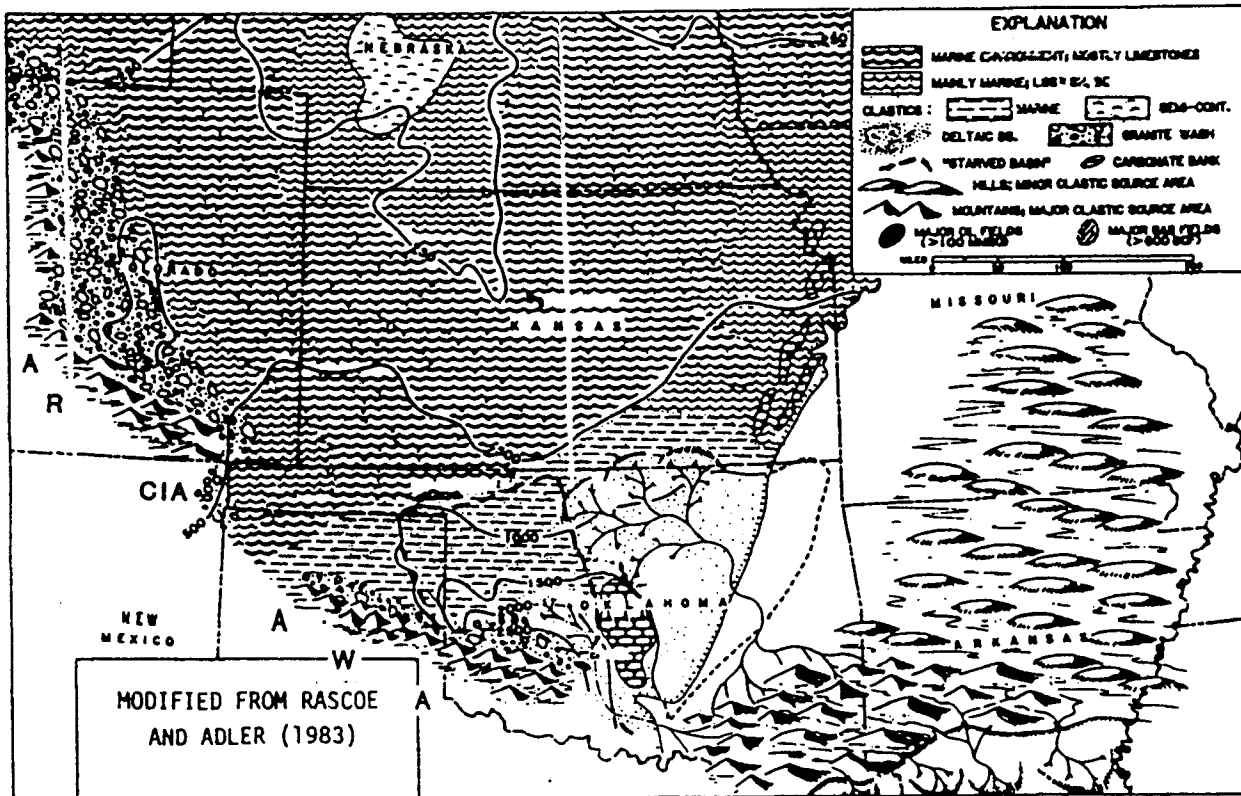


FIGURE 18—LITHOFACIES, PALEOGEOGRAPHY, AND ISOPACH MAP OF STRATA DEPOSITED DURING MISSOURIAN (Pennsylvanian) in southern midcontinent (Rascoe and Adler, 1983).

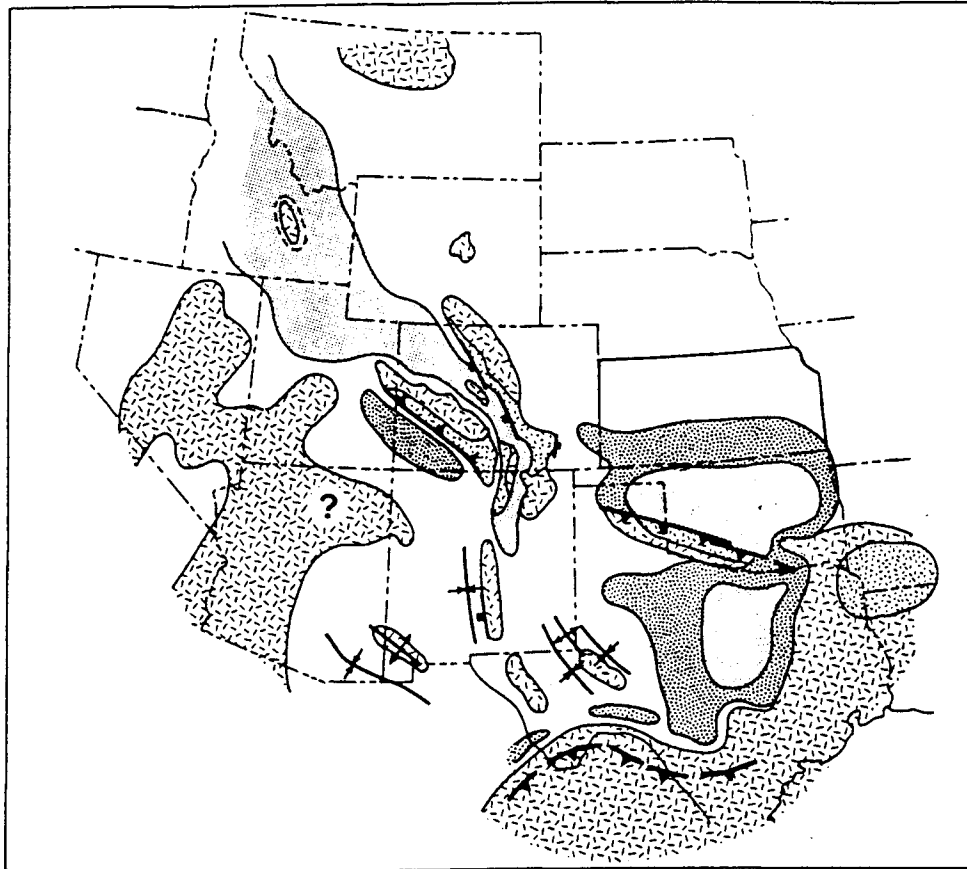


FIGURE 19—MISSOURIAN TECTONIC FEATURES WITH AVERAGE SUBSIDENCE RATES FOR MISSOURIAN TIME: white areas  $\Rightarrow$  0.05 to 0.2 m/ka; dark stippled pattern  $\Rightarrow$  0.05 to 0.2 m/ka; and lighter stipple  $\Rightarrow$  0.2 to 0.3 m/ka. Subsidence in Arkoma basin in waning stages during the Missourian (Kluth, 1986).

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.

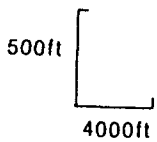
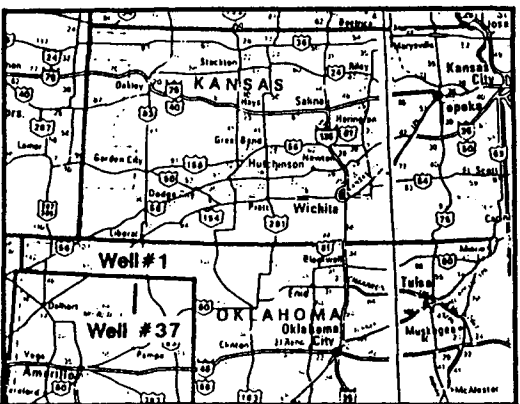
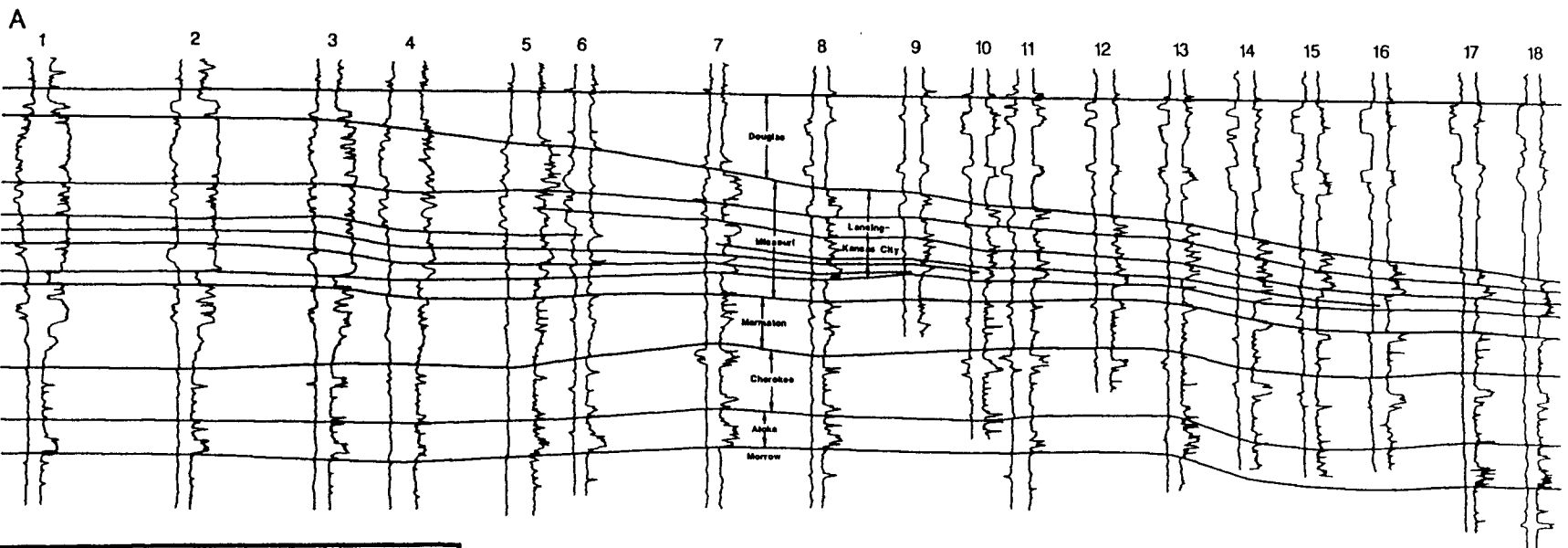
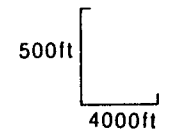
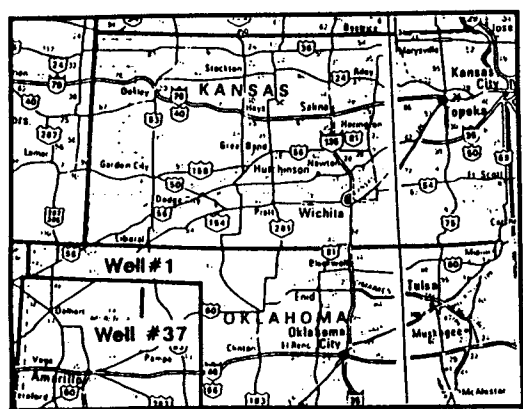
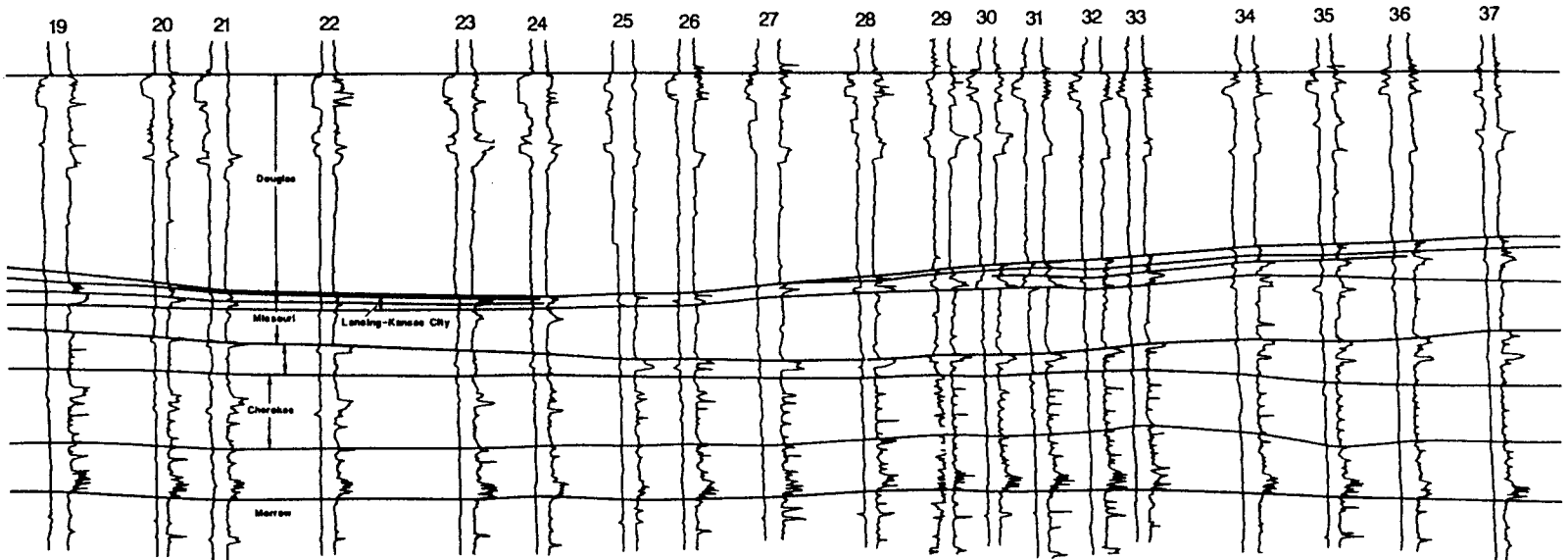


FIGURE 20—STRATIGRAPHIC WIRELINE-LOG CROSS SECTION ACROSS SHELF EDGE OF NORTHWESTERN ANADARKO BASIN IN HANSFORD COUNTY, TEXAS. Datum is Virgilian Heebner Shale (from George Moore, circa 1974).

A'



# Cyclothem concept

## General nature of Upper Pennsylvanian (Missourian) stratigraphy

Upper Pennsylvanian (Missourian, Kasimovian, early Stephanian) strata of the midcontinent United States are characterized by thin cyclical successions of variable percentages of carbonate and siliciclastic rocks, with thicknesses of less than 75 ft (25 m) to 150 ft (50 m). Comprehensive overviews of Pennsylvanian cyclic sedimentation are found in Merriam (1964) and Heckel (1977, 1984, 1985). Cycles of sedimentation or "cyclothem" developed on shelf areas of the midcontinent generally have thin but widespread transgressive basal lithofacies overlain by thicker regressive strata (fig. 21, Heckel, 1977). These cyclothem are commonly separated from bounding strata by surfaces that are commonly associated with diagenetic and textural features indicative of subaerial weathering (Watney and Ebanks, 1978; Watney, 1980; Prather, 1981; Schutter and Heckel, 1985; Goebel et al., 1989). Variations in thickness, areal extent, and lithofacies in typical cyclothem suggest varying

degrees of marine inundation of the craton (Heckel, 1980, 1984, 1986; Watney, 1984). Additional omission surfaces that define distinctive subcyclothem sequences are commonly imbedded within many cyclothem successions on the shelf. Cyclothem 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).

Cyclothem 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 cyclothem in the eastern shelf of the Midland basin and the northern midcontinent (fig. 22, Boardman and Heckel, 1989). Correlations reflect synchronous marine inundation in both areas.

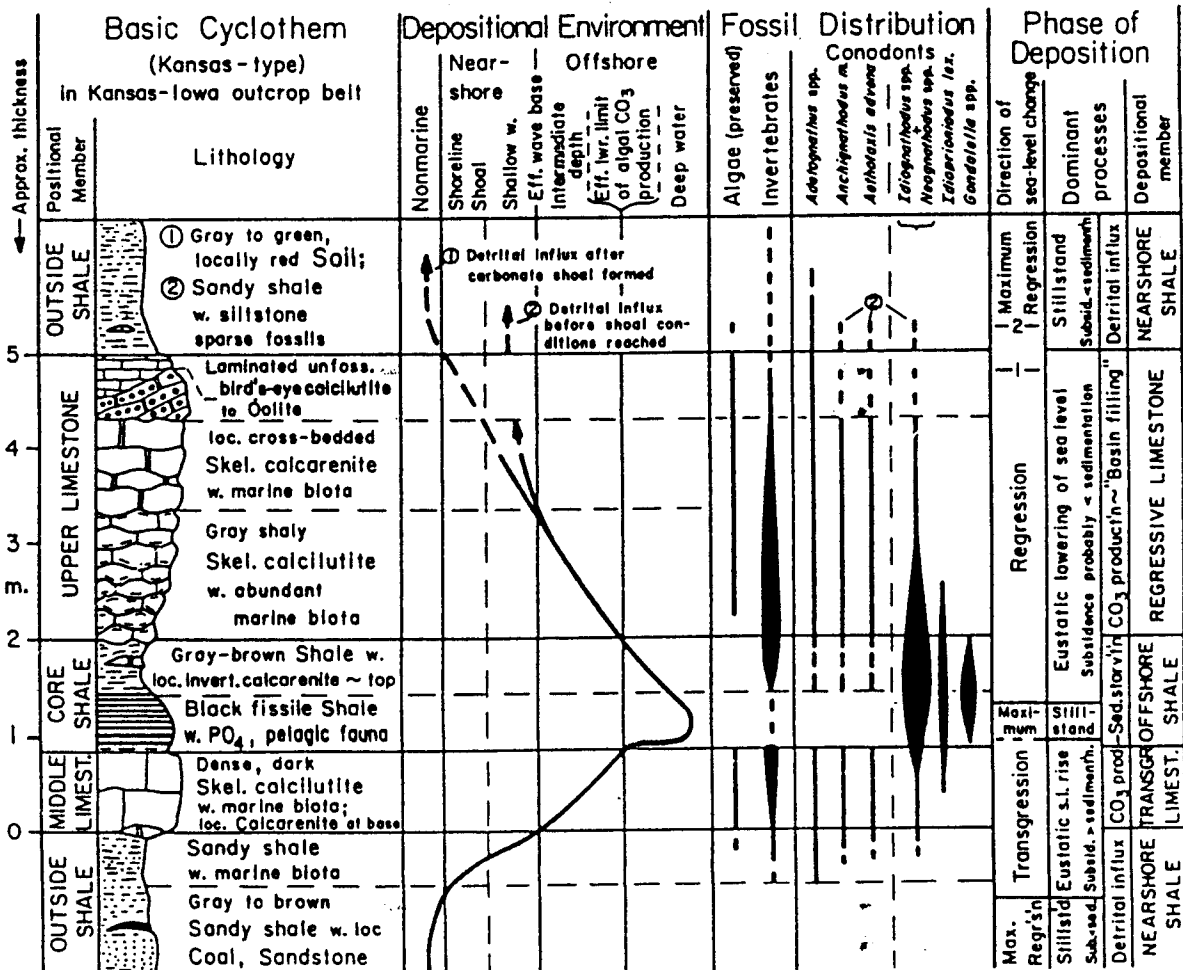


FIGURE 21—BASIC KANSAS CYCLOTHEM CHARACTERIZING CARBONATE-DOMINATED STRATA IN THE NORTHERN MIDCONTINENT SHELF (Heckel, 1977, 1989).

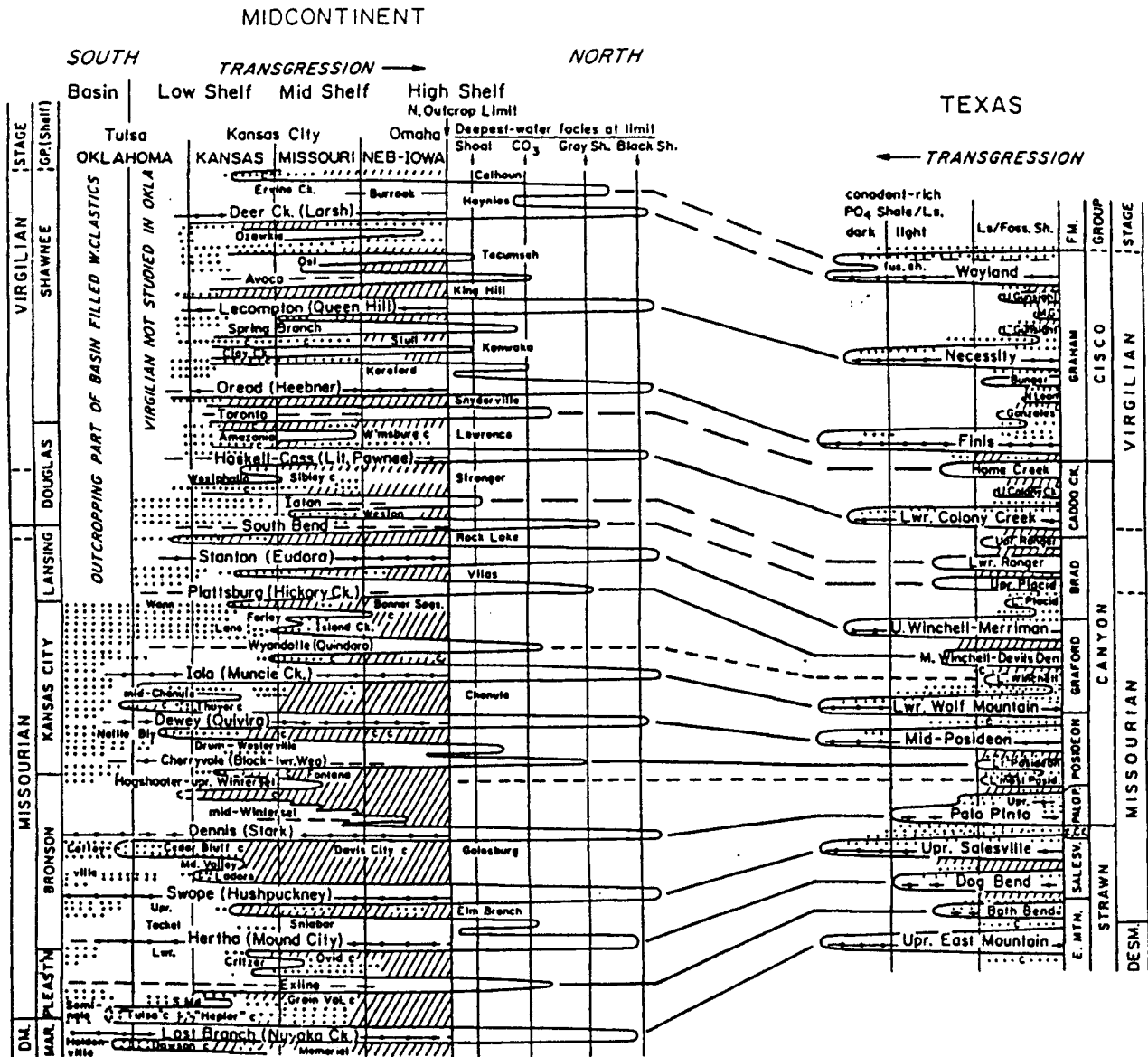


FIGURE 22—GLACIAL-EUSTATIC SEA-LEVEL CURVES FOR EARLY UPPER PENNSYLVANIAN SUCCESSION IN NORTH-CENTRAL TEXAS AND MIDCONTINENT CORRELATED USING BIOSTRATIGRAPHY. CURVES DEPICT MAXIMUM INUNDATIONS BASED ON OCCURRENCE OF BLACK SHALE AND LOW STAND BASED ON EXTENT OF SUBAERIAL EXPOSURE (BOARDMAN AND HECKEL, 1989).

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

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

Foraminiferal, ammonoid, and conodont zones have also been used by Ross and Ross (1987) to extend correlations of similar Pennsylvanian marine inundations globally (fig. 23). 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. 21). 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.

## Core shale

The core shale overlies the middle limestone in the typical Kansas cyclothem (fig. 21). 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 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 (figs. 24–26, Stark, Hushpuckney). 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 (figs. 25 and 26), a long-term positive element.

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

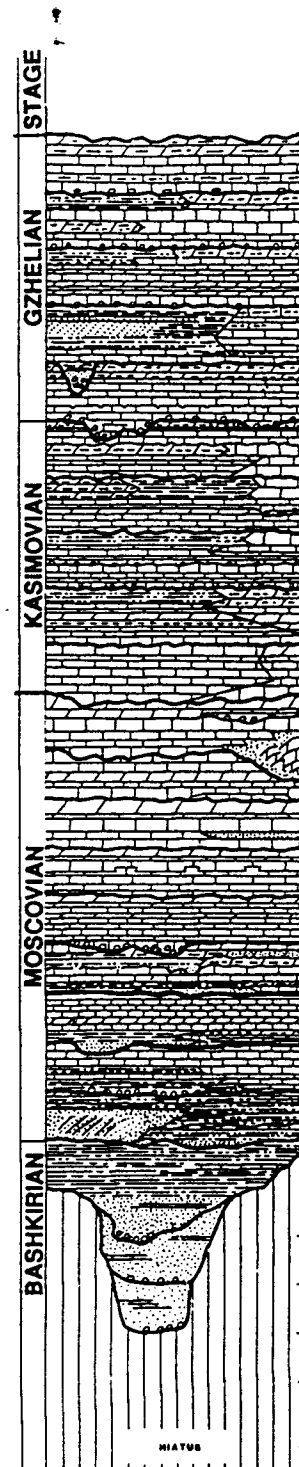


FIGURE 23—STRATIGRAPHIC SECTION OF CARBONATE-DOMINATED MIDDLE AND UPPER CARBONIFEROUS SHELF CYCLOTHEMS ON RUSSIAN PLATFORM. Kasimovian is equivalent to Missourian and earliest Virgilian (Ross and Ross, 1988).

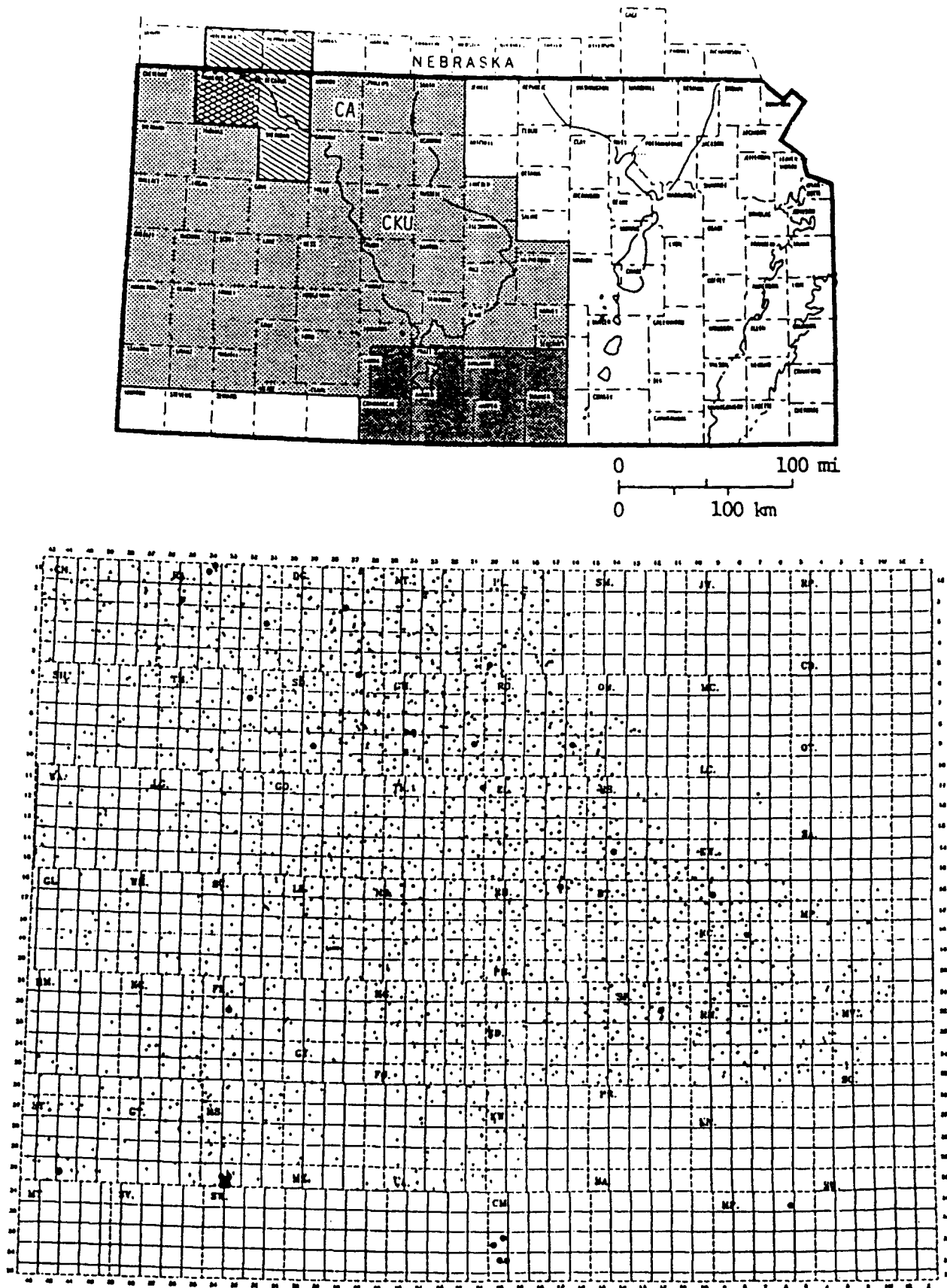


FIGURE 24—INDEX MAP OF WESTERN KANSAS SHELF STUDY AREA WITH LIGHT-STIPPLED AREA IN UPPER MAP COINCIDING WITH SUBSURFACE CONTROL SHOWN IN LOWER MAP. AREA OF LOWER MAP THE SAME AS SUBSEQUENT MAPS SHOWN OF WESTERN KANSAS.

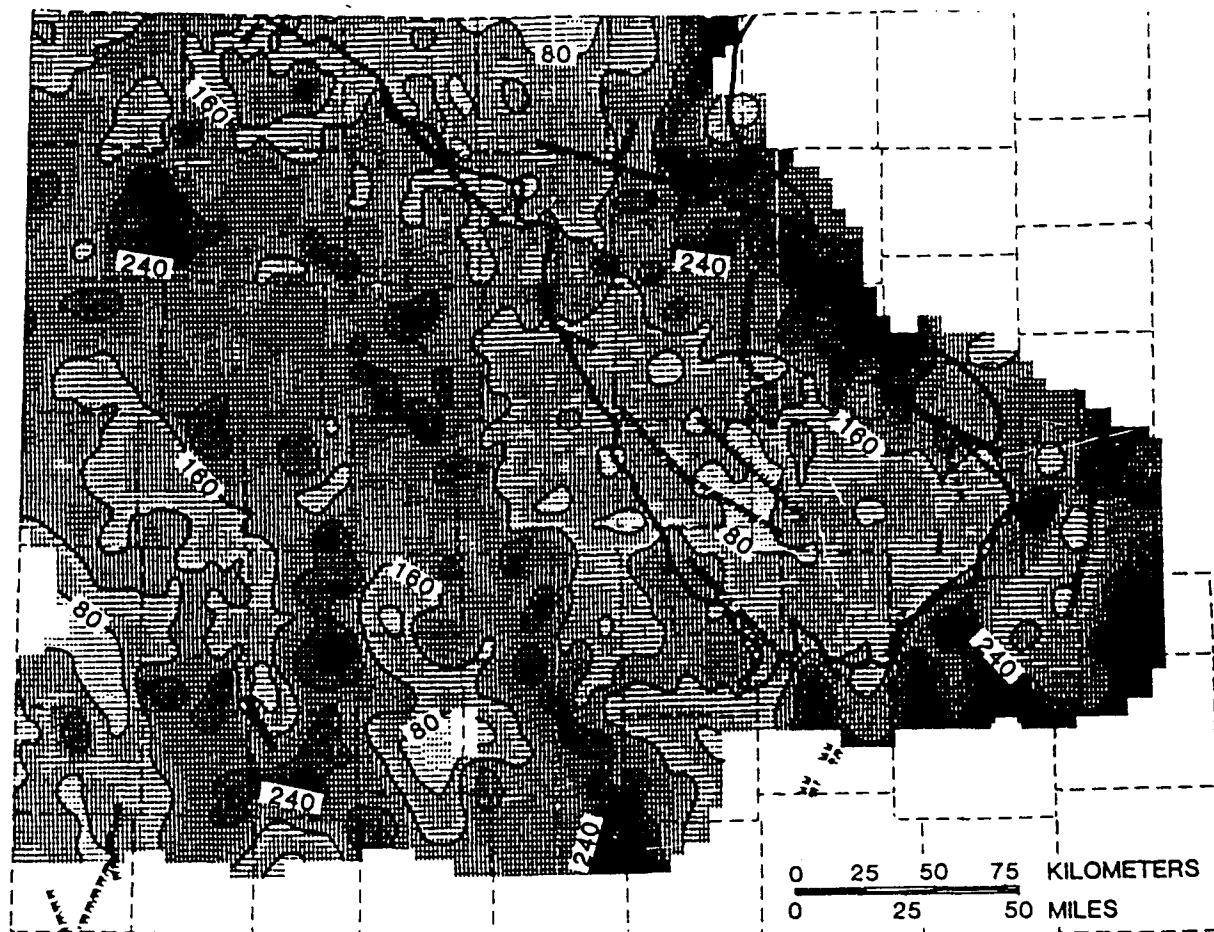


FIGURE 25—MAXIMUM GAMMA RADIATION (API UNITS) OF MISSOURIAN STARK SHALE FOR SHELF AREA IN WESTERN KANSAS. Values in excess of 160 API units (darker gray) are associated with black shale. Heavy line in eastern portion of map outlines northwest-southeast-trending Central Kansas uplift. Mapped area and control shown in fig. 24.

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 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 (fig. 27). 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 the companion conference volume (Coveney et al., 1989). 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 cy-

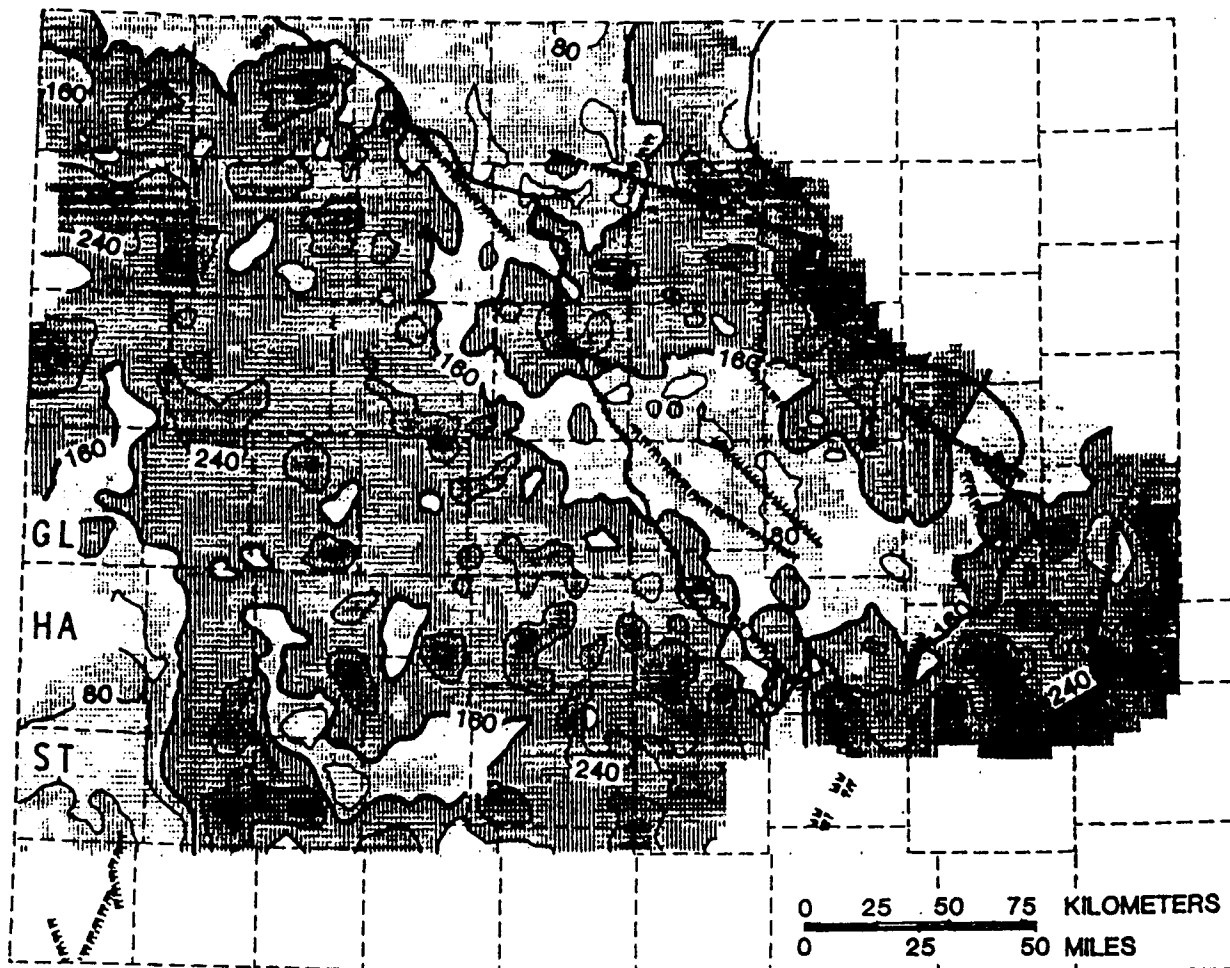


FIGURE 26—MAXIMUM GAMMA RADIATION (API UNITS) OF MISSOURIAN HUSHPUCKNEY SHALE FOR AREA ON WESTERN KANSAS SHELF. Values in excess of 160 API units (darker gray) are associated with black shale. Area of high gamma radiation is slightly more widespread here compared to Stark Shale. However, both shales are very areally extensive marker beds.

clothem 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. 21). 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. Evidence will be presented during the course of the trip that supports most of the thinning and facies change

resulting from a declining surface elevation on which the carbonate accumulated along a platform margin, slope, and basinal setting. Siliciclastic sedimentation from the south became increasingly important as the Arkoma basin progressively filled. The "Layton" sandstones are an example of such a siliciclastic unit.

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

### Outside shale

The outside shale, the uppermost unit of the Kansas-type cyclothem, exhibits considerable variability among different cyclothem (fig. 21). 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 clastic 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. In the Pleasanton interval examined on the field trip, clastic influx was significant, but was not as important during deposition of the lower Kansas City strata, and then increased again during deposition of the upper Kansas City and Lansing groups. 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. This enigmatic relationship will be addressed during the course of the trip.

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 (e.g., Stop 5). 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. The paleosols seen at Stops 7 and 8 on top of Bethany Falls limestone and superjacent outside shales are splendid examples of remnants of ancient soils. Moreover, these paleosols can be traced across the northern carbonate shelf from Iowa to southeastern Kansas; they also are present westward in cores through the subsurface of western Kansas and southwestern Nebraska. Spatial trends of subaerial exposure have also been recognized on the shelf (Watney, 1980). Areas interpreted to be higher shelf locations generally exhibit evidence of more intense subaerial weathering and commonly early meteoric diagenesis (Watney and Ebanks, 1978; Watney, 1980; Heckel, 1983).

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

### Causal mechanisms for cyclothem development

Contrasting and widespread facies changes in cyclical sequences indicate a significant contribution from allogenic controls (Heckel, 1977; Watney, 1984, 1985a; Boardman and Malinky, 1985; Heckel, 1986).

Glacial-eustatic control has been invoked most often by those who subscribe to allogenic causes for stratal cyclicity (Wanless and Shepherd, 1936; Wanless and Cannon, 1966; Crowell and Frakes, 1975; Heckel, 1977; Crowell, 1978; Denton and Hughes, 1983; Heckel, 1986; Crowley et al., 1987; Veevers and Powell, 1987). The analogue used in these arguments is the sea-level change associated with advance and retreat of Pleistocene continental glaciers. These Pleistocene glacial advances and retreats produced high-frequency sea-level changes with magnitudes on the order of

330–500 ft (100–150 m), periodicity around 100,000 years, and rates of sea-level change around 10 m (33 ft)/thousand years (Ka; Donovan and Jones, 1979).

Autogenic causes, due to internal feedback mechanisms that operated within the depositional system, are also argued to have produced these same cyclothem strata, e.g., Duff and Walton (1962), Donaldson (1974), Ferm (1975), Brown (1972), and Galloway and Brown (1973). All of these studies dealt with strata dominated by deltaic sedimentation and heavily influenced by local (autogenic) sedimentary processes, thereby limiting the potential for correlation between individual delta systems. However, even in these areas of significant autogenic control, recent studies, e.g. by Brezinski, (1984), 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, interdeltic 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.

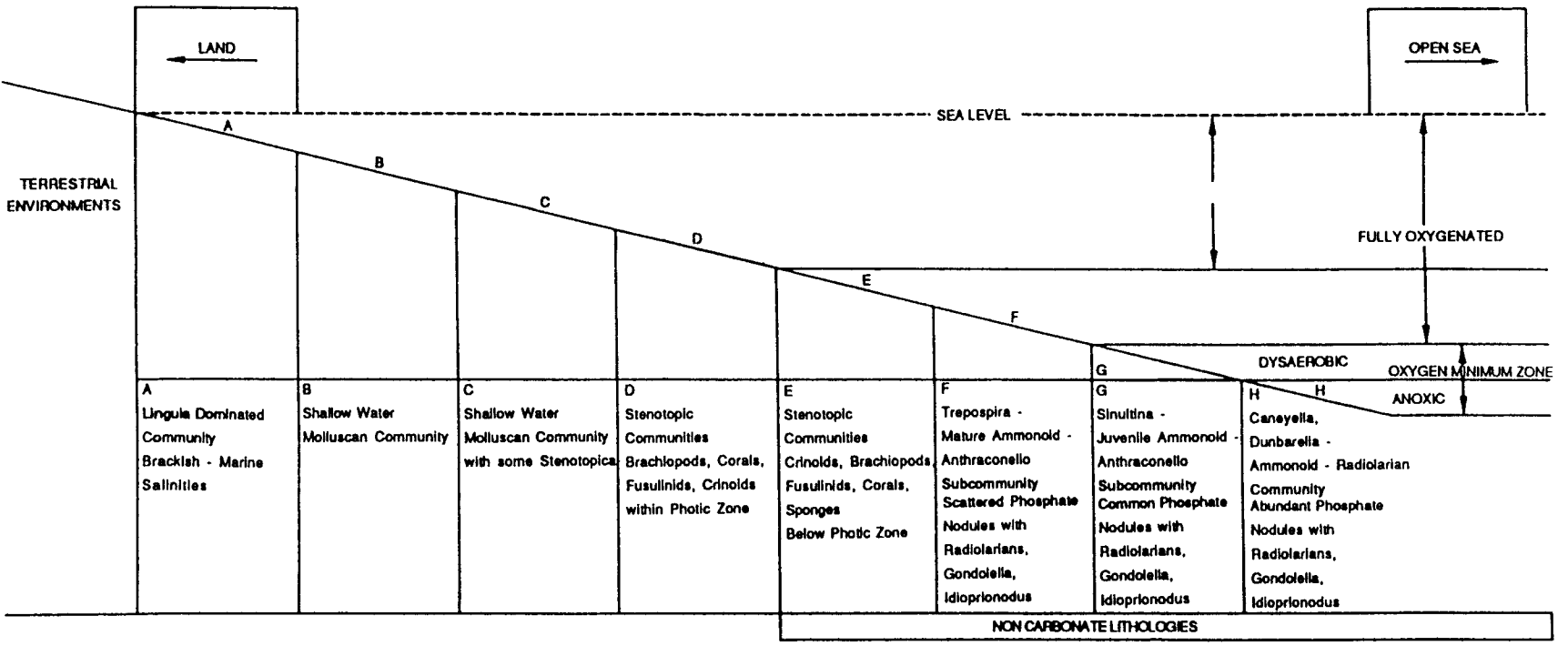


FIGURE 27—OFFSHORE-ONSHORE MODEL FOR PENNSYLVANIAN COMMUNITY SUCCESSION RELATED TO WATER DEPTH AND OXYGENATION OF OVERLYING WATER MASSES (Boardman et al., 1984).

# 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 utilized throughout the text and during the course of the field trip are included in appendix A.

Sequence-stratigraphic analysis can provide crucial information about the genesis of stratigraphic units through analysis of stacking geometry (fig. 28, 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.

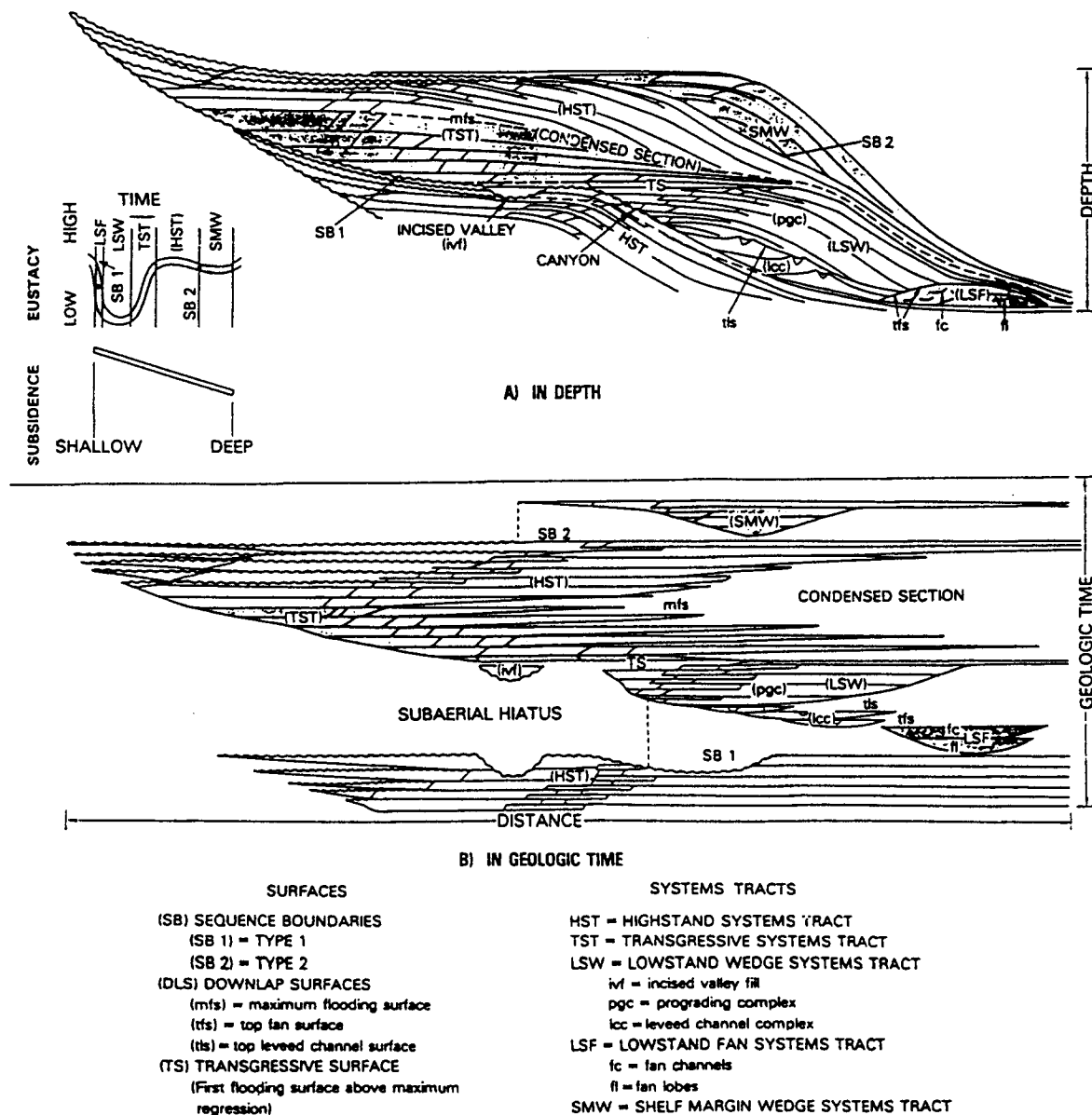


FIGURE 28—DEPOSITIONAL SEQUENCE DEPOSITED ALONG SHELF MARGIN DUE TO OSCILLATION IN SEA LEVEL AND CONSTANT SUBSIDENCE (Haq et al., 1987). Stratal units and surfaces are defined further in appendix A.

- 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.

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

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

- 1) Vertical-sequence analysis:
  - a) Describe strata in terms of depositional environment and relative water depth (relative sea-level change) and evidence for shallowing or deepening trends; identify potential marker beds (thin distinctive units to aid in correlation)
  - b) Describe surfaces: bedding planes (frequency and nature; distinguish diagenetic from depositional); association of surfaces with facies dislocation; ranking of facies dislocation according to water-depth change; establish evidence of subaerial exposure or prolonged nondeposition, e.g., hardground developed in subaqueous marine environment

- c) Draw profiles of sections providing interpretation of genetic units and water depth; genetic units consisting of
  - *flooding or transgressive units* (usually associated with base of depositional sequence; usually thin limestone or coal on shelf areas in Pennsylvanian depositional sequences) of
  - *condensed sections* (may be associated with accumulation of organic matter, e.g., black shale or hardgrounds);
  - *shallowing-upward unit* (shallowing carbonate or siliciclastic succession or combination; thickest and most complex component of a sequence; frequently associated with multiple parasequences
  - *paleosol development* (may represent sequence or possibly parasequence boundary if it forms a surface).

## 2) Correlation between localities

- a) Establish correlations of marker beds and surfaces, utilizing lithostratigraphic, paleontologic, geophysical, or geochemical data (preferably through continuous or detailed systematic sampling).
  - b) Identify the depositional sequence(s). Correlate major genetic units and bounding surfaces associated with a depositional sequence using all information available.
  - c) If possible, extend control to the 3rd-dimension and over more extensive areas of shelf, shelf margin, and into basin to address stratal geometries in more comprehensive manner and evaluate allogenic and autogenic causal mechanisms (eustatic, subsidence).
- The temporal distinction of sedimentary sequences also provides the data base to
- a) define detailed paleogeography;
  - b) address rates, duration, and magnitude of events responsible for sedimentation;
  - c) possibly improve the ability to predict facies for economic development.

## Recognition of sequence-stratigraphic components in Upper Pennsylvanian cyclothems

### Flooding unit

The flooding unit is either absent or thin (zero to several 10's of feet thick) with a sharp basal contact (fig. 29). It is readily identified through vertical-sequence analysis in outcrop or core. The flooding unit commonly 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

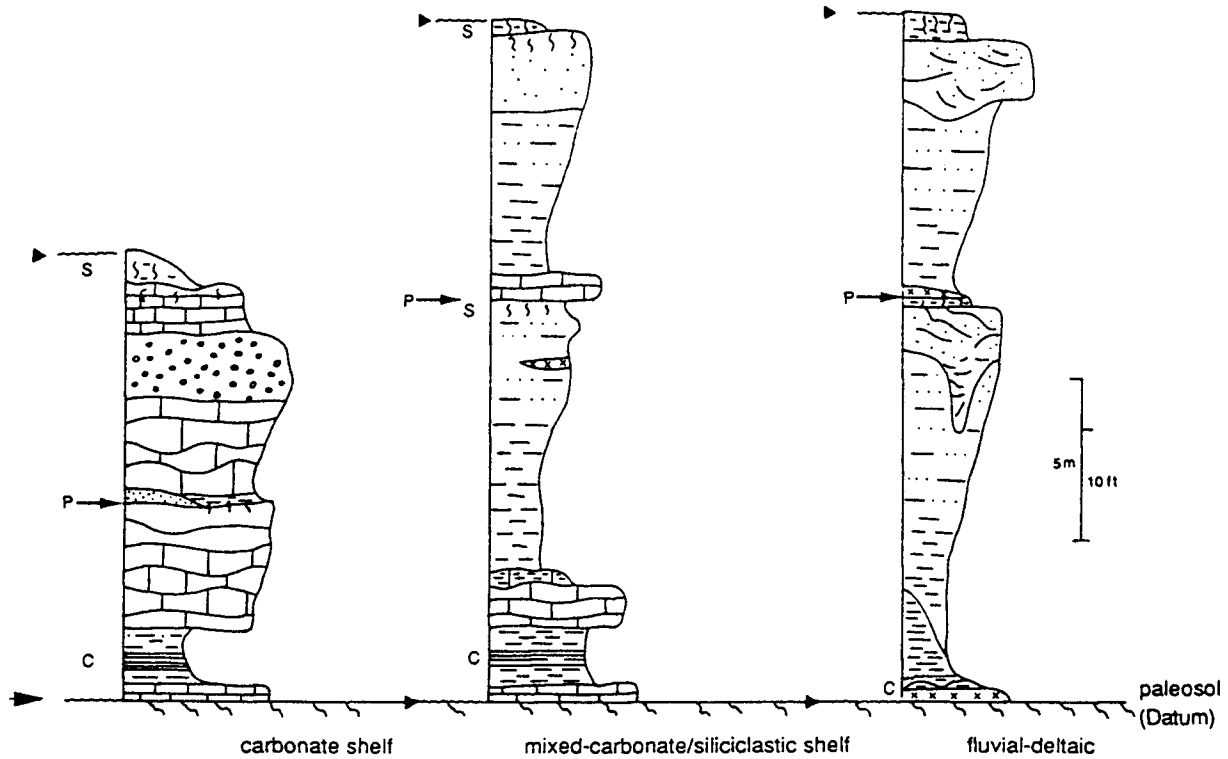


FIGURE 29—VERTICAL PROFILES OF SELECTED TYPES OF DEPOSITIONAL SEQUENCES OBSERVED IN PENNSYLVANIAN STRATA OF THE MID-CONTINENT. Simple shallowing-upward sections shown.

base and are overlain commonly by normal marine strata at the top that were likely deposited below normal and storm wave base. Clam borings, pyritization of skeletal debris, and preservation of small to moderate amounts of organic debris are common components of the carbonate-flooding units. The lower contact usually separates distinctly different depositional facies resulting in *facies dislocation*, e.g., a paleosol beneath a marine limestone. Carbonate buildups, although uncommon in this unit, are spectacularly developed locally. Carbonate mounds that developed during deepening events, and locally kept pace with rising base level thicken abruptly to over 50 ft (15 m; e.g., the Captain Creek Limestone, Heckel, 1975). In contrast, the flooding unit may only consist of a few inches of bioclastic-shell packstone or other shallow-water marine-carbonate rock. Heckel (1984) has ascribed variations in thickness of the transgressive limestone (his term for the flooding unit) to varying rates of inundation of the shelf and to differences in the slope of the surface that is being inundated.

Widespread coals capped by invertebrate skeletal lag or limestone locally are characteristic of some flooding units (fig. 29). Marine sandstones and siltstones that compose the flooding unit also include reworking of underlying deposits or renewed detrital deposition. Whether erosion or deposition occurs during deepening was likely dependent on

steepness of depositional slopes (energy level), climate, marine-circulation patterns, and rate of deepening.

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

Hallock and Schlager (1986), in their studies of Holocene carbonate settings, conclude that reefs and most carbonate-sediment-producing organisms flourish in nutrient-deficient systems. However, these organisms undergo significant reduction in sediment production during increasing nutrient supply, which often occurs during submergence of a carbonate shelf. Flooding is thought to produce a biotic crisis due to nutrient excess. While increased nitrate and phosphate would stimulate growth of some organisms, other more deleterious effects apparently lead to net decreased sediment production, e.g., reduced water transparency limiting the depth range for some corals and calcareous algae, and consequently reduced sediment production.

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

The sensitivity of a carbonate platform to flooding is a function of local conditions. For example, the euphotic zone, below which reefs composed of zooxanthellate corals will not survive, ranges from 170 m (561 ft) in the Gulf of Aqaba to 18 m (59 ft) around Barbados (Hallock and Schlager, 1986; fig. 30). The shallower the euphotic zone, the more susceptible the area is to diminished  $\text{CaCO}_3$  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 ( $\sim 8\text{m}$  [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 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. 29). 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. 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, e.g., the upper Hushpuckney Shale seen in Stop 7. These gray shales, albeit thin ( $< 1\text{ ft}$  [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 (e.g., the Hushpuckney and the Stark shales, figs. 25 and 26, 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 nekto-benthic 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  $< 20\text{ ppm}$  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 suggest 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

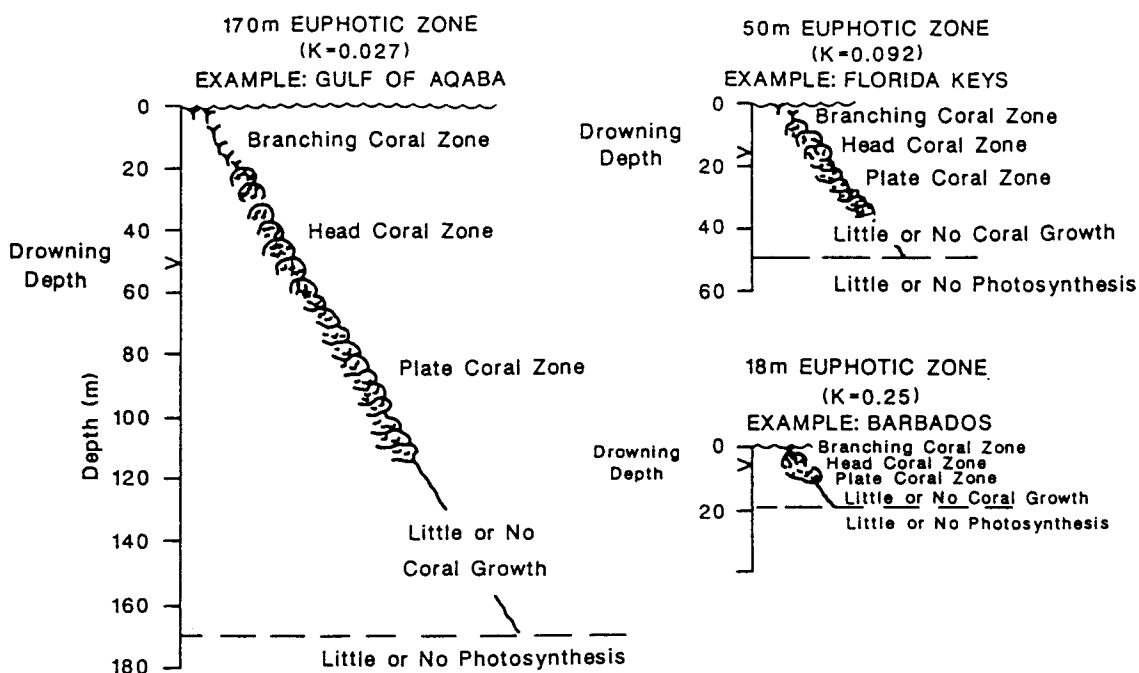


FIGURE 30—ILLUSTRATIONS SHOWING INFLUENCE OF WATER CLARITY ON ZOOXANTHELLAE [SIC] (ZOOCHLORELLATE) CORALS. "K" is the extinction coefficient of light. Drowning depth shown is approximate submergence depth required to physically drown that reef. (Hallock and Schlager, 1986).

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 fauna that have been interpreted as an assemblage related to depth (fig. 27, Boardman et al., 1984). Biotic assemblages reflecting similar dysoxic conditions are commonly found in other Paleozoic shales. Perhaps these biotic zones may be indirectly 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. 29). 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 vary 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 (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) basin (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<sup>2</sup>); 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. 27). 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 well-developed paleosol horizons and subaerially exposed surfaces seen on the trip include: top of the Sniabar Limestone and lower Elm Branch Shale (Stops 7, 11), top of the Bethany Falls Limestone and lower Galesburg Shale (Stops 7, 8), and the blocky mudstone below the Cedar Bluff Coal in the Galesburg Shale and the top of the Bonner Springs Shale (Stop 13). Subaerial-exposure horizons are also present within the depositional sequence at the tops of shallower parasequences, e.g., subaerial exposure within the Winterset Limestone (Heckel and Watney, 1985).

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

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

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 31—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.

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). The upper surface of the Bethany Falls Limestone at Stop 8 is dominated by small-scale karsting. Nevertheless, well-preserved, laminated calcrete occurs within 20 mi (32 km; Heckel, 1985).

## Depositional-sequence development in the midcontinent

### Sequence development in the western midcontinent craton

Prominent subsidence and structural relief along the northern border of the Anadarko basin in the panhandle of Texas is found on the cross section in fig. 20. The Lansing-Kansas City groups thin from a thickness of nearly 1,000 ft (305 m) of carbonate deposits along the northern shelf margin to 60 ft (18 m) over a distance of 20 mi (32 km). Siliciclastic mud, density-current deposited sands, and, locally, allodapic carbonates shed from adjoining shallow shelves, accumulated in the basinal areas. The rate of thinning is approximately 50 ft/mi (9.4 m/km) into the basin that was sediment starved during the Missourian. Seismic stratigraphy and subsurface studies suggest that relief across the shelf was in excess of 1,000 ft. (305 m; Kumar and Slatt, 1984). The sediment surface was apparently deep enough to

preclude carbonate accumulation. As will be shown later in the modeling paper (Watney et al.), modulation in sea level favored the development of sediment-starved conditions. Rapid rise in sea level often led to strong reduction in carbonate production and siliciclastic influx.

Another stratigraphic cross section, using the Heebner Shale as the datum, extends northward from southwestern Kansas onto the Central Kansas uplift. The Lansing-Kansas City groups thin northward onto the shelf and over the uplift from 620 ft (189 m) down to 285 ft (87 m; fig. 32). The Central Kansas uplift represents a positive basement element, tectonically active in the Early Pennsylvanian. Late Pennsylvanian strata onlap and eventually covered the uplift as sea level rose and the region continued to subside toward the Anadarko basin. However, subsidence over the Central Kansas uplift appears to have been slower than the surrounding shelf area, perhaps related to basement heterogeneity (Watney, 1985b).

Regional assessment of depositional sequences in western Kansas was established through the description of some 40 cores and correlation of 2,500 wireline logs covering 72,000 m<sup>2</sup> (186,000 km<sup>2</sup>) of shelf (fig. 24). Three sequences are traced in a cross section of cores from north (landward) to south (basinward) across the shelf in western Kansas (fig. 33). Wells 2, 3, and 4 on the cross section are on the Central Kansas uplift. Even though tectonism associated with the uplift occurred 20 million years prior to deposition of these units, differential relief is indicated in the lithologic profiles. Subaerial hiatal surfaces separate individual depositional sequences; individual sequences show considerable thinning over the uplift. Other evidence of positive relief includes

- 1) loss of black shales over the crest of the Central Kansas uplift where a condensed section is probably still represented by phosphatic and skeletal-lag deposits found near the base of cored sections;
- 2) more abundant shallow-water carbonate facies in the sequence over the uplift and upper shelf;
- 3) evidence for intensified subaerial exposure in upper-shelf settings.

Northward, and presumably even higher on the shelf in a landward direction, well #5 (fig. 33) indicates solution-karst development and red-siltstone deposits containing abundant rhizoliths and caliche horizons. Also, mixed-clast carbonate-pebble conglomerates attest to significant weathering and local erosion of the carbonates on the upper shelf in southwestern Nebraska. The marine facies of the I-Zone (Cherryvale) regionally laps out across northern Kansas. This is not erosional or related to clastic influx, but represents maximum extent of marine inundation on the shelf.

Basinward, in southwestern Kansas, the clastic influx was minimal due to the deep Anadarko basin to the south and the long distance from the minor clastic influx to the north. Due to a lower shelf elevation, greater accommodation space was created and thus provided for thicker deposits recording greater preservation of sedimentary events. Due to the ramplike setting during the Dennis and underlying Swope sequences, thick and extensive oolite deposits accumulated

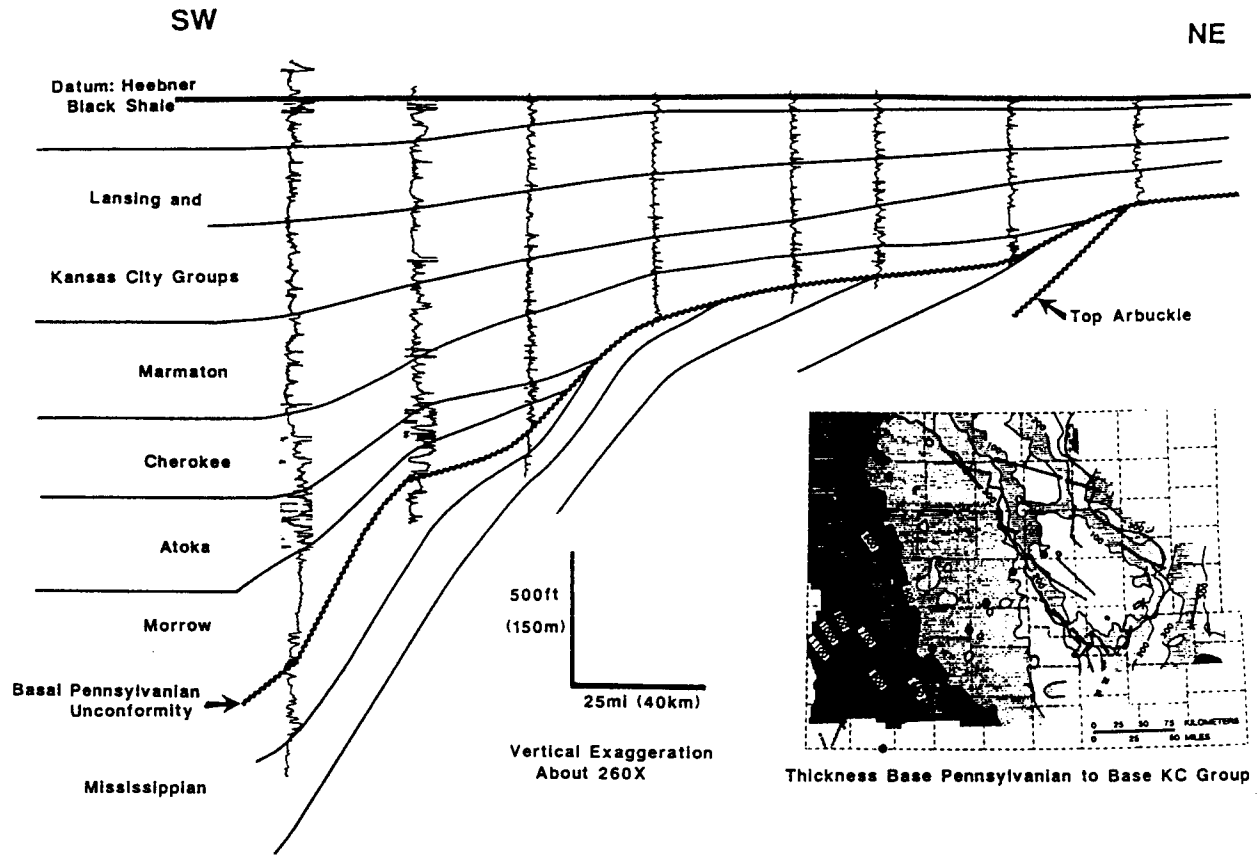
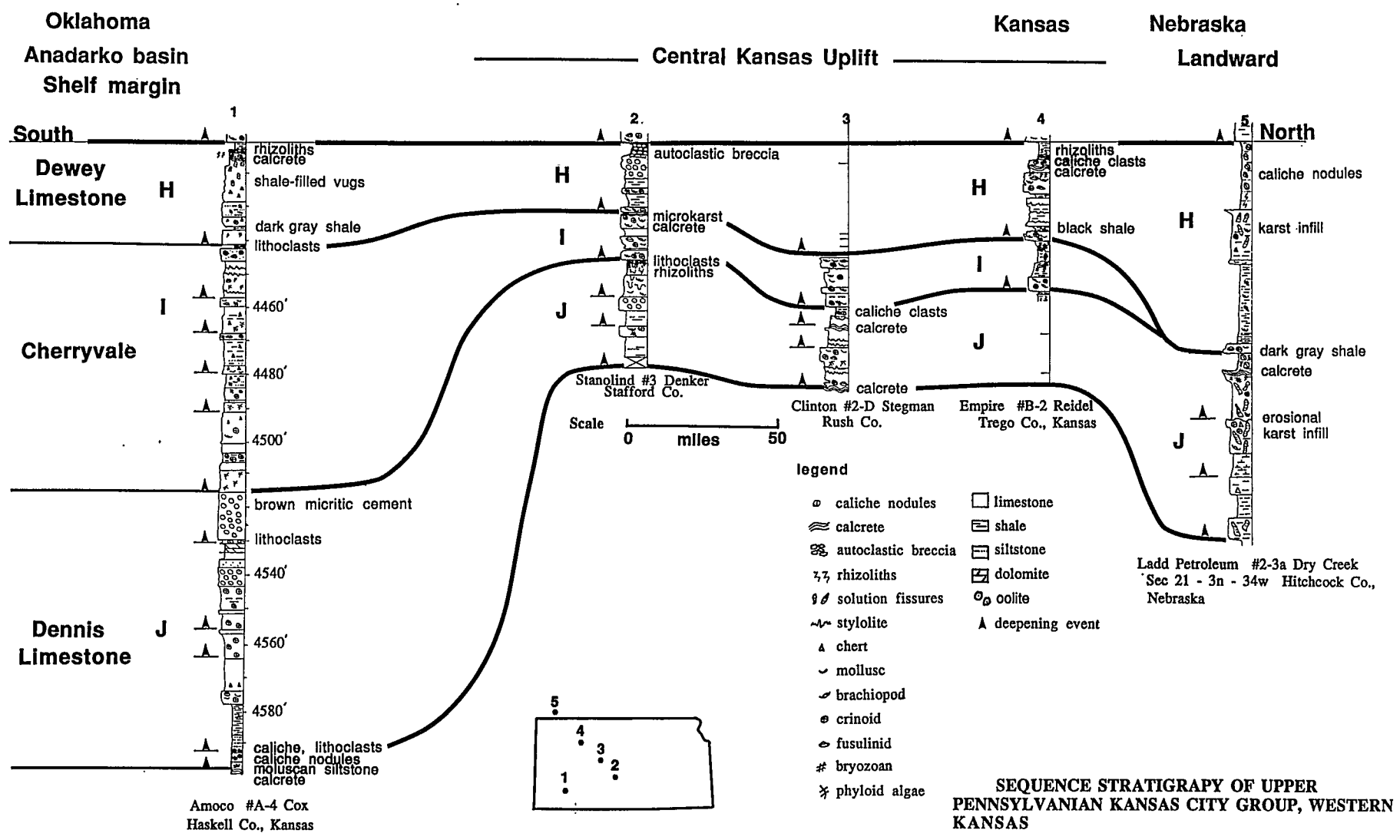


FIGURE 32—REGIONAL SOUTHWEST-TO-NORTHEAST STRATIGRAPHIC CROSS SECTION OF LOWER TO UPPER PENNSYLVANIAN STRATA IN WESTERN KANSAS. Datum is Heebner Shale. Section extends from near margin of Anadarko basin on south onto Central Kansas uplift on north. Inset map illustrates thickness of interval from base of Kansas City to base of Pennsylvanian.

FIGURE 33 (next page)—CROSS SECTION OF FIVE WELLS BASED ON CORE DESCRIPTIONS. Includes three carbonate-dominated depositional sequences: Dewey (H-zone), Cherryvalle (I-zone), and Dennis (J-zone) extending from southwestern Kansas to southwestern Nebraska. Wells 2, 3, and 4 are located on Central Kansas uplift.



over southwestern Kansas (covering approximately 16,000 mi<sup>2</sup> [41,000 km<sup>2</sup>; Watney, 1984). Minor events of deepening and shallowing during deposition of the Cherryvale sequence on the inferred ramp led to multiple, thinner grainstones. In contrast, the overlying Dewey sequence retained uniform thickness across the shelf, reflecting more constant conditions.

The Dennis and Dewey sequences shown in fig. 33 and the underlying Swope sequence all contain widespread black shales, each of which is locally lost over the Central Kansas uplift, and all of which grade to gray shale northward. All sequences are bounded by subaerial hiatal surfaces, and all transgressive units are relatively thin.

A gamma-ray spectrolog of the Amoco #A-4 Cox well from Haskell County in southern Kansas illustrates lithofacies succession and the characteristic log response of the depositional sequences in the western craton (fig. 34, Amoco Cox). This well is also well No. 1 in fig. 33. The graphic log on the right margin depicts the lithofacies succession. The sequence boundaries coincide with the subaerial-exposure surfaces, also coinciding here with a facies-dislocation surface associated with marine flooding of the succeeding depositional sequence. Notably, the sequences and most associated facies elements are correlative with the wireline-log response, thus facilitating subsurface 3-D mapping. The natural gamma-radiation log clearly denotes the marine condensed sections. These are organic-rich shales in the case of the Swope, Dennis, and Dewey sequences and a dark crinoidal wackestone in the Cherryvale sequence. Elevated uranium concentrations are the sources of the gamma-ray peaks in the condensed sections (fig. 34). In contrast, thorium appears to be elevated relative to uranium in certain paleosols reflecting the concentration of thorium under more strongly oxidizing conditions (Doveton, personal communication, 1989).

The lithofacies components have been mapped (Watney, 1984, 1985 a and b). The wireline logs, calibrated with cores, permit regional characterization of the sequences across the shelf. Isopach maps of the four depositional sequences are included in figs. 35-38. These maps are interpreted in figs. 39 and 40, revealing progressive structural modification of the shelf.

The shelf profiles in western Kansas during development of the five sequences from Swope to Iola are depicted in fig. 41. A ramp profile and oolite accumulation characterize Swope and Dennis sequences, while a platform and isolated phylloid-algal-mound development characterize the Dewey sequence. Differential subsidence was episodic, apparently spanning several sequences during the duration of each tectonic episode.

Fig. 42 illustrates relative levels of marine inundation on the western craton above and into the sediment-starved Anadarko basin. The section is constructed in time and resembles a Wheeler diagram. Major condensed sections are noted, such as the Hushpuckney, Stark, and Muncie Creek shales. A computer-simulated version of this diagram is included in the attached paper by Watney et al. Dominant

causal mechanisms for Pennsylvanian sequence development are eustatic fluctuations and subsidence related to development of the adjoining Anadarko basin.

Constraints on defining shelf elevation and the extent of inundation (illustrated in figs. 41 and 42) during accumulation of each sequence are provided in fig. 43a. Two diagrammatic cross sections from the western craton depict prominent geologic features influencing distribution and character of depositional sequences on the northern and southern edges of the Anadarko basin (fig. 43b and c). Reefal and algal mounds were episodically deposited during the Missourian over fault blocks along the Wichita Mountain front (Dutton, 1982), while carbonate-dominated deposits accumulated on the northern shelf of the Anadarko basin. Local submarine fans and allodapic carbonate-debris flows consisting of shallow-water detritus accumulated in the sediment-starved basin along the northern and northwestern flanks of the Anadarko basin.

As described above, both platform and ramp settings developed on the northern shelf. Fig. 44a, b, and c illustrates diagrammatic sequences formed in each of these environments. Fig. 45 illustrates a conceptual version of a portion of the Dennis sequence which accumulated on a ramp setting. A flooding unit and condensed section characterized by landward onlap and a shallowing-upward succession characterized by downlap and toplap are indicated. Sea level apparently fell to expose a majority of the shelf, resulting in the offlapping facies succession. Stops 6 and 7 present evidence for analogous development in the Dennis sequence in eastern Kansas.

Parasequence correlations have not been established but are extremely critical to interpretations suited to prediction of favorable reservoir rocks. Shelf elevation is also critical to refined interpretations and is the subject of further investigation.

## Sequence development in the Arkoma Basin and adjoining shelf in eastern Oklahoma

Bennison (1985) and his collaborators in biostratigraphy have assembled a remarkable view of the upper Desmoinesian and lower Missourian depositional sequences in the siliciclastic-dominated fluvial-deltaic sedimentary regime in the Arkoma basin (shown earlier as fig. 16). The Arkoma basin and adjoining northern shelf were progressively filled by these prograding clastic deposits. However, the progradational episodes were strongly modulated by now well-defined marine depositional sequences that are temporally equivalent to those in the western craton and on the northern carbonate shelf extending to Iowa. Condensed sections punctuate the siliciclastic and carbonate successions both in the basin and far onto the shelf and strongly suggest that a rapid eustatic rise interrupted deltaic progradation. The same condensed sections have now been correlated to the Midland basin of Texas, suggesting more than simple local

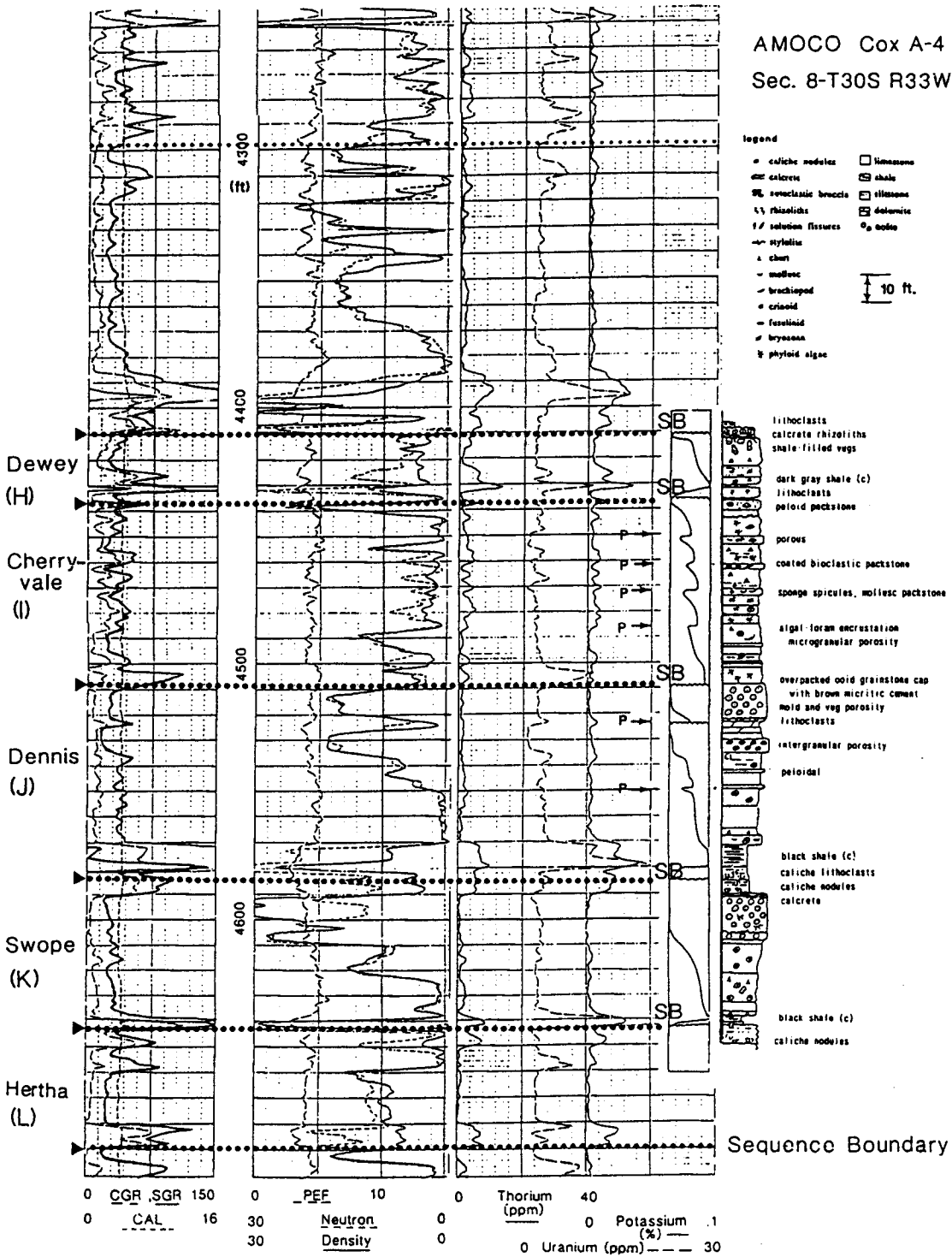


FIGURE 34—GAMMA-RAY, NEUTRON-DENSITY, AND URANIUM, THORIUM, AND POTASSIUM PROFILES (GAMMA-RAY SPECTROLOG) AND GRAPHIC CORE DESCRIPTION OF DENNIS, CHERRYVALE, AND DEWEY SEQUENCES FOR AMOCO COX A-4 WELL LOCATED IN HASSELL COUNTY, SOUTHWESTERN KANSAS. Well is labeled #1 on cross section and index map in fig. 33.

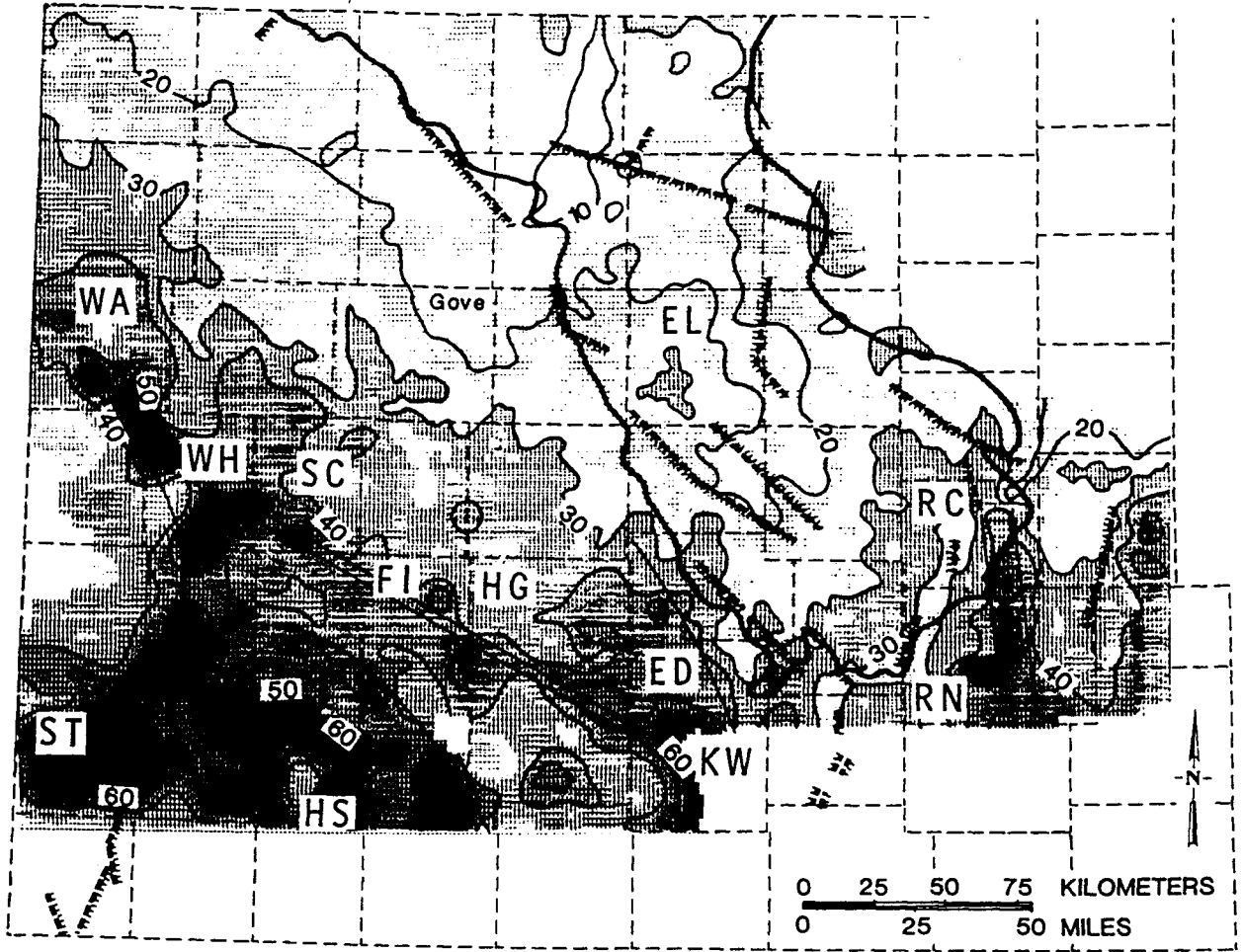


FIGURE 35—ISOPACH MAP SWOPE (K-ZONE) SEQUENCE. Key as in fig. 38.

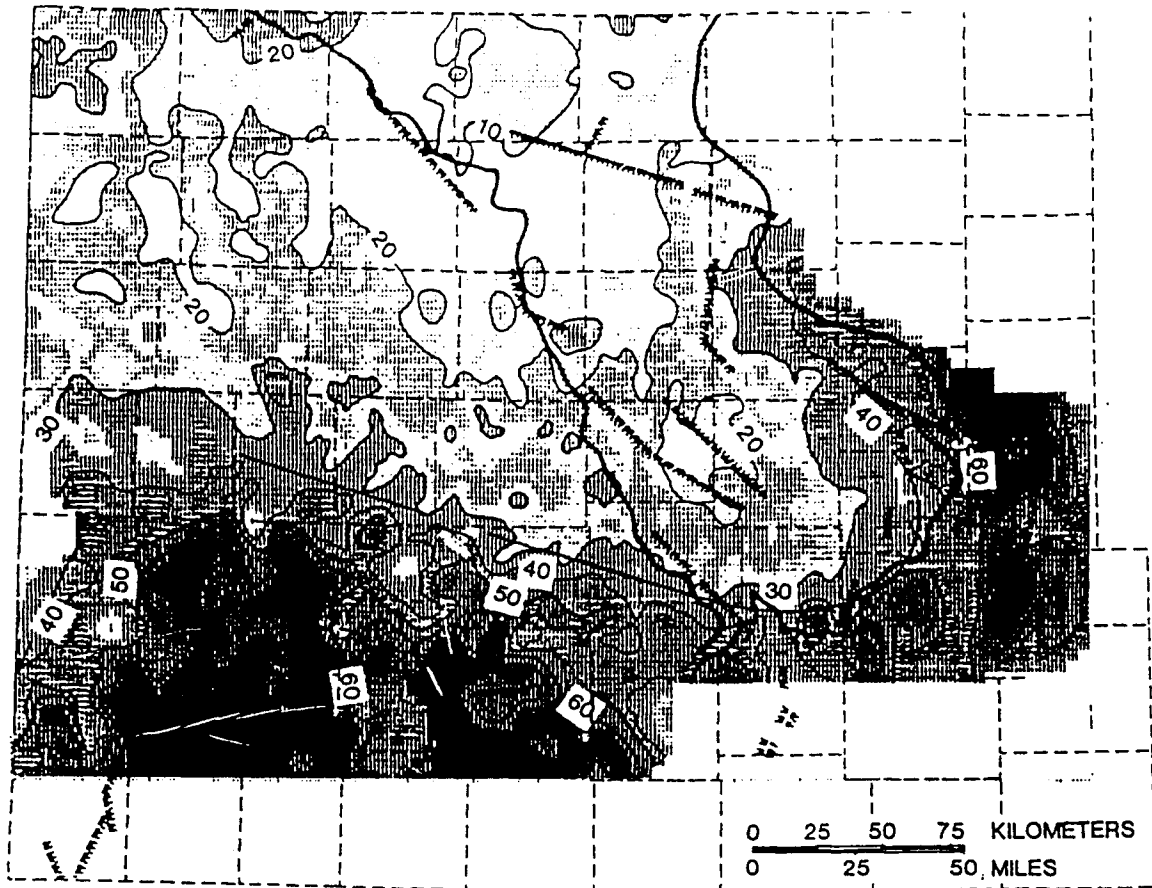


FIGURE 36—ISOPACH MAP OF DENNIS (J-ZONE) SEQUENCE. Key as in fig. 38.

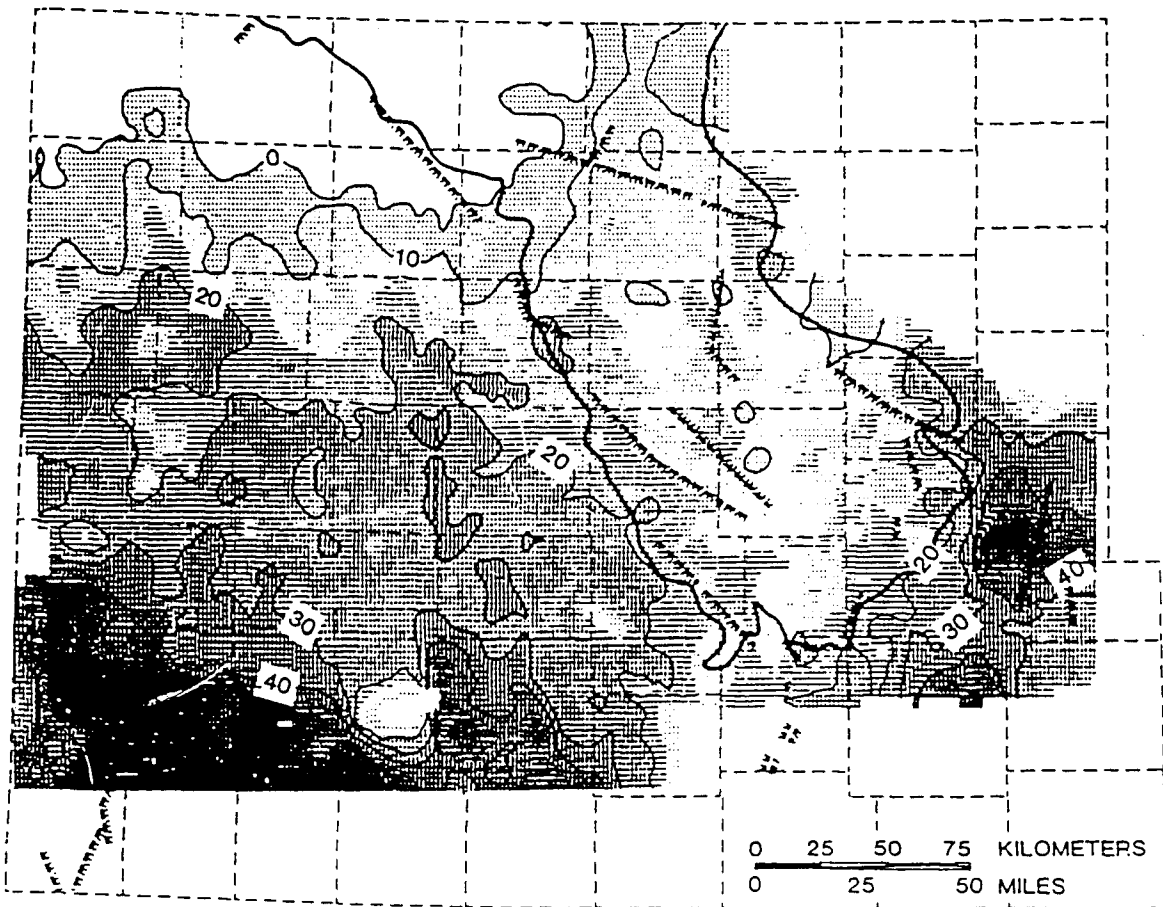


FIGURE 37—ISOPACH MAP OF CHERRYVALE (I-ZONE) SEQUENCE. Key as in fig. 35.

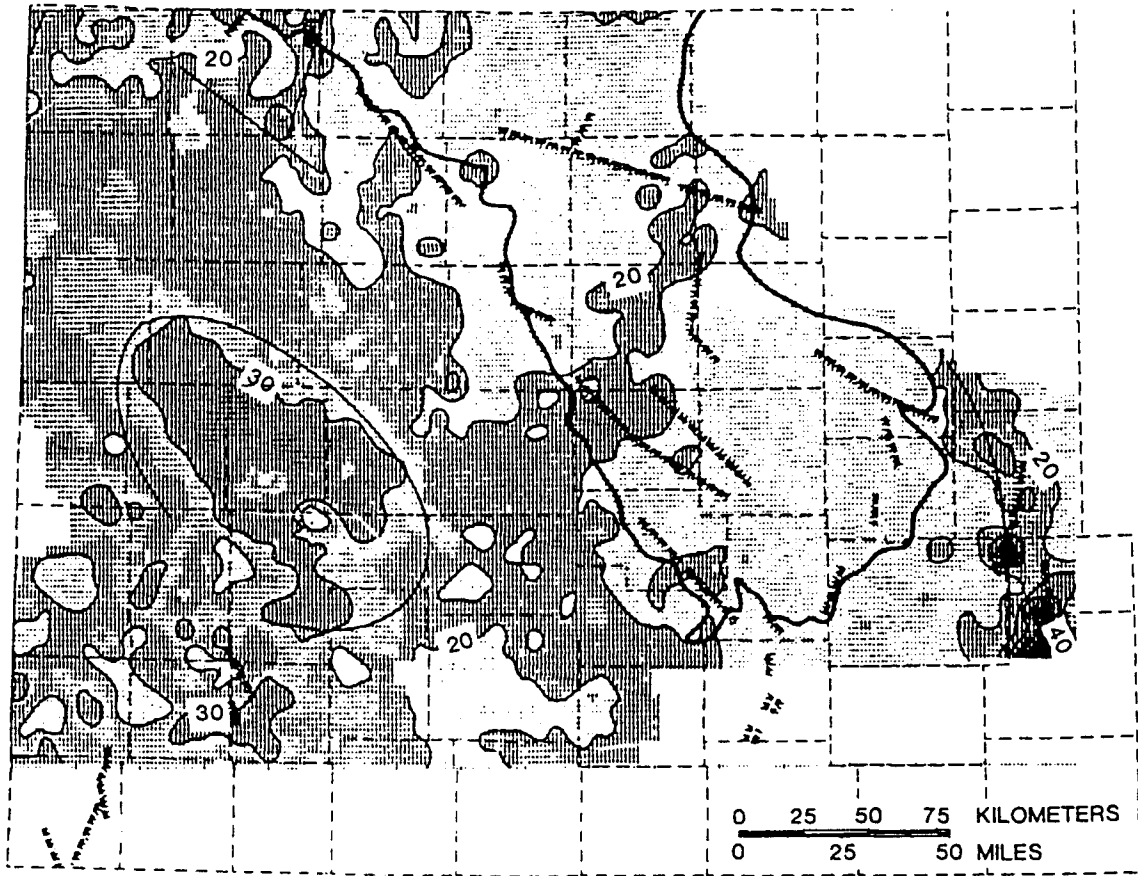


FIGURE 38—ISOPACH MAP OF DEWEY (H-ZONE) SEQUENCE ON WESTERN KANSAS SHELF. Mapped interval includes initial flooding surface to top of marine interval at base of thin paleosol. Contour interval in feet. Heavy line outlines Central Kansas uplift. Hatchured lines locate prominent basement faults.

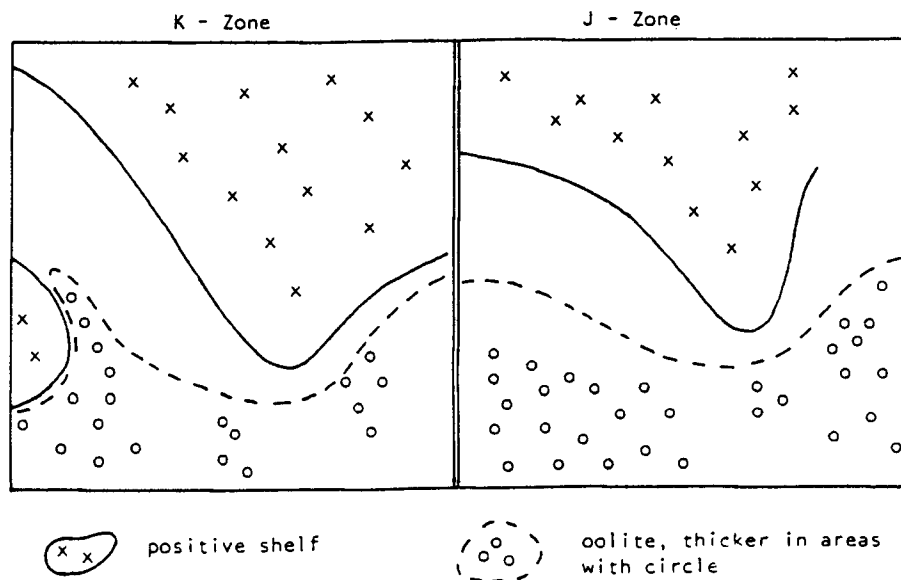


FIGURE 39—SHELF CONFIGURATION AND DOMINANT SHALLOW-WATER CARBONATE FACIES ASSOCIATED WITH K-ZONE (SWOPE) SEQUENCE AND J-ZONE (DENNIS) SEQUENCE. Interpretation based on isopach and facies analysis of sequence units from cores and wireline logs.



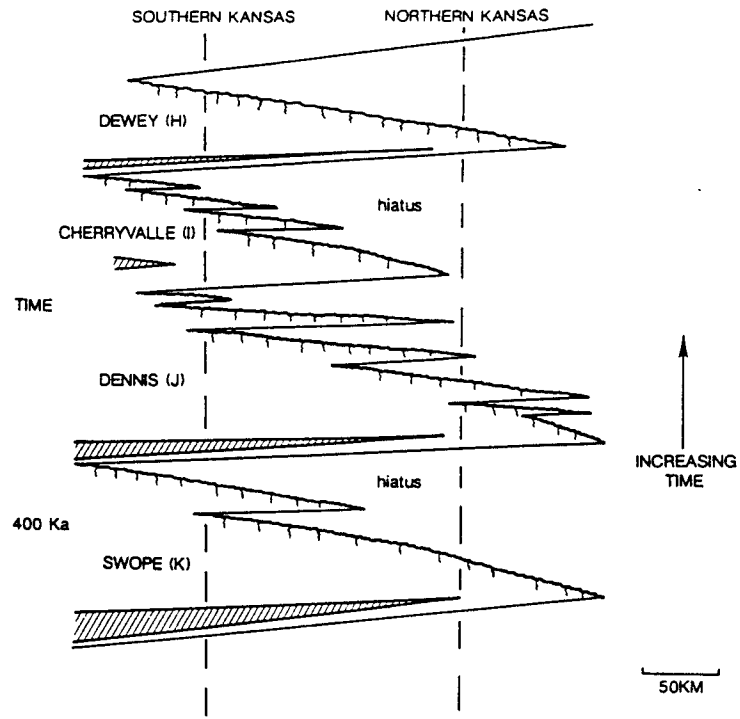
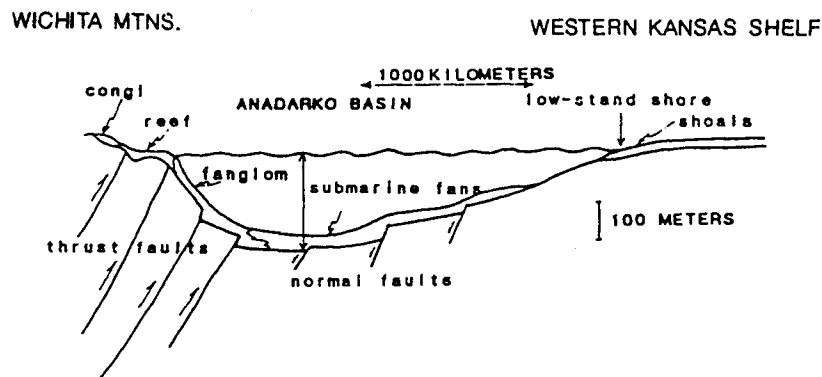


FIGURE 42—EXTENT OF LOWER MISSOURIAN MARINE INUNDATIONS ONTO SHELF IN WESTERN KANSAS AND WESTERN NEBRASKA.

a

Sequence	Develop.	Flooding	Condensed	Shallowing	Paleosol	Reservoir
(G) Iola	thick	thick	thick, black	thick grnst.	intense, conglom.	local
(H) Dowey	thin	medium	medium, mod. blk.	low energy upper shelf	mod. to intense	local
(I) Cherry-valle	thin to very tk.	thin	limited	complex	mod. to intense	northern near onlap
(J) Dunnis	Mod. to thick	thin	well dev., blk.	complex thick shoal	moderate	excellent intergran.
(K) Swope	Mod. to thick	medium	well dev., blk.	thick shoal	mod. to intense	good to excellent
(L) Hertha	thin to moderate	thin	thin	mod. to thin	intense	locally very good

b



c

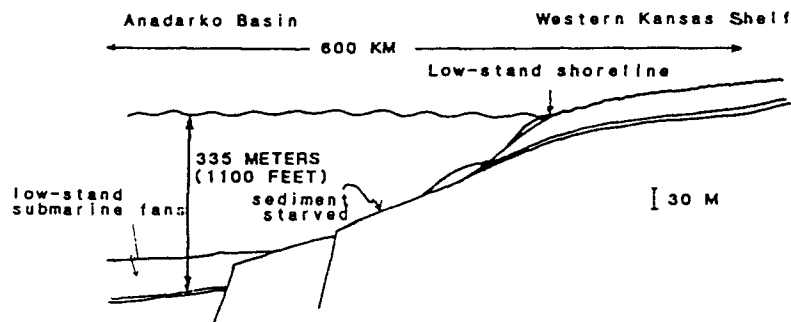


FIGURE 43—a) TABLE ON CONSTRAINTS TO DEFINING SHELF CONFIGURATION AND RELATIVE SEA-LEVEL INUNDATION in western Kansas during accumulation of lower Missourian sequences; b) DIAGRAMMATIC PROFILE OF WESTERN ANADARKO BASIN during accumulation of lower Missourian depositional sequences; c) CLOSER VIEW AT NORTHERN EDGE OF ANADARKO BASIN and adjoining shelf illustrating low-stand shoreline.

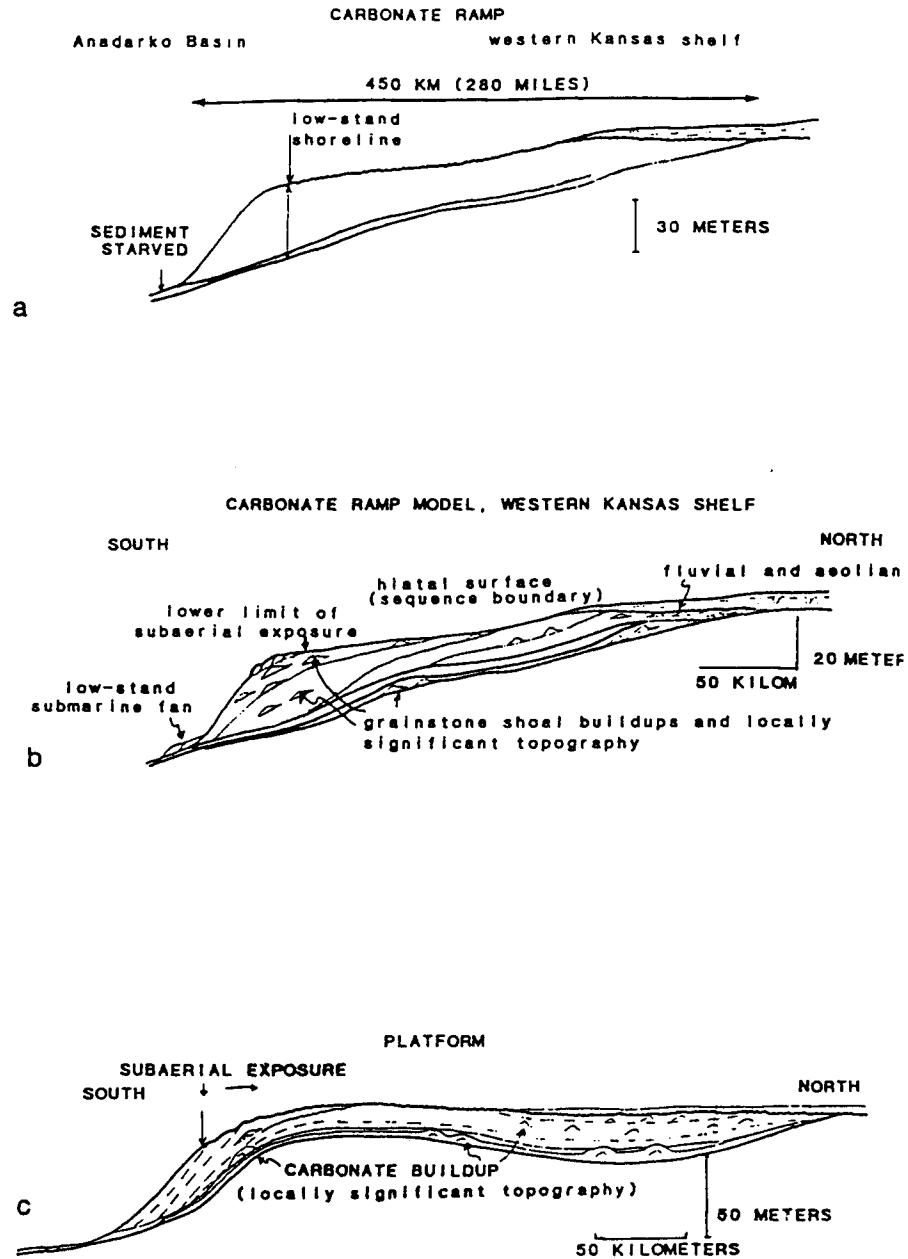


FIGURE 44—**a**) GEOMETRY OF A HYPOTHETICAL MISSOURIAN CARBONATE RAMP deposited on western Kansas shelf during active subsidence; **b**) POSSIBLE INTERNAL GEOMETRY OF A MISSOURIAN DEPOSITIONAL SEQUENCE deposited on ramp in western Kansas; **c**) DEPOSITIONAL SEQUENCE WHICH ACCUMULATED IN A PLATFORM SETTING during quiescence of subsidence.

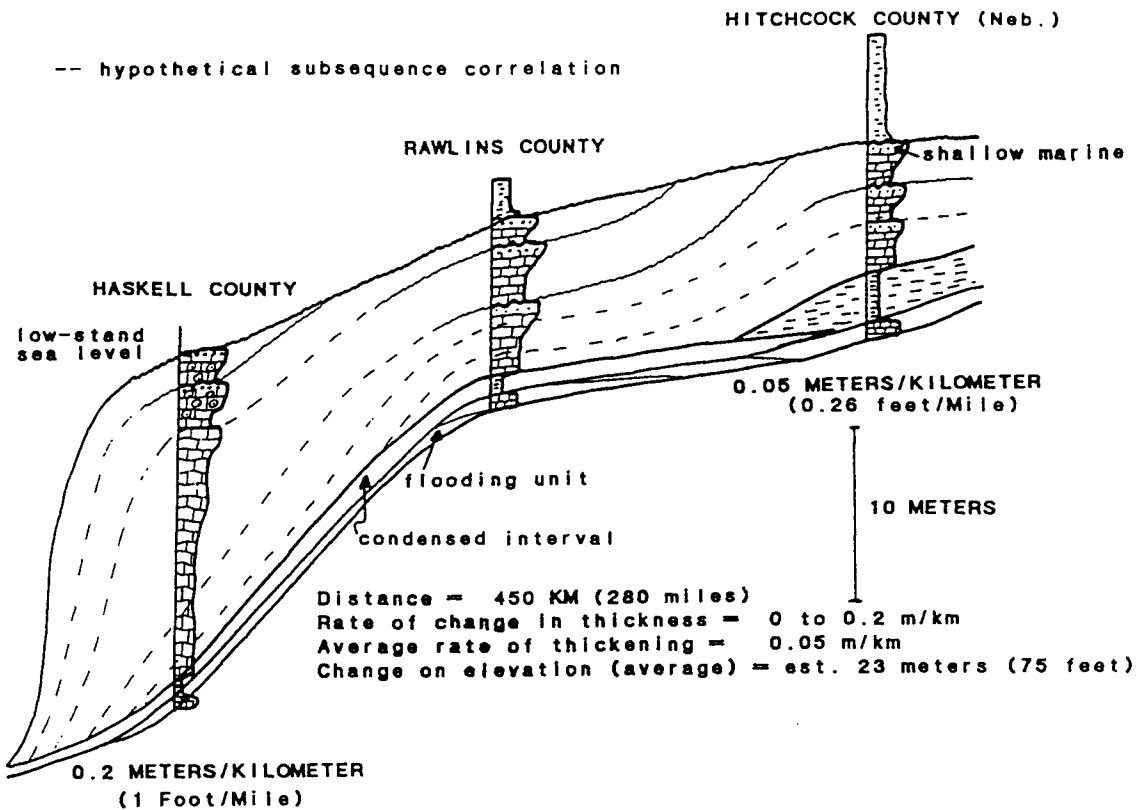


FIGURE 45—CONCEPTUAL VIEW OF GEOMETRY AND INTERNAL STRATIGRAPHY OF DENNIS SEQUENCE (J-ZONE) IN WESTERN KANSAS.

rise and fall in relative sea level (Boardman and Heckel, 1989).

Although earlier Desmoinesian clastic wedges did not advance significantly across the Arkoma basin, the Missourian sequences show increasing northerly advancement of the clastic wedges. By upper Missourian and Virgilian time, these clastic deposits spilled onto the shelf reaching as far as south-central Kansas (Reno County) where they reached the edge of the Central Kansas uplift. The early Missourian Pleasanton, Hertha, and lower Swope sequences are represented by sediment-starved conditions in northern Oklahoma and southern Kansas. Sediment-starved sequences dominated by condensed sections form these basinal deposits. These will be seen in cores from the northern edge of the basin and in Stop 12.

Basin subsidence was still a significant factor in the development and geometry of the sequences. Part of the broadening of the clastic wedge is attributed to progressive widening of the foreland basin increasing the extent for sediment accommodation (Beaumont, 1981). Beaumont's forward model of foreland-basin deformation fits well with the observed overall pattern of broadening, but shallowing,

regional subsidence. However, the observed sequences reflect a modulation that occurred at a higher frequency and amplitude over much broader areas in varying tectonic settings. Interbasinal correlation of these sequences in varying depositional settings further supports a eustatic origin of these sequences. Tectonism plays a secondary role in the development of the sequence.

Depositional topography is strongly suggested from the rock record preserved along the margin of a clastic wedge deposited in the Arkoma basin. Clinoformal (downlapping) sandstone and shale deposits developed along the basinward side of maximum thickening (Bennison, 1985). The clinoform strata contain sedimentary structures indicative of heavy tractive sand load and debris transport. Topographic relief is also suggested by increasing evidence of fluvial deposition and red-bed accumulation along the more southern, proximal topset beds of several of the depositional sequences in the Tulsa, Oklahoma, area and south (Bennison, 1985). This also suggests that fall in sea level was sufficient on the upper slopes to permit accumulation of ferric oxides as had occurred along the upper reaches of the northwestern craton shelf in northwest Kansas and southwestern Nebraska (Watney, 1980; DuBois, 1985).

## Sequence development on the eastern Kansas shelf and shelf margin

The field trip will examine the northern-shelf and upper basin-margin extensions of the Arkoma basin. Fig. 3 depicts the Pleasanton, Hertha, Swope, and Dennis sequences along a section extending from near Kansas City, Missouri, to near Coffeyville, Kansas. As indicated in Bennison's cross section in the Arkoma basin (fig. 16), the Pleasanton, Hertha, and lower Swope sequences reflect sediment starvation in the northern Arkoma basin. The condensed sections (connected by continuous lines), including the Mound City and Hushpuckney shales, converge in a basinward direction. Subaerial hiatal surfaces are developed on the northern shelf at the tops of the sequences. However, practical sequence definition is facilitated in the subsurface through identification and correlation of the condensed sections through lithostratigraphy, biostratigraphy, and natural gamma-radiation profiles. The isolation of parasequences and detailed mapping of stratal architecture of the depositional sequences is in progress by a number of workers.

The upper, northern shelf shown on the top half of the cross section (fig. 3) contains a 150+ ft (46+ m) thick deltaic shale and sandstone succession in the Pleasanton sequence. The Pleasanton thickens to more than 200 ft (61 m) in eastern Kansas. However, the southern margin of the deltaic unit thins abruptly southward in Neosho and Bourbon counties, resulting in local depositional topography. This slope is much more abrupt than the structural ramp that was maintained during several sequences in western Kansas (~20 ft/mi, 3.8 m/km along the Pleasanton delta front vs. 1 ft/mi, 0.2 m/km along the ramp in western Kansas). The resulting effects on subsequent sequence development are substantial.

A series of isopach maps of the depositional sequences are presented in the order of deposition (figs. 5–12; Pleasanton, Hertha, Swope, and Dennis). The map and cross section depict a continued, more basinward progradation of each succeeding sequence through this interval. The Hertha sequence is composed of up to 100 ft (30 m) of thick carbonate bank dominated by a phylloid-algal-mound facies. The bank is developed in the Sniabar Limestone above the condensed section of the Mound City Shale. The Critzer Limestone is part of a lower sequence included here in the top of the Pleasanton. The accretion of this carbonate bank extended the shelf over 19 mi (30 km) basinward during Hertha time. This amounts to an effective progradation rate of 0.16 to 0.08 km/ka (0.1–0.05 mi/ka), depending on whether sequence duration is taken to be 200 ka minimally or 400 ka maximally (Heckel, 1986). The nature of the amalgamation of this bank in the context of shelf development is the subject of a dissertation by John French.

Basinward, the carbonate-bank facies grades into a basinal-carbonate facies consisting of dark organic-rich, argillaceous, crinoidal, brachiopod, spirorbid, encrusting foraminiferal wackestone. Maximum carbonate accumulation occurred at the seaward margin of the slope break where increased accommodation occurred, probably favoring optimum nutrient supplies due to current action.

The Swope sequence is complicated, due to at least two episodes of marine inundation (resulting in parasequences), as well as both carbonate- and siliciclastic-sediment accumulation. The lower carbonate is the Bethany Falls, in most places a shallow-water shelf carbonate. It comprises the upper limestone of the Swope Sequence on the northern shelf, e.g., at Stops 7, 8, and 9.

Isopachs of the Bethany Falls Limestone, Ladore Shale, Mound Valley Limestone, and Galesburg Shale are shown in figs. 8–11. These form a successive stack of lithofacies comprising the Swope sequence in the basin. Shelfward all that is present, or at least recognized, is the Bethany Falls Limestone and the Galesburg Shale. The Galesburg Shale on the lower shelf is in part a paleosol that contains limestone lithoclasts; it also contains a thin upper marine shale reflecting the onset of flooding associated with the succeeding Dennis sequence. Along the lower shelf margin and basin, the Galesburg Shale and Ladore Shale are primarily marine sandstones and shales. They apparently filled the basin during sea-level lowstand basinward of the Hertha carbonate bank. The Mound Valley Limestone is thought to represent a parasequence in the Upper Swope sequence, with the associated marine inundation terminating Ladore Shale deposition. Prior to the influx of siliciclastics, Mound Valley Limestone phylloid-algal-mound complexes were deposited along the lower slopes in the northern Arkoma basin margin. Bennison (1985) also notes a marine punctuation in the siliciclastic wedge in Oklahoma, which includes the "Layton Stray Limestone" as proposed by Bennison. While the Mound Valley Limestone represents a pause in siliciclastic influx during the Swope sequence, Galesburg Shale accumulation represents the resurgence of the deltaic systems during low stand and the influx of coarse, more proximal siliciclastics into basins in southern Kansas. The actual sources of these sandstones and shales in Kansas have not been fully established. However, they are low-stand deposits, probably reflecting some bypassing on the northern shelves. Plant debris is a very common component in these deposits, particularly in the lower portion of the Ladore Shale. Large woody-plant fragments may reflect the accelerated erosion on the uplands during the low-stand conditions. Sandstones that developed in the Galesburg and Ladore shales are locally known as the "Layton Sandstones" in the subsurface and have been very good oil and gas producers.

The Canville Limestone (flooding unit) and the Stark Shale (condensed section) overlie the Swope sequence. The stratigraphic thickness of the Stark Shale compared to the Nuyaka Creek Shale (condensed section at the base of the Pleasanton sequence) interval is noticeably similar across the shelf and shelf margin into southern Kansas (fig. 3). This occurred in spite of rapid thinning of the Pleasanton sequence and the subsequent outbuilding of the shelf created by the Hertha and Swope sequences. The uniform thickness of this succession suggests that the tectonic setting of this portion of the shelf was stable while progradation occurred. Sea-level change and its interaction with local topography can be studied and compared with areas of more sustained tectonic subsidence in western Kansas. The Dennis sequence was

deposited as a carbonate bank northward from those of the underlying units (fig. 3). This backstepping appears to reflect generation of significant accommodation space on the shelf along a linear hinge line that parallels the axis of the Arkoma basin. Backstepping or at least aggradation is also suggested for the Dennis sequence in the siliciclastic wedge in Oklahoma (fig. 16).

A total interval isopach from the Nuyaka Creek to the top of the Winterset primarily reflects long-term (>1 ma)

accommodation due to subsidence and sedimentary infilling (fig. 13). However, as sequence-stratigraphic mapping indicates, this sediment-filling process during short-term (<1 ma) steps is modulated by eustatic change. Figs. 46–52 are a series of conceptual diagrams depicting the paleogeography of the shelf-to-basin transition in southern Kansas during the early Missourian. The isopach maps, cross section, and working conceptual diagrams will be used throughout the course of the field trip.

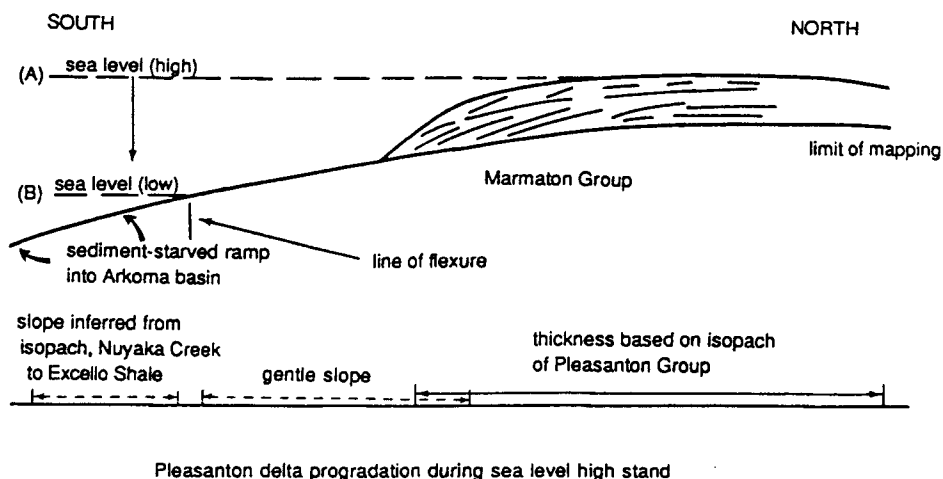
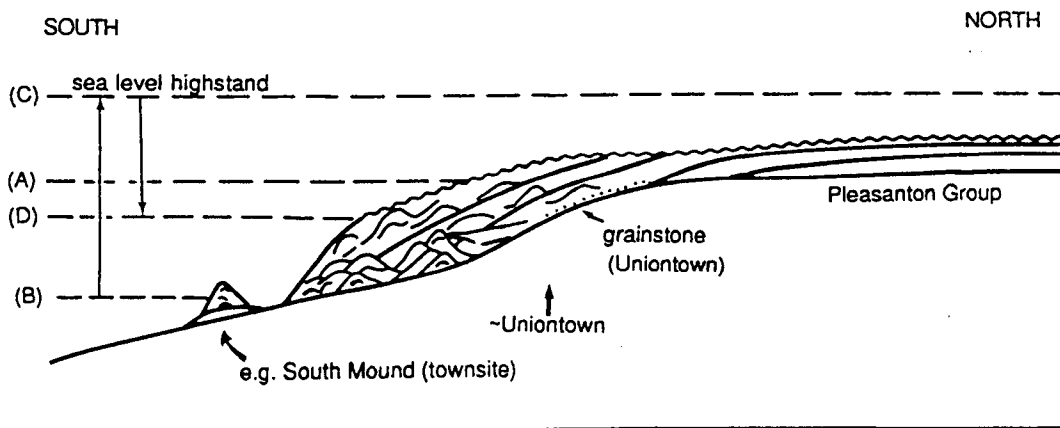


FIGURE 46—PRELIMINARY DEPOSITIONAL MODEL OF PLEASANTON SEQUENCE ALONG NORTH-SOUTH TRAVERSE IN EASTERN KANSAS FROM KANSAS CITY ON THE NORTH TO COFFEYVILLE, KANSAS ON THE SOUTH, A DISTANCE OF 150 MI (240 KM). SEDIMENT-STARVED BASIN TO SOUTH. 150+ FT (45+ M) OF DEPOSITIONAL TOPOGRAPHY ON SOUTHERN SLOPE IN ADDITION TO REGIONAL SOUTHERLY SLOPE INTO BASIN STRONGLY INFLUENCES GEOMETRIES OF SUPERJACENT DEPOSITIONAL SEQUENCES.

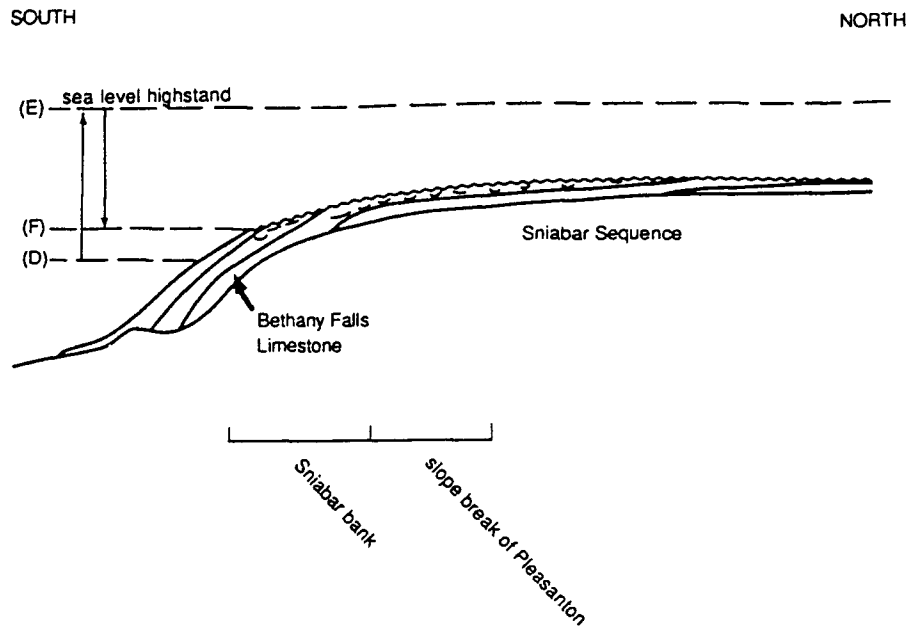


Sea level rise from B to C allows carbonate growth on shelf

Sea level fall from C to D associated with carbonate progradation basinward and subaerial exposure on shelf

Carbonate growth in basinward location during lowstand in sea level (incipient to continued progradation of shelf)

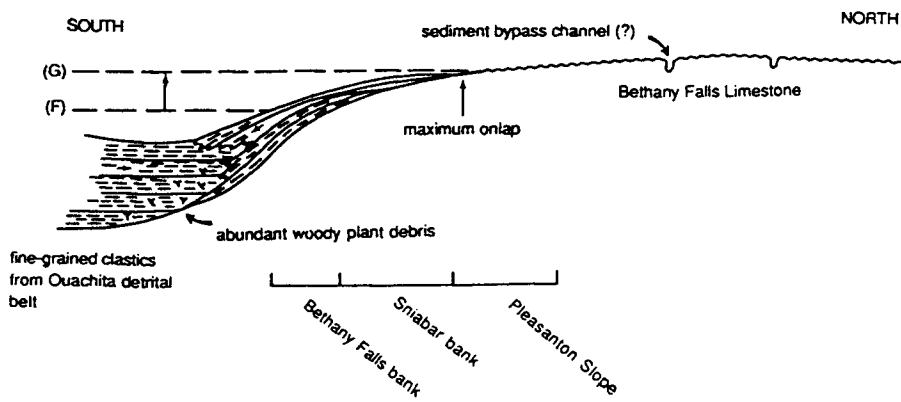
FIGURE 47—PRELIMINARY DEPOSITIONAL MODEL OF CARBONATE-DOMINATED HERTHA SEQUENCE IN EASTERN KANSAS BETWEEN KANSAS CITY AND COFFEYVILLE, KANSAS. ACCRETIONARY WEDGE, 100 FT (30 M) THICK, CONSISTING OF A COMPLEX OF PHYLLOID-ALGAL BUILDUPS DEVELOPED ALONG EDGE OF PLEASANTON DELTAIC PLATFORM. SHELF MARGIN EXTENDED 17 MI (30 KM) BASINWARD DURING HERTHA SEQUENCE. SEDIMENT-STARVED TO SOUTH WITH LOCAL ISOLATED BUILDUPS DURING LOW STAND. UNIFORM CYCLOTHEMIC ACCUMULATION ACROSS NORTHERN SHELF.



Sea level rise from D to E - carbonate deposition on shelf

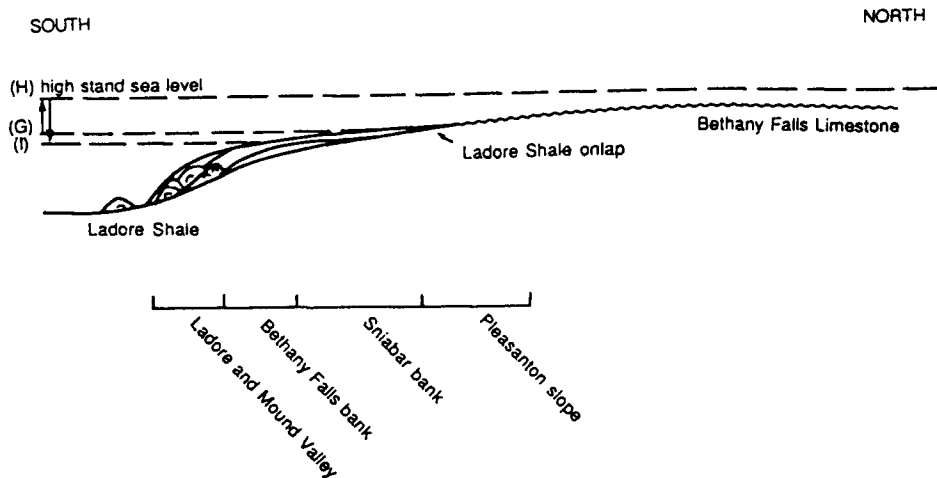
Sea level fall from E to F - Carbonate margin progrades basinward beyond previous Sniabar shelf margin. Sequence culminates in subaerial exposure on shelf.

FIGURE 48—PRELIMINARY DEPOSITIONAL MODEL OF CARBONATE-DOMINATED BETHANY FALLS LIMESTONE OF SWOPE SEQUENCE ALONG TRAVERSE BETWEEN KANSAS CITY AND COFFEYVILLE. Additional southerly extension of shelf margin toward sediment-starved conditions to south.



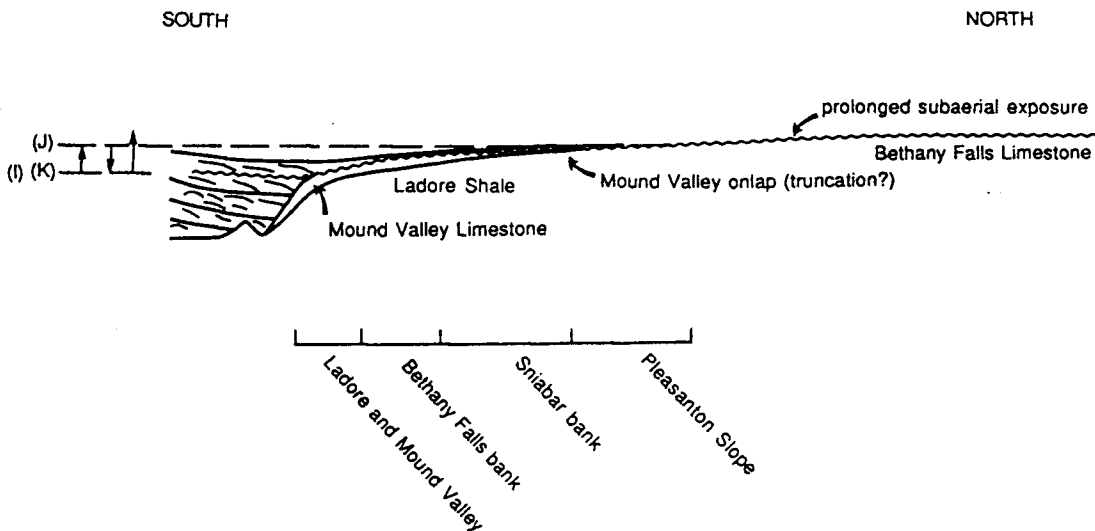
Sea level rise from F to G - Continued bypass of sediment basinward. The Ladore laps out shelfward, with clastics primarily derived from the Ouachitas although northerly source has not entirely been discounted as illustration indicates.

FIGURE 49—PRELIMINARY DEPOSITIONAL MODEL OF LADORE SHALE (lower Layton sandstone interval) deposited during lowstand in mid-portion of Swope sequence.



Continued sea level rise from G to H - local carbonate deposition (Mound Valley) takes over on shelf margin (replacing Ladore Shale deposition). Sea level drop from H to I - progradation of carbonate basinward-- local carbonate growth in basinward location; local subaerial exposure on most shelfward locations.

FIGURE 50—PRELIMINARY DEPOSITIONAL MODEL OF MOUND VALLEY LIMESTONE ALONG TRAVERSE FROM KANSAS CITY TO COFFEYVILLE. Accumulation of carbonate occurs in basin as response to minor marine flooding in the upper Swope sequence. Additional southwesterly extension along southern shelf.

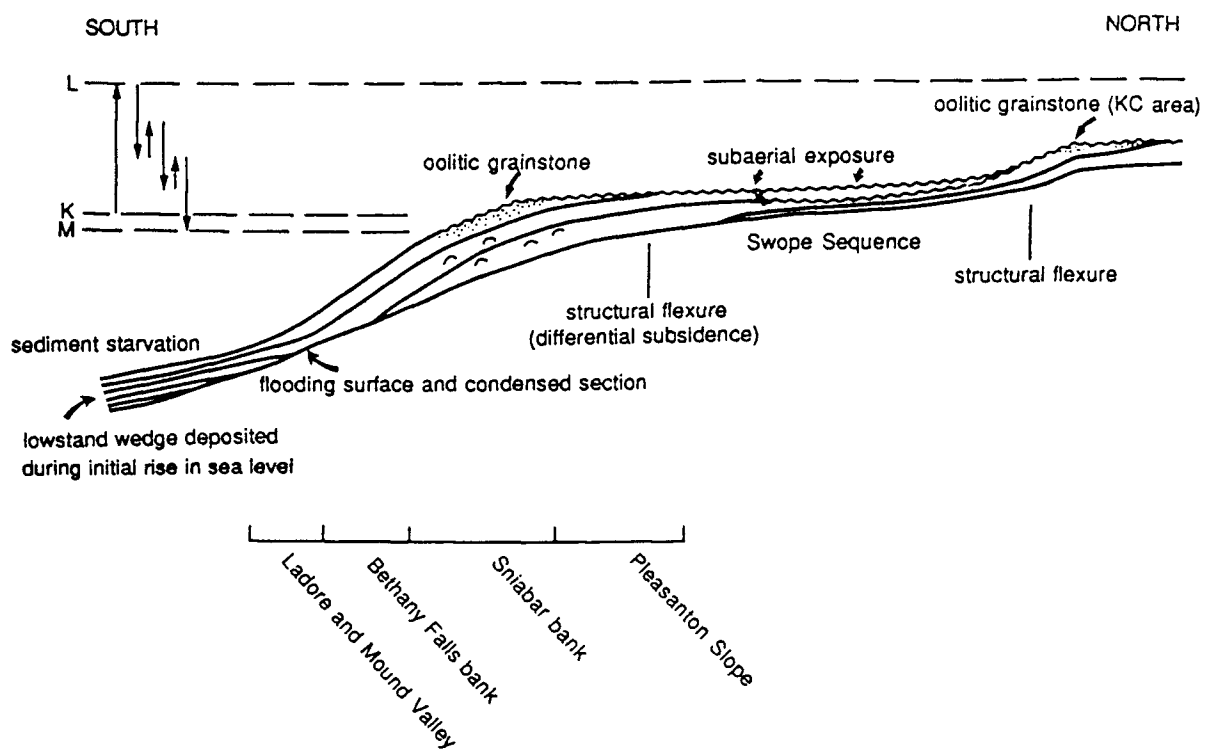


Sea level rise from I to J - progradation of coarser clastics from Ouachitas; basin filling prior to renewed subsidence

Sea level fall from J to K - paleosol and coal development, local erosion, surface merges with top Mound Valley exposure surface landward which merges landward with Bethany Falls exposure surface

Sea level rise from K - renewed influx of coarse clastics from Ouachitas during gradual rise in sea level as part of lowstand portion of Dennis Sequence (?)

FIGURE 51—PRELIMINARY DEPOSITIONAL MODEL OF GALESBURG SHALE (upper Layton sandstone interval) deposited during low stand at the close of the Swope sequence and the initial flooding associated with the Dennis sequence.



Sea level rise K to L - major marine inundation with major shelfward shift in carbonate deposition; renewed subsidence results in northward backstepping of shelf margin. Sea level fall from L to M with minor oscillations results in basinward progradation of carbonates.

FIGURE 52—PRELIMINARY DEPOSITIONAL MODEL OF THE DENNIS SEQUENCE associated with renewed subsidence.



# Appendix A

## Sequence-stratigraphy terminology

Summarized here is terminology utilized in sequence-stratigraphic interpretations as presented by Haq et al. (1987; fig. 28) and for a carbonate shelf by Vail (1987; fig. A-1). 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, retrograda-

tional, or aggradational depending on the ratio of depositional rates to accommodation rates.

*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. 28). 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. 28). 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. 28 and A-1). This appears to be most difficult to identify on a seismic section but is easy to identify in the rocks.

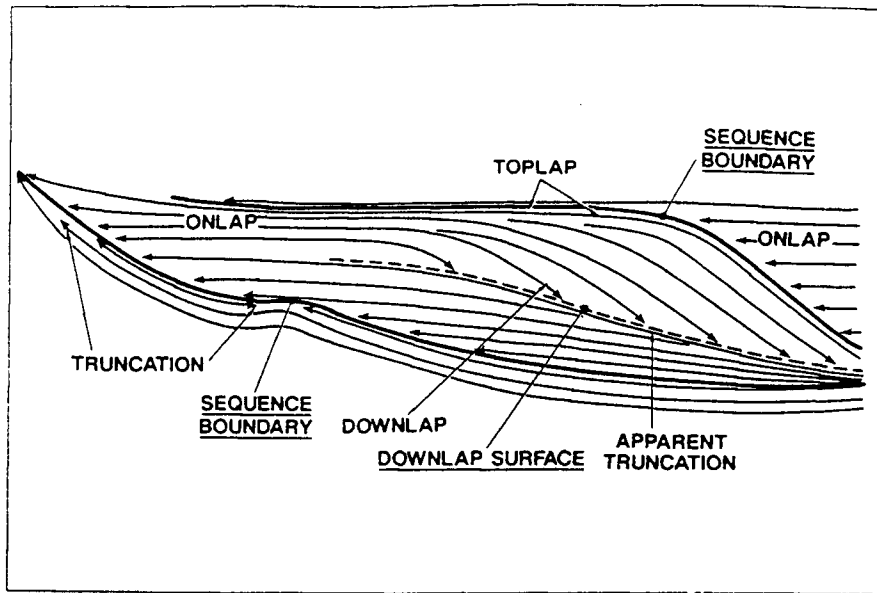


FIGURE A-1—TYPES OF DISCONTINUITIES IN A DEPOSITIONAL SEQUENCE (from Vail, 1987).

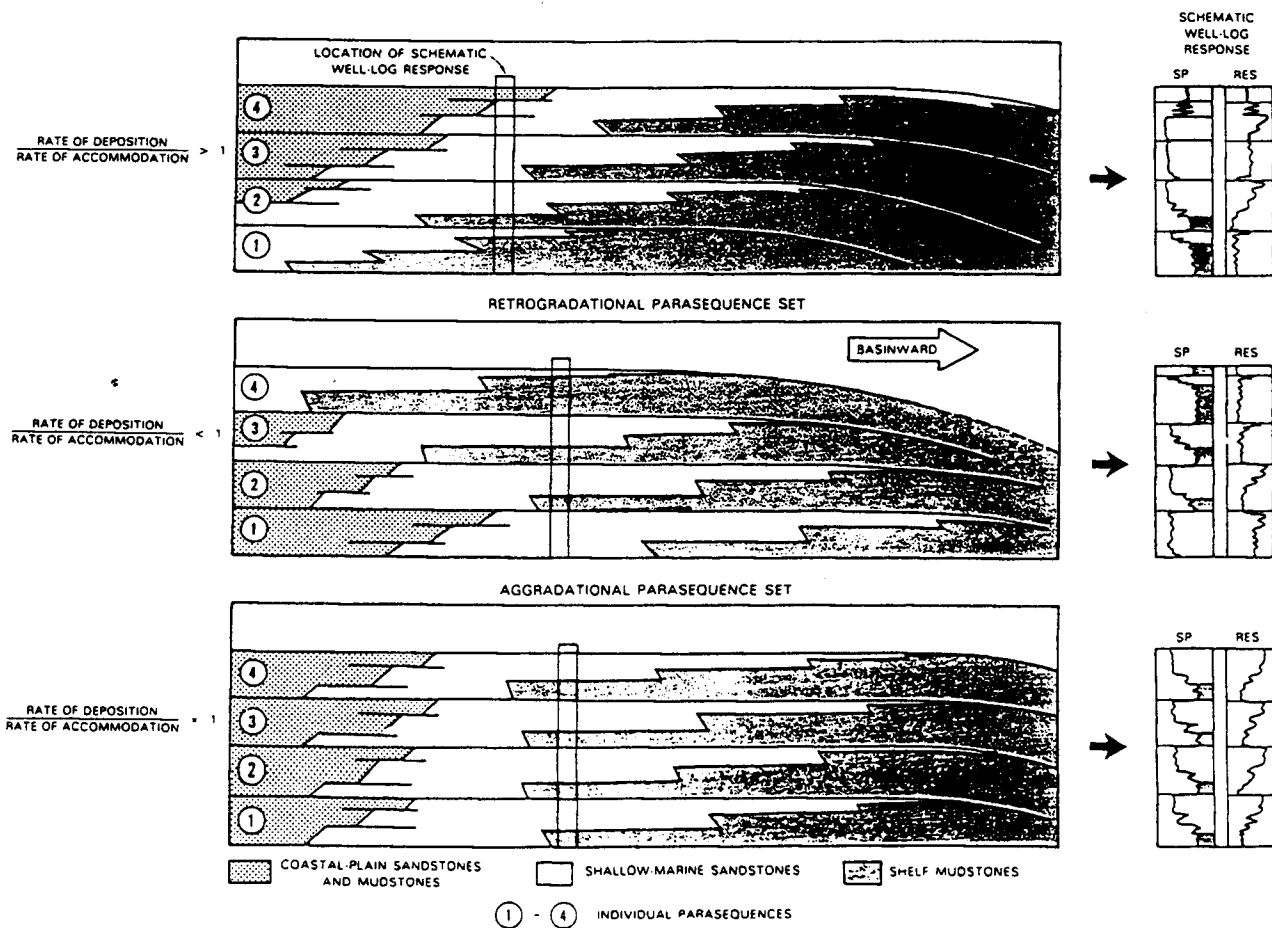


FIGURE A-2—EXAMPLES OF PROGRADATIONAL, RETROGRADATIONAL, AND AGGRADATIONAL PARASEQUENCE SETS for shelf with schematic well-log response (from Van Wagoner et al., 1987).

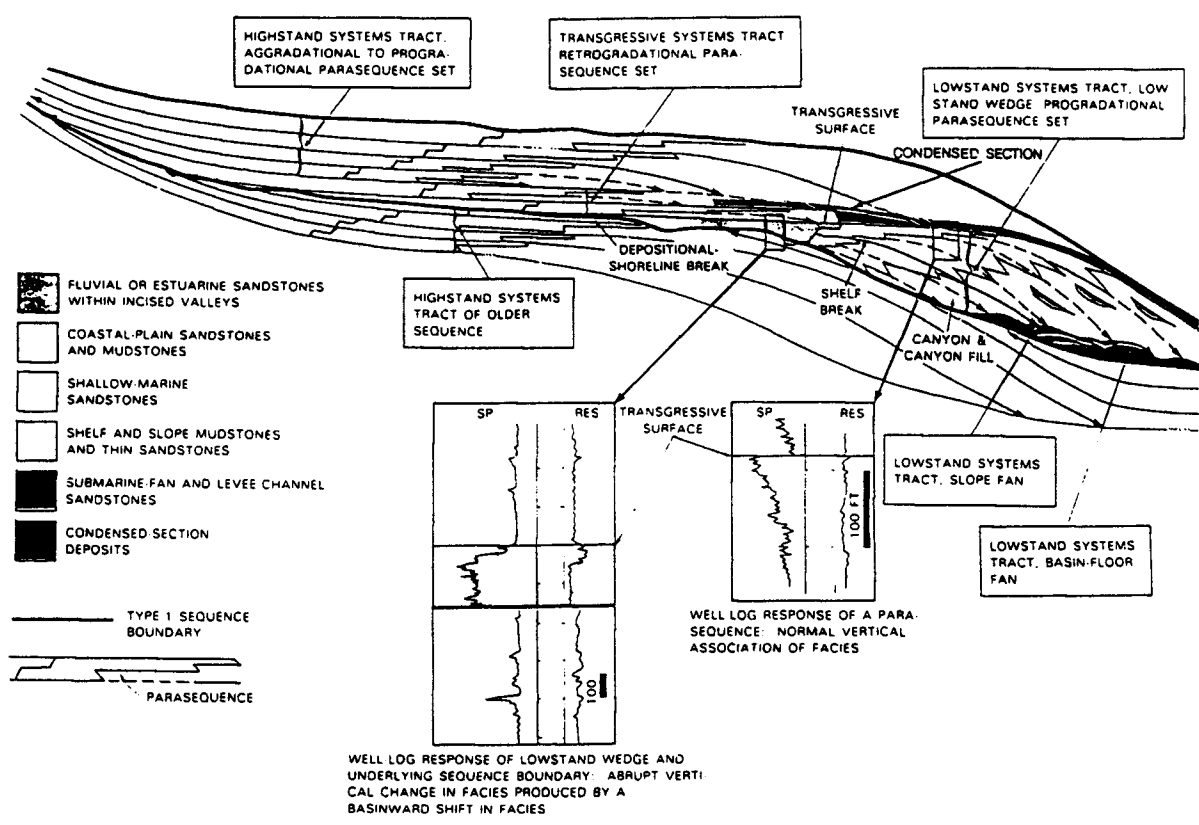


FIGURE A-3—EXAMPLE OF PARASEQUENCE GEOMETRIES in context of crossing a type 1 sequence boundary (from Van Wagoner et al., 1987).

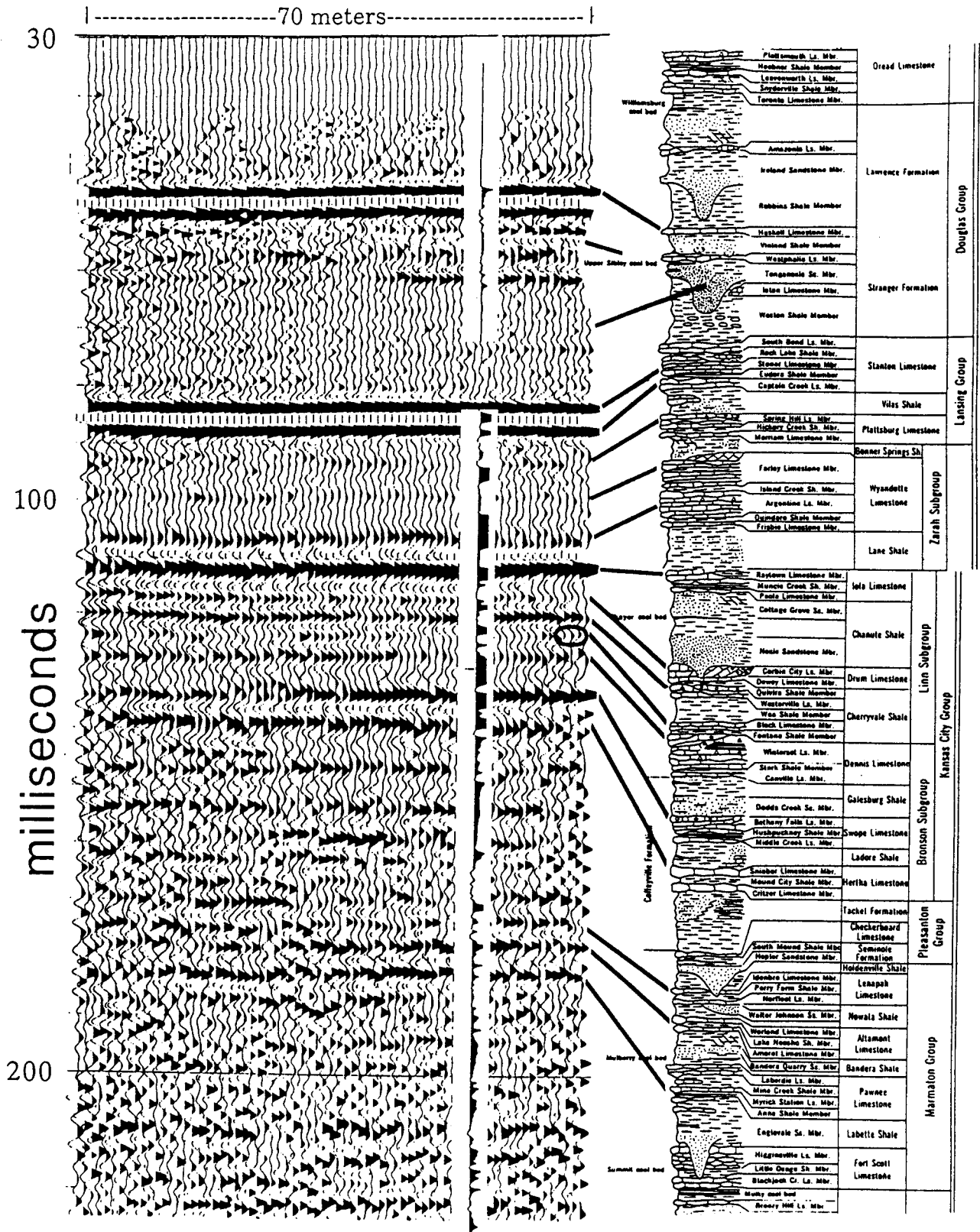


FIGURE A-4—SEVENTY-METER (231-FT)-LONG REFLECTION SEISMIC PROFILE USING 50-CALIBER GUN AS SOURCE. Frequency content in profile is between 300 and 500 hertz with resolution down to 1 m (3.3 ft; Knapp and Watney, 1987). Stratigraphic column shown on right side. Synthetic seismic trace illustrated in column with seismic profile.

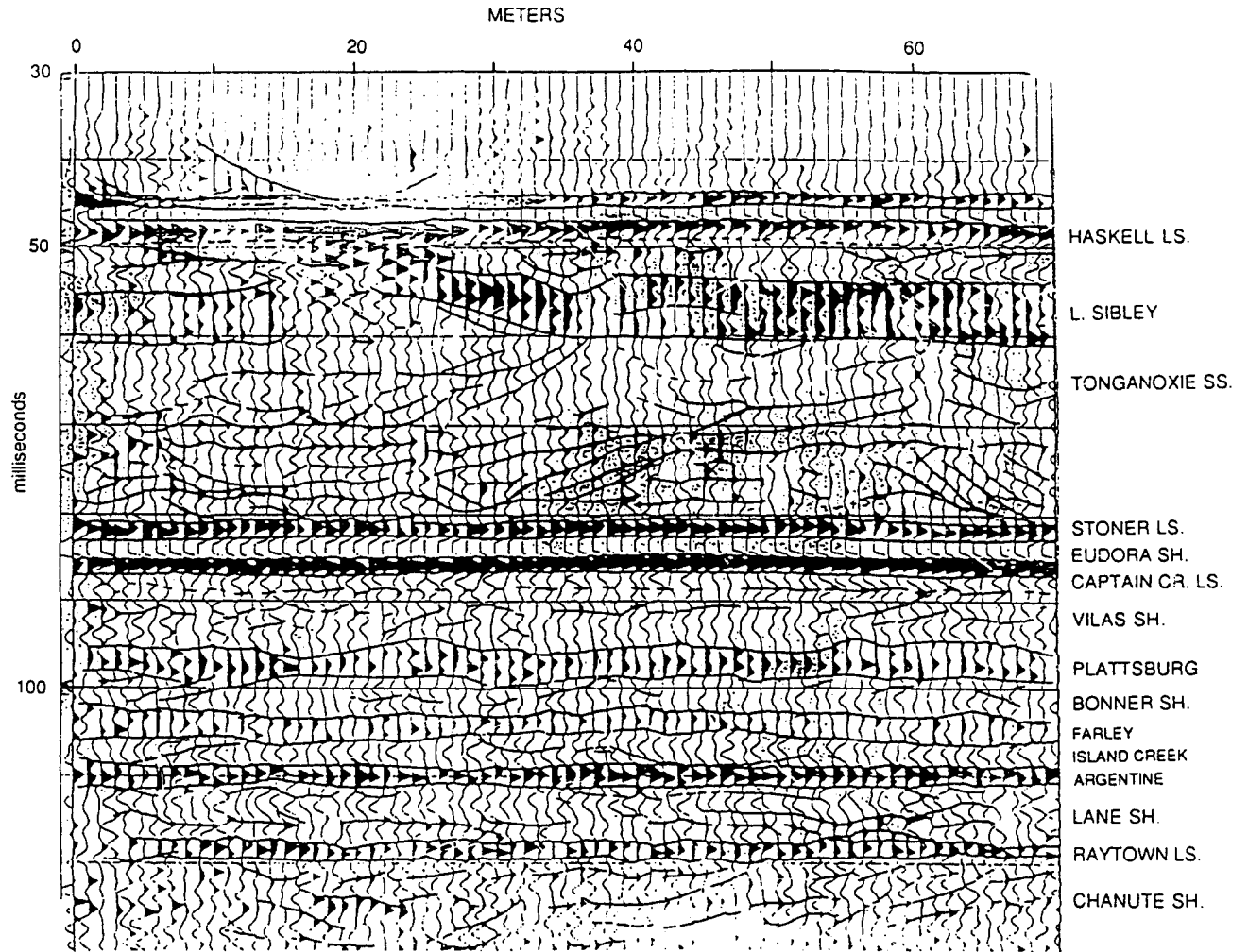


FIGURE A-5—DETAILED SECTION OF UPPER PART OF SEISMIC PROFILE SHOWN IN FIG. A-4.



# Application of high-resolution reflection seismology to eastern Kansas cyclothems

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The successful application of reflection seismology to the detailed study of eastern Kansas cyclothems has been accomplished with the use of two properties:

1. The successful recording of high-frequency data with dominant frequencies of 250 Hz or greater and upper frequency limits of 500 Hz or greater. This band width tunes to the general thicknesses of the dominant layers of the cyclothems.
2. The use of unusually small geophone intervals, or fine lateral sampling, which detects detailed lateral variations in the beds.

Resolution is easily and precisely defined mathematically, yet some of the important aspects of the work that is being done minimize some of the important properties of resolution. To think only in terms of "resolution" is to limit ourselves. We need also to think in terms of "detection" and "thin bed response."

## Resolution

Mathematically, resolution is defined by the time duration (pulse-width) of the seismic-energy pulse or wavelet. The details of the definition may vary from researcher to researcher and differ according to how one defines the pulse-width, for instance, where the wavelet begins and where it ends. However, that detail is not necessary to this discussion. No matter how pulse-width is measured, it depends on two frequency-domain properties, amplitude and phase.

The wavelet is a discrete bundle of finite seismic energy. To be a discrete bundle, it is required that the energy decrease toward zero as time increases from the peak of the energy. That is, it must be a transient signal which tapers on and tapers off. Being convergent toward zero as time increases and being of finite energy satisfies the stability requirement of the wavelet. The more rapidly the convergence toward zero occurs, the shorter the wavelet. The definition of a wavelet according to some researchers (i.e. Robinson, 1963; Robinson and Treitel, 1980) requires that the wavelet have a definite onset. This concept follows physical reality. That is, the source of the wavelet commences at some discrete origin time. The wavelet is then allowed an infinite time to settle down and return to zero. That is physical reality and is called causality or the one-sided property. Something causes the wavelet and the wavelet does

not exist before the cause. However, mathematically we can derive wavelets that taper in both time directions, to positive infinity and to negative infinity. The zero-phase wavelet is an example. They are computationally convenient, so we use them frequently in models. They also have the highest resolution for a given amplitude spectrum (Schoenberger, 1974), so we may try to process the data to contain them. That is, by phase filtering, a wavelet can be transformed to zero-phase.

The phase spectrum is usually the weak link of our knowledge. It is frequently ignored or neglected either because we know nothing of it or because we can do nothing about it. The phase relationship of the various frequency components of the wavelet determines (or is determined by) the dispersion (smearing) of the energy (Robinson and Treitel, 1965, 1980). Minimum smearing occurs when all frequencies are in phase at some instant of time. These wavelets are zero-phase wavelets and have a symmetric distribution of energy which converges toward zero on both sides of the peak as time increases. Zero-phase wavelets are mathematical and are not physically realizable, not causal. For causal, or physically realizable wavelets, minimum smearing is achieved with minimum-phase wavelets. By definition, a minimum-phase wavelet is the unique wavelet for a given amplitude spectrum which concentrates the energy as close as possible to the onset of the wavelet (Robinson and Treitel, 1964, 1980). Both zero phase and minimum phase have phase spectra that are simple functions (zero phase is trivial). Fig. 1 compares minimum- and zero-phase wavelets. For the record, the phase spectrum of maximum complexity, a random function, results in an infinite dispersion of energy which is random or static-type noise. If the amplitude spectrum statistically contains all frequencies at equal amplitude, it is white noise, just as white light contains all colors of the spectrum. If the noise is band-limited, it is colored.

Phase is an important property of the wavelet. Once phase is understood and under control, resolution is defined in terms of bandwidth of the amplitude spectrum of the wavelet. In short, resolution is directly proportional to the bandwidth of the wavelet. The broader the bandwidth, the greater is the resolution. The extremes of this statement are easily illustrated. For instance, if we have a single frequency (minimum bandwidth possible), the wavelet is monochromatic, a pure sinusoidal function (of one frequency) which propagates from negative infinity to positive infinity without

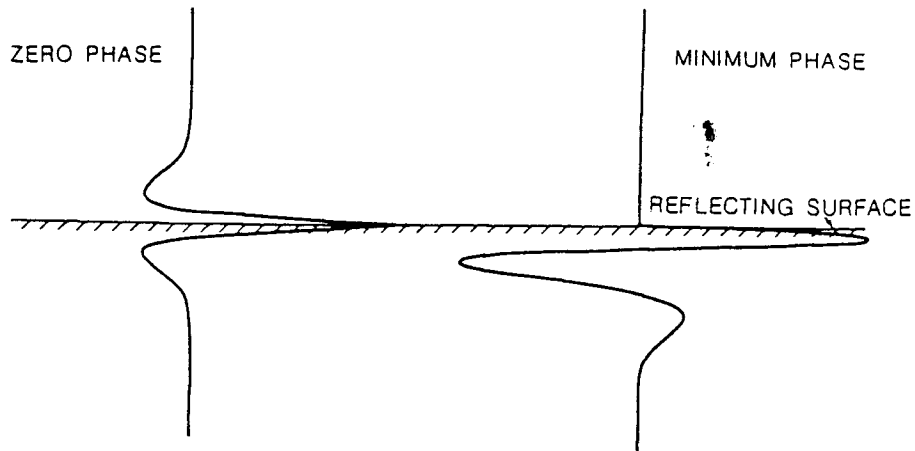


FIGURE 1—THE RESPONSE OF ZERO-PHASE AND MINIMUM-PHASE WAVELETS TO A REFLECTING INTERFACE.

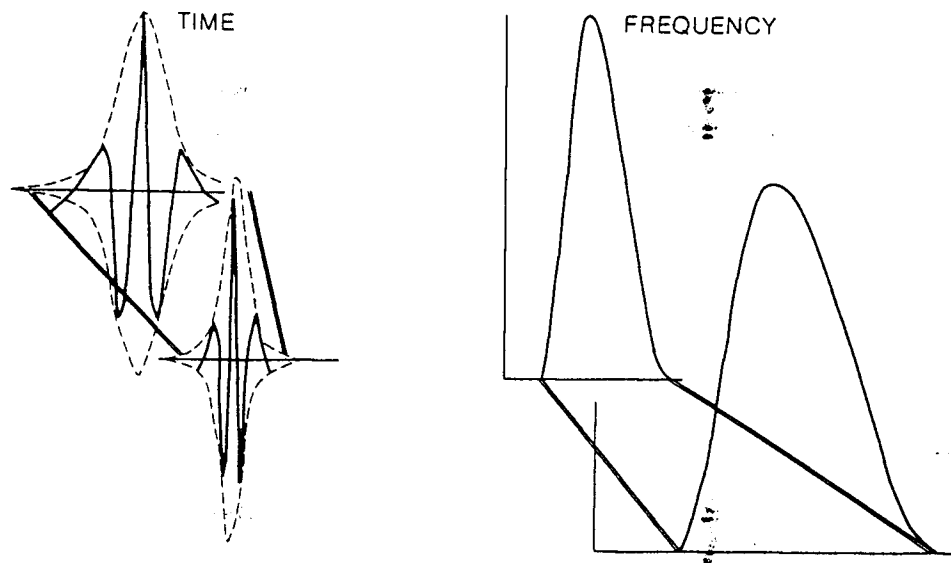


FIGURE 2—THE SCALING PROPERTY OF FOURIER TRANSFORM THEORY: reducing the time width of the wavelet increases the frequency bandwidth. That is, increasing bandwidth shortens the wavelet width and improves resolution.

decay or change of amplitude. A pure sine wave is an example. Such a wavelet has zero resolution. On the other hand, if we record an amplitude spectrum which contains all frequencies of equal amplitude and zero or minimum phase, we have the maximum bandwidth possible, and we have an infinitesimally thin spike for a wavelet. This is maximum resolution. In fact, it is infinite resolution.

Thus resolution depends on bandwidth, not frequency. As long as the bandwidth is equal, resolution is

equal, independent of the frequency values. (Again phase is not considered.) This dependency is on bandwidth with a linear scale. Some researchers think that it depends on bandwidth as measured in octaves\*, a logarithmic scale, but that is not true. They reason that for a given bandwidth in octaves and a similar phase spectrum, the wavelet maintains a similar shape as frequency changes. To change the shape of the wavelet, the frequency band in octaves must be changed. However, although the shape is similar at higher frequencies,

\*One octave is an increase (or decrease) of frequency by a factor of two. For instance, 100 to 200 Hz and 2 to 4 Hz are both one octave. On a logarithmic frequency scale, the distance is the same for each. Significant changes in frequency are frequently considered in terms of fractions of an octave, relative frequency changes instead of absolute frequency changes. Think of music as an example; changing from one note to the next is a step of relative frequency change, not one of absolute frequency change.

the wavelet is narrower in time, or higher in resolution than it is at lower frequencies. For a given bandwidth in octaves, as frequency increases, the linear bandwidth increases, pulse width decreases, and resolution improves (fig. 2). For example, 20 Hz to 80 Hz is two octaves, the frequency bandwidth is 60 Hz. 100 Hz to 400 Hz is also two octaves, and the frequency bandwidth is 300 Hz. Resolution is improved five-fold with the high-frequency bandwidth.

For most practical purposes, the acquisition of seismic data (and most scientific data) is limited by octaves. For example, most seismic work is limited to about three octaves. If that work can be done at higher frequencies, the resolution will improve. So, even though resolution is not theoretically constrained by frequency, for practical purposes and assuming good quality work, resolution is proportional to frequency.

## Detection

In the process of attempting to obtain data with the highest possible resolution, the bandwidth is often stretched to extreme limits. As a result, high- and low-frequency noise are often accepted on the data so that the wavelets will contain the maximum bandwidth. As data get noisier and noisier, small-amplitude events will tend to disappear into the noise level. The trick of good processing is to maximize bandwidth and also maximize the detectability of small events. One especially does not want to lose sight of the objective. We first need to see the event (detection). Then we can worry about maximizing its resolution. Sometimes to see an event, frequency-band limitations are required. That is the cost of detection. Fortunately there are other criteria such as coherency which can also be used to enhance an event without loss of bandwidth. Coherency takes advantage of the continuity of an event from one trace to the next.

## Thin-bed response

Although thin-bed response is made clearer and less confusing by high-resolution data, the fact is that to measure the thickness of a thin bed is not a question of resolution or frequency bandwidth. The basic problem is that the wavelength of the signal must be similar in dimension to that of the bed thickness. If it is much longer than the bed thickness, the determination is less reliable and with increasing length becomes impossible. If it is much shorter, the problem is not one of a thin bed. The thin-bed problem assumes that the bed is thin compared to the dominant wavelength of the wavelet.

To demonstrate that the thin-bed problem is not a question of resolution, remember that in freshman college physics, soap-film thicknesses are measured using monochromatic light and principles of interference. The seismic thin-bed problem can be approached from the same stance. An advantage of having broad-band data is that interference problems are less disruptive. If the concern were only the

resolution of isolated thin beds, broad-band data would not be needed.

The difference between thin-bed response and thick-bed response is that thick-bed response has a separate response for the top and bottom of the bed, the two wavelets do not interfere, and the amplitude of the wavelet depends on reflection strength (reflection coefficient). For thin beds, reflections from the top and bottom of the bed interfere. The result is a single wavelet response which approximates the time derivative of the original wavelet. The amplitude response depends on the thickness of the bed. When the bed thickness is  $1/4$  wavelength, the amplitude of the response is at a maximum, exceeding the amplitude of the thick-bed reflection. As the bed gets thinner, the amplitude diminishes approximately linearly with thickness (Widess, 1973). The approximation of the response to the derivative also improves as the bed gets thinner, and the frequency of the response increases slightly. Therefore, very thin beds will have a low-amplitude, high-frequency response. This discussion relates mainly to isolated thin beds. For repetitive thin beds (cyclothem), the tuning effect is enhanced.

Fig. 3 illustrates seismic response to cyclothem layering as a function of bed thinning. The left side of the figure is the seismic response, the far right-hand trace represents the section. The layering might be considered, for example, interbedded limestone and shale, although any two contrasting rock types could be chosen. The cyclothem are blocked into groups in which the beds are progressively thinning with depth. The dominant frequency of the wavelet is about 400 Hz. The first group, between .060 and .100 sec are thick beds (.00250 sec or 3 to 4 m [10–13 ft]). Velocities of 2,000 to 3,000 m (6,600–9,900 ft)/sec are assumed for the "shales," and velocities of 4,000 to 5,000 m (13,200–16,500 ft)/sec are assumed for the "limestones." The tops and bottoms of the layers are seen as discrete events, for instance, a peak at the top of the "limestone" and a trough at the base of the "limestone" or top of the "shale."

The rest of the section is thin-bed response. From .100 to .140 sec individual layers are .00125 sec thick. This might represent limestones that are 2 to 3 m (7–10 ft) thick and shales that are about 1 m (3.3 ft) thick. Although there is a slight time-shift, one can consider the peaks to represent the "limestones" and the troughs the "shales." (Phase-shift processing,  $90^\circ$  in this case, can correct the time-shift error.) The response of the thin beds tunes the seismic response to a frequency of 400 Hz. Note also that because of constructive interference of the tops and bottoms of the beds, the amplitude of the response is greater than the thick-bed response.

From .140 to .180 sec, individual layers are .00100 sec thick (1 to 2.5 m [3.3–8 ft] or less), and the seismic response is tuned to 500 Hz. From .180 to .220 sec, the layers are .00083 sec thick (1 to 2 m [3.3–7 ft] or less), and the seismic response is 600 Hz. Amplitude is diminished only because the seismic signal has reduced response at the higher frequencies. At the bottom of the seismogram, layers are .00050 sec thick (less than 1 m [3.3 ft]). The seismic response would be 1,000 Hz, but the seismic signal does not contain

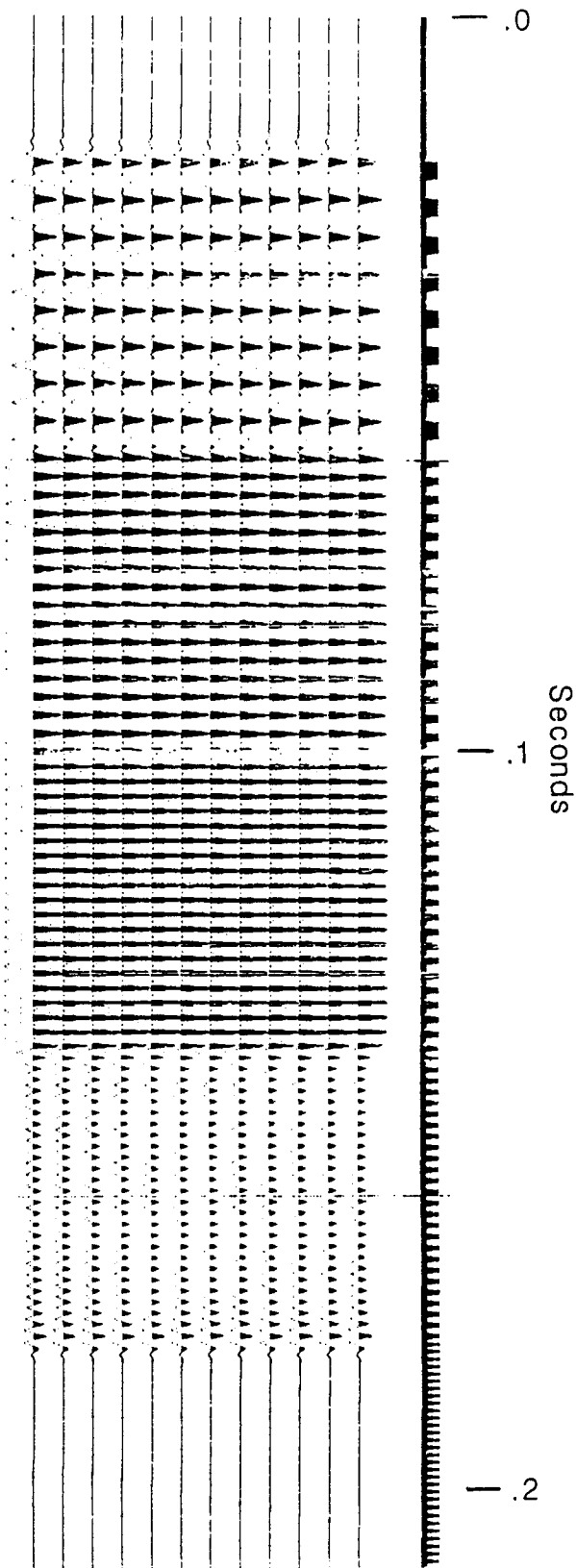


FIGURE 3—SEISMIC RESPONSE OF CYCLOTHEMS: the left-hand side is the seismic response and the far right-hand trace is the "velocity" log, the layering. Dominant frequency of the wavelet is about 400 Hz. Tuning and increased frequency occurs with increased thinning.

that frequency. All other frequencies are filtered from the response, hence, no record. This emphasizes that the important element of thin-bed detection is to have high frequencies in the signal. The model of fig. 3 does not contain interbed multiples which would exist on real data, but interbed multiples would only serve to enhance the tuning effect of the response.

With dominant frequencies of about 250 Hz, the seismic response of many of the beds in the Upper Pennsylvanian cyclothem of eastern Kansas is one of thin beds (fig. 4). Each bed has a single wavelet associated with its response. Seismic data can be phase-filtered so that the thin-bed response of a limestone layer is that of a peak and the thin-bed response of intervening shales is that of a trough. To some extent, amplitude and frequency response depend on bed thickness, but the interaction of reflections from adjacent beds, differences in reflection strength, and other factors modulate the quantification of the results.

## Lateral resolution

It has been found that lateral change of cyclothem can occur in short intervals and that trace spacings on the order of 1 m (3.3 ft) are required on the processed seismic sections to see them (see Knapp, *in* Franseen and Watney, 1989). In general, this spacing detects events which change within the distance of 4 m (13 ft) or less. Close trace spacing improves the lateral continuity of a reflection and when that reflection changes, one is then both more certain that the change has taken place and is not just noise and is better able to quantify the nature of the change.

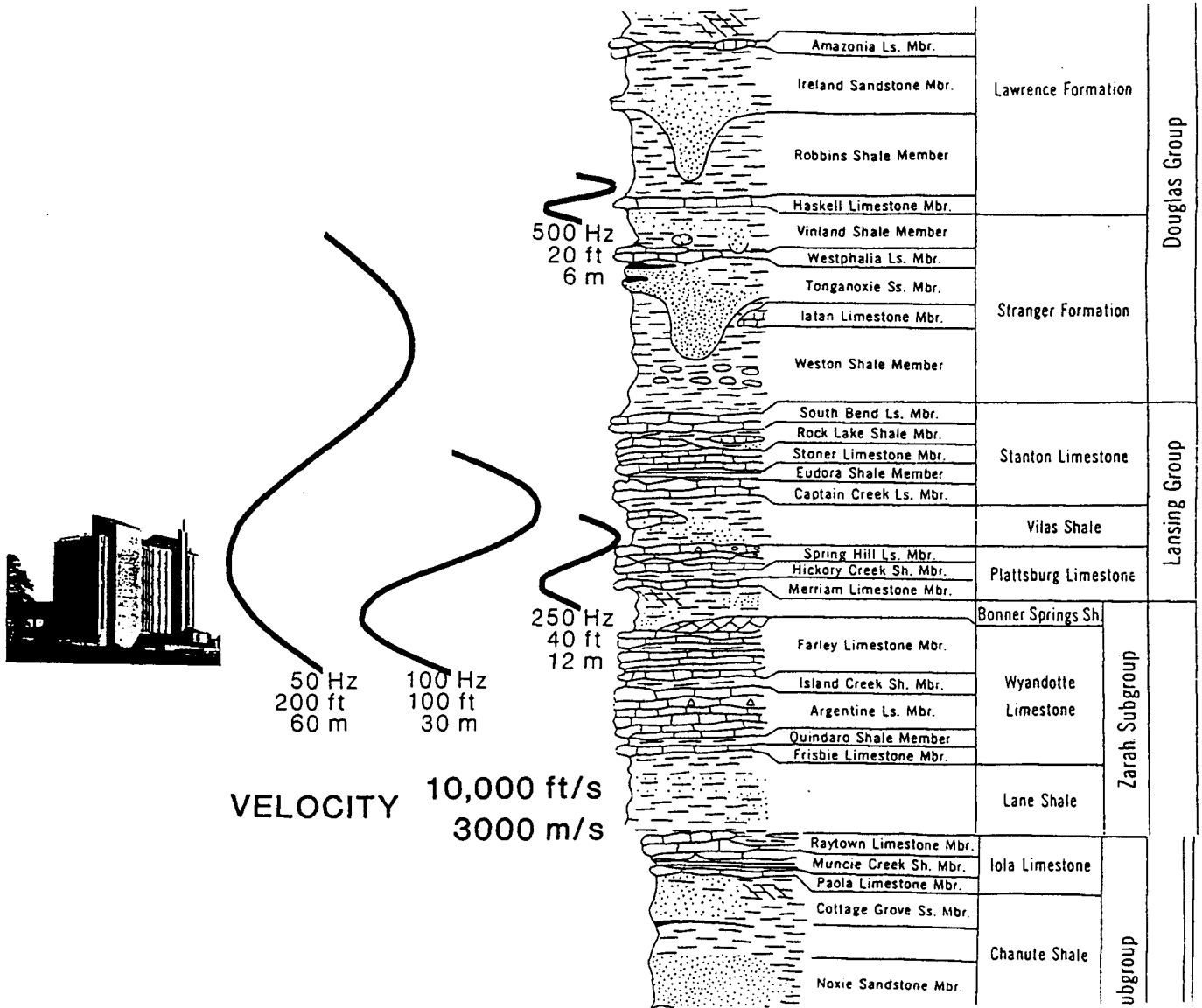


FIGURE 4—COMPARISON OF SEISMIC WAVELENGTHS TO THE UPPER PENNSYLVANIAN SECTION OF EASTERN KANSAS. The picture of Moore Hall which is about 75 ft (23 m) tall serves as a scale.



# Computer simulation of coastal-marine sedimentary sequences influenced by glacial-eustatic sea-level fluctuations

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Kansas Geological Survey, Lawrence, Kansas 66047

## Introduction

### Quantitative modeling of depositional sequences

Forward computer models simulating sedimentation are under development at the Kansas Geological Survey. The goal of the modeling is to incorporate quantitative information on rate, duration, and mechanisms of processes which affect sedimentation (Watney et al., 1989). Depositional-sequence analysis and the characterization of temporally defined units are fundamental to this modeling. Refined models are sought here integrating geologic- and seismic-imaging information in an optimum shelf-to-basin transition that we believe can constrain information on parameters affecting sedimentation. Modeling offers considerable po-

tential in testing scenarios of sequence genesis and can be used to construct time- stratigraphic views of the sequences. Process-response data obtained from modeling of near-surface field laboratories can potentially be extended to equivalent-age petroleum reservoirs in the deeper subsurface to aid in reservoir prediction. Sedimentary modeling is an area of aggressive research in the geosciences providing a means to integrate and quantify geoscientific information (e.g., Grotzinger, 1986; Read et al., 1986; Turcotte and Willemann, 1983; Turcotte and Kenyon, 1984).

The model characteristics are listed in table W-1. The parameters of the model are provided in table W-2. The sea-level curve is assumed to be asymmetric such as the late

#### INFERRED QUATERNARY SEA LEVEL CHANGES DUE TO GLACIATION

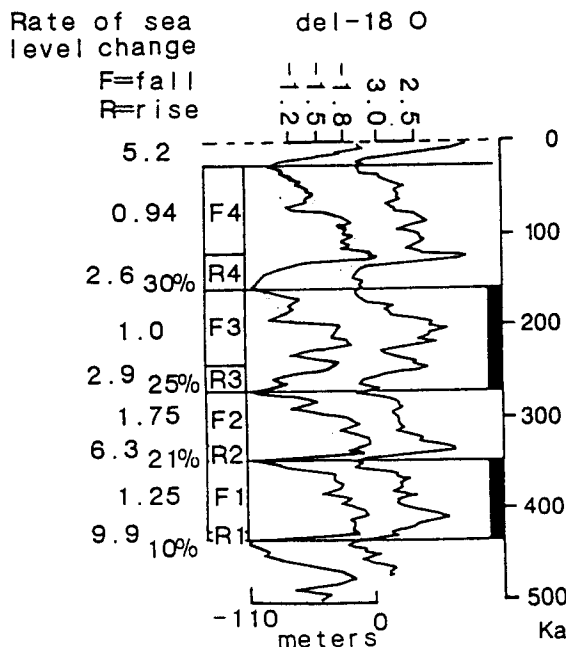


FIGURE W-1—OXYGEN ISOTOPIC RECORD OF FORAMINIFERA RECOVERED FROM LATER PLEISTOCENE- AND HOLOCENE-AGE DEEP-SEA SEDIMENTS OBTAINED FROM CORES TAKEN IN CARIBBEAN (from Denton and Hughes, 1983). Dates on right margin in kiloyears before present. Isotope curves scaled in meters of sea-level change related to volume of ice and resulting eustatic change. Rates of rise (R) and fall (F) indicated in meters per kiloyear for major cycles of rapid rise and slower fall in sea level.

TABLE 1—MODEL CHARACTERISTICS.

- one-dimensional forward model
- process-response simulation of stratigraphic units derived from depositional sequence analysis
- interactive Pascal model on IBM and compatibles
- modular program structure for ease in modification
- data input from digitized file or keyboard
- output on HP-color plotter

TABLE 2—MODEL PARAMETERS.

- subsidence rate
- average sediment accumulation rate
- sea level
- retardation and acceleration factors
- sedimentation or erosion during emergence

Pleistocene that is utilized here (fig. W-1). Coastal-margin depositional sequences developed during the Pleistocene closely resemble Pennsylvanian sequences including flooding units, condensed sections, shallowing-upward packages, and subaerial surfaces. Late Pleistocene depositional sequences are discrete, sharply bounded packages representing deeper water (high-stand) deposits overlain by shallow-water (low-stand) units (Abbott et al., 1989).

### Quaternary sedimentation analogue for glacioeustasy

Coastal sedimentation during the Quaternary has been visibly modulated by glacial eustasy due to extreme changes in sediment accommodation provided for by rapidly changing sea level. An examination of events in the late Pleistocene (<850,000 yrs B.P.) indicates that glacial eustasy is characteristically asymmetric with high-frequency, high-amplitude sea-level fluctuations.

Rates of rise during the last half-million years range from 2.5 to 10 m (8–33 ft)/ka while fall in sea level was generally less than 1 m (3.3 ft)/ka (fig. W-1). Workers such as Matthews, Fillon, Williams, Imbrie have determined that the  $\delta\text{-O}^{18}$  curves in this situation predominantly reflect ice volume. As the lighter  $\delta\text{-O}^{16}$  is tied up in a building continental glacier, the  $\delta\text{-O}^{18}$  increases in ocean water. A 0.11 per mil change in  $\delta\text{-O}^{18}$  is equal to approximately 10 m (33 ft) change in sea level (Williams, 1988).

Durations of high-stand conditions during the last 850,000 years of the Pleistocene were on the order of 100,000 years. These major asymmetric cycles were interrupted by smaller inferred rises and falls in sea level.

Predicted fluctuations in ice volume based on orbital parameters of precision, obliquity, and eccentricity explain much of the larger scale variability in sea level. However, studies of the early stages of ice buildup during the Late Tertiary such as the work of Berger suggest that particular continent and ocean settings also produce unique characteristics of ice buildup and retreat such as extent of ice buildup and ice-melting processes. Accordingly, during other ice ages continental glaciation such as the late Paleozoic would probably be defined by a unique set of surface conditions on the Earth in addition to Earth's orbital parameters. Physical processes coupled with geological conditions further tailor ice buildup and retreat. The combination of these mechanisms are now being investigated by researchers using computer simulations for both retrodiction of past glacial events and prediction of future ice buildup or retreat.

Distinctive depositional sequences were developed during the Pleistocene along coastal settings as sea level rose and fell. Local conditions such as sediment type and supply, shelf configuration, and tectonic setting result in significant variation in the nature of these sequences. Nevertheless, a distinctive sedimentary architecture developed in both carbonate and siliciclastic shelf settings leading to generalized conceptual depositional models associated with distinctive rapid and extreme fluctuations in sea level.

The general vertical succession of stratal units that comprise Quaternary depositional sequences on the Atlantic shelf are listed in table W-3 (Evans, 1979). These are very similar to those sequences developed in the midcontinent during the Late Pennsylvanian. The *flooding unit* or transgressive systems tract (according to sequence nomenclature) is the initial phase of sedimentation. It is characteristically thin. It is commonly composed of reworked strata of the underlying depositional sequence. The flooding unit is succeeded by a *condensed interval* consisting of glauconite, phosphorite, or carbonate debris. The condensed section was deposited when sediment accumulation was reduced. This stratal unit is addressed in the modeling as a *retardation factor* or what some call *lag time*.

The condensed interval is succeeded by a shallowing-upward deposit that ranges in thickness from zero to 10's of meters thick depending on the sediment type and competence of sediment input. This unit is succeeded by an extensive, but commonly subtly developed subaerial-exposure surface. This exposure during the Pleistocene on the continental shelves is characterized by limited erosion with preservation of substantial relict topography (Evans, 1979). Unconsolidated siliciclastics underlying these surfaces are seldom significantly disturbed. Alternatively, sedimentation along the coastal area is nonexistent.

The nature of the processes forming condensed sections is of major interest in forward modeling since relationships of rates, durations, and magnitude of sediment-accommodation space and sedimentation are ultimately sought. Studies of sedimentation during the latest glacioeustatic rise during the Pleistocene–Holocene transition such as by Hallock and Schlager (1986) suggest that diminished sedimentation and drowning are related to periods of high rates of sea-level rise coupled with the disruption of local conditions such as nutrient supply, biologic activity, and water circulation. Anoxic bottom-water conditions or high organic productivity were common to areas on continental shelves during Quaternary flooding events, e.g., accumulation of sapropels in the Black Sea as described by Calvert et al. (1987). Limited periods of anoxic or high organic productivity have led to significant accumulations of organic matter.

TABLE W3—GENERALIZED SUCCESSION OF QUATERNARY COASTAL SEDIMENT ACCUMULATION (Evans, 1979).

increasing time ↓	a) flooding unit
	b) condensed section (glauconite, phosphorite, carbonate debris flooding unit)
	c) shallowing-upward coastal deposits
	d) widespread subaerial exposure - hiatus

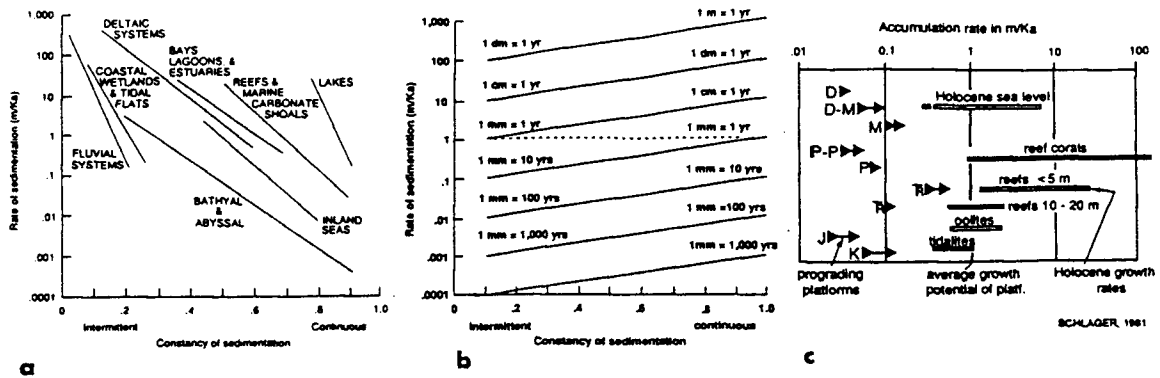


FIGURE W-2—**a**) RATE OF SEDIMENTATION VS. CONSTANCY OF SEDIMENTATION FOR VARIOUS DEPOSITIONAL ENVIRONMENTS (from Schindell, 1980); **b**) RELATIONSHIP OF SEDIMENTATION RATE AND CONSTANCY OF SEDIMENTATION TO SEDIMENT ACCUMULATION (diagonal lines; from Schindell, 1980); **c**) COMPARISON OF SEDIMENT ACCUMULATION RATES OF Holocene carbonate deposits compared to Holocene sea-level change and sediment-accumulation rates estimated from various carbonate platforms (from Schlager, 1981).

The forward computer model developed here to simulate coastal sedimentation under glacial-eustatic control is based on process and sediment response. A key input parameter is sediment-accumulation rate for a depositional sequence. Schindell (1980) noted that rates of sedimentation and constancy of sedimentation in various depositional settings are wide ranging (figs. W-2 a and b). His results were based on an extensive inventory of data from the literature from which rates and duration could be estimated.

Sediment-accumulation rates of stratigraphic units represent the product of short-term sedimentation rate and constancy of sedimentation (fig. W-2c). Sedimentation rates can be very great in examples such as the Mississippi River delta. However, rapid rates of change in sea level modulate even this very competent siliciclastic depositional system so that accumulation rates are actually highly variable in time.

Rapidly rising sea level at the end of the Pleistocene led to widespread drowning of carbonate platforms as described by Hallock and Schlager (1986) and other workers. The retardation in sediment-accumulation rates and development of a condensed section is thought to be due, in part, to nutrient excess developed during the rapid rise of sea level. As a result, while normal carbonate sedimentation such as reefs and oolites have the potential of accumulating at rates of meters to 10's of meters/ka under stable or uniform conditions, the average accumulation rates in Quaternary sequences are about an order of magnitude less than this.

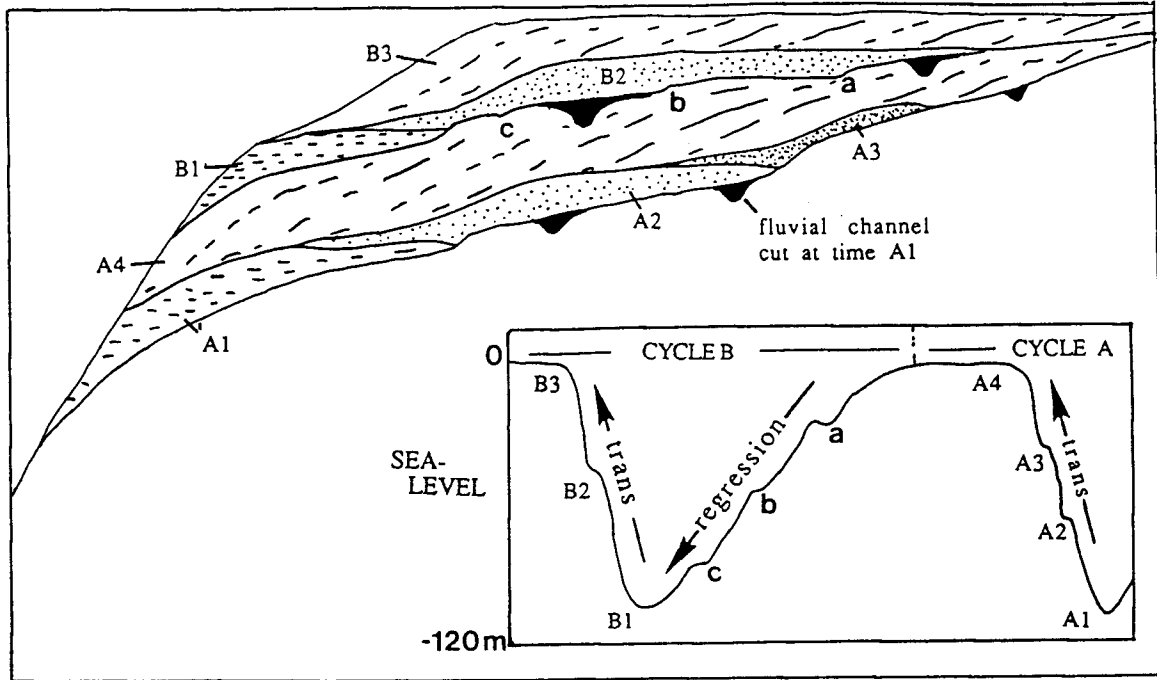
The algorithm used to calculate a retardation factor is theoretically based on several parameters relating to sediment type, shelf setting, and local environmental conditions. At this time only arbitrary factors are used to examine the interaction and sensitivity of this factor in generation of sequences.

Coastal-depositional sequences generated in the Pacific during the Quaternary, including the Great Barrier Reef, are described in a conceptual model by Carter et al. (1986; fig. W-3). Geologic constraints which existed in de-

veloping the two-dimensional conceptual model including gradual subsidence. At least under the constraints of these particular stable shelf settings, the resultant depositional sequences were obviously controlled by cycles of rapidly rising sea level and slower fall.

As Carter et al. (1986) indicate, both rises and falls are staggered with numerous stillstands. Hiatal surfaces develop over much of the shelf, both during low-stand and early high-stand conditions. Most of the sediment accumulation occurs during high-stand conditions when sediment-accommodation potential is greatest. Sediment progrades from the shoreline toward the basin margins. In more isolated offshore and outer shelves, rapidly rising sea level may limit sedimentation altogether leading to long-term drowning of these areas, e.g., many continental shelves around the world today are still receiving little or no sedimentation in water depths in excess of 50 m (165 ft).

Abbott et al. (1989) describe in more detail a vertical profile of several Pleistocene cyclothems [sic] in North Island, New Zealand, strongly modulated by rapid rise and slower fall in sea level (fig. W-4). Early Pleistocene slope and basin successions associated with symmetric sea-level fluctuation are characterized by rapid transgressive surfaces (flooding) followed by high-stand siltstone accumulation. Low-stand sandstone and carbonate strata rest in gradational contact upon the low-stand siltstones. Late Pleistocene strata characterized by more asymmetrical and greater magnitude in sea-level change result in thin flooding deposits and accumulation of a condensed interval during high stand. However, erosion is noted at the top of the high-stand facies prior to deposition of the low-stand deposit. Abbott et al. (1989) interpreted this erosion as due to a more rapid fall in sea level or that the shallow-water shelf underwent erosion prior to deposition during low stand. Ensuing lag time is also suggested between high-stand and low-stand deposition, at least in some situations. This will be the object of further discussion during the field trip.



- rapid progradation on flatter shelf
- generally good preservation,
- erosion only locally significant

CARTER, CARTER, AND JOHNSON (1986)

FIGURE W-3—CONCEPTUAL MODEL OF COASTAL SEDIMENTATION IN THE PACIFIC ASSOCIATED WITH TWO QUATERNARY MARINE INUNDATIONS. Rapid rise and gradual fall in sea level result in thin flooding units and thicker prograding high-stand sediment packages. Low stand results in local erosion and channeling on shelf.

Sedimentation during the Quaternary on the Mississippi River delta also was modulated by glacioeustasy. The delta is developed along the southern margin of the United States, consisting of punctuated depositional sequences compartmentalized by both condensed and subaerial hiatal surfaces. A conceptual depositional-sequence model based on cores was interpreted by Frazier (1974). Sequence boundaries were dated using C-14 ages of peat of older underlying sequences and mollusks that were indigenous to the transgressive or flooding facies tract consisting of bay, inner neritic, and surf-zone environments.

A depositional-sequence model prepared for the Holocene St. Bernard delta complex by Loutit et al. (1988) based on Frazier's (1974) study is shown in fig. W-5. The entire depositional sequence was deposited during the last 6,000 years under waning stages of sea-level rise following the last glaciation. This sediment wedge accumulated primarily during the existing sea-level high stand as indicated from the depositional-facies distribution shown in the lower cross section. An average sediment-accumulation rate for this delta lobe is 11 m (36 ft)/ka, a very large number. During this time the sediment wedge prograded basinward at a rate of approximately 20 km (12 mi)/ka. Obviously, other settings have undergone considerably less sedimentation during

the same sea-level change depending on depositional system and shelf configuration.

### Application of Pleistocene analogue to the late Paleozoic ice age

Field evidence for major late Paleozoic continental glaciation on portions of Gondwanaland has been acquired over the last several decades by workers such as Crowell and Frakes (1975). Geologic conditions during which this ancient ice age existed appear to have been very similar to the late Cenozoic. First-order sea level was falling during both periods exposing large areas of the continents. This established conditions suited for accumulation of continental ice. Climate also became cooler as sea level fell promoting ice buildup. Also Gondwanaland drifted over the south pole, providing an ideal site for ice buildup during the late Paleozoic.

The frequency or duration of these depositional sequences is another parameter that is needed for the computer model. Heckel (1985) proposed a relative sea-level curve for the Missourian that he attributed to glacioeustasy.

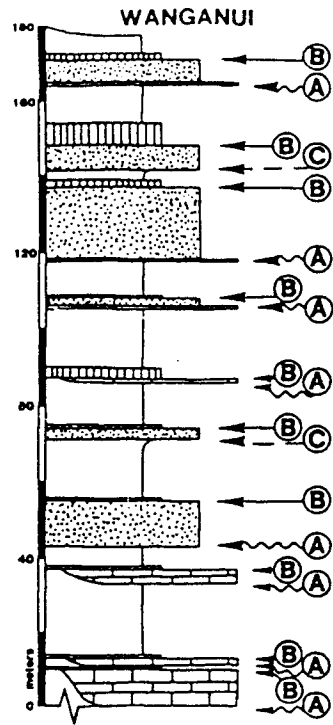
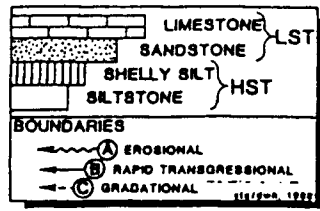


FIGURE W-4—LATE PLEISTOCENE-AGE CYCLOTHEMIC SUCCESSION FROM COAST OF NORTH ISLAND, NEW ZEALAND, that accumulated during asymmetric sea-level fluctuation (from Abbott et al., 1989).

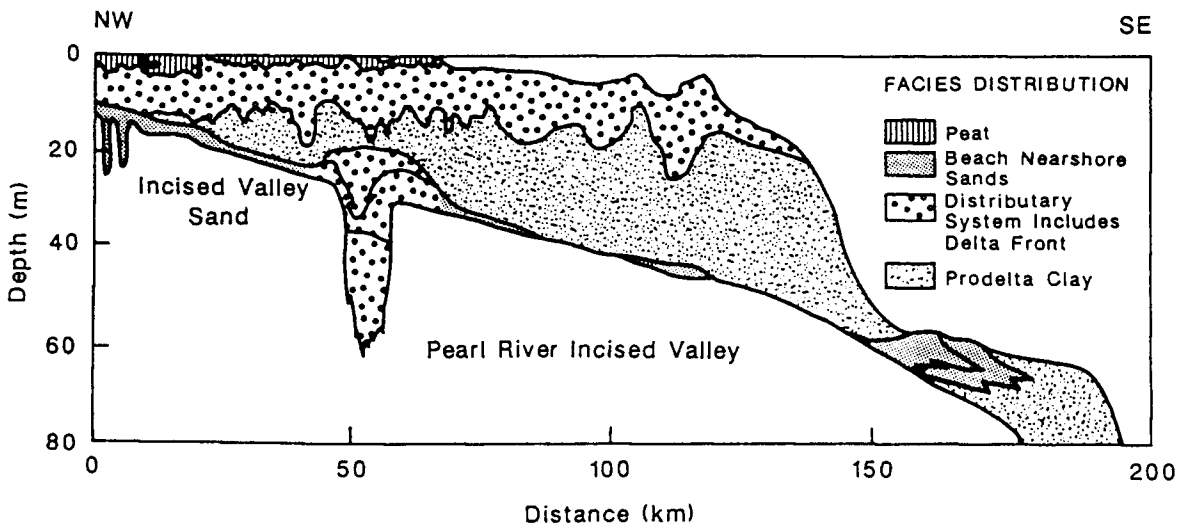
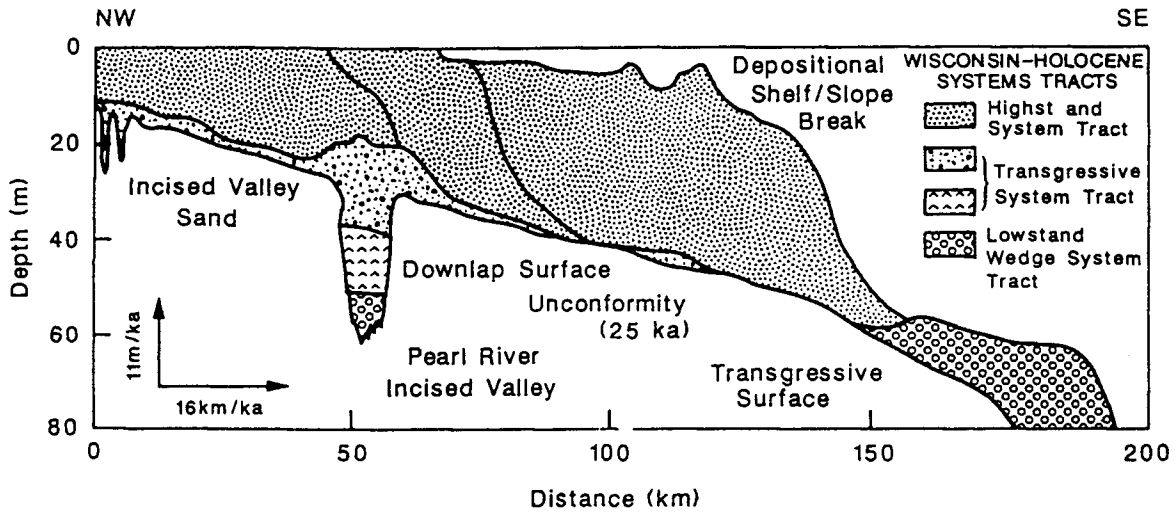


FIGURE W-5—Upper diagram) LATE WISCONSIN-TO-HOLOCENE DEPOSITIONAL SEQUENCE OF ST. BERNARD DELTA COMPLEX OF MISSISSIPPI RIVER along traverse running southeast from New Orleans. Three episodes of deltaic progradation during highstand intersected by traverse, all part of one depositional sequence. Lower diagram) DIACHRONOUS LITHOFACIES DISTRIBUTION ALONG SAME TRAVERSE in same depositional sequence (modified from Frazier, 1974, by Loutit et al., 1988).

The maximum duration of each depositional sequence was estimated by Heckel as 400,000 years. The magnitude of eustatic change was estimated by Heckel as 100 m (330 ft).

Regional studies of Missourian strata have been conducted in the subsurface of Kansas providing a three-dimensional view of the distribution of depositional facies of these sequences. Fig. 18 from introduction to the guidebook illustrates lithofacies and paleogeography for the area in Kansas under consideration (Rascoe and Adler, 1983). Depositional sequences developed in western Kansas were previously described in the introduction to the field trip (see p. ). A chart describing the parameters used in sedimentary modeling of the Missourian depositional sequences in Kansas is provided in fig. W-6.

### Western Kansas modeling

The objective of the forward computer model was to incorporate processes and mechanisms as parameters to simulate the development of Missourian depositional sequences on the midcontinent shelf. The model produces

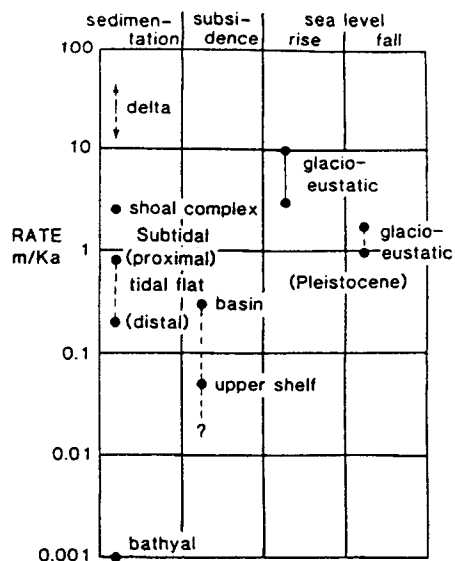


FIGURE W-6—RANGES IN SEDIMENT ACCUMULATION RATES AND SUBSIDENCE USED IN MODELING PENNSYLVANIAN CYCLOTHEMS COMPARED TO RATES OF CHANGE IN SEA-LEVEL RISE AND FALL FROM QUATERNARY ANALOGUE.

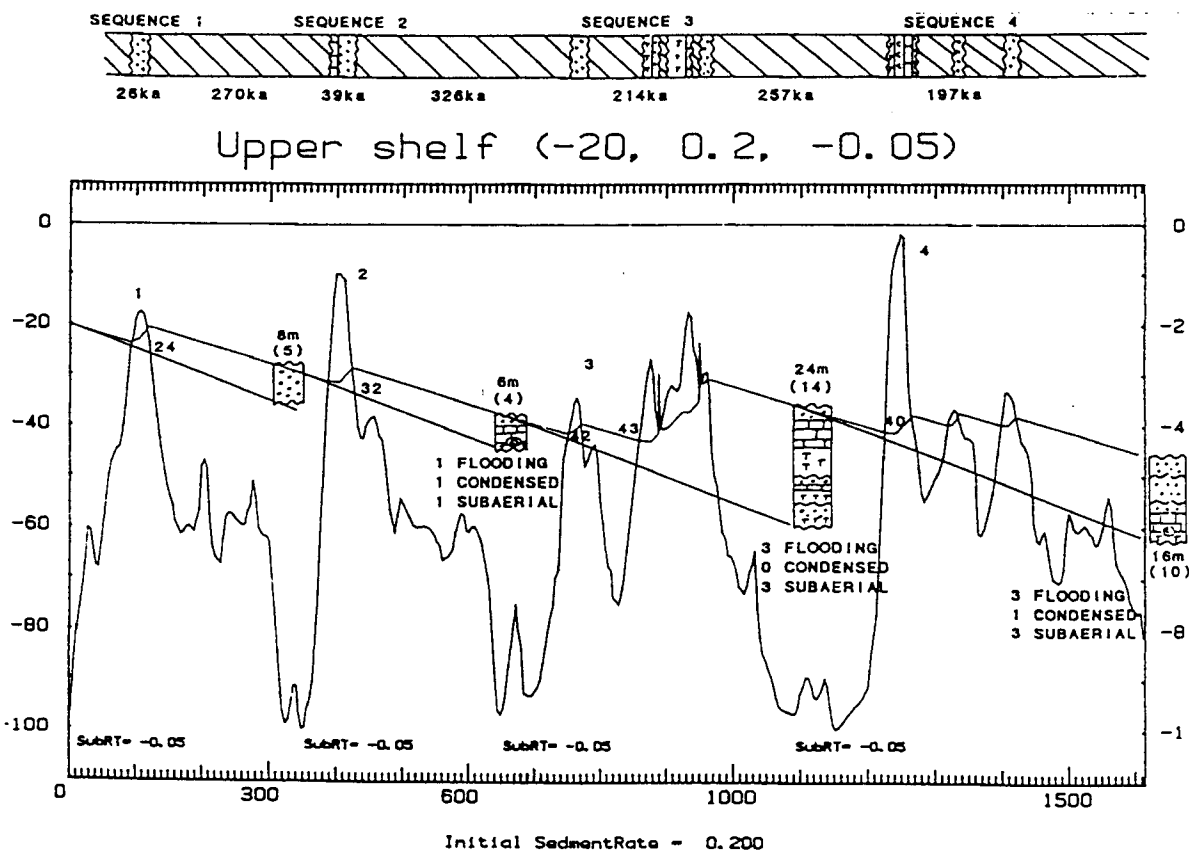


FIGURE W-7—ONE-DIMENSIONAL COMPUTER SIMULATION (FORWARD MODEL) OF MISSOURIAN DEPOSITIONAL SEQUENCE LOCATED AT UPPER PORTION OF WESTERN KANSAS SHELF. Process-response model runs from parameters that include initial sediment-surface elevation, sediment-accumulation rate, subsidence history, and sea-level history. Resultant sediment columns shown in depth and time for four sequences of marine inundation. Sea level remains same between other two models at different shelf positions. Sediment-surface elevation, sediment-accumulation rate, and subsidence vary across the shelf.

Generated sediment columns shown in depth (vertical) and time (horizontal). Columns include flooding unit (T's), condensed section (c), shallowing-upward subtidal carbonate strata (brick pattern), and shallow-water carbonate sediment deposited in less than 3 m (10 ft) of water (dotted). Wavy lines indicate subaerial-exposure surfaces.

Minor oscillations in sea level may result in parasequence development, if magnitude is great enough and water depth shallow enough to create distinctive change in lithofacies.

elevations of various datum surfaces through time. The resulting water depths, for example, can be translated into expected depositional facies.

The modeling is designed to be interactive so that it can be used iteratively to produce an optimum solution. Presently, results are only an approximation, as is the conceptual model. The modeling procedure provides means to test scenarios and to refine geologic interpretation.

Three models are shown in succession, the first one for the *upper shelf* (fig. W-7), then a *mid-shelf* location (fig. W-8), and finally a *lower-shelf* margin location (fig. W-9). The reference elevation is an arbitrary maximum highstand in sea level in meters. The initial sediment-surface elevation is assigned more negative values across the shelf according to the arguments presented earlier. The sea-level curve is a modified version of the del-O18 of the Pleistocene. The period of each major rise and fall of sea level has been expanded from 100k to 400k years. The amplitude still remains at 110 m (363 ft).

The subsidence curve originates from the initial sediment surface of each sea-level cycle. The sediment-surface elevation is controlled by an initial sediment-accumulation rate for these carbonate-dominated sequences. The rate is modified according to a retardation factor derived from an algorithm dependent upon rate of rise in sea level and an acceleration factor when the water depth gets less than 5 m (17 ft). When water depths become greater than 50 m (165 ft), the accumulation rate is assigned 0.01 m (0.03 ft)/ka. If

the euphotic zone is estimated to be 20 m (66 ft), it would be more appropriate to use that value for reduced sediment accumulation.

The difference between the sea-level curve and the sediment surface is water depth. This water depth is essentially accommodation space for additional sediment provided by both subsidence and sea-level fluctuation.

The sedimentary columns shown here are simply drawn to depict the nature of sediment type according to the water depth in this carbonate setting. Transgressive or flooding units, condensed sections, and shallow-water deposits are specifically identified. The vertical columns are in depth (meters) and the horizontal ones at the top of the plot are in time.

The upper-shelf setting is defined by high initial sediment elevation and slow average subsidence. The four depositional sequences shown are relatively thin due to limited duration of marine inundation and prolonged subaerial exposure. Initial sediment surface elevation declines for the first three cycles. Subsidence continues to lower the sediment surface elevation during episodes of subaerial hiatus. This could be easily modified to add subaerial deposition or erosion. The complicated sea-level curves of cycles 3 and 4 result in several flooding and shallowing-upward packages with limited subaerial exposure between them. Thicknesses and facies are comparable to those observed in Missourian sequences in western Kansas.

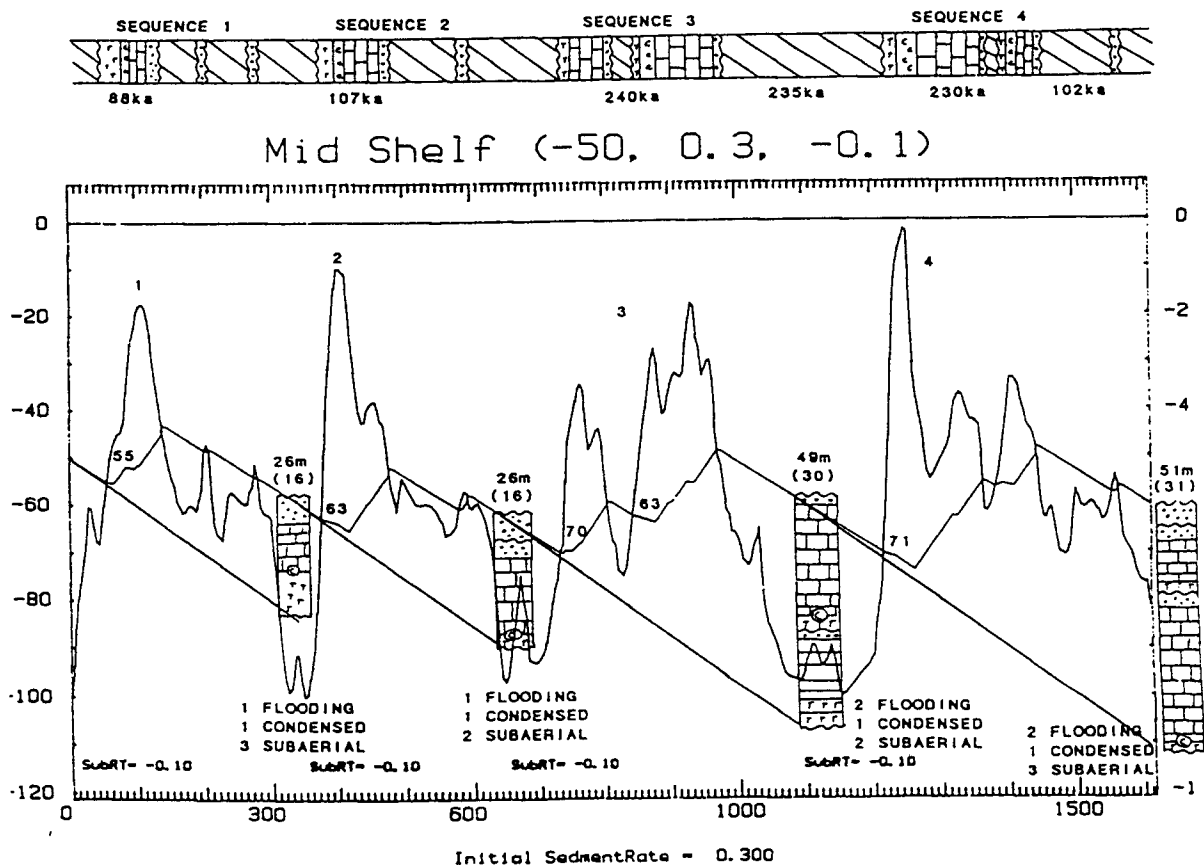


FIGURE W-8—COMPUTER SIMULATION OF MISSOURIAN DEPOSITIONAL SEQUENCE FROM MID-POSITION ON WESTERN KANSAS SHELF.

The model for the middle shelf illustrates the same four sea-level cycles (fig. W-8). However, the initial sediment-surface elevation is lower and the average sediment accumulation and subsidence rates are greater. Increased accommodation space over longer periods of time results in greater thicknesses. The lower shelf intercepts additional sea-level events not found higher on the shelf. The condensed sections in this simulation are generated both during the rapidly rising sea levels and when water depth reaches 50 m (165 ft) or more. Listed below each vertical-sediment column are the numbers of flooding events, condensed sections, and subaerial surfaces generated in the simulation.

Initial shelf elevation at the beginning of each sequence continues to fall as a reflection of the inability of sediment to fill all of the space created by subsidence.

The lower shelf model (fig. W-9) again has the same sea-level signature, but reflects increased sediment-accumulation rates and subsidence values, the latter corresponding to the estimates of Kluth (1986). Lower elevations on the shelf intercept additional portions of the sea-level curve and accordingly complicate the sedimentary response with multiple flooding, condensed sections, and subaerial-exposure events.

Subsidence in the lower-shelf simulation is substantial and even though sediment accumulation has increased, the sediment pile has not kept pace because of interruptions in sedimentation rate while subaqueous and subaerial hiatus

surfaces developed. The increase in absolute time and the proportion of time occupied by condensed sections becomes significant on the lower shelf. In contrast, duration of subaerial exposure has diminished relative to the upper shelf, as interpreted from the geologic record.

Finally, because of substantial loss in sediment-surface elevation by the beginning of cycle 4, sediment starvation results. Unless the subsidence rate diminishes or significant lateral progradation of the margin occurs with greatly increased accumulation rates, this lower shelf position becomes part of the deep Anadarko basin. Accordingly, the carbonate-shelf margin would backstep to a location northward or landward from this modeled site. Halving the subsidence rates would eliminate these sediment-starved conditions in the fourth sequence.

The Pennsylvanian shelf margins along the perimeter of the Anadarko basin have advanced and retreated several times. Punctuated sea-level variation coupled with episodes of tectonic subsidence probably have resulted in producing abrupt migrations of the shelf margin.

Results of the one-dimensional simulations can include a Wheeler diagram of time versus distance for the four sequences modeled (fig. W-10).

In addition, sequences can be presented in depth cross sections that integrate the model results at different shelf locations developed at a particular time. The cross section in fig. W-11 uses a datum on the elevation of the

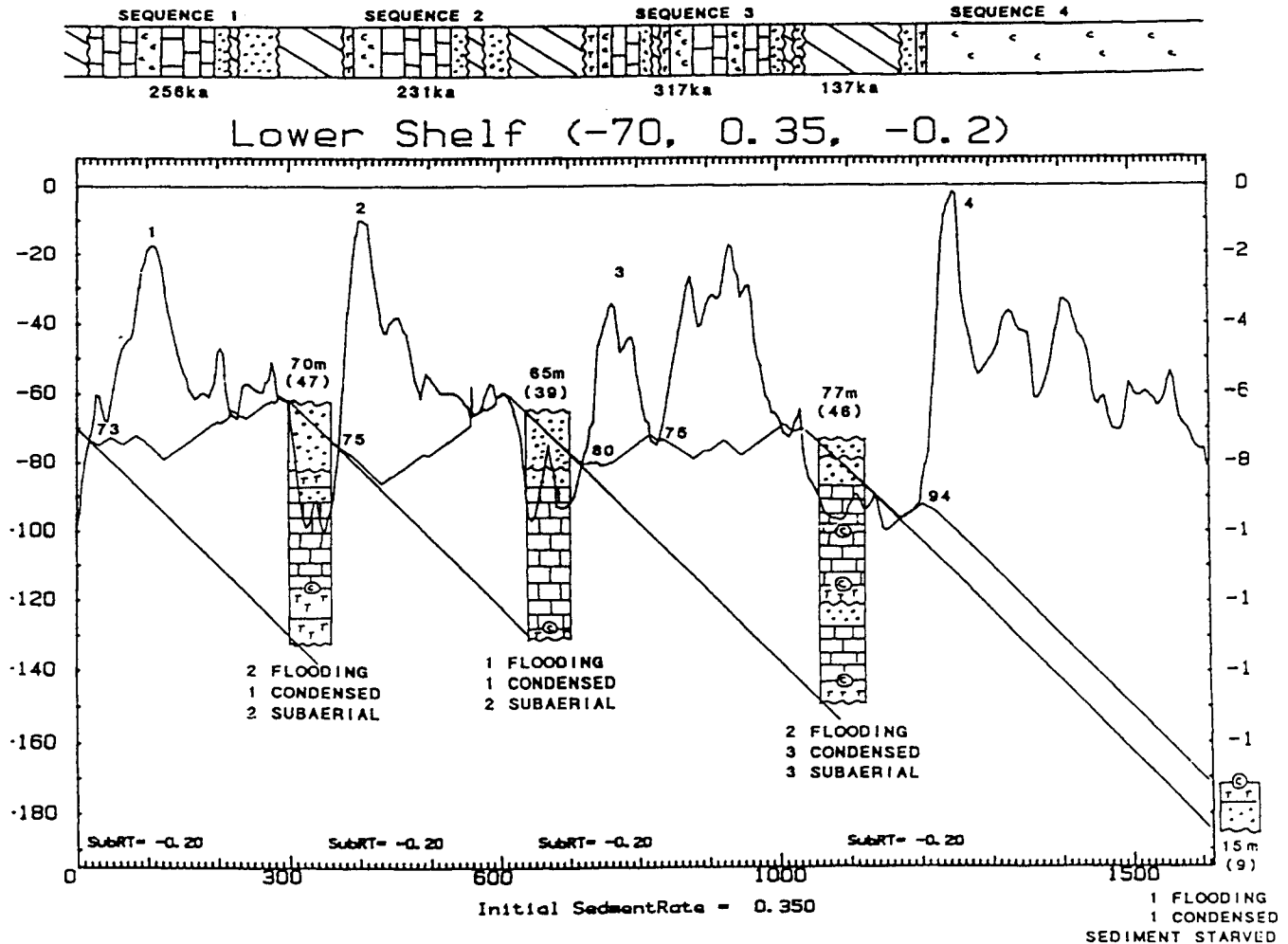


FIGURE W-9—COMPUTER SIMULATION OF MISSOURIAN DEPOSITIONAL SEQUENCE FROM LOWER PORTION OF WESTERN KANSAS SHELF.

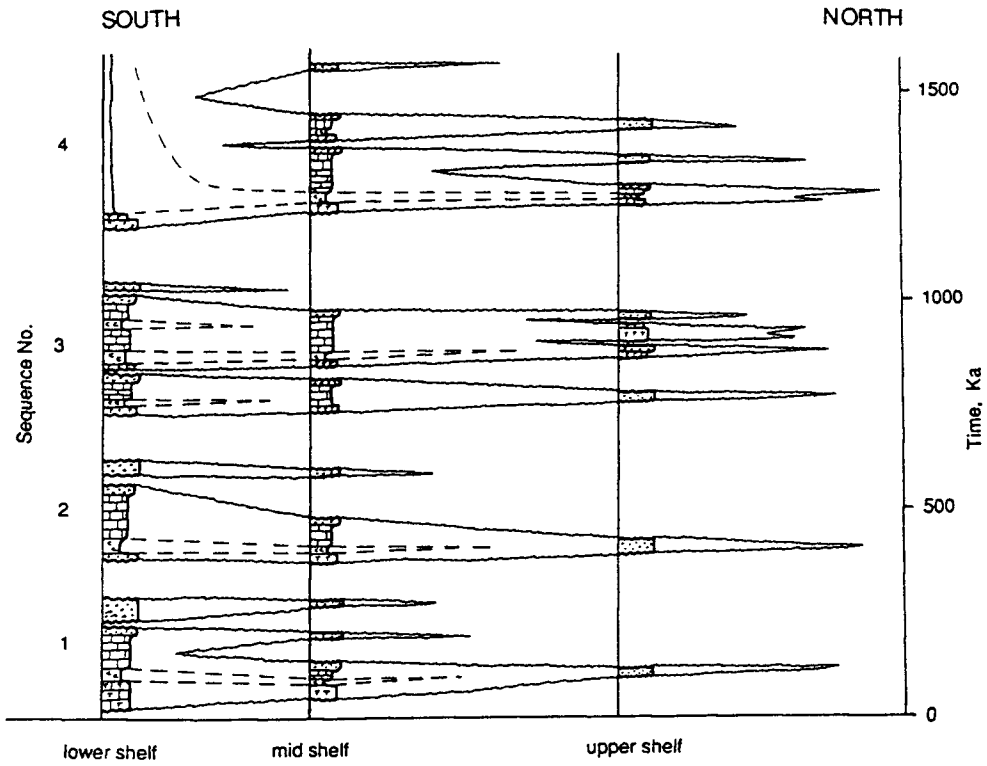


FIGURE W-10—SIMULATION RESULTS PRESENTED AS TIME-DISTANCE (WHEELER) DIAGRAM FOR UPPER, MIDDLE, AND LOWER SHELF SETTINGS. Time-stratigraphic columns derived from model results illustrated in figs. W-7, W-8, and W-9.

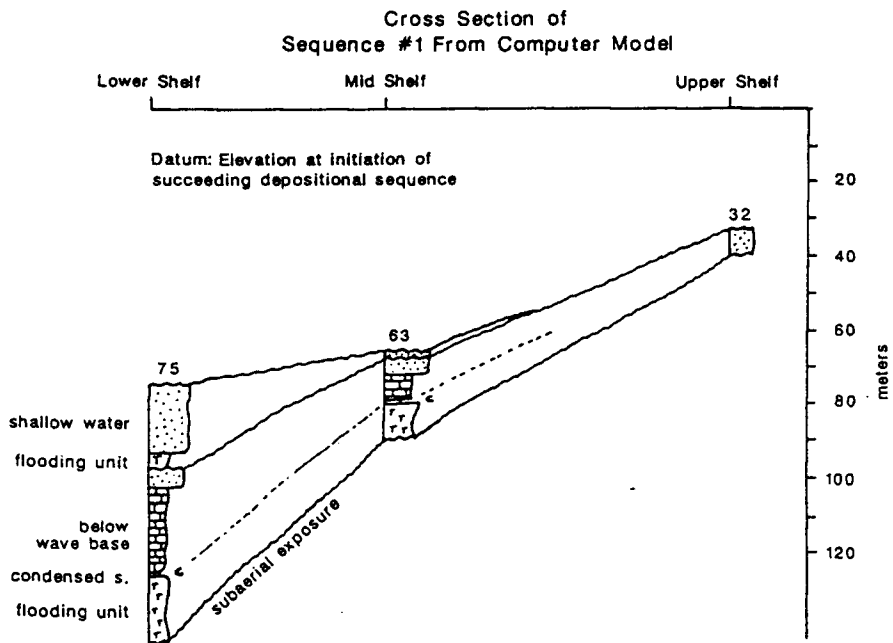


FIGURE W-11—DEPTH-DISTANCE CROSS SECTION FOR SEQUENCE #1 based on output from simulation results for upper, middle, and lower shelf locations at the time succeeding marine inundation begins.

upper sediment surface at the initiation of the succeeding depositional sequence for three positions on the shelf.

### Eastern Kansas modeling

The present working scenario indicates no subsidence during accumulation of the pre-Dennis Missourian sequences in southeastern Kansas (see interpretive sequence cross sections in figs. 47–52 in introduction to guidebook). Accordingly, all shelf-sediment accommodation space is provided by sea-level inundation and varying stable-shelf elevation. At least 50 m (165 ft) of change is noted across the slope of the Pleasanton delta. For modeling, a lower shelf elevation of -70 m (-231 ft) comparable to the lower shelf in western Kansas and a basin elevation of -100 m (-330 ft) appear to be reasonable estimates. Observed thicknesses of depositional sequences that accumulated in a basinal setting are less than 5 m (17 ft). No subaerial exposure is indicated at these lower elevations. Water depth was also sufficient to effectively shut down carbonate accumulation while the basin setting was distal from a source to eliminate most siliciclastic influx. Initial modeling results using sediment-starved conditions developed below 50 m (165 ft) and the same sea-level range of 160 m (528 ft) as used in western Kansas resulted in thick sedimentary deposits in a basinal setting at a shelf elevation of 100 m (330 ft). Changing sediment-starved water depth to 20 m (66 ft) led to limited sediment accumulation as observed (fig. W-12). Eventually,

sediment thickness is great enough to where longer periods of shallow-water sediment accumulation occurred. Faster and longer sediment accumulation would restore the site to a shelf setting without changes in subsidence or lack thereof.

Local water clarity or nutrient supply could have substantially lowered carbonate productivity and led to a decreased euphotic zone, a parameter that needs further investigation (vis-a-vis Hallock and Schlager, 1986). If water depths dropped to less than 20 m (66 ft), then normal carbonate accumulation could occur in what was previously sediment-starved, basinal conditions. For example, the Mound Valley Limestone, an upper parasequence of the Swope sequence, was deposited in a lower shelf and basin-margin setting. The basin had become partially filled by a low-stand clastic wedge of Ladore Shale, reducing the water depth. Carbonate accumulation occurred during initial flooding associated with this parasequence when siliciclastic sedimentation was reduced.

On the lower shelf, carbonate strata accumulate to fill available accommodation space provided by sea-level inundation when water depths become sufficiently shallow to permit carbonate production. If no subsidence occurs, sedimentation during the younger sequences eventually becomes increasingly more limited in duration and increasingly shallower as sediment-surface elevation increases (fig. W-13). The model shows peaks of inundation followed by considerable episodes of subaerial exposure. However, by the beginning of the Dennis sequence, the shelf margin and associated

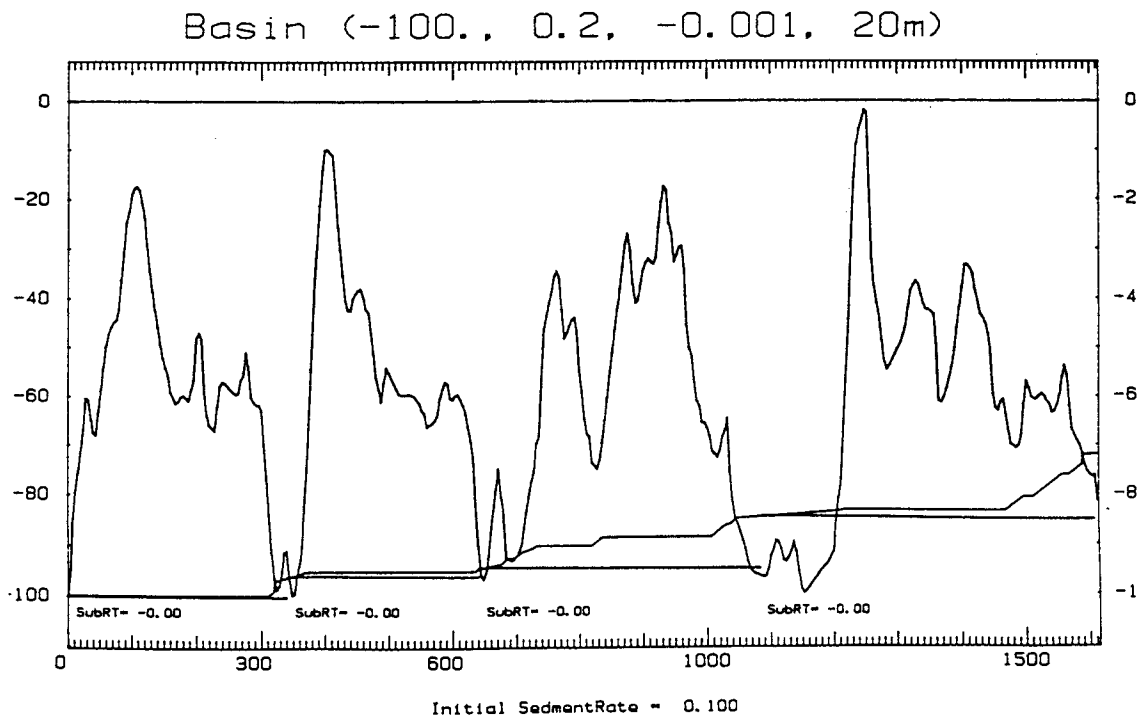


FIGURE W-12—COMPUTER SIMULATION OF BASIN SETTING IN SOUTHEASTERN KANSAS. No subsidence, euphotic limit set at 20 m (66 ft; no substantial carbonate accumulation), initial sediment-surface elevation set equal to -100 m (-330 ft).

margin-carbonate buildup appears to have backstepped on the shelf in southern Kansas (fig. 52). Rather than a simple, thin shallow-water carbonate deposit for the Dennis sequence, the associated sedimentary record is complicated by numerous, distinctive parasequences (see discussion in Stops 6 and 7). Structural flexing and accelerated subsidence may have created this backstepping episode.

The fourth sequence shown in the model of fig. W-13 developed in association with renewed subsidence. Rather than a single episode of sediment accumulation, multiple episodes (parasequences) of sediment accumulation are developed as sea level and subsidence both track downward at similar and realistic rates. The elevation of the sediment surface then closely follows a trend of smaller scale rises and falls in sea-level elevation, encouraging parasequence development.

### Summary

Modeling provides the opportunity to examine various scenarios. Further information can constrain the

parameters to develop a unique solution. Once model results become sufficiently sophisticated, inferences made from available subsurface data can define locations of potential sites of favorable reservoir development.

The modeling illustrated here is the initial attempt in quantitative process-response simulation of Missourian cyclothemic strata. Glacial-eustatic fluctuations tailored from Pleistocene events appear to be appropriate for generating Paleozoic cyclothemic strata in the midcontinent. However, more sophisticated inversion procedures are needed to convert rock observations (including geophysical data) to process as a function of time for modeling. Time-series variation of process interpretations from site to site over considerable distances should provide means to distinguish coherent signals with regional and local significance such as eustasy, tectonism, and autogenic processes. Once this threshold of operation is reached, the potential for prediction of depositional sequences may be realized. This approach should be applicable to other age strata. The Pennsylvanian of the midcontinent is simply well suited to this approach.

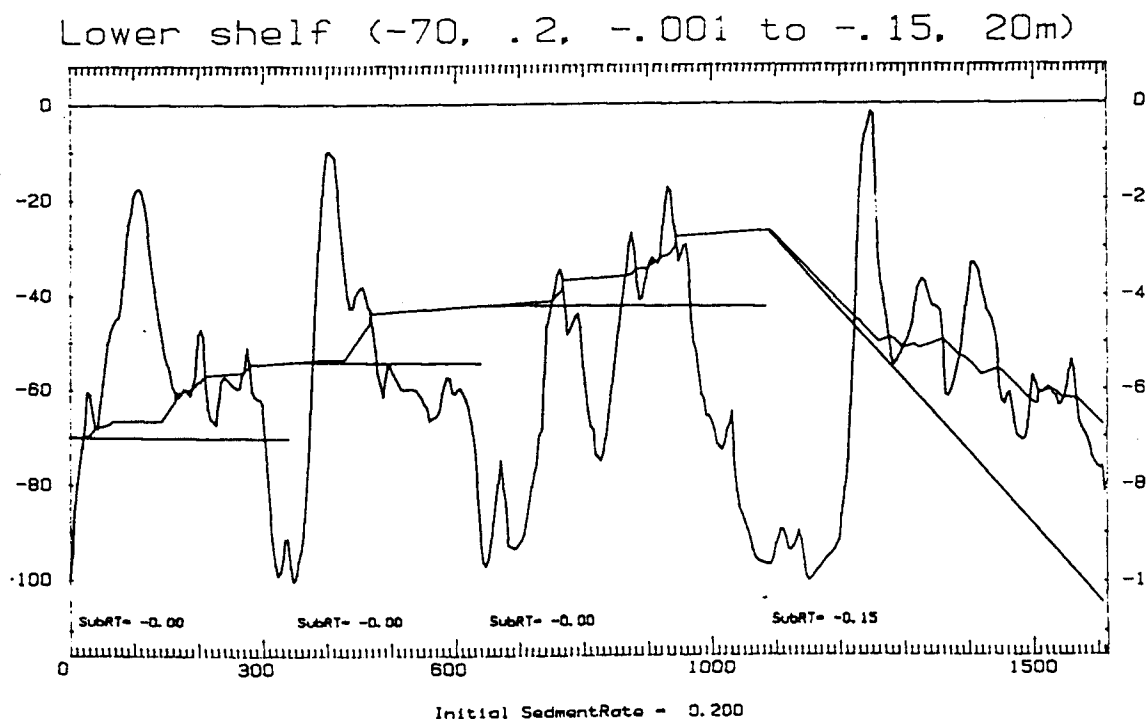


FIGURE W-13—COMPUTER SIMULATION OF LOWER SHELF SETTING IN SOUTHEASTERN KANSAS. No subsidence for first three sequences and moderate subsidence invoked during development of fourth sequence. Euphotic limit set again at 20 m (66 ft). Gain in sediment-surface elevation until fourth sequence when subsidence begins.



# Road Log

## October 14-15, 1989

### Itinerary

TABLE 1—FIELD-TRIP ITINERARY

DAY 1 Saturday, October 14, 1989

	Lawrence	Leave: 8:00 a.m. (20 min.)
1.	Edgerton	Arrive: 8:20 (SE SE SE sec. 2, T. 13 S., R. 21 E.) Johnson County Leave: 9:00 (15 min.)
2.	Desoto	Arrive: 9:15 (NE NE SW sec. 6, T. 13 S., R. 22 E.) Johnson County Leave: 10:15 (20 min.)
3.	Holliday Drive	Arrive: 10:35 (W/2 NE sec. 6, T. 12 S., R. 24 E.) Johnson County Leave: 11:35 (15 min.)
4.	I-435/I-70	Arrive: 11:50 (NE SW sec. 13, T. 11 S., R. 23 E.) Wyandotte County Leave: 12:50 (10 min.)  Lunch 40 min. Arrive: 1:00 Leave: 1:40 (15 min.)
5.	Holliday Drive South	Arrive: 1:55 (C sec. 6, T. 12 S., R. 24 E.) Johnson County Leave: 2:20 (30 min.)
6.	Gregory Road	Arrive: 2:50 (NE NE SE sec. 12, T. 48 N., R. 33 W.) Leave: 3:20 (10 min.)
7.	Raytown	Arrive: 3:30 (SW SW NW sec. 6, T. 48 N. T. 32 W.) Jackson County, MO Leave: ~4:30

Return Lawrence at 5:30 to 6:00 p.m.

DAY 2 Sunday, October 15, 1989

- |     |   |  |
|-----|---|--|
|     | Lawrence  | Leave: 7:00 a.m.<br>52 miles   |
| 8.  | Farlinville N.  | Arrive: 8:20 (E/2 SW sec. 34, T. 20 S., R. 23 E.)<br>Linn County<br>Leave: 9:20<br>(30 min.)       |
| 9.  | Xenia NW  | Arrive: 9:50 (C S/L SW sec. 23, T. 23 S., R. 22 E.)<br>Bourbon County<br>Leave: 10:10<br>(10 min.) |
| 10. | Drive by Xenia NE (10A), Mapleton NW (10B), Turkey Creek East (10C) |  |
| 11. | Uniontown   | Arrive: 11:05 (C N/2 sec. 34, T. 25 S., R. 22 E.)<br>Bourbon County<br>Leave: 12:15                |
|     | Lunch w/travel<br>(45 min.)   |  |
| 12. | Ogeese East   | Arrive: 1:00 (S2 S2 SE sec. 7, T. 29 S., R. 20 E.)<br>Neosho County<br>Leave: 1:20<br>(40 min.)    |
| 13. | Big Hill  | Arrive: 2:00 (NW NW SW sec. 7, T. 32 S., R. 18 E.)<br>Labette County                               |

Field trip ends 3:00 p.m.

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# 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

Arrive: 8:20 AM

Leave: 9:00 AM

(15 minutes to Stop 2)

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. 21.

A complete Kansas cyclothem represents a major marine inundation in a shelf setting. Carbonate-dominated cyclothem 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 cyclothem 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

*At all stops the exposed interval will be described from base to top.*

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., in Franseen and Watney, 1989).

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

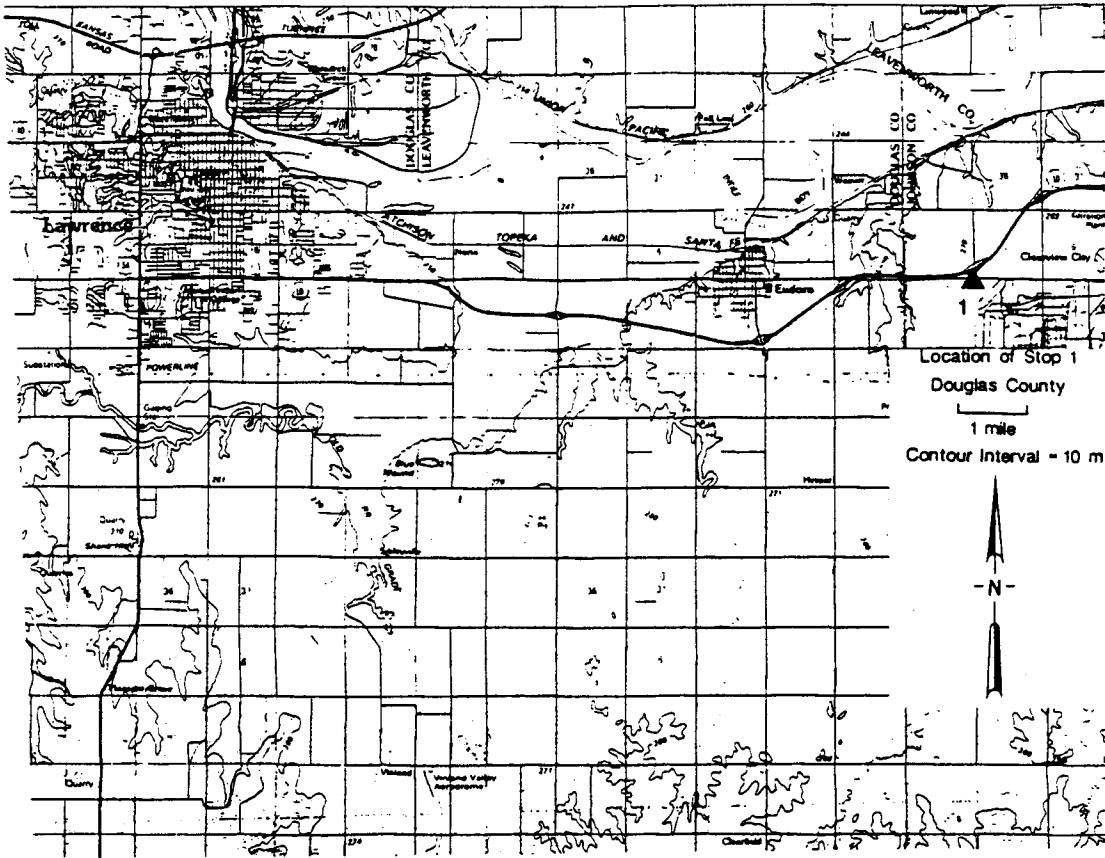


FIGURE 1-1—LOCATION MAP FOR STOP 1, EDGERTON EXIT ON HIGHWAY 10 EAST OF LAWRENCE.

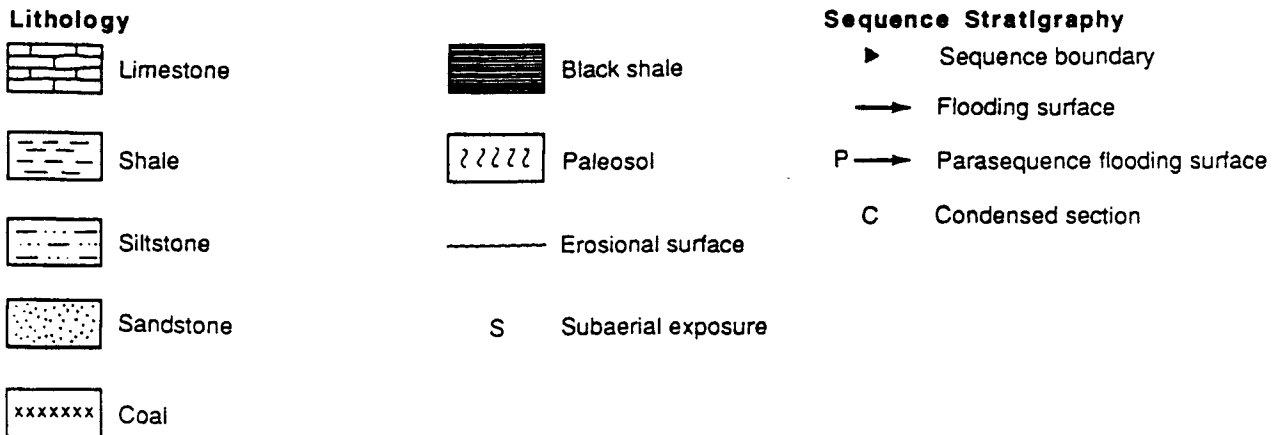


FIGURE 1-2—LEGEND WITH MAJOR LITHOLOGIES, SURFACES, AND SEQUENCE-STRATIGRAPHIC TERMS.

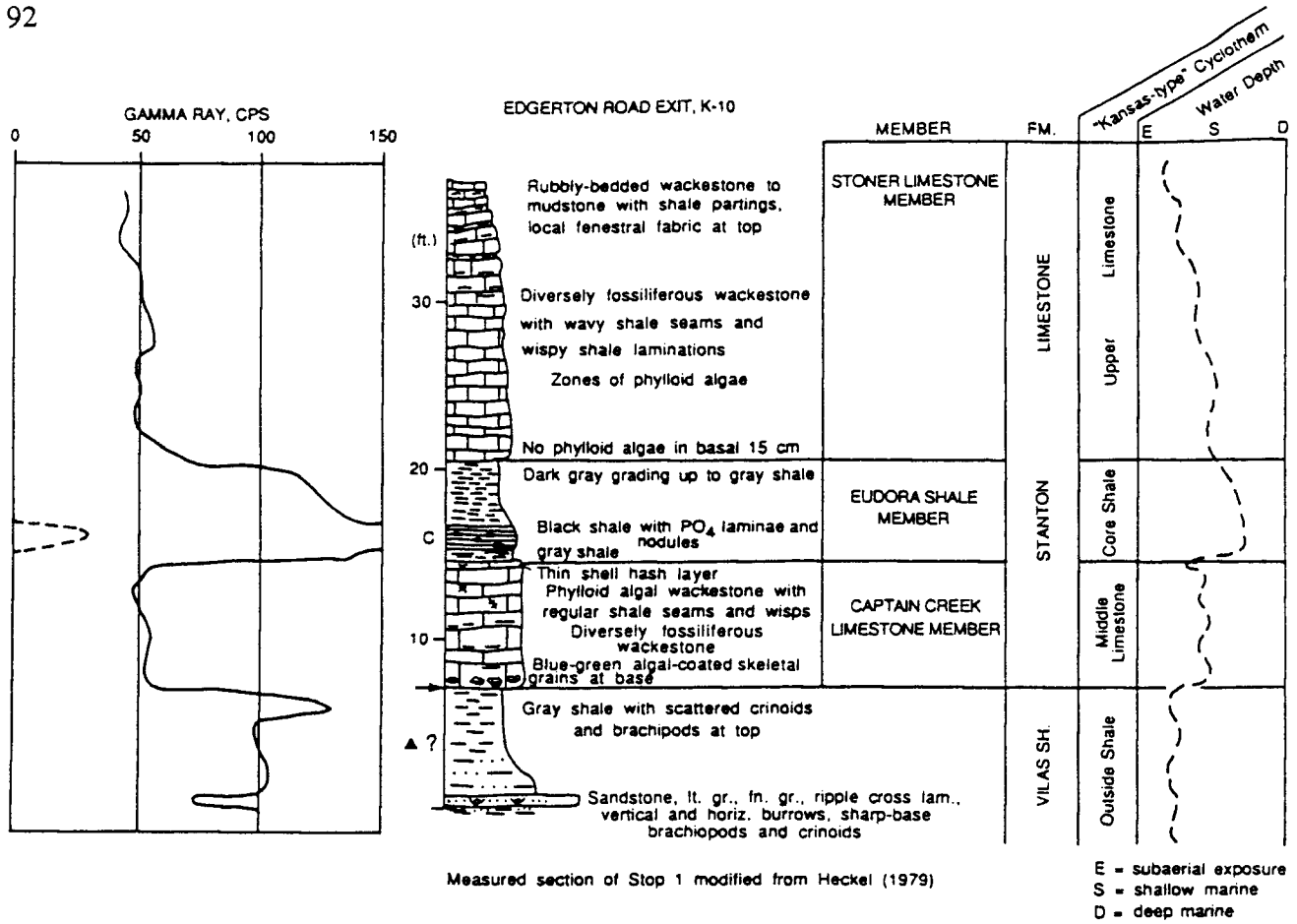


FIGURE 1-3—MEASURED SECTION OF STANTON LIMESTONE AT STOP 1. Natural gamma-ray profile obtained with hand-held gamma scintillation counter. Symbols used in graphic columns are shown in fig. 1-2.

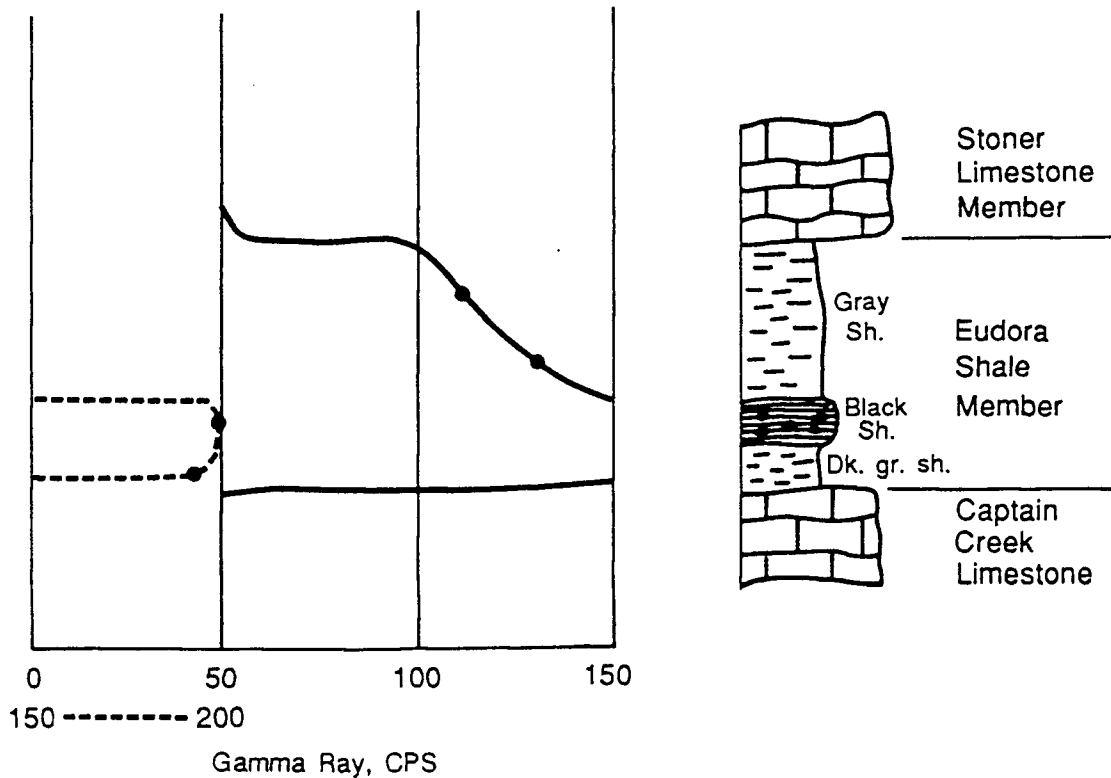


FIGURE 1-4—FOUR-FOOT (1.2-M)-THICK SECTION OF EUDORA SHALE EXPOSED ALONG I-435, 14 mi (23 km) east of Stop 1. Section is very similar to that seen at Stop 1.

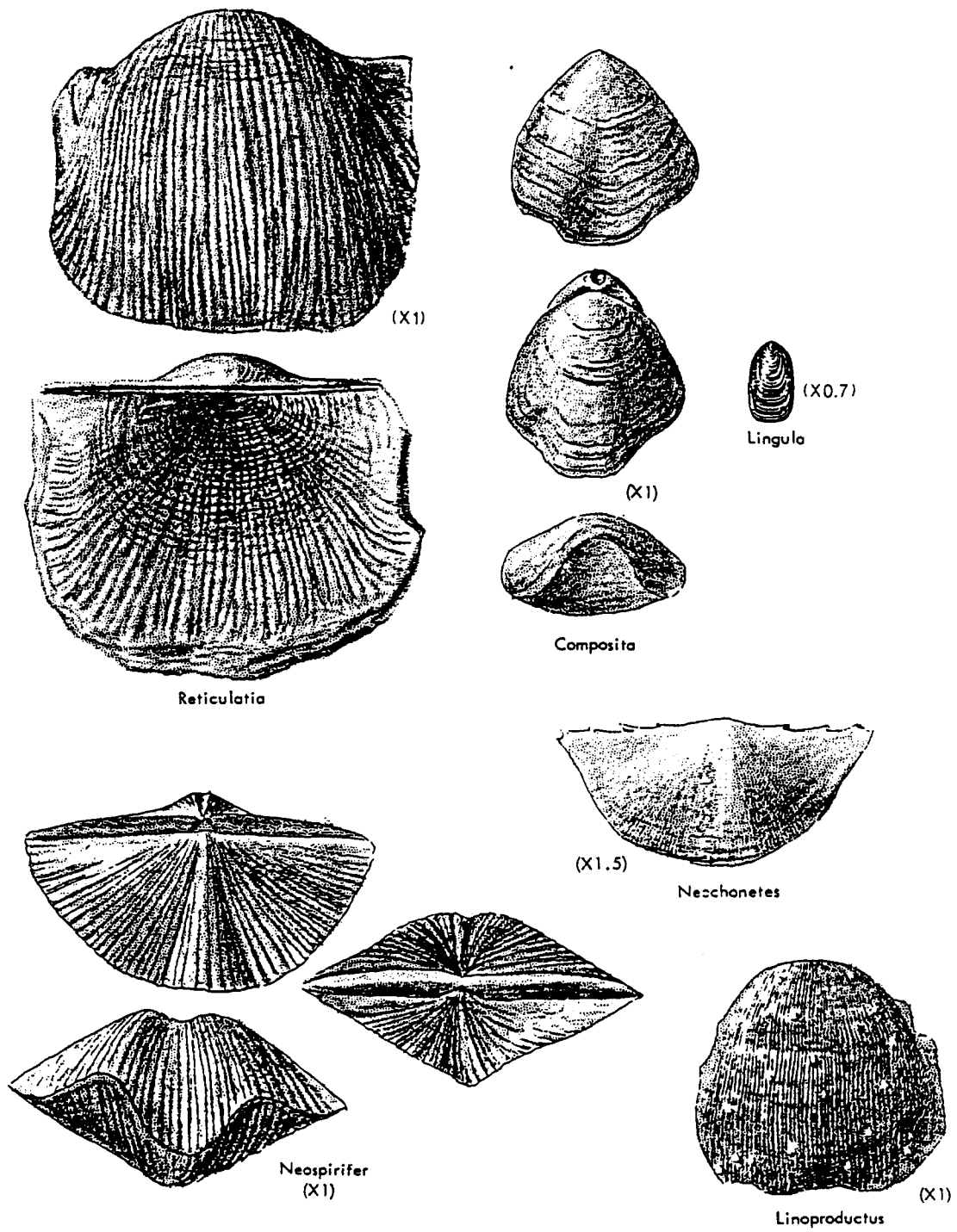


FIGURE 1-5—COMMON MACROFOSSILS OCCURRING IN UPPER PENNSYLVANIAN STRATA (from Moore, 1964).

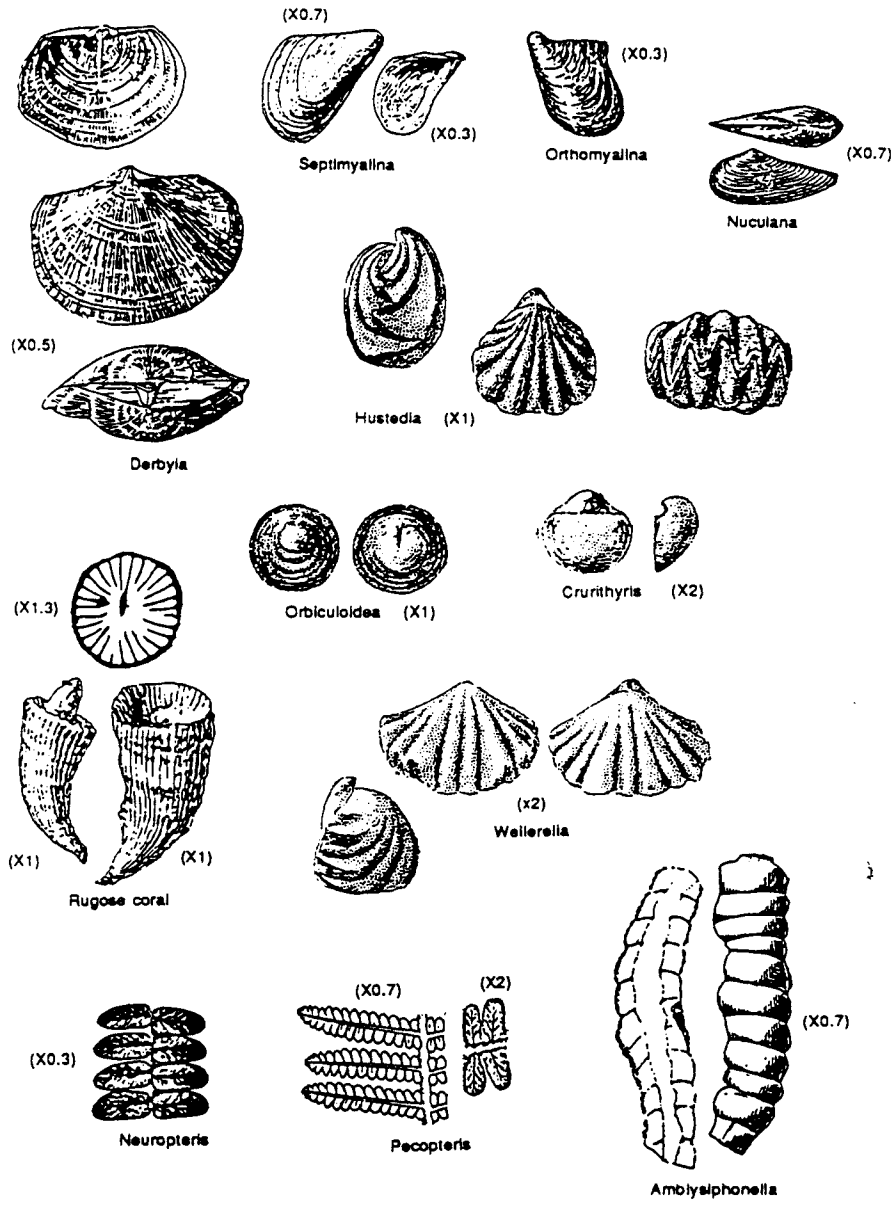


FIGURE 1-6—COMMON MACROFOSSILS OCCURRING IN UPPER PENNSYLVANIAN STRATA (from Moore, 1964).

## Stop 2 Desoto roadcut on south side of K-10 Highway, 5 mi (8 km) east of the Desoto exit: Wyandotte Limestone (Argentine Limestone, Island Creek Shale, Farley Limestone), Bonner Springs Shale, Merriam Limestone, Hickory Creek Shale

Location: NE NE SW sec. 6, T. 13 S., R. 22 E., Johnson County, Kansas

Arrive: 9:15 AM

Leave: 10:15 AM

(20-minute drive to next stop)

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

### Introduction

Stop 2 is located 8 mi (12.9 km) east from Stop 1 on Highway 10 (fig. 2-1). A cross sectional view from east to northwest of this outcrop (figs. 2-2 and 2-3, cross section and index map) shows the relationships between the underlying "Lane" Shale (which is in quotes due to a recently discovered miscorrelation), the outside shale of the underlying Iola cyclothem, and the two main members of the Wyandotte Limestone, the Argentine and Farley limestones. The Wyandotte Limestone at this stop consists almost entirely of phylloid-algal wackestone. It represents a vertically stacked series of broad algal banks, typical of platform buildups that developed across this area in response to the interplay between sea-level changes and the underlying depositional topography (Crowley, 1969).

The area to the east of this outcrop, where both the "Lane" and Wyandotte are thin, has been interpreted as a paleotopographic low on the "Lane" deltaic platform, where circulation was presumably restricted (Crowley, 1969; fig. 2-3). This outcrop is located on an area of Wyandotte bank development, on the northwestern side of the underlying "Lane" platform (fig. 2-4). The Wyandotte Limestone bank rapidly thickens off the northwest flank of the elongate, shale-dominated "Lane" delta, attaining thicknesses exceeding 80 ft (24 m) (figs. 2-4, 2-5, and 2-6). The combination of increased accommodation and normal-marine circulation to

the northwest and the southeast is inferred to have promoted bank development in these directions.

Recent work by Arvidson (1988) has established that the "Lane" Shale continues to thin regionally to the southwest (basinward) from the Kansas City area. In Miami County, 25 mi (40 km) south of this stop the "Lane" becomes a mere shale seam that separates the Iola from a very thin Argentine Limestone south of Paola, Kansas. This reflects the southern terminus of the delta platform. The phylloid-algal mounds of the Wyandotte Limestone occur at lower and intermediate levels on the slopes of the Lane delta.

The Island Creek Shale separating the Farley and Argentine Limestones thickens southward and westward in front of the "Lane" deltaic platform, forming another deltaic unit that thickens in areas where the Argentine Limestone and "Lane" Shale are both thin. The Farley Limestones form localized banks over the broader Argentine buildups; part of such a buildup is visible at this stop. The Farley Limestone is continuous to the south over the thicker Island Creek Shale and to the north across the upper shelf. The Farley Limestone pinches out (laps out) in southern Iowa 160 mi (260 km) north of this site, lower on the shelf than other Missourian marine inundations (fig. 2-7; Heckel, 1986, 1989). Cores of the Farley Limestone 100 mi (160 km) north in northwestern Missouri contain two separate carbonate beds (Heckel, 1985).

### Stratigraphy

The measured section for Stop 2 is found in fig. 2-8. The stratigraphy of the Wyandotte Limestone is considerably more complex than the Stanton Limestone seen at Stop 1. Harris (1985) previously attributed the shale beds in the Farley Limestone to pulses of deltaic sedimentation. New evidence, including both surfaces that exhibit erosion as well as shoal-water lithologies that are succeeded by marine flooding, supports relative changes in base level as the primary cause of the alternating shale and limestone deposition represented here.

The *Wyandotte Limestone* includes the thin basal Frisbie Limestone Member which is a middle limestone of the Wyandotte cyclothem and a flooding unit of the Wyandotte sequence (fig. 3a). This unit is succeeded by the *Quindaro Shale*, a low radioactive core shale (condensed section). The *Argentine Limestone* is an upper limestone of the Kansas cyclothem and is a shallowing-upward unit within the depositional sequence. The *Island Creek Shale* and the

*Farley Limestone* comprise the upper members of the Wyandotte Limestone. The Farley Limestone, which has two members here, is either an additional limestone within a Kansas cyclothem, or a separate cyclothem that lacks a middle limestone and core shale.

Evidence at this exposure and in others of the same interval indicates that both units of the Farley Limestone represent parasequences (which represent relatively minor episodes of marine flooding) in the overall upward-shallowing package of the Wyandotte sequence. This is consistent with the fact that the Farley Limestone laps out at higher shelf positions, indicative of less extensive inundation. Moreover, there is no condensed section developed in this package, again suggesting that relatively moderate water depths were attained.

The base of the exposure at Stop 2 is within the middle portion of the Argentine Limestone (fig. 2-8). The Argentine Limestone consists of a wavy-bedded phylloid-algal wackestone with abundant brachiopods and crinoids. Wispy shale seams are common.

The upper few feet of the Argentine Limestone contain gray mottles. The upper few centimeters are silicified, with scattered dark-red mottling. The upper surface rises some 7 ft (2.1 m) to the west across the length of this exposure. In addition, sharp, irregular, cm-scale relief is apparent on this surface in most places examined. Unequivocal evidence for subaerial exposure is not apparent at this surface; rather, it may represent a hardground or firmground that developed during reduced rates of sedimentation associated with marine flooding.

The *Island Creek Shale* includes up to 5 ft (1.5 m) of a basal gray siltstone and one to several beds of coarse-grained encrinite overlain by gray fossiliferous shale. An isolated occurrence of a chaetided-like carbonate mass was found in an encrinite bed on the north side of this exposure. The unit rests on the flooding surface and was deposited prior to renewed accumulation of phylloid algae.

The gray shale and basal encrinite both thin noticeably westward onto the higher surface of the Argentine Limestone. The shale pinches out, with only a thin layer of encrinite that rests directly on the upper surface of the Argentine Limestone remaining.

The encrinite represents a flooding unit, with subsequent deepening and deposition of clay below wave base. A similar encrinite occurs below a shale separating the Argentine and the Farley limestones on Highway 69 near Louisburg, Kansas, 25 mi (40 km) to the south.

The Farley Limestone is composed of two carbonate units separated by a thin silty to calcareous shale. The Farley units are lithologically quite variable locally, although both are phylloid-algal wackestones at this exposure. The units vary from skeletal lime packstone and lime mudstone to crossbedded ooid grainstone to the northeast in northern Johnson and Wyandotte counties. The basal lower Farley Limestone consists of 20 ft (6.1 m) of phylloid-algal carbon-

ate exhibiting low gamma radiation, closely resembling the Argentine Limestone. There appears to be very little variation in facies here except for a basal argillaceous interval. However, the lower Farley Limestone varies considerably within the west side of Johnson and Wyandotte counties, ranging in thickness from 8 ft (2.4 m) at Stop 3, 8.5 mi (13.7 km) northeast, to 23 ft (7 m) of interstratified limestone and shale 7 mi (11 km) north. The intercalated shale and carbonate facies of the Lower Farley could reflect the proximity to the active Island Creek delta as suggested by Harris (1985).

The upper 7 ft (2.1 m) of the lower Farley Limestone is gray and mottled. The top contains isolated shallow depressions filled with a few centimeters of carbonate lithoclastic conglomerate indicating that submarine(?) erosion preceded deposition of the overlying siltstone of the middle Farley shale.

The middle Farley shale is a thin (1 ft, 0.3 m), but continuous siltstone along the length of the exposure. It is interpreted as representing another flooding episode of an uppermost parasequence of the Wyandotte sequence.

The *upper Farley Limestone* is the thinnest of the three limestones. It contains a lower bed of algal-coated skeletal grains in a lime mud-supported matrix. This bed is succeeded by another phylloid-algal wackestone similar to those strata below. The limestone is capped by lenses of burrowed packstone to grainstone suggesting shallowing and perhaps reduced sedimentation rate. Although shoal-water conditions are noted, no subaerial exposure is indicated along this surface.

The outside shale of the Wyandotte cyclothem is the *Bonner Springs Shale*. It is also the uppermost unit in the shallowing-upward Wyandotte sequence. Until recently, the silty and sandy Bonner Springs Shale could be seen to pinch out in a quarry (now destroyed) on the other side of the south face of this exposure (fig. 2-9A and B). Thinning can be seen from east-to-west across the upper portion of the south face. The cross section (fig. 2-2) indicates that the shale maintains a uniform thickness locally. This pronounced thinning of the Bonner Springs Shale is considered to have resulted from local erosional truncation, based on information from the initial investigations of Enos and Herman (this volume, Stop 4) and work of Harris (1985). Stop 4 will focus on the complex nature of the Bonner Springs Shale and the nature of processes that occurred during marine inundation related to the overlying sequence.

Stop 5 will show a more normal Bonner Springs Shale with a paleosol developed near its upper surface. The subaerial event is widespread, but as evidenced here, it is locally eroded and not preserved. Nevertheless, extensive erosion and paleosol development reflects termination of the Wyandotte sequence.

The overlying flooding unit associated with another major marine inundation of the Plattsburg sequence is the Merriam Limestone. This is also a middle (transgressive) limestone of the Kansas cyclothem. The lower portion of the

Merriam Limestone consists of a skeletal wackestone (Harris, 1985), with a 1-ft (0.3-m)-thick bed of skeletal wackestone to packstone capping the unit.

The *Hickory Creek Shale* overlies the Merriam Limestone. It is the core shale of the Plattsburg Limestone and the condensed section of the Plattsburg sequence. No black, fissile facies nor elevated gamma-ray count is associated with the shale. Sparse faunas are generally open marine

except in topographic lows where the Bonner Springs Shale has apparently been eroded (Enos and Herman, this volume, Stop 4). The lows contain dark-gray shale with fauna diagnostic of low-oxygen conditions (Boardman et al., 1984). The variation is comparable to the Eudora Shale of the Stanton sequence. Local changes in the Eudora Shale are attributed to positive topographic relief where more regional black fissile facies locally change to dark-gray facies.

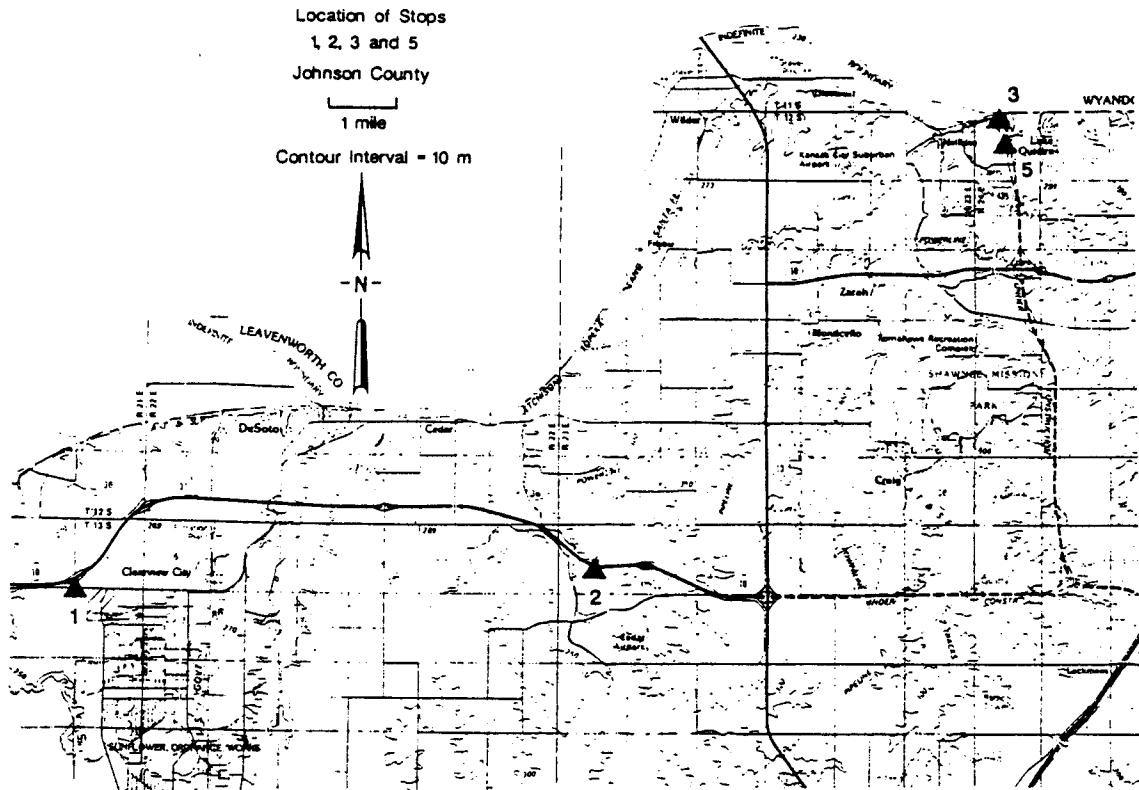


FIGURE 2-1—LOCATION MAP SHOWING STOPS 1, 2, 3, AND 5 IN JOHNSON COUNTY, KANSAS.

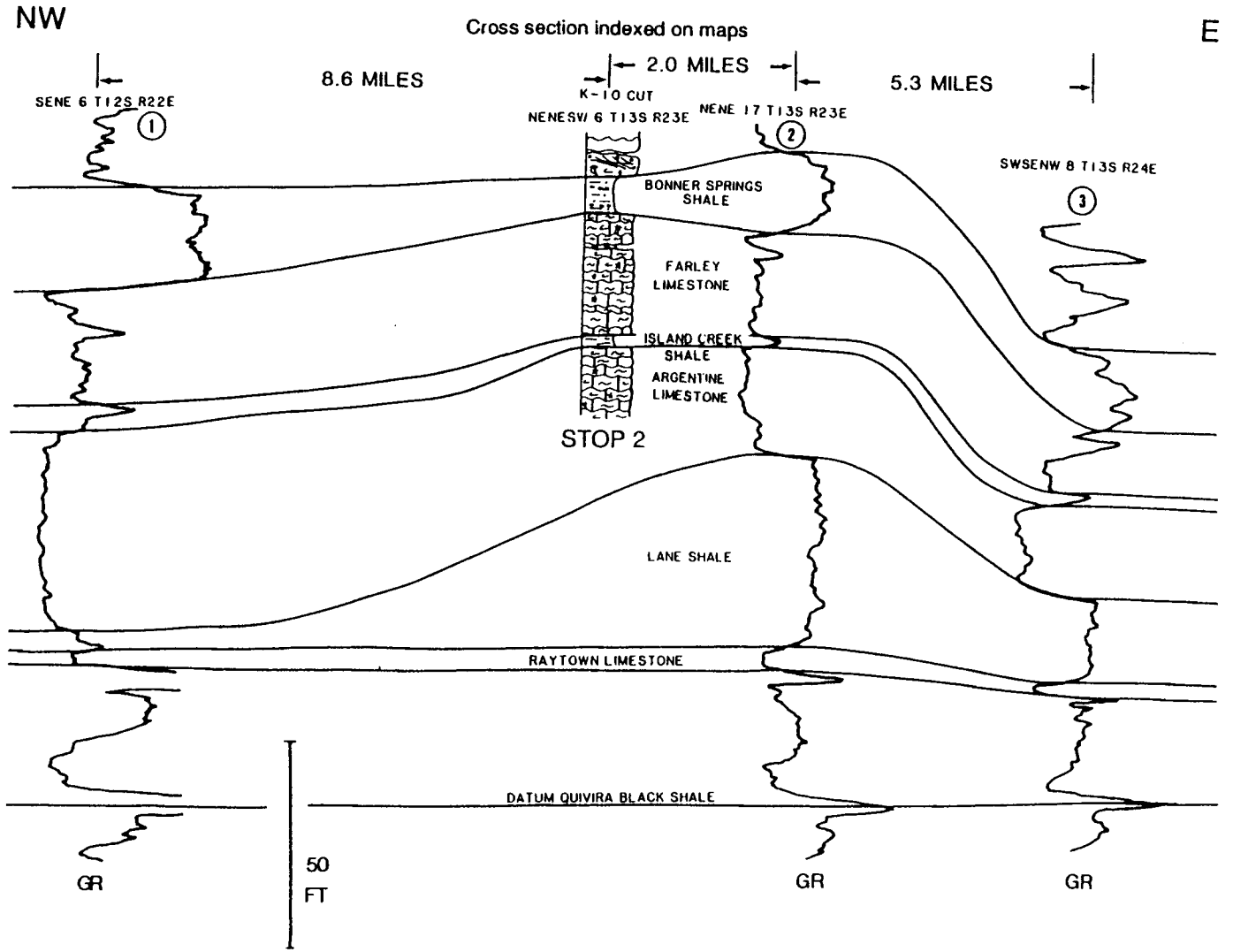


FIGURE 2-2—NORTHWEST TO EAST STRATIGRAPHIC CROSS SECTION CONSTRUCTED FROM GAMMA-RAY PROFILES FROM WELL LOGS NEAR STOP 2. The Stop 2 measured section is located in the middle of this cross section. Index map to section is found in fig. 2-3. Note the local topographic high associated with Lane Shale. The cross section is a strike section with respect to shelf-basin.

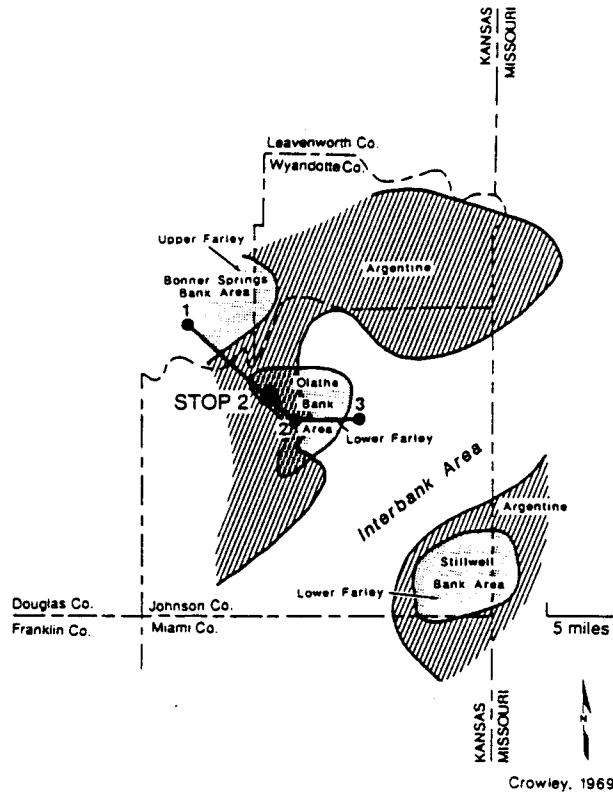


FIGURE 2-3—LOCATION OF PHYLLOID-ALGAL BANKS IN THE WYANDOTTE LIMESTONE IN THE KANSAS CITY AREA. Location of wells used in cross section of fig. 2-2 shown on this map.

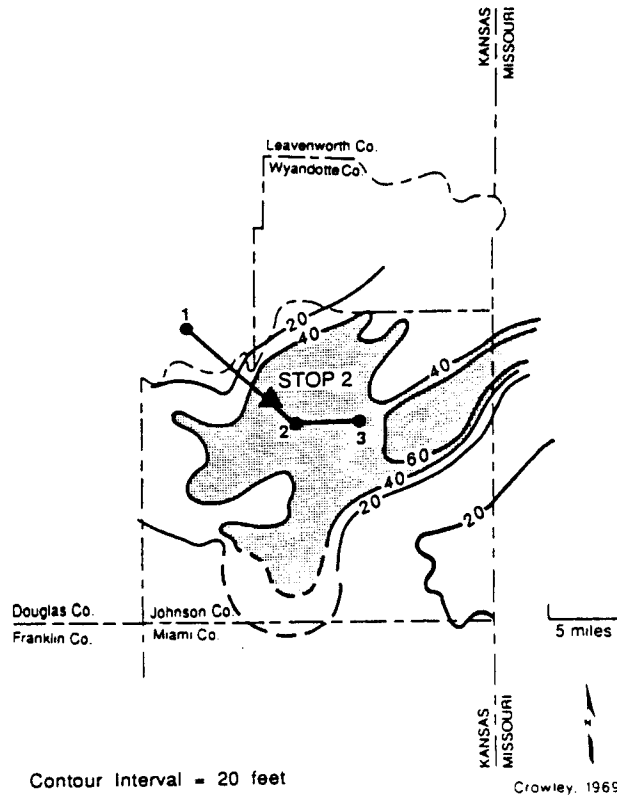


FIGURE 2-4—THICKNESS OF "LANE" SHALE IN FEET. Wells used in cross section of fig. 2-2 are shown.

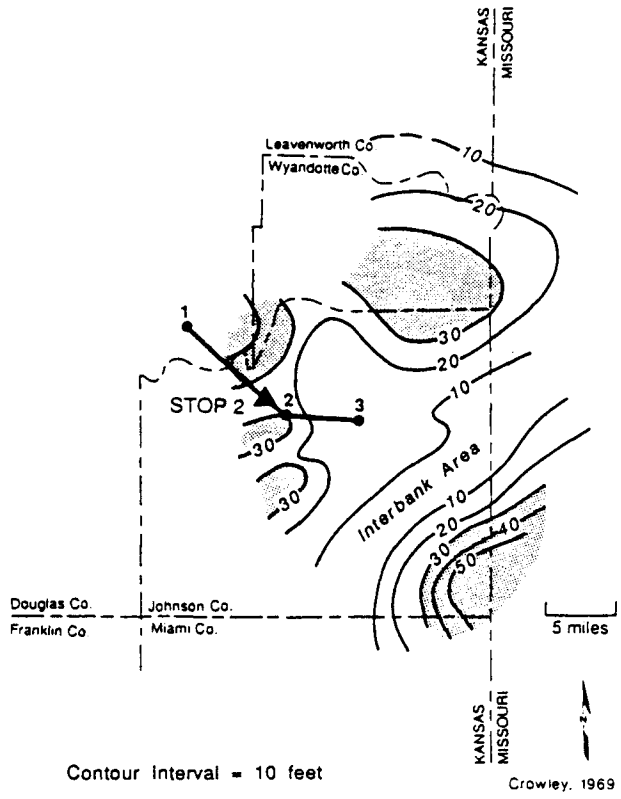


FIGURE 2-5—THICKNESS OF ARGENTINE LIMESTONE MEMBER OF WYANDOTTE LIMESTONE.

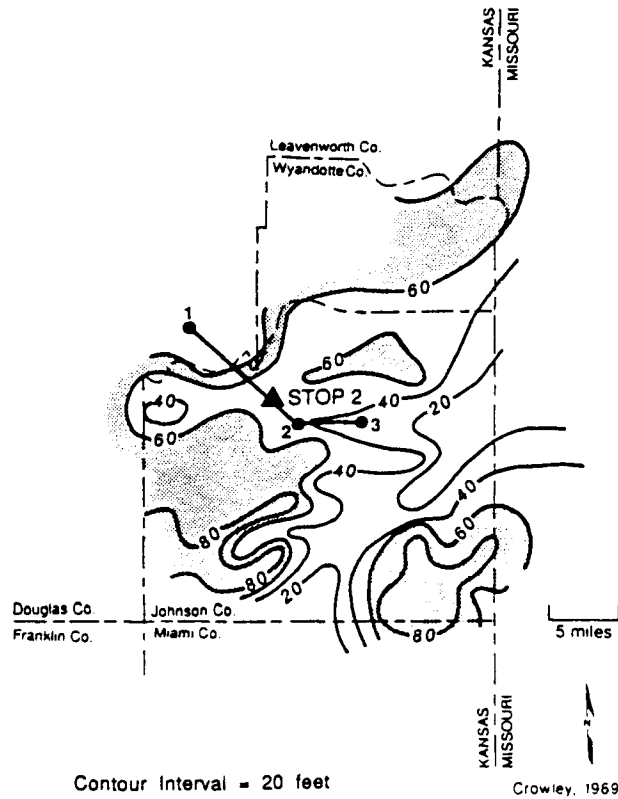


FIGURE 2-6—THICKNESS OF WYANDOTTE LIMESTONE WHICH IS COMPOSED OF THE ARGENTINE AND TWO FARLEY LIMESTONES.

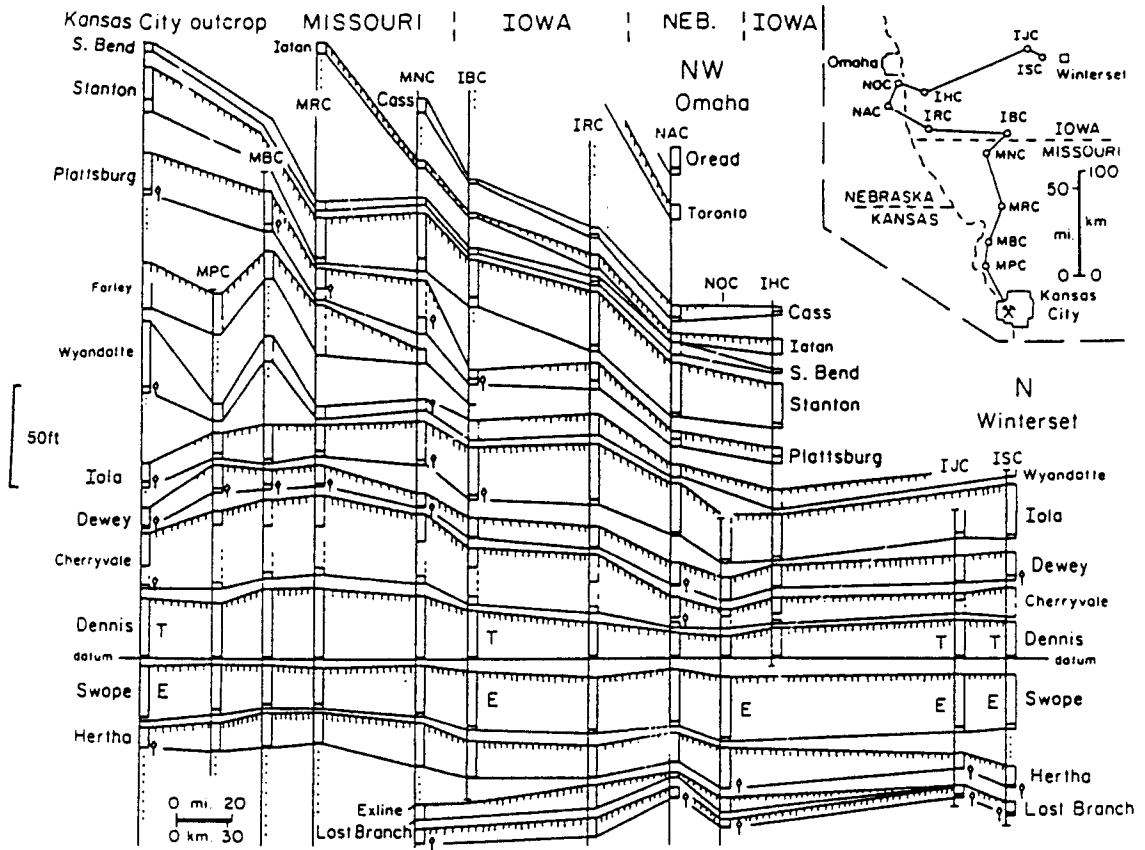
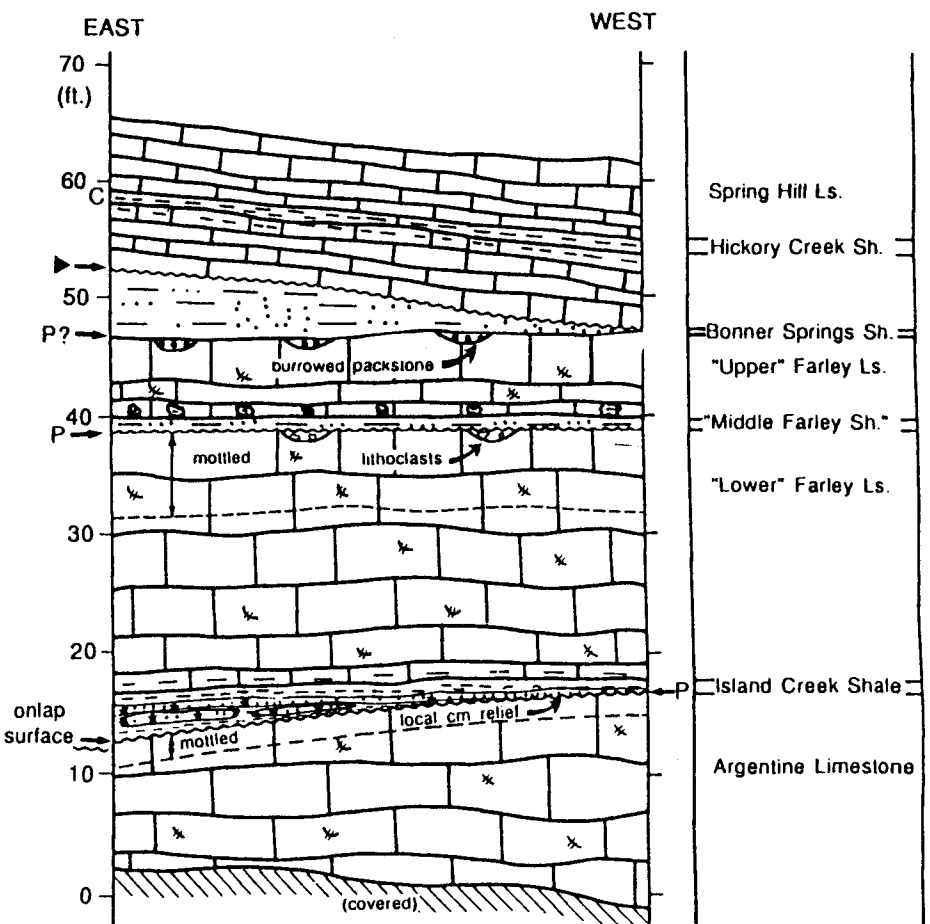


FIGURE 2-7—CORRELATION OF MISSOURIAN ROCKS ON NORTHERN MIDCONTINENT SHELF FROM KANSAS CITY TO CENTRAL IOWA BASED ON LONG CORES. Lateral continuity of major marine limestone-dominated cyclothem separated by terrestrial formations, mostly paleosols, where the siliciclastic unit is thin and deltaic deposits where the siliciclastic unit is thick. Note the dominance of paleosols (hatched contacts) developed on the upper (regressive) limestone (from Heckel, 1989).



measured on west side of south exposure

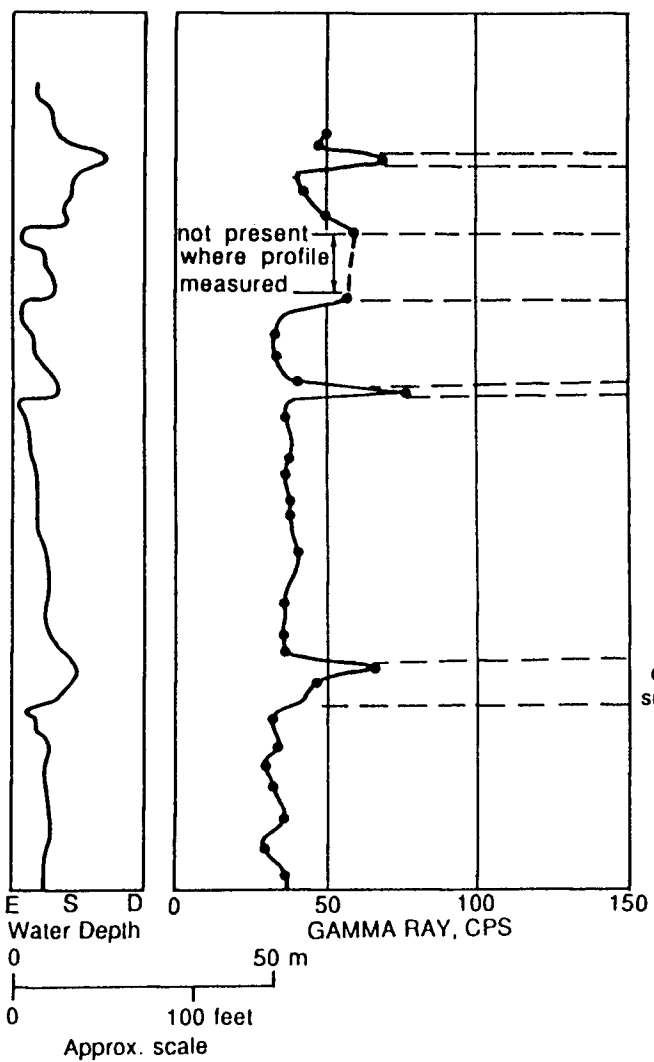


FIGURE 2-8—DETAILS OF THE MEASURED SECTION AND GAMMA-RAY PROFILE OF STOP 2.

FIGURE 2-9 (A AND B)—A QUARRY THAT PREVIOUSLY EXISTED ON THE HILL IMMEDIATELY SOUTH OF THE SOUTHERN OUTCROP OF STOP 2. View is to the northwest. The units from bottom to top include LF, lower Farley Limestone; UF, upper Farley Limestone; BS, wedge of Bonner Springs Shale; ME, Meriam Limestone, thickening as BS thins; HC, thin Hickory Creek Shale; SP, Spring Hill Limestone. Height of rock wall in center of photograph is approximately 40 ft (12 m). Photo by Paul Enos.

FIGURE 2-9 (C AND D)—WEST-FACING ROAD CUT EXPOSURE AT STOP 3 (HOLLIDAY DRIVE). Strata shown in this exposure from bottom to top include MC, Muncie Creek Shale; RT, Raytown Limestone; LA, "Lane Shale"; FR, Frisbie Limestone; QU, Quindaro Shale; and AR, Argentine Limestone.

**A**

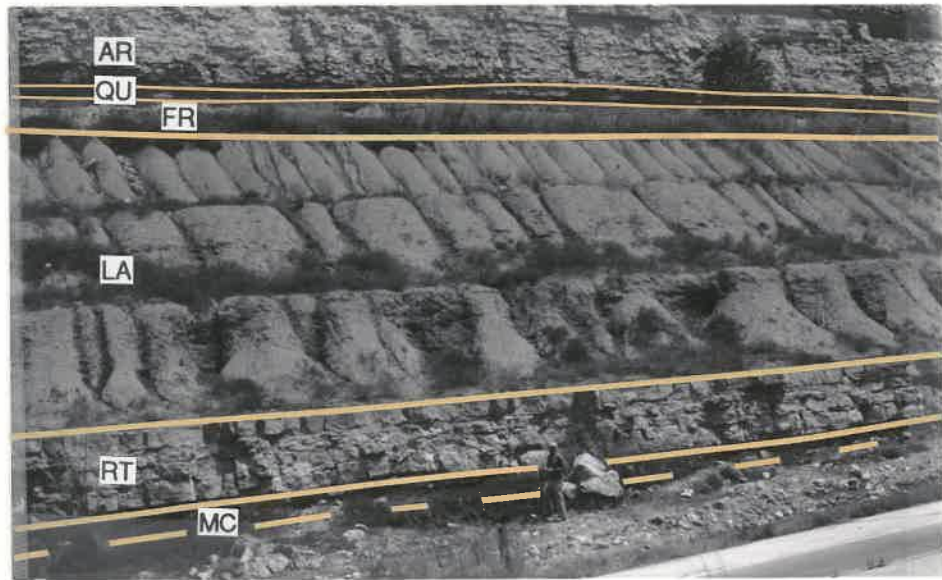


**B**





C



D

## Stop 3 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.)

Arrive: 10:35 AM

Leave: 11:35 AM

(15-minute drive to next stop)

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

### Introduction

These outcrops in the vicinity of Stop 3 (identified by the letters A, B, C, and D in fig. 3-1), 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. 3-1). Fig. 3-2 (a, b, c, and d) is a composite measured section as

prepared by Scott Johnsgard, 1984. Fig. 2-9 (C and D) includes a photo of west-facing exposure at Stop 3. The Bonner Springs Shale presented in this measured section (fig. 3-2 c and d) will be the focus of Stop 5. The gamma-ray profile and relative water-depth curve are included in fig. 3-3 (a and b). A gamma ray-neutron log from a nearby well has been correlated to the lithologies of this exposure (fig. 3-4).

### 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 (see appendix A).

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.

As was discussed at Stop 2, 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 is being prepared 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. 3-4). 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. 3-3b). 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 (fig. 2-4). This unit consists mostly of phylloid-algal wackestone at this locality and is capped by 3 ft (1 m) of coated skeletal packstone. As at Stop 2, no subaerial exposure is noted on this surface.

The *Farley Limestone* is developed as two distinct units as at Stop 2. Both units are notably thinner than at Stop 2 where they are phylloid-algal buildups, built farther down the flanks of the "Lane" delta than here at Stop 3. Here at Stop 3 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. As seen at Stop 3, it is an intertidal and shoal-water facies, perhaps suggesting that that location was more positive during deposition of the Farley Limestones than to the south at Stop 2. Best access to the Farley Limestone and the upper Argentine Limestone is on the west side of the road.

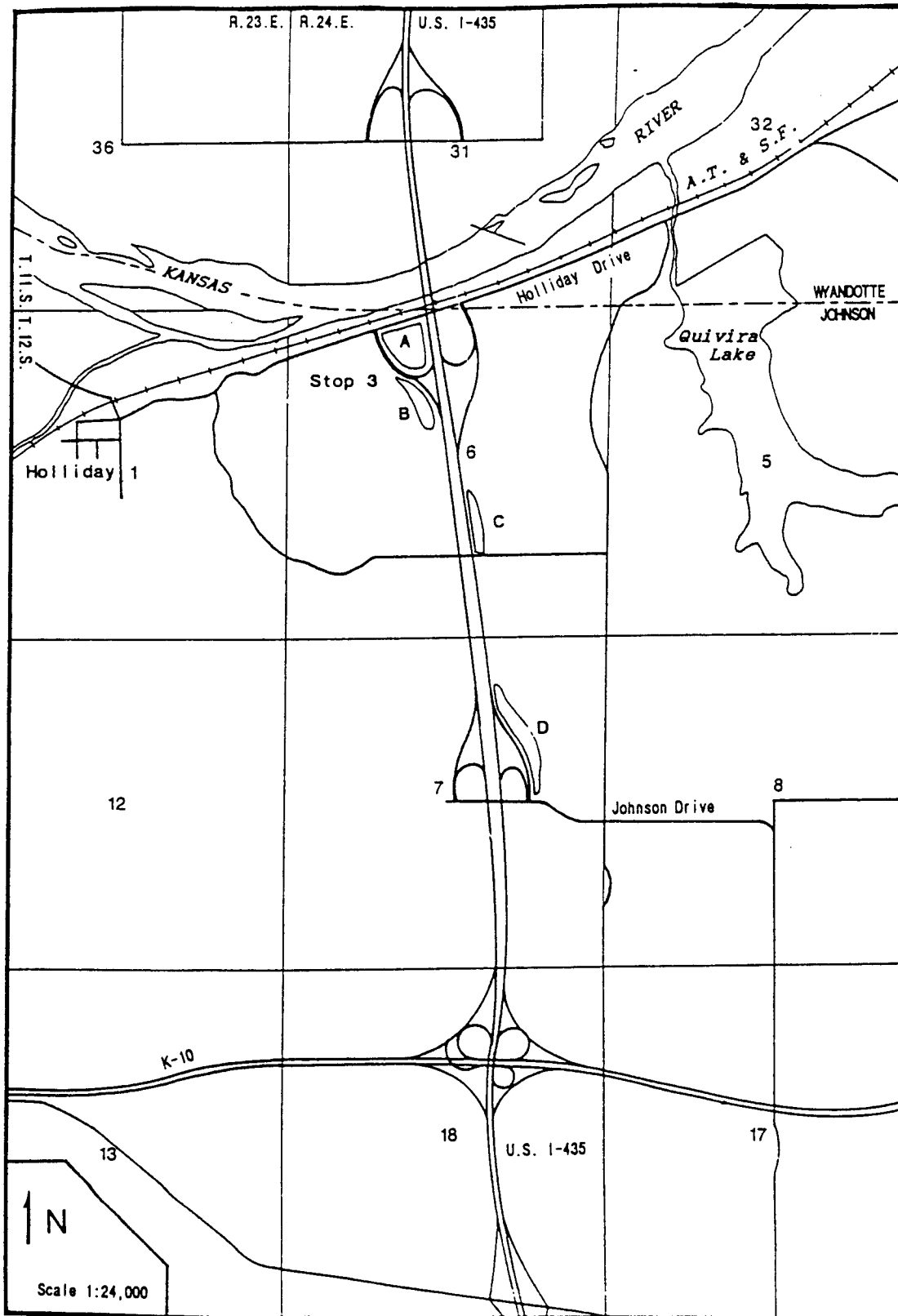
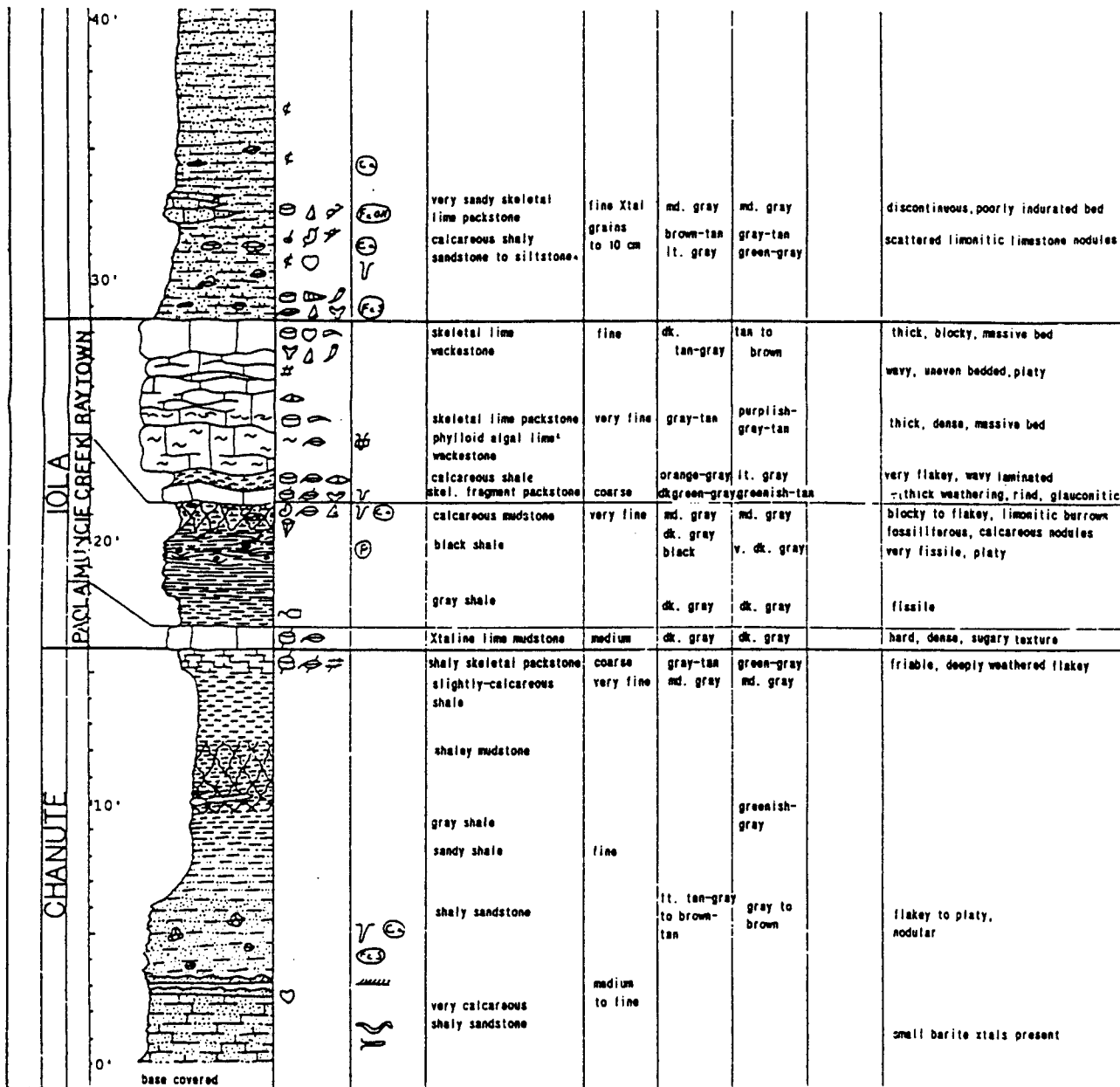


FIGURE 3-1. LOCATION MAP OF STOP 3 AND SITES A, B, C, AND D USED IN PREPARING MEASURED SECTION PROVIDED WITH STOP 3 (fig. 3-2, from Johnsgard, 1984).

a

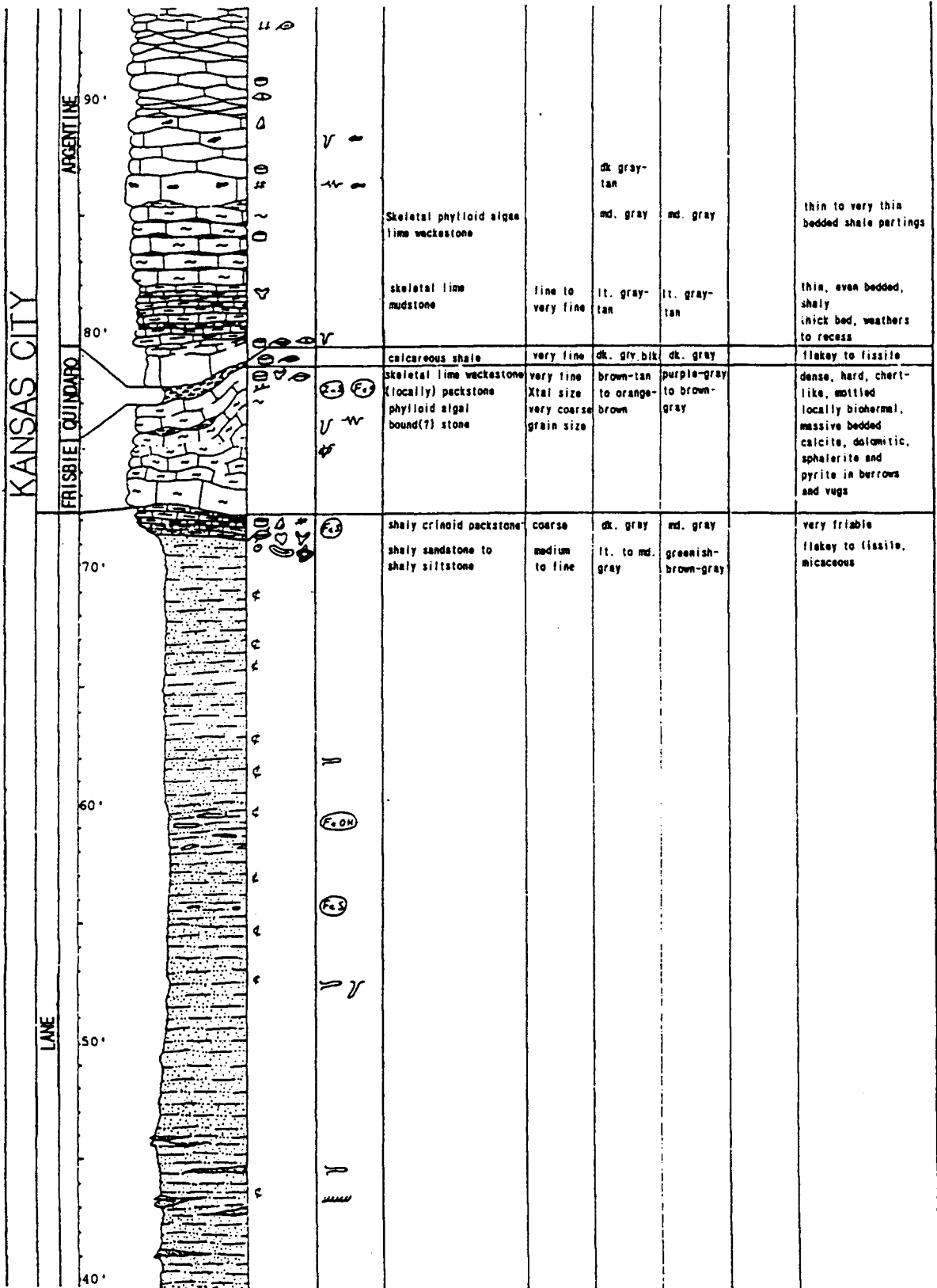


KEY TO SYMBOLS

FOSSILS	FOSSILS	PARTICLES	SED. STRUCT.	DIAGEN. FEAT.
Dermal Stromat. Algae	Brachiopod, General	Limestone Lithoclast	Imbricate Grains	Stylolites
Green, Codiacean Algae	Spirifer Brachiopod	Shale Lithoclast	Vertical Burrow	Dolomitized Burrow
Phylloid Algae	Productid Brachiopod	Pelletoid	Horizontal Burrow	Dolomite Xtals
Plant Fragments	Lingulid Brachiopod	Calcite Grains	Boring	Chert Nodules
Fusulinid	Colloid Cephalopod	Ooid	Ripple Scale X-lamina.	Selenite Xtals
Encrusting Worm	Nautiloid	Onkolith	Groove	Manganese Dendrites
Conularid	Gastropod	Coated Grain	Prod/Bounce	Phosphate Nodules
Solitary Coral	Bivalve	Shells	Flute	Calcium Carbonate Mod.
Fenestrate Bryozoa	Crinoid	Fossil Fragments	Load Cast	Sphalerite
Ramose Bryozoa	Echinoid		Tracks and Trails	Pyrite/Marcasite
Encrusting Bryozoa	Shark Tooth		Feeding Trace	Limonite Module

FIGURE 3-2 (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



C

BONNIER SPRINGS			shaly sandstone	fine	md. gray	pink-gray	platy to fissile
			sandy lithoclastic mollusc lim packstone	very coarse	md. brown	lt. gray	blocky, limoitic single channel(s) shaped bed
			shaly sandstone	fine	md. gray	md. gray to lt. gray	platy, fissile
			sandy shale	very fine			
			gray shale				
			shaly sandstone	fine			
			ripple laminated shaly sandstone	medium to coarse		lt. gray	very micaceous
			shaly sandstone	fine		md. gray	
			sandy shale gray shale	very fine			fissile, shaly
FARLEY			skeletal phylloid algae lim wackestone to packstone	very fine	gray-tan	pale pink-tan	thick bedded, massive
			stromatolitic(?) skeletal lim 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			
			lim 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 stromatolitic skeletal lim wackestone	fine medium	dk. brown orange to tan-gray	lt. brown orange-tan	wavy to nodular bedded, domal stromatolitic(?) laminae
			phylloid algal lim mudstone	fine	pink-tan to gray	pale pink-gray	sparse ooids & calcite grains
WANDOTTE ISLAND CREEK			shaly sandstone	very fine	lt. gray	lt. gray	flakey
			coated grain packstone skeletal wackestone	very fine Xtal size very coarse grain size	tan-gray	brown-tan	3 even, distinct beds shells w/calcite, dolomite Xtals wavy bedded, "clay seams" present
			coated grain packstone skeletal lim mudstone	very fine		gray-tan	

Q

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

a

STOP 3 HOLLIDAY DRIVE

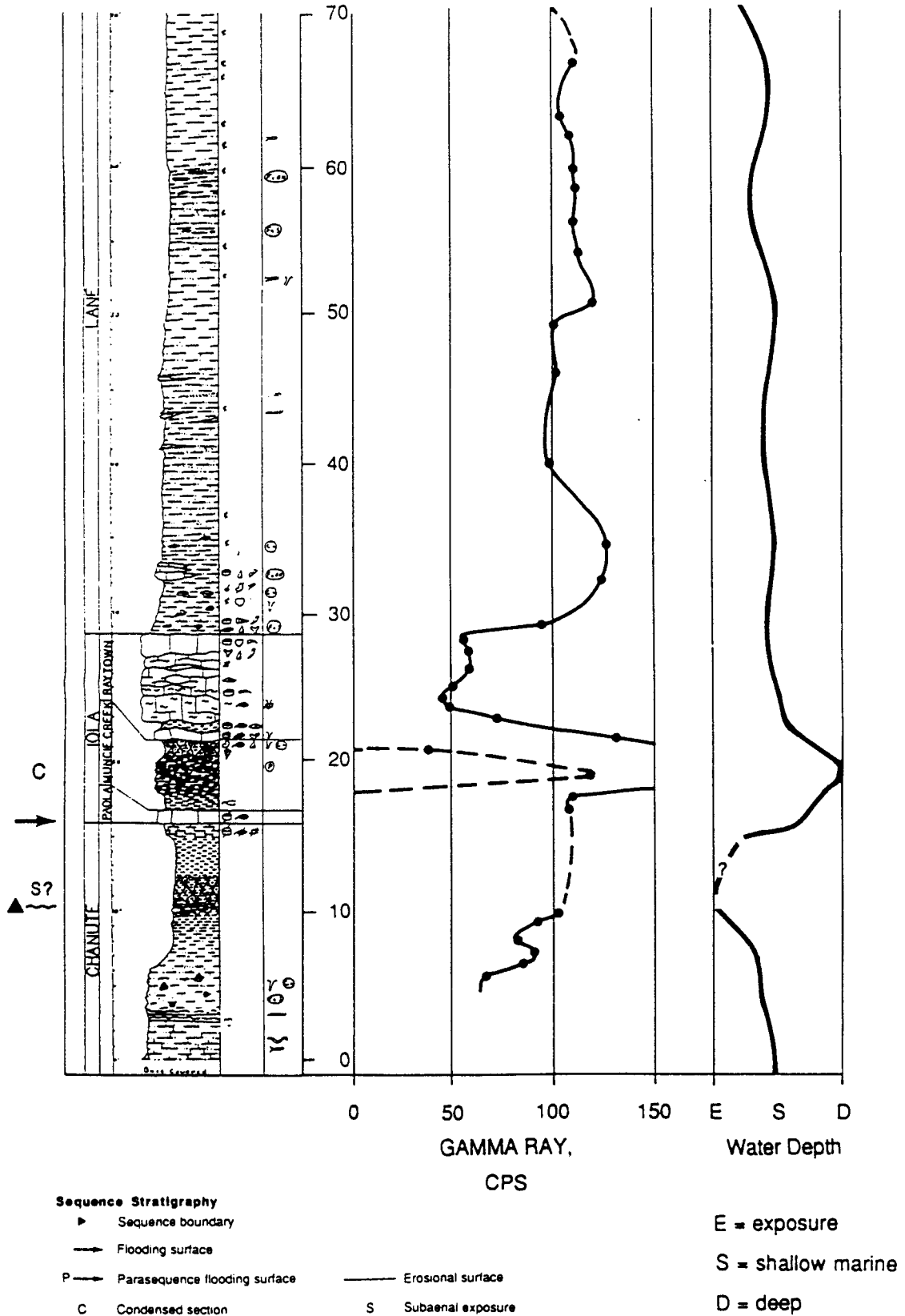
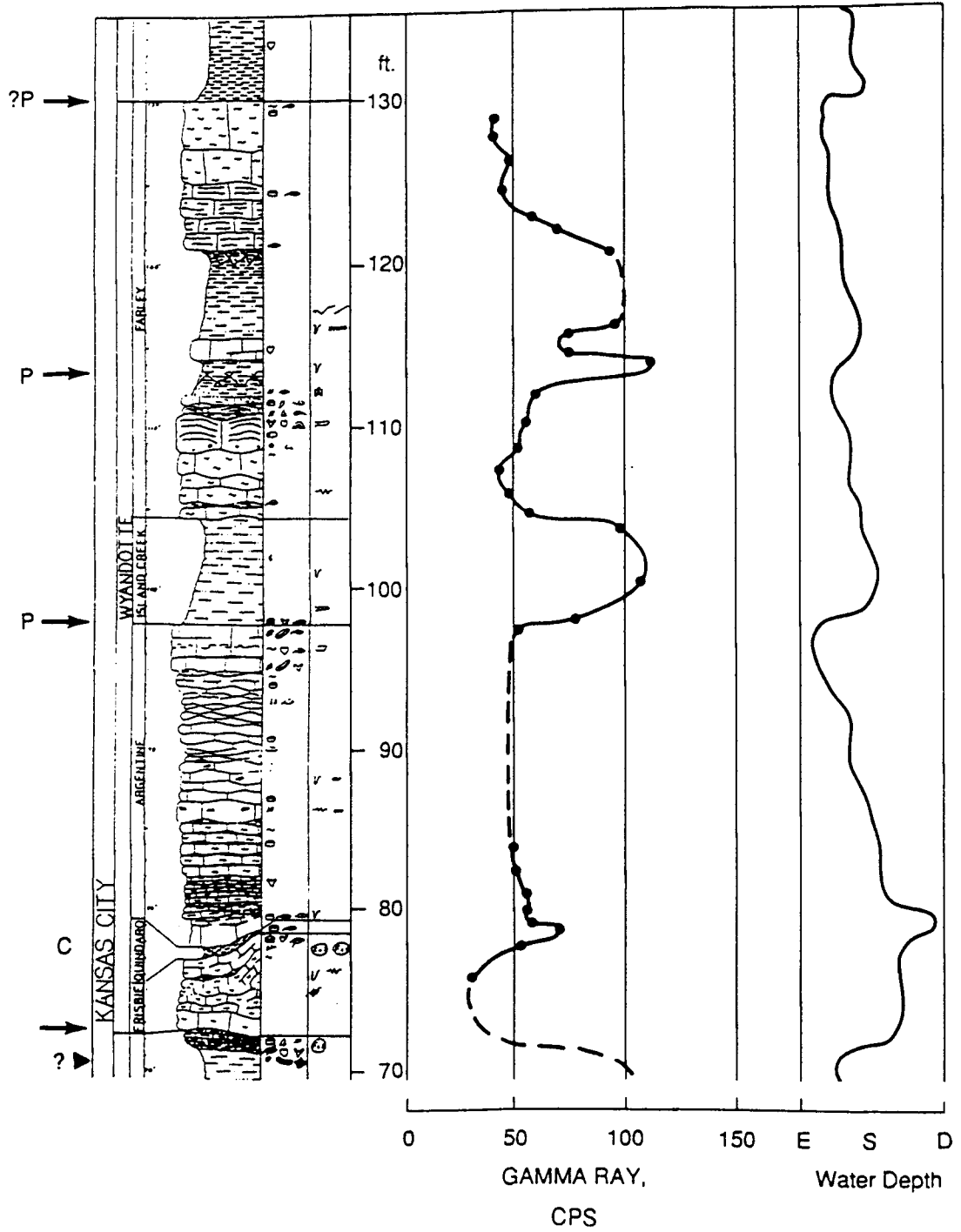


FIGURE 3-3 (A AND B)—STRATIGRAPHIC SECTION NATURAL GAMMA-RADIATION PROFILE, WATER-DEPTH CURVE, AND SEQUENCE CLASSIFICATION (extreme left) for lower portion of measured section in fig. 3-2.

b

STOP 3 HOLLIDAY DRIVE



E = exposure  
 S = shallow marine  
 D = deep

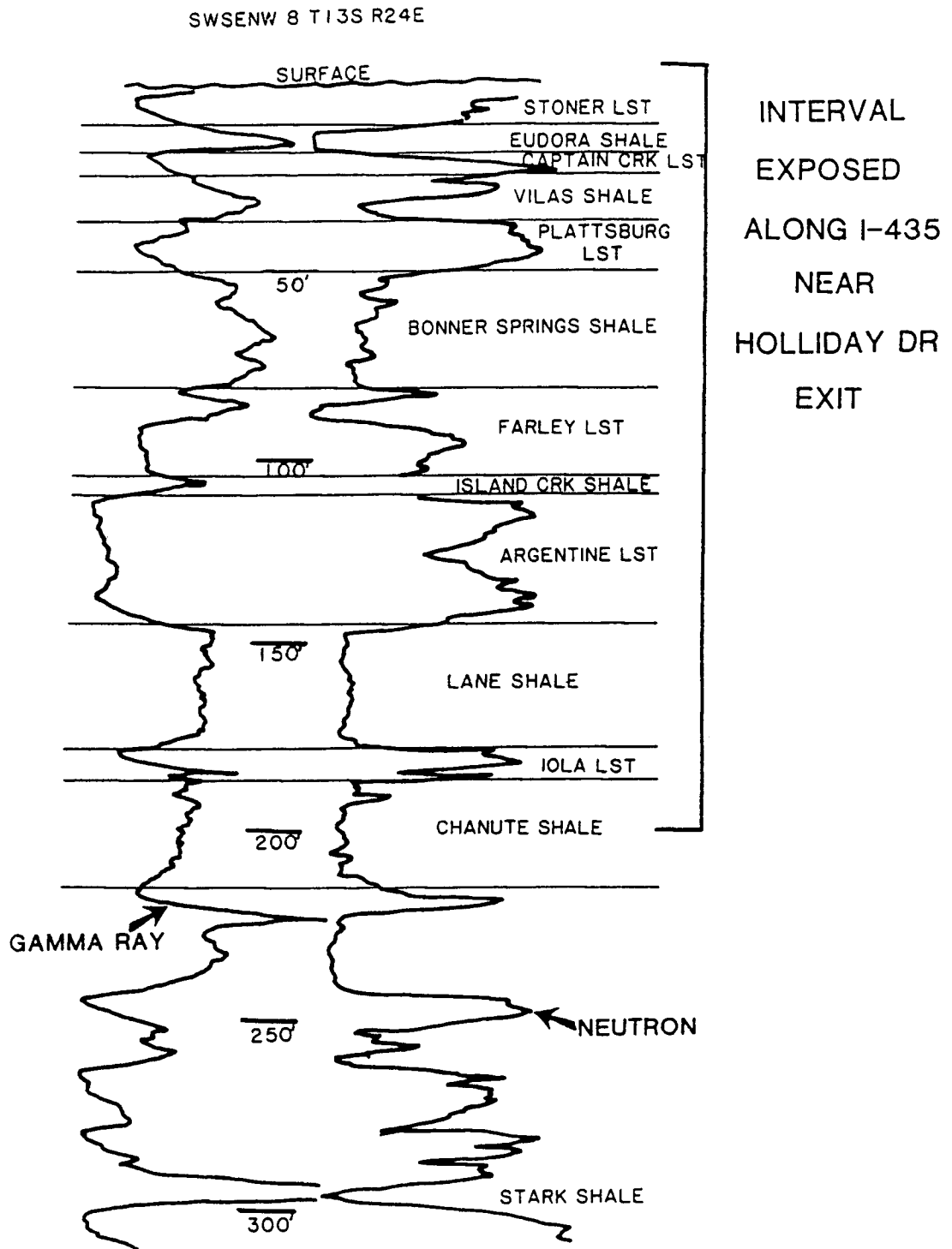


FIGURE 3-4—CORRELATION OF FORMATIONS IN LANSING AND KANSAS CITY GROUPS BASED ON GAMMA RAY-NEUTRON LOG OF WELL LOCATED NEAR STOP 3.

# Stop 4 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

Arrive: 11:50 AM

Leave: 12:50 AM

(10 minutes to lunch; lunch stop 40 minutes)

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

## Introduction

At Stop 2 the depositional setting of the Bonner Springs Shale was briefly described as the outside shale of the Wyandotte Cyclothem. The Bonner Springs Shale also includes the boundary between the Wyandotte and Plattsburg sequences. The events which occurred at this boundary will be the focus of Stops 4 and 5 (fig. 3). Erosional downcutting, channel sandstones, marine backfilling of erosional topography, and laterally extensive paleosol development near the top of the Bonner Springs Shale at Stop 4 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,

#4, focuses on a spectacular example of multiple episodes of erosional scouring and backfilling in the Bonner Springs Shale. In the succeeding stop (#5), 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 4 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. 4-2. The index map (fig. 4-1) of the interchange locates the measured sections. Fig. 4-3 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 4 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  $\pm 0.32$  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. 4-2). 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  $7.95 \pm 2.36$  m ( $26.2 \pm 7.8$  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 spiriferid brachiopods, high-spined gastropods, and shell fragments occur near the top of the shale and within some sandstones. Trace fossils include vague burrows in both shale and sandstone intervals; *Zoophycos* and *Protovirgularia* traces in channel siltstones; well-developed U-tubes in a nodular mudrock near the top and starfish impressions in blue-gray claystone in the lower half (location VII; Harris, 1985, p. 35).

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

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

The *Hickory Creek Shale* is a poorly developed core shale, probably the thinnest and palest in the entire Missourian Series. The unit is also the condensed section of the Plattsburg Sequence (fig. 4-2). The average thickness in 13 measured sections of "normal" development in Wyandotte and Johnson counties is  $18.1 \pm 5.7$  cm ( $7.2 \pm 2.3$  inches); the range is from 7 to 27 cm (3–11 inches). Although the Hickory Creek is reported to contain a black, platy, carbonaceous zone in northern Johnson County and Wyandotte County (Newell, 1935, p.

72; Jewett and Newell, 1935, p. 181), we have not seen this development nor is it reported in this area by O'Connor (1971, p. 23), Mann (1957, p. 261) nor Ball et al. (1963, p. 13). The Hickory Creek is apparently nowhere developed as a black, fissile, phosphatic shale characterized by a "hot" gamma-ray response typical of core shales in the subsurface (Bryan Stephens, personal communication, 1987).

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

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

### Observations at I-70/I-435 Interchange

Taking it from the base up, the Bonner Springs Shale is fairly typically developed as a uniform, blue-gray shale with a few thin sandstone beds and the maroon marker bed near the top at section VII (fig. 4-2). Nowhere else in the exposures is the Bonner Springs typical. North-east 300 to 850 m (1,000–2,800 ft, sections VIII–X, ramps E–N and N–E) the Bonner Springs interval is represented by up to 8.7 m (29 ft) of sandstone overlain by 1 m (3.3 ft) of sandy shale beneath a typical Merriam Limestone section (section IX). The upper bed of the underlying Farley Limestone Member is abnormally thin (0.75 cm [0.3 inch]) and shows very abrupt local relief with a bevel of 60 cm (24 inches) in thickness. A layer of lime-mud pebbles and bivalve shells plastered onto the Farley Limestone probably reflects reworking of the uppermost Farley prior to deposition of the sandstone. Small clasts of gray shale, less than 1 cm (0.4 inch) in diameter, are abundant throughout the sandstone, particularly in the base where beds of shale chips compose about half of the bulk. These shale clasts apparently represent the missing typical development of Bonner Springs Shale, ergo the victim of local erosion along with the top of the Farley Limestone.

The sandstone contains a few brachiopods (Harris, 1985), pectins, and high-spined gastropods. The overlying shale contains these fossils as well as fenestrate bryozoans and unidentified shell fragments. The sandstone is extensively ripple cross-laminated with a few

festoon sets up to 30 cm (12 inches) thick. An excellent set of climbing ripple-drift cross-lamination is developed near the base. Current directions are persistently toward the east-southeast. Herringbone crossbedding is evident near the base, but no orientations could be measured.

This sandstone, which apparently eroded the entire Bonner Springs and beveled the top of the Farley Limestone, is truncated by a distinct hemi-channel form that removed all but 1.9 m (6.3 ft) of the sandstone in section X (fig. 4-2). The channel form is filled with 2.3 m (7.6 ft) of silty shale; silty, pebbly sandstone; and shale; it extends to the fossiliferous shale beneath the Merriam in Sections IX and VIII. This channel-form sand/shale sequence is in turn beveled by yet another hemi-channel form represented by abrupt westward thickening of the Merriam Limestone from 0.9 m (3 ft; possibly truncated by modern erosion) in section IX through 2.4 m (8 ft) in section VIII and 4.0 m (13 ft) in section X.

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

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

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

Finally, the Spring Hill Limestone also thickens in section V to about 6 m (20 ft). In section MB, 700 m (2,310 ft) southeast, the Spring Hill is 3.9 m (12.9 ft) thick and in section II, about 1,200 m (3,960 ft) east, it measures 3.4 m (11.2 ft). Bedding is disrupted and somewhat

thickened at the base of the wavy-bedded interval in the lower Spring Hill where the Merriam thickens in section VIII.

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

### Interpretation of Bonner Springs Shale channels

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

Shale is the result of [subaerial] erosion...along an unconformity."

We agree with Harris that the upper surface of the Bonner Springs is erosional, liberally sculpted by channels, both at and near the top, and with both Heckel and Harris that subaerial exposure near the close of Bonner Springs deposition is indicated by the data cited above. Marine transgression began, however, before the end of Bonner Springs deposition as indicated by marine fossils in the uppermost portion at a few localities. This marine interval is truncated along with the underlying subaerial nodular carbonate and maroon shale. Moreover, the fill of each of the three superposed channels is marine. The sandstone contains a few brachiopods at the base as well as pectins and high-spired gastropods (sect IX, fig. 4-2). 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 be incised into underlying units by fluvial, storm, or tidal erosion. Fill of the channels variously with sandstone, shale, and muddy limestone, each with exclusively marine or brackish fossils, limits the possibilities. Terrestrial processes would require repeated erosion without deposition, preservation of narrow channels, and repeated marine transgressions to fill the channels, each of which appears improbable even in isolation. Channelization in violent storms such as hurricanes is known (cf. Ball et al., 1967); however, it involves breaching of local barriers and does not produce elongate channels such as indicated for the Merriam. Also, deposits of violent storms are chaotic mixtures of mud and coarser clasts, typically in thin sheet-wash blankets (Hayes, 1967; Ball et al., 1967; Perkins and Enos, 1968) deposited in the upper flow regime. Storms would also fill any pre-existing channels with such chaotic deposits.

Each channel studied appears to truncate less erodible deposits, either more cohesive or coarser grained than those that fill the channel. This suggests that cut and fill were either in different environments or at different intensities. The presence of extensively bored and encrusted pebbles at the base of Merriam channels also suggests a finite period during which the channels were open before final filling. Apparently the channels were cut by rather ephemeral, strong currents and filled under different and varied sedimentary regimes. Tropical storm deposition is a possibility in the low latitudes of the Pennsylvanian in the midcontinent (Heckel, 1983; Ziegler et al., 1979). In channels filled by carbonate or argillaceous deposits, however, the muddy texture of the sediment; its resolution into a number of distinct, well-defined beds; and the occurrence of brachiopods in growth position all attest to lack of strong currents during channel fill. Processes active over long periods are also indicated by the thick sequence of low-energy deposits. It cannot be demonstrated, however, that processes of long duration cut the channels.

Tidal currents appear to be the only common submarine process capable of producing the channel forms and marine sediments developed at the Bonner Springs-Plattsburg transition. Herringbone crossbedding developed locally in the sand-filled channel supports a

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

Is it reasonable to infer episodic high-tidal energy in the shallow "tideless seas" (Shaw, 1964) of the mid-continent? 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.).

Lunar tides are essentially lacking in many modern shallow seas, such as Florida Bay and the Bahama Banks (Ginsburg, 1956; Enos and Perkins, 1979). Wind is capable of moving large bodies of water, however, and producing rather energetic "tidal" currents (Enos and Perkins, 1979; Hardie, 1977). This was probably the prevalent condition in vast epeiric seas of the midcontinent. Wind-generated water movements would be more focused into strong currents during lowered sea levels of early transgression and late regression, where high-energy deposits are concentrated.

The uppermost shale and limestone beds in the Merriam thicken somewhat, but do not display toplap. This suggests continued presence of a shallow channel and a rise in base level with the transgression, as deduced by Heckel from the conodont assemblages (*in* Watney et al., 1985, p. 34). The persistence of channels would also explain thickening of the Hickory Creek shale and Spring Hill Limestone where the Merriam is thickest. Effective scouring of the channels almost certainly ceased early in Merriam deposition, as indicated by muddy lithologies and

upward changes in bed geometry. Scouring was not a factor during maximum transgression represented by the Hickory Creek, a core shale (Heckel, 1985). Either channels were cut deep enough so that they were not completely filled during Merriam deposition, or differential compaction of the thicker channel fill maintained some relief during deposition of the other cyclothem members. Toplap in the lower Merriam indicates that the channel was filled to an effective wave base, but continued rise in sea level apparently removed this constriction.

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

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

The change in lithologic character of the Hickory Creek Shale with the increase in thickness at I-70/I-435 interchange also suggests a depression on the sea floor. Local bathymetric highs have been called upon to explain the loss of black color, carbon content, and fissility within core shales where they projected through a pycnocline that produced anoxic conditions elsewhere on the sea floor (Heckel, 1977). The Hickory Creek is nowhere developed as a black, fissile, carbonaceous shale, but the *Trepostirid-Paleoneilo* assemblage in the thickened Hickory Creek contains forms closely related to those that occur under dysaerobic conditions at the top of the oxygen-minimum zone (Boardman et al., 1984). With no record of a regional pycnocline, the reduction in oxygen level probably reflects stagnation in a local depression, the relict channel. This thickened Hickory Creek Shale will be pointed out on the northeast corner of the interchange.

## Discussion

The concentration of channels within and at the top of the Bonner Spring Shale suggests that the simple Irwin-Shaw model of seas transgressing over an essentially planar surface (Irwin, 1965; Shaw, 1964) is not invariably appropriate to transgression in midcontinent 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."

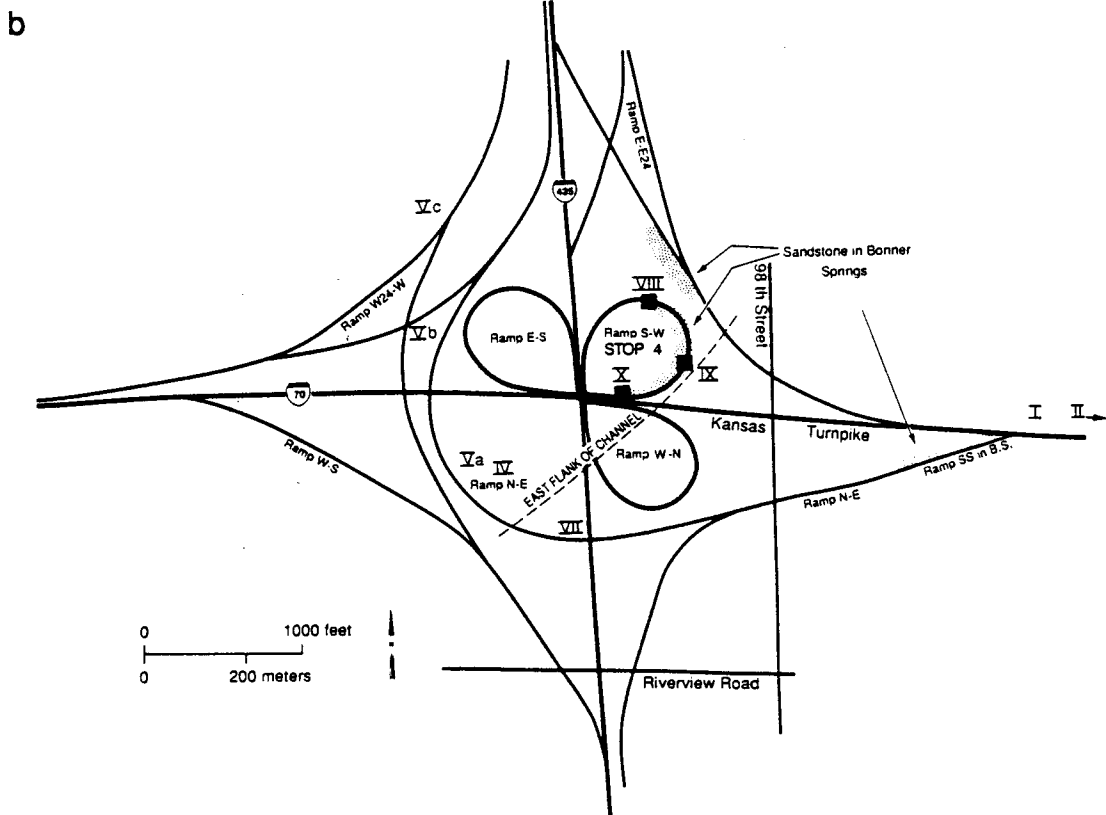
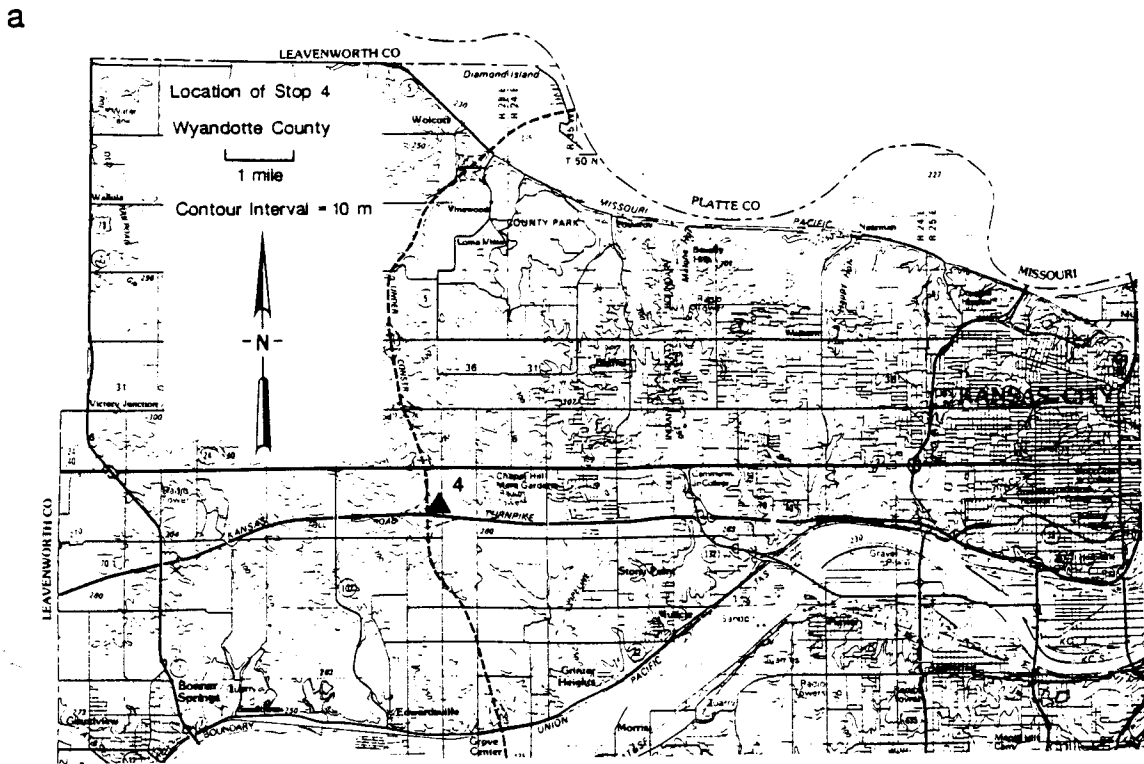


FIGURE 4-1(A and B)—Location map for Stop 4 in Wyandotte County (A) and index map showing intersection with location of Stop 4 along northeastern cloverleaf of interchange of I-70 and I-435 and location of measured sections used in cross section (fig. 4-2a and b) identified with Roman numerals. Stippled pattern represents sandstones of Bonner Springs.

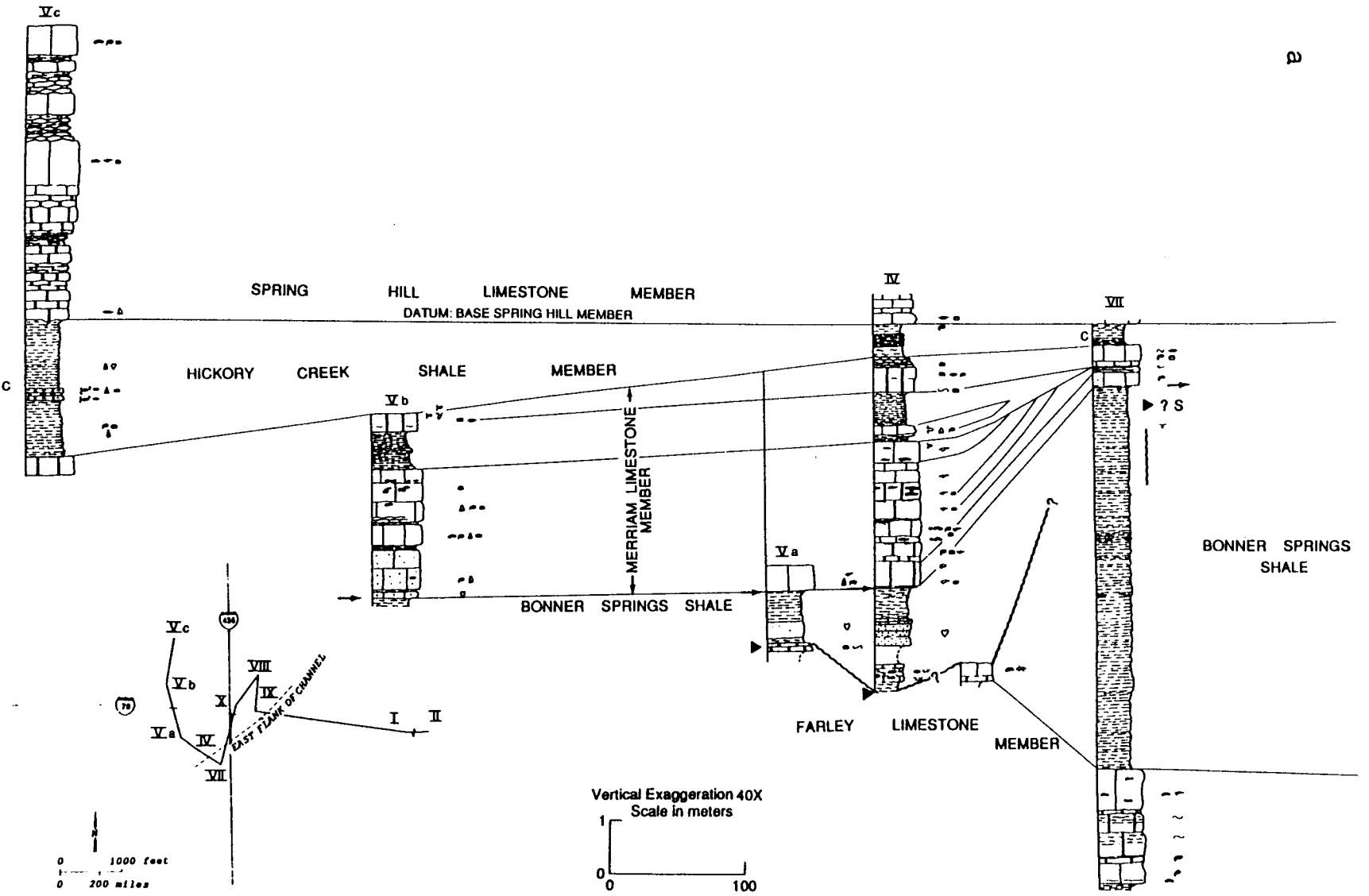


FIGURE 4-2(a and b)—Northwest-to-east stratigraphic cross section through I-70/I-435 interchange area based on measured sections and interpretations (less sequence interpretations) by Enos and Herman, in ms. Datum for the cross section is the base of the Spring Hill Limestone. Uppermost Farley Limestone, Bonner Springs Shale, Merriam Limestone, Hickory Creek Shale, and Spring Hill Limestone are included in section.

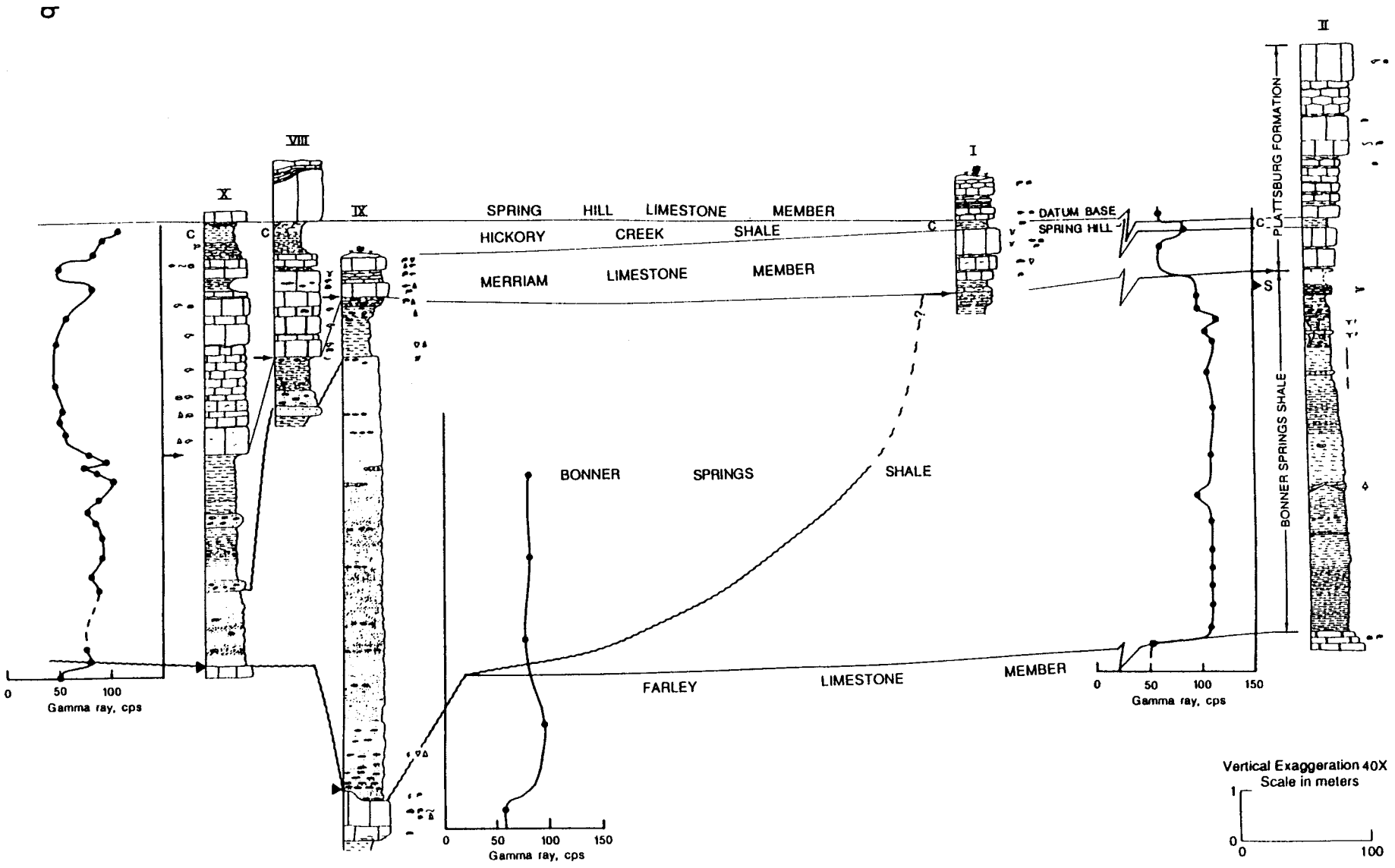


FIGURE 4-3(A and B)—Bonner Springs Shale at Stop 4 showing sandstone of Bonner Springs (BS) resting on locally eroded upper Farley Limestone (UF) near section X. Sandstone is cut by erosional surface beneath a hemi-channel form which extends up to near the base of the Merriam Limestone (ME). Hemi-channel is filled with sandstone. 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]).

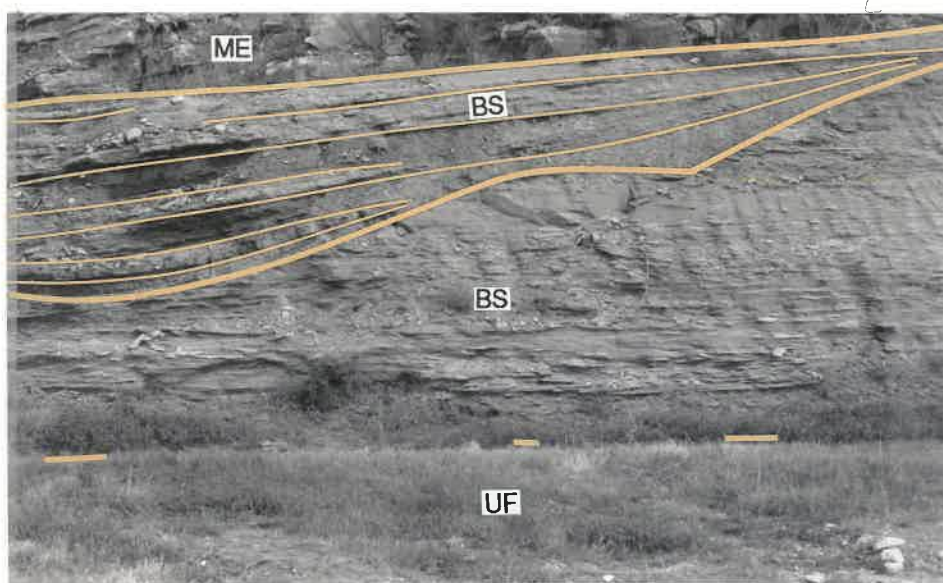
FIGURE 4-3(C and D)—South side of Stop 4, northeast clover-leaf of intersection of I-70/435, between sections X and IX. Large channel-form sandstone in Bonner Springs Shale passes diagonally (northeast-to-southwest) through this exposure. Sandstone is cut by deep erosional surfaces beneath hemi-channel 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.

FIGURE 4-3(E)—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.

FIGURE 4-3 (F)—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.



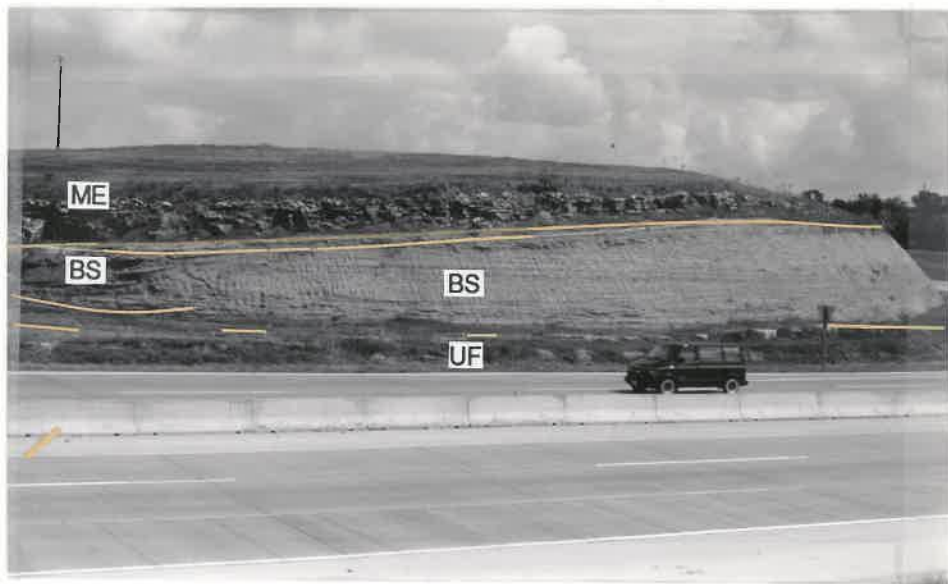
**A**



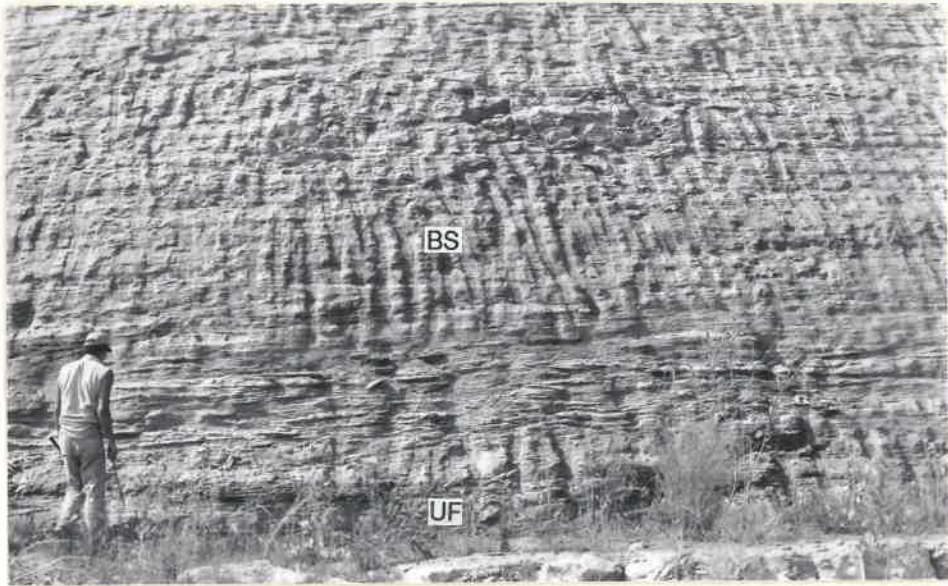
**B**



C



D



**E**



**F**

## Stop 5 I-435 south of Holiday Road exit

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

Arrive: 1:55 PM

Leave: 2:20 PM

(30 minutes to next stop)

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

### Introduction

Stop 5 is located on fig. 2-1. The measured section of the interval seen was obtained on the east roadcut near Stop 5 (fig. 3-2c and d). Fig. 5-1 provides three photos illustrating the paleosol developed at the top of the Bonner Springs Shale, the focus of Stop 5.

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.

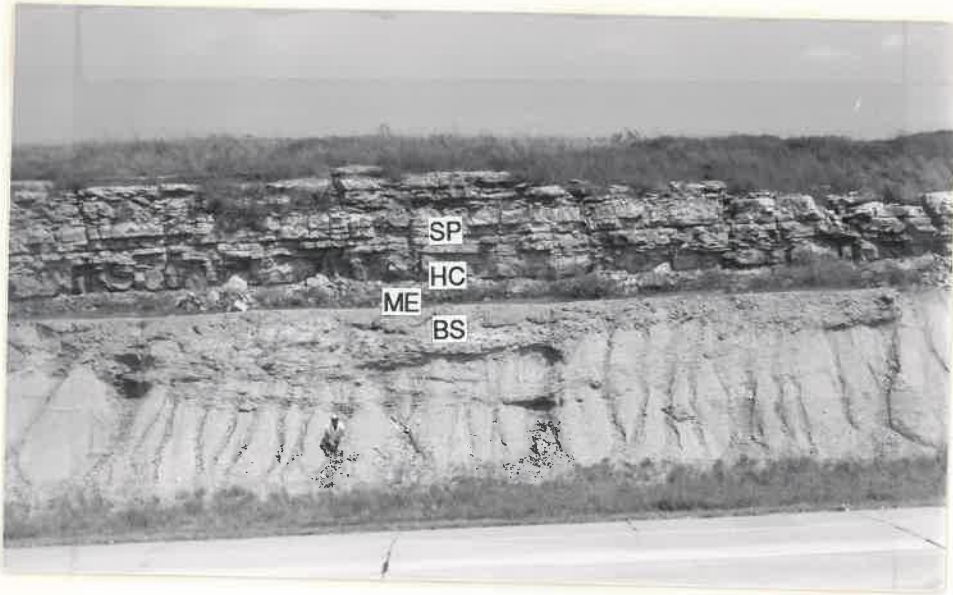
The nodular and brecciated appearance of the yellow-weathering carbonate is probably due to displacive crystal growth, enhanced compaction of the shale around semi-lithified carbonate, and growth of plant roots. Thin sections of the carbonate zone indicate microcrystalline calcite with scattered fragments 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. 5-1). Types of peds are illustrated in fig. 5-2.

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 5. This interval contrasts with the section examined at Stop 4. 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 5-1 (A)—West-facing exposure at Stop 5 (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 4. Paleosol is unusually thick in association with a lenticular sandstone located at the position of the letters, BS. Derek Herman provides a scale.

FIGURE 5-1(B and C)—Paleosol developed near top of Bonner Springs Shale from west-facing slope in the highway median at Stop 5. 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.



**A**



**B**



**C**





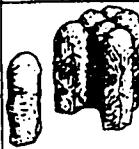

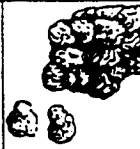
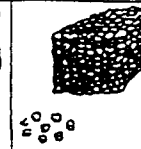
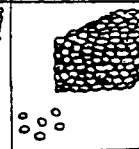
TYPE	PLATY	PRISMATIC	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR	CRUMB
SKETCH							
DESCRIPTION	tabular and horizontal to land surface	elongate with flat top and vertical to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking 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 disturbance 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 5-2—Classification of soil peds (from Retallack, 1988).



## Stop 6 Southeast exit ramp off I-435 at Gregory Road: Parasequence within the Winterset Limestone Member of the Dennis Limestone Formation

Location: sec. 7, T. 48 N., R. 32 W., Jackson County, Missouri

Arrive: 2:50 PM

Leave: 3:20 PM

(10 minutes to next stop)

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

### Overview of trip to this point, and a view down the road

Stop 5 was the last exposure of the Lansing Group that we will see; the remainder of the trip will focus on the lower Kansas City Group. The Lansing Group sections observed through Stop 5 were successions of mixed siliciclastic and carbonate deposits, with carbonate units representing the marine inundations and siliciclastic sequences representing deltaic progradation during times of base-level stillstand and fall. Minor eustatic fluctuations during overall falling sea level resulted in parasequence development, reflected in the occurrence of stacked carbonate and siliciclastic deposits that are separated by discrete flooding surfaces associated with abrupt facies dislocation. Variations within these parasequences may have been controlled by autogenic processes such as distributary avulsion; the mixed siliciclastic and carbonate facies in the lower Farley Limestone may be an example of this.

Sequence-stratigraphic concepts appear to be effective in deciphering the packaging of cyclothemic deposits. Even so, unequivocal evidence for subaerial exposure is not always identifiable, and evidence exists (as described at stop 3) that some of the major sequences that resulted from widespread marine inundation (such as the Iola) are not bounded by subaerial surfaces at middle- and lower-shelf positions. Surfaces of facies dislocation as well as condensed sections are definitive markers that provide practical means to begin understanding the temporal significance of the stratigraphic succession.

The necessity of utilizing sequence-stratigraphic principles, especially with regard to the recognition and correlation of hiatal surfaces, will become increasingly apparent on the second day of this trip as we examine the more complex lithologic successions and stratal geometries that developed in lower-shelf and basin-margin settings.

### Introduction to Stop 6

Stop 6 and 7 are located on the index map shown in fig. 6-1. In Stop 6 we will examine the upper portion of the

Winterset Limestone Member of the Dennis Limestone (Kansas City Group; fig. 3a and b). The measured section of the sequence exposed at Stop 7, 1.5 mi (2.4 km) north of here, indicates the stratigraphic position which is the focus of this stop (fig. 6-2). Fig. 6-3 includes three photos of the skeletal and oolitic grainstone present in the upper portion of the Winterset Limestone.

The Dennis sequence does not exhibit a well-developed carbonate marine-flooding unit this high on the shelf, but does contain a deep-water condensed section represented by the black Stark Shale. The Stark rests on a well-developed paleosol in the Galesburg Shale, which can be seen at the north end and lowest stratigraphic position of this exposure. The Swope-Dennis sequence boundary is placed at this contact. The Stark Shale is overlain by the upward-shoaling Winterset Limestone, which is in turn overlain by the shallow-water Fontana Shale at the top of the Dennis sequence. The Fontana Shale contains coal in western Kansas City near the Holiday Drive exposure. Paleosol development in the Fontana Shale has also been described on this part of the shelf in the Kansas City area.

The Winterset Limestone in this area contains at least three and possibly four parasequences. The best developed of these parasequences are characterized by basal marine shales that abruptly overlie shallower-marine carbonates, with the upper portion of each of these minor cycles consisting of an upward-shallowing carbonate succession (fig. 6-2).

The uppermost parasequence (a) is well-exposed at this stop (fig. 6-3). The shale at the base of this unit marks a marine flooding event and is probably a condensed interval. It contains abundant conodonts, including forms such as *Idioproniodus* that Heckel and Baesemann (1975) interpret as indicative of relatively deep water. It is a good local marker that will also be seen at Stop 7. Overlying this shale is a cross-stratified skeletal and oolitic grainstone, which varies in thickness from about 13 ft (4 m) near the north end of the outcrop to perhaps only 7 ft (2.1 m) at the south end. The unit

displays foreset beds with tangential bases that contain lag concentrations of the brachiopod *Composita* and other skeletal debris. The foresets dip northward (landward) toward the upper shelf.

A similar cross-stratified grainstone is also present approximately 1.5 mi (2.4 km) to the north at Stop 7, but the unit is there only about 6 ft (1.8 m) thick. This is therefore an unusually thick Winterset grainstone in this area.

## Discussion

This oolitic grainstone resembles the oolitic reservoir zones common within many Lansing–Kansas City oil fields in western Kansas. Sea level and shelf configuration combined to provide conditions conducive for the development of these potential-reservoir facies, but variations in thickness and areal extent of individual oolitic packages were almost certainly due to autogenic processes such as local topography and the distribution of storm washovers.

Fifty miles (80 km) south of stop 6 near Jingo, Kansas (fig. 6-4) the Winterset Limestone also contains three shale seams, each associated with a sequence of carbonates that is similar to that seen near Kansas City (fig. 6-5). Because the same number of packages occurs in the Winterset at both Raytown and Jingo, it is tempting to consider them as the same four parasequences. However, work by Schutter (1983, p.909) indicates that the same conodont assemblage found in the medial Winterset shale (discussed above) in Kansas City occurs in a zone at the top of the Stark Shale (just below the Winterset Limestone) at Jingo (Heckel and Watney, 1985). Work is underway by Felton and Heckel to verify these correlations within the Winterset. Correlations made to date suggest that the lower 10 ft (3 m) of the Winterset at Kansas City are not present at Jingo (Heckel and Watney, 1985). If these preliminary correlations are correct, then basinward thinning and downlap of highstand Winterset carbonates onto the Stark Shale are indicated.

Carbonate-dominated parasequences are developed in the Winterset across most of the northern midcontinent shelf. The relatively minor base-level fluctuations reflected in the Dennis parasequences are also represented in the Winterset over 450 mi (725 km) to the west in southwestern Nebraska (fig. 6-6; Dubois, 1985). In this inferred high-shelf position on the flanks of the transcontinental arch, the normally black Stark Shale is a dark-gray to maroon silty shale

containing crinoids and brachiopods. Subaerial weathering in this region was intense and probably took place in a semi-arid, oxidizing setting (Watney, 1980). Dubois (1985) examined 30 cores over 180 mi<sup>2</sup> (465 km<sup>2</sup>) and found two persistent, well-defined shallowing-upward carbonate packages separated by thin marine shales in the Winterset. In Haskell County in southwest Kansas, near the shelf margin of the Anadarko basin, two parasequences occur in the Winterset equivalent in Victory field in the Amoco A-4 Cox core (fig. 6-4). In this location repeated marine inundations during generally shallow-water conditions led to the stacking of oolite deposits. More than 10 ft (3 m) of a lower oolite are overlain by an additional 14 ft (4.3 m) of oolitic grainstone. These two units are separated by 2 ft (0.6 m) of peritidal carbonate that is abruptly overlain by less than 1 ft (0.3 m) of marine grainstone that contains clasts of caliche; this grainstone marks the marine flooding associated with the upper parasequence. The grainstone is overlain by a thin, open-marine wackestone that is overlain by the upper oolite. This type of stacking resulted in very thick (>40 ft, 12 m) accumulations of porous grainstone that covered broad areas of the inferred ramp (Watney, 1984).

This well-defined parasequence development appears to be a common feature of the Dennis sequence across the entire midcontinent shelf. This may in part be related to regional tectonic reactivation in the Arkoma and Anadarko basins that resulted in flexure and tilting of the shelf. This is suggested in maps of the Dennis sequence, which indicate that its shelf margin has backstepped northward in southeastern Kansas relative to underlying units (fig. 12). This is also indicated in a conceptual diagram (fig. 45). One-dimensional computer simulations indicate that similar rates of subsidence and rates of falling sea level would favor parasequence development during minor sea-level fluctuations (figs. W-13).

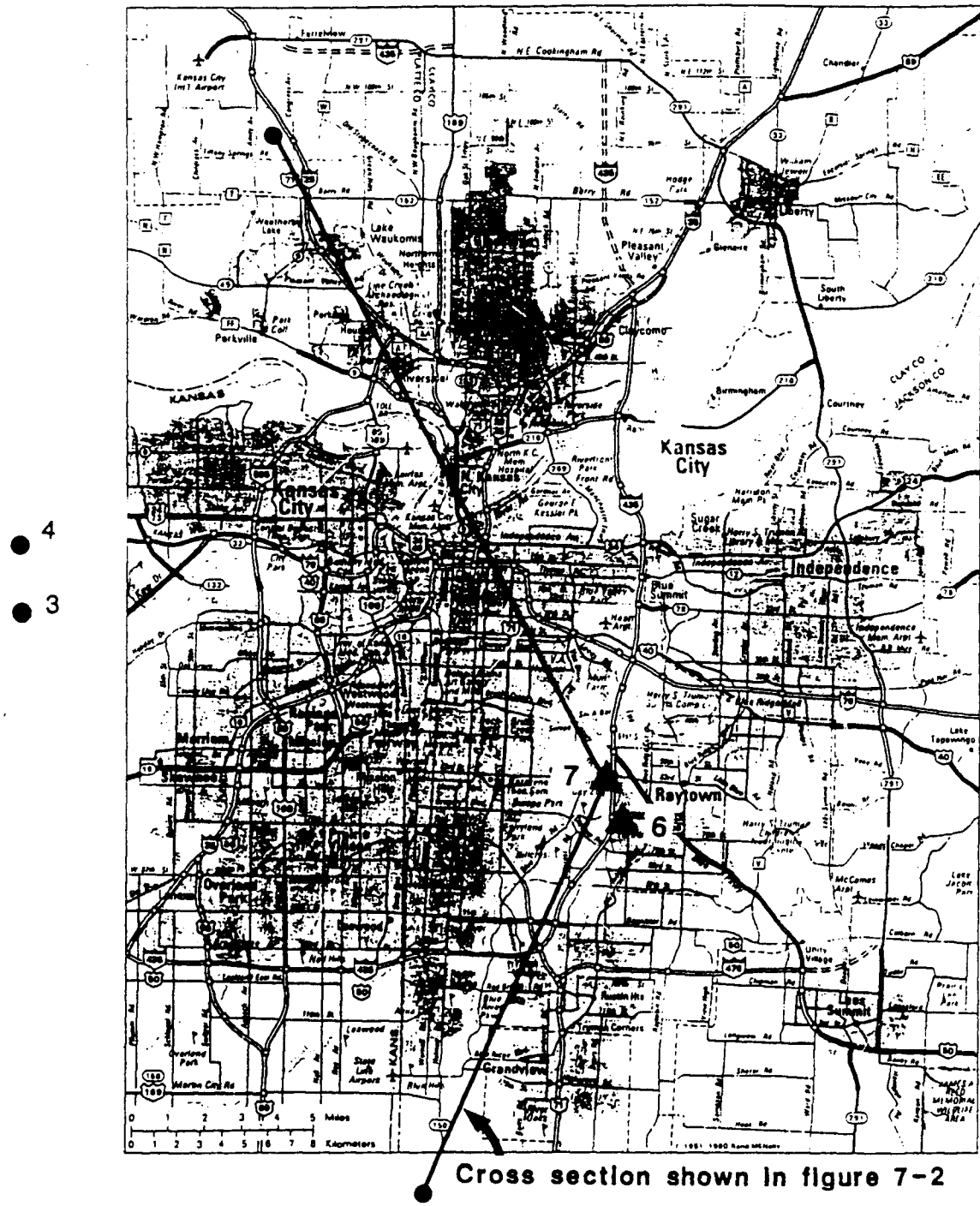


FIGURE 6-1—Index map showing locations of Stops 6 and 7 and locations of well logs used in constructing cross section of fig. 7-2.

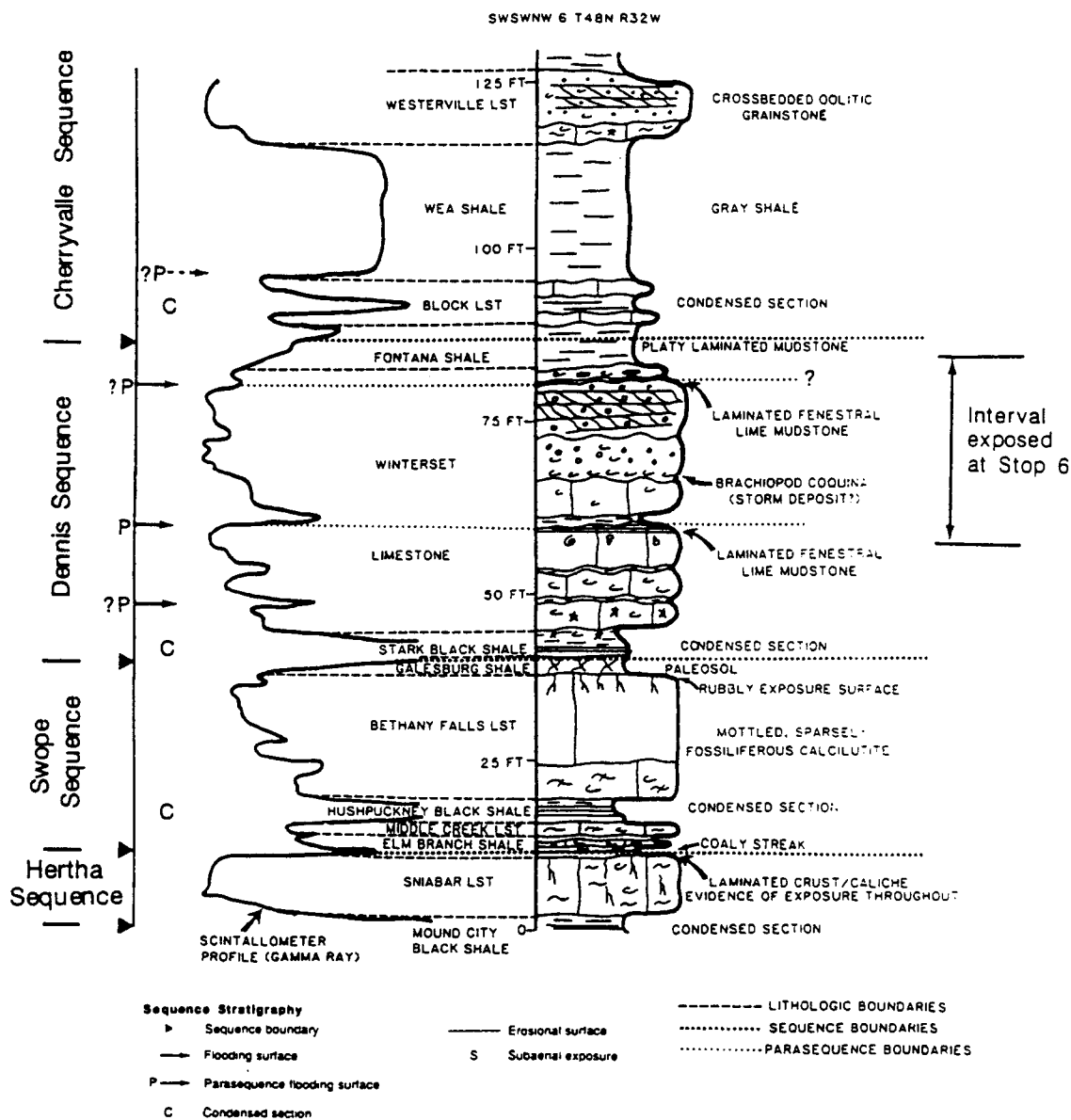


FIGURE 6-2—Measured section used from Stop 7 at Raytown located 1.5 mi (2.4 km) north of Stop 6. Interval examined here in Stop 6 of the upper Winterset Limestone is bracketed.

FIGURE 6-3(A and B)—West-facing exposure of the upper Winterset Limestone on the Gregory Road exit off northbound I-435 at Stop 6. Large, well-developed, north-dipping foreset beds in oolitic and skeletal grainstone dominate this outcrop of the upper parasequence of the Dennis sequence. MS, medial shale (marker) located at the base of the parasequence; OG, oolitic grainstone; LM, platy, laminated mudstone developed at the top of the Winterset Limestone. Stick (lower left) provides scale (1 ft [0.3 m] divisions).

FIGURE 6-3 C)—Low-angle, tangential, sharp-based fining-upward set of a large foreset bed from lower portion of grainstone containing abundant articulated *Composita* brachiopods and skeletal fragments (arrow).

FIGURE 6-3(D)—Lower 3 ft (1 m) of grainstone bed showing sharp base of grainstone on remnants of wackestone over shale/nodular limestone interval (medial-shale marker). Arrow in photo identifies one of several sharp, scoured, tangential bases of foresets containing *Composita* and coarse skeletal lag.

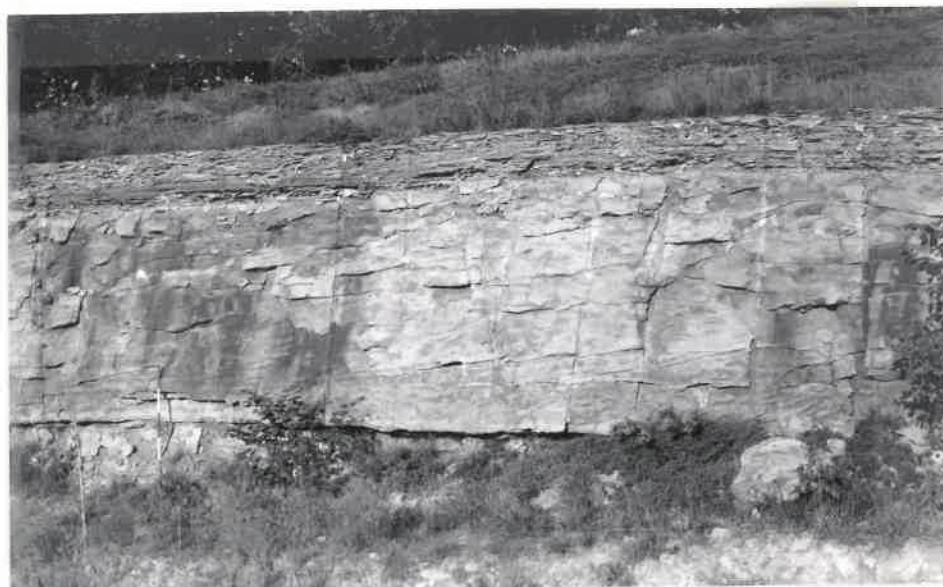
**A****B**



FIGURE 6-4—Index map for region indicating locations of Stops 6 and 7 with reference to Jingo locality (in eastern Kansas), the Amoco Cox core in southwestern Kansas, and the area studied by DuBois (1985).

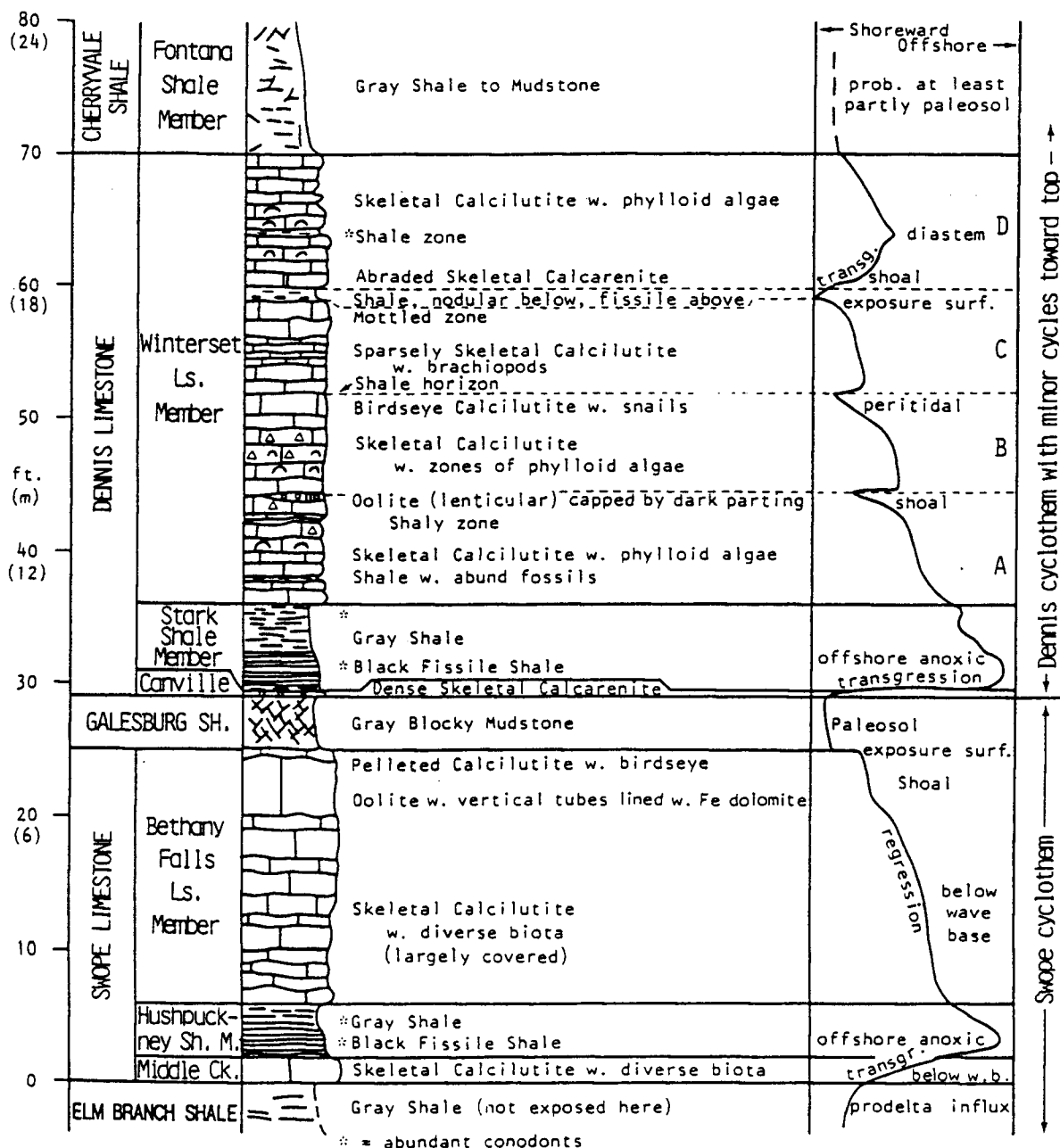
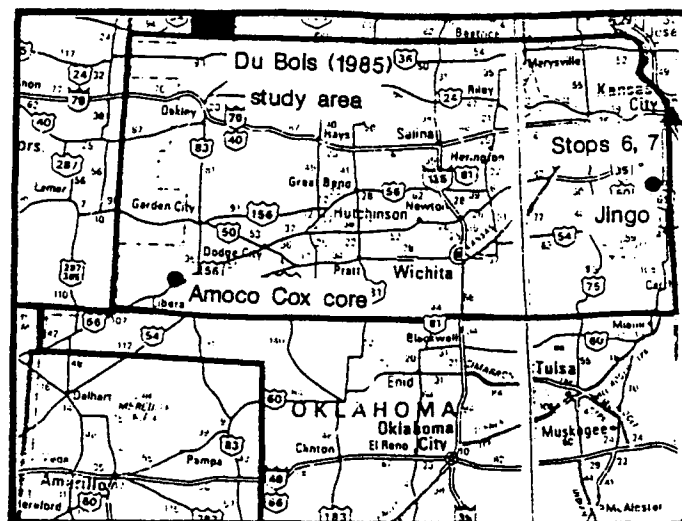


FIGURE 6-5—MEASURED SECTION OF DENNIS AND SWOPE LIMESTONES FROM THE JINGO LOCALITY (SW SE sec. 31, T. 18 S., R. 25 E.), Miami County, Kansas (from Heckel and Watney, 1985).



# Stop 7 Raytown section along I-435 just south of 350 Highway: Hertha, Swope, and Dennis cycles

Location: SW SW NW sec. 6, T. 48 N., R. 32 W., Jackson County, Missouri

Arrive: 3:30 PM

Leave: 4:30 PM

(return to Lawrence for dinner and evening program)

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

## Introduction

This is a superbly exposed, continuous sequence of the lower Missourian rocks that are currently a major focus of our investigations in southeastern Kansas (figs. 7-1, 7-2; the cross section index for fig. 7-2 is found in fig. 6-1). Familiarity with the variability of these units throughout most of Kansas allows us to put this important outcrop into a regional stratigraphic context.

The units exposed at this location will be described in ascending order. For the sake of brevity, only salient features of the individual units are mentioned. These comments will hopefully foster further discussion. The stratigraphic relationships and regional variations of these units is best understood by reference to the measured section (fig. 7-1).

## Stratigraphy

The *Mound City Shale* is the lowermost unit exposed here. The upper portion is exposed beneath a small waterfall a few hundred feet downstream of the main outcrop. The Mound City is a widely correlative, relatively deep-water deposit that represents the condensed section within the Sniabar sequence. The portion that is visible here consists of a few centimeters of alternating black shale and dark-gray shale that contains *Chondrites*. This alternation may reflect fluctuations in bottom-water oxygenation that occurred in this relatively high-shelf setting; basinward (to the south) a black, phosphatic facies is well-developed in the Mound City.

The *Sniabar Limestone* is the high-stand deposit of the Sniabar depositional sequence. At this location, as well as at most locations to the south, it is primarily a relatively open-marine phylloid-algal and skeletal wackestone. Scattered clusters of rugose corals that appear to be in growth position are found in this unit near the bridge adjacent to this stop.

The upper portion of the Sniabar exhibits abundant evidence of subaerial exposure. Depressions along the surface of the unit are layered with laminated calcrete. Chalky microcrystalline caliche that contains clasts of laminated calcrete occurs along the upper few centimeters of the Sni-

abar, in direct contact with the presumably open-marine skeletal wackestone. In addition, rhizolith systems 3–5 cm (1.2–2 inches) in diameter made up of calcrete as well as mm-sized tubules penetrate extensively through much of the Sniabar Limestone. Some beds within the Sniabar appear more altered than others. Associated in situ brecciation and micritization of the host carbonate is pervasive, with multiple episodes of subaerial exposure possible. Internal dissolution and calichification of the unit apparently occurred while only the upper part was exposed, in similar fashion to observed diagenesis of Pleistocene carbonate rocks in south Florida and the Bahamas (H. Wanless Jr., personal communication, 1988).

Although it is only 9 ft (2.7 m) thick here, the Sniabar Limestone forms a carbonate-bank complex up to 90 ft (27 m) thick roughly 120 mi (190 km) to the southwest of here in association with thinning of the underlying Pleasanton siliciclastic platform. An exposure of the margin of bank will be seen at Stop 11 on the second day of the trip.

The *Elm Branch Shale* is about 2.5 ft (0.8 m) thick and consists of an unfossiliferous gray mudstone succeeded upward by a coaly stringer, fossiliferous shale, and a thin carbonate. The Sniabar–Swope sequence boundary is placed at the coaly stringer, which marks the initial marine incursion.

The *Middle Creek Limestone* is about 2 ft (0.6 m) thick and is a dark-gray to gray phylloid-algal wackestone. The Middle Creek is the regionally extensive marine-flooding unit near the base of the Swope sequence. Brachiopods, bryozoans, and corals that are commonly bored occur at and near the base of the unit. Patches of phylloid algae that appear to be in growth position are also common in the Middle Creek Limestone.

The *Hushpuckney Shale* is the black, phosphatic, highly radioactive condensed section within the Swope sequence. It can be correlated from this location into Oklahoma, Iowa, and eastern Colorado, everywhere maintaining its black, phosphatic character except on major positive features of the shelf (fig. 26). Uranium concentrations in this shale vary locally from 20 to 200 ppm (Coveney, 1985). Enrichment of other metals is common in the Hushpuckney

Shale as shown by analyses from Iowa and Missouri, including a location near this exposure (fig. 7-3, Martin, 1982).

The Hushpuckney Shale is an excellent marker bed (fig. 4) that represents one of the most significant glacial-eustatic inundations in the midcontinent (Heckel, 1986). The transition from Middle Creek Limestone to black Hushpuckney Shale is typically knife-sharp, in contrast to transitional changes at the bases of other condensed sections. The upper portion of the Hushpuckney Shale consists of gray shale that is transitional with the overlying Bethany Falls Limestone. Occurring within this transition are dark-shale-filled burrows that have tentatively been identified as *Zoophycos*. Although it is a common trace fossil in many marine settings, *Zoophycos* tends to be more common in some relatively deep-water (Ekdale and Bromley, 1984) or poorly oxygenated (Savrda and Bottjer, 1987) settings.

In contrast to the Hushpuckney Shale, the overlying *Bethany Falls Limestone* reflects deposition in relatively shallow, open-marine to very shallow, apparently restricted-marine conditions. The basal bed is made up of nonargillaceous light-gray skeletal wackestone that contains abundant blue-green-algal-coated skeletal grains and scattered phylloid algae as well as scattered worms and tubular Foraminifera. Above that, the Bethany Falls consists of an interval of relatively open-marine phylloid-algal and skeletal wackestone that passes upward into virtually unfossiliferous lime wackestone to mudstone.

The rather abrupt transition from the presumably deep-water Hushpuckney Shale upward into algal limestone with essentially no intervening deep-shelf carbonates appears to represent a period of shallowing during which carbonate sedimentation was inhibited. Renewed carbonate accumulation may be related to high-stand progradation of the carbonate platform from the north (landward).

In many places to the south of this location the upper Bethany Falls Limestone consists of oolitic grainstone that is similar to the reservoir facies in coeval strata in central and western Kansas. This will be seen at Stop 8 on the second day of this trip. However, at this stop the upper portion of the Bethany Falls Limestone is a rubbly, brecciated unit that contains abundant mm-sized tubular rhizoliths. This surface is believed to record the effects of prolonged subaerial exposure and can be traced in outcrops and cores across the northern midcontinent shelf.

The distinct mottling as well as localized in situ brecciation, both of which extend down into the Bethany Falls, are also believed to be associated with subaerial exposure. The mottling, which is characteristic of the Bethany Falls, appears to be related to the infiltration of meteoric water during the exposure event. Nollsch (1983) found that the dark mottles were microspar and that the lighter areas were less-altered micrite. He noted that the dark microspar was isotopically lighter in both carbon and oxygen than the micrite and suggested that these variations were due to meteoric diagenesis. Heckel (in press) suggests that the microspar nodules reported by Steinen (1982) in lime mud on Andros Island in the Bahamas are analogous to the mottles in

the Bethany Falls. Steinen (1982) attributed the development of the Holocene nodules to meteoric phreatic diagenesis.

The *Galesburg Shale* at this location is a blocky mudstone less than 3 ft (1 m) thick that is covered in most places. It represents a period of extended soil formation during the exposure event that terminated deposition of the Swope depositional sequence (Schutter and Heckel, 1985). Southward (basinward) in Kansas this unit thickens into a lithologically heterogeneous siliciclastic package that attains thicknesses of more than 130 ft (40 m) near the Oklahoma border. These sediments were derived in large part from the Ouachita mountain front to the south. Major clastic wedges made up of fluvial-deltaic and density-current deposits filled much of the basin during this episode. Some sediment bypassing across the northern shelf is also indicated; provenance studies are being initiated in order to ascertain the relative importance of these potential source areas in east-central Kansas. Deltas and associated submarine fans prograded across the Arkoma basin through eastern Oklahoma and onto the edge of the carbonate shelf in southeastern Kansas (see introduction for further paleogeographic information). These sands converge and thin northward to form important oil and gas reservoirs in combination structural-stratigraphic and structural traps in parts of southern Kansas and northern Oklahoma, where they are termed the "Layton sandstones." A thick section of more basinal Galesburg Shale will be seen at the last stop on the second day (Stop 13).

Southward (basinward) the Ladore Shale and the Mound Valley Limestone occur between the Bethany Falls and the overlying Galesburg Shale (figs. 9, 10, and 11); at this upper-shelf location these units were most likely either not deposited or eroded. The stratal architecture and significance of the Ladore and Mound Valley will be examined in several stops on the second day. In addition, cores that span the basin-to-shelf setting and illustrate the dramatic stratal changes that occur in the Swope sequence, including development of the Mound Valley Limestone and Ladore Shale, will be available for your perusal this evening.

The *Stark Shale* is the condensed section within the Dennis sequence. In most places south of this location a marine flooding unit, the Canville Limestone, is present above the Galesburg, but at this relatively high shelf position it is poorly developed or absent. The Hushpuckney and Stark shales and associated marine-flooding units are widely correlative intervals that can be traced southward into the detrital-sedimentary pile in Oklahoma 300 mi (483 km) distant (fig. 16) and over 400 mi (644 km) west across the carbonate shelf into western Kansas.

The *Winterset Limestone* is the internally complex upper Dennis carbonate unit previously described in the exposure at Stop 6. It has tentatively been divided into three parasequences (minor sequences) at this location; about 50 mi (80 km) to the south near Jingo this unit consists of at least three and probably four parasequences. Some of these minor shallowing-upward units may be due to eustatic pulses, while others may be entirely local in origin. Note the occurrence of the thicker medial shale and the parasequence boundary it

overlies and the *Composita* brachiopod bed below the cross-stratified oolitic grainstone. Note also that the oolitic unit is only 6 ft (1.8 m) thick here while in Stop 6 the equivalent deposit is up to 13 ft (4 m) thick. Autogenic processes controlled thickness and facies variations within this parasequence.

The *Composita* bed is continuous and uniform in thickness along this exposure. The brachiopods are commonly coated with blue-green algae, with the coatings being thicker in the upper part of the bed. Upward-oriented geopetal fabrics are common. Sediments in this bed may have been transported by storm currents and later coated during day-to-day current activity. Subsequently, this bed was covered by cross-stratified skeletal and oolitic sand. Uncoated brachiopods and other skeletal debris accumulated at the toes of foresets here, much like at Stop 6.

The platy mudstone on top of the oolitic grainstone contains lenticular beds of sharp-based marine grainstone containing wood fragments. This is tentatively interpreted as an event bed that was deposited in a peritidal setting.

The *Fontana Shale* consists of platy, laminated mudstone near the base, passing upward into more radioactive gray shale. The upper boundary of the Dennis sequence is placed in that transitional interval.

The *Block Limestone* is a very fossiliferous marine-flooding unit of the Cherryvale sequence.

The *Wea Shale* is present in the upper portion of this exposure.

The *Westerville Limestone* exposed at the top of this roadcut is a phylloid-algal wackestone overlain by cross-stratified oolitic and skeletal grainstone. This unit thickens to over 20 ft (6 m) of grainstone locally around Raytown, 0.5 mi (0.8 km) to the east, and can be seen across I-435 from high points on this exposure; there it is a thicker cross-stratified grainstone. The Westerville may be equivalent to the Drum oolite at Independence, Kansas. The Cherryvale sequence, of which the Westerville is a part, apparently consists of five distinct shoaling-upward units in an 80-ft (24-m)-thick section in the Amoco Cox core in Haskell County in southwestern Kansas. While the Cherryvale is a thick unit here and in southwestern Kansas, the Cherryvale marine inundation reached only as far as the northwestern Kansas shelf (fig. 37).

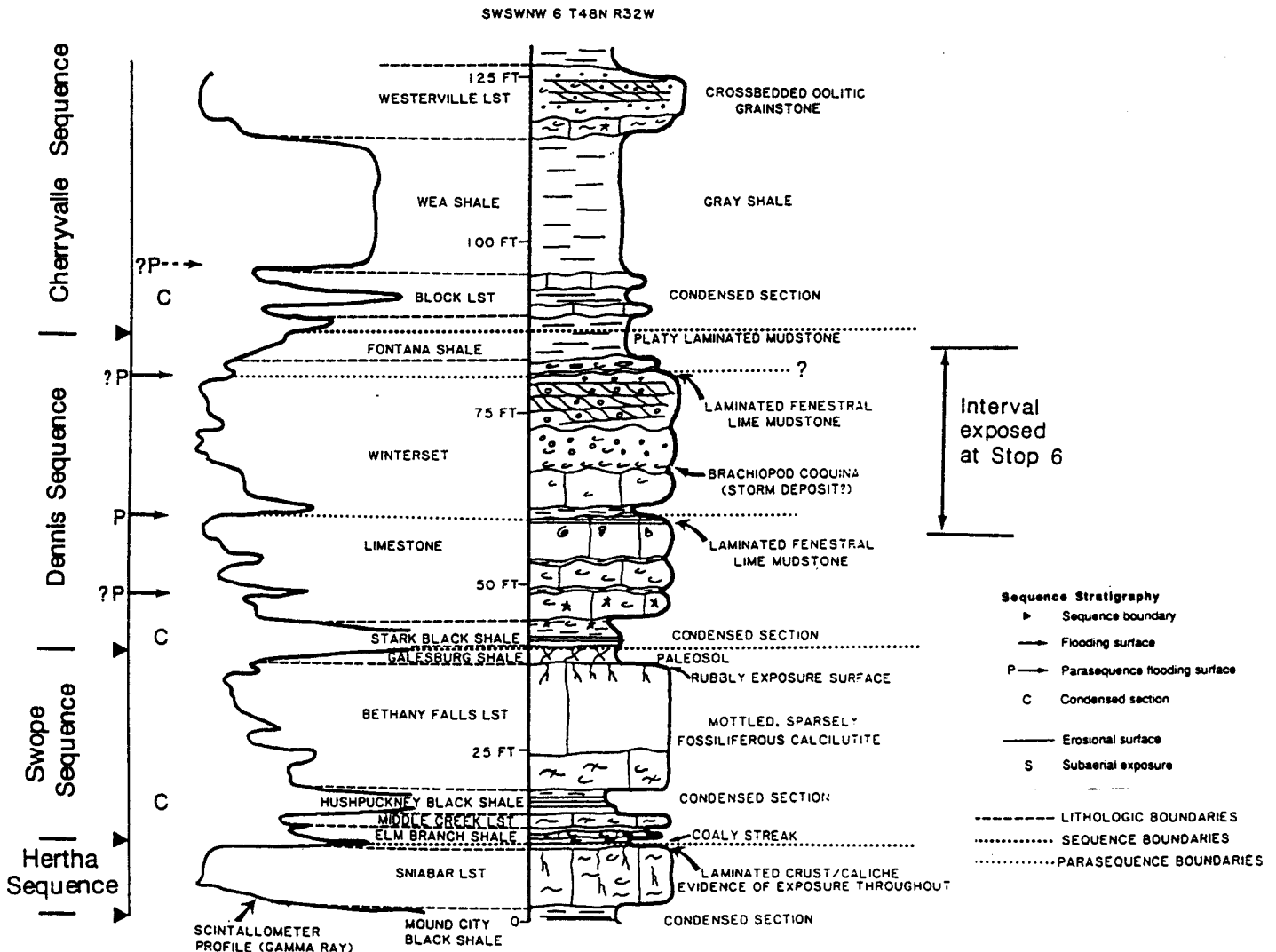


FIGURE 7-1—MEASURED SECTION OF STOP 7 (Raytown) accompanied by gamma scintillometer profile (recording every 1 to 2 ft). Formations listed down middle of diagram. Sequence-stratigraphic terms are indicated on the left.

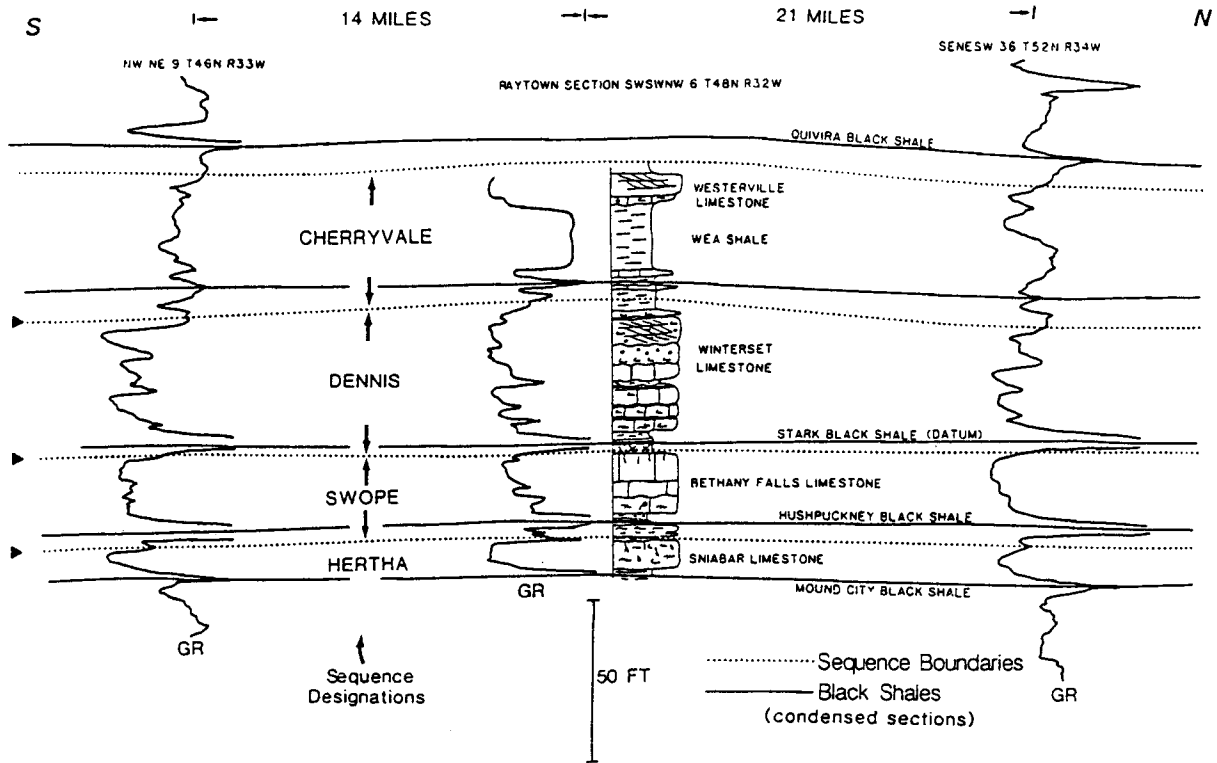


FIGURE 7-2—NORTH-SOUTH STRATIGRAPHIC GAMMA-LOG CROSS SECTION (STARK SHALE DATUM) FROM WELLS IN VICINITY OF STOP 7 (index map in fig. 6-1). Correlations based on gamma-ray character of lithologic units. Sequence boundaries are established with lithologic information carefully correlated to gamma profiles.

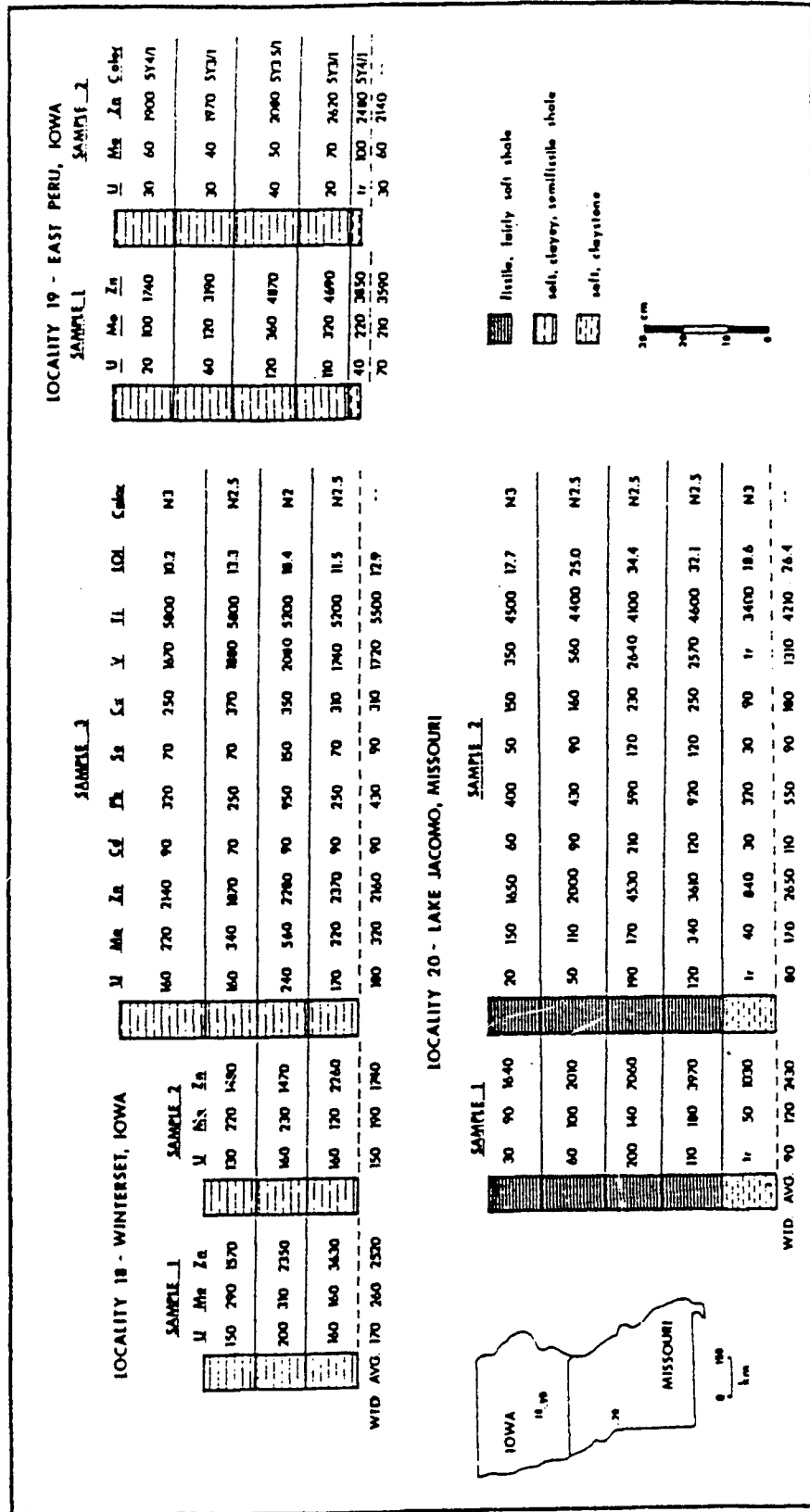


FIGURE 7-3 (table)—SELECTED TRACE-ELEMENT CONTENTS (PPM) AND LITHOLOGIES OF THE HUSHPUCKNEY SHALE (inset locality map). Metals determined by XRF for lower portions of unit only. LOI (wt%) determined at 900 C. Distances between samples is 3 m (10 ft) and 6 m (20 ft) at Locality 18 and 3 m (10 ft) at Localities 19 and 20 (Martin, 1982).



## Stop 8 Farlinville North quarry: Mid to upper Bethany Falls Limestone, Galesburg Shale, Canville Limestone, Stark Shale, lower portion of the Winterset Limestone

Location: E/2 SW sec. 34, T. 20 S., R. 23 E., Linn County, Kansas

### DAY 2

Arrive: 8:20 AM

Leave: 9:20 AM

(30 minutes to next stop)

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

### Introduction

Exposed at this stop are the upper portion of the Swope sequence and the lower portion of the Dennis sequence. This location is a lower shelf setting about 55 mi (17 km) south-southwest of Stop 7, in which the Swope and Dennis sequences were also observed (figs. 1 and 4). Fig. 8-1 provides a map of the local area around Stop 8. The emphasis at this stop will be on the sedimentologic and stratigraphic relationships associated with the shallowing-upward phase of Swope deposition, the Swope-Dennis sequence boundary, and the overlying marine flooding, condensed-section development, and initial shallowing-upward succession of the Dennis sequence (fig. 3).

### Stratigraphy

The upper 13 ft (4 m) of the Bethany Falls Limestone is exposed in the lower wall of the quarry (figs. 8-2 and 8-3). The total thickness of the Bethany Falls is 23 ft (7 m) in a roadcut on Highway 7, located 1 mi (0.3 km) to the southwest of the quarry.

Here in the quarry the lower 7 ft (2.1 m) of the Bethany Falls is composed of light-gray to gray skeletal wackestone and packstone that is typically mottled. Parts of this unit have been altered to light-gray, chalky microspar; in places, fabric relationships suggest vertical piping of the fluids that were responsible for this alteration.

The upper 6 ft (1.8 m) of the unit consist of cross-stratified oolitic grainstone to packstone. The oolitic foresets overlie an apparently scoured surface at the top of the underlying finer-grained unit. Remnants of unfossiliferous, laminated lime mudstone have been observed at the top of the lower unit immediately beneath the oolite on the west wall of the quarry. The presence of this lime mudstone suggests that shallowing to a peritidal setting may have occurred prior to deposition of the oolite; evidence of subaerial exposure at this surface remains equivocal, however. Detailed petrogra-

phy and carbon-isotope profiling may yield answers to these questions.

Although the Bethany Falls at this location is in a lower shelf setting than it was in the Kansas City area, evidence of intense subaerial exposure is still apparent. A discontinuous, brown micritic carbonate that is riddled with what appear to be root tubules occurs in the uppermost portion of the unit. Vertical pipes filled with greenish, shaly material are also ubiquitous in the upper few feet of the Bethany Falls Limestone. This piping is associated with vugs and cavities, many of which extend upward to the top surface of the unit (fig. 8-3). There is considerable small-scale (<1 ft or 0.3 m) relief on this surface where it is exposed in the quarry, but no larger-scale solution features have been observed here. Abundant oomoldic porosity in the underlying upper Bethany Falls probably resulted from an influx of meteoric water during this exposure event. Coeval K-zone reservoirs in western Kansas typically produce from similar oomoldic reservoirs. Further work is underway to understand the regional patterns and significance of this type of early diagenesis in the context of sequence stratigraphy and petroleum-reservoir development.

The *Galesburg Shale* overlies the Bethany Falls Limestone. It is a complex unit about 1.5 ft (0.5 m) thick. The basal portion of the Galesburg is a greenish blocky mudstone interpreted as the paleosol associated with post-Swope exposure. The upper part of the unit is a sandy siltstone that contains a limited marine fauna; it records the initial phase of the marine incursion that resulted in deposition of the Dennis sequence. The boundary between the Swope and Dennis sequences is placed at the top of the paleosol.

The *Canville Limestone* is a marine-flooding unit and represents a continuation of the major marine flooding associated with the Dennis sequence. Myalinid clams occur over the lower surface of the Canville Limestone. Bored spiriferid brachiopods and scattered fish plates mark the

upper surface of the unit immediately beneath the Stark black shale. These features indicate reduced rates of sedimentation, which probably resulted from an increasing rate of base-level rise and the resulting deep-marine conditions unsuitable for carbonate producers.

Above the Canville Limestone lies the *Stark Shale*, the condensed section of the Dennis sequence. This shale is for the most part black, fissile, phosphatic and rich in conodonts, some of which can be seen with a hand lens by the patient observer. Fragments of woody-plant material also occur in the Stark at this quarry. A gray, silty shale overlies the black shale. This interval becomes increasingly calcareous upwards, and brachiopods, bryozoa, and crinoids become common. A similar biota is found in the base of the overlying *Winterset Limestone*, which also contains phylloid algae.

### Farlinville North roadcut

Approximately 1.5 mi (0.5 km) from the quarry entrance we cross the edge of the Bronson escarpment, along which is exposed the Bronson Subgroup of the Kansas City Group. In a roadcut just southwest of the quarry (fig. 8-1), the top of the Pleasanton and the Hertha and Swope cyclothems are exposed (fig. 8-4). This succession typifies these strata in a mid- to lower-shelf setting. Although the thicknesses of

most of these units are about the same as their counterparts at Raytown (Stop 7, end of day one), there is evidence in this section that the depositional histories of these sequences have been recorded with more fidelity than higher on the shelf. This is true regarding both the marine-flooding event that initiated Dennis sequence deposition (see above), and in the *Elm Branch Shale*, which includes the lower portion of the flooding unit of the Swope sequence. About 4.5 ft (1.4 m) of thin sandstone overlain by a stromatolitic molluscan lime mudstone represents the initial flooding event of the Swope sequence. A thin shale separates this limestone from several feet of Middle Creek Limestone, which is the marine-flooding unit immediately below the condensed section represented by the Hushpuckney Shale.

The *Critzer Limestone* has not yet been examined on the trip, but becomes important in Stops 9 and 10. It lies beneath the Mound City Shale, which includes the lower sequence boundary and condensed section of the Hertha sequence. At the Farlinville North quarry, the Critzer Limestone is 2.5 ft (0.8 m) thick, a thickness typical of this unit at this shelf position. At the upper-slope break in the underlying Pleasanton, the Critzer attains thicknesses of up to 25 ft (almost 8 m) or more. Marine flooding associated with Critzer deposition probably caused the cessation of Pleasanton delta progradation in this area and led to formation of the relatively steep Pleasanton slope along the shelf-to-basin transition in southeastern Kansas (figs. 4 and 5).

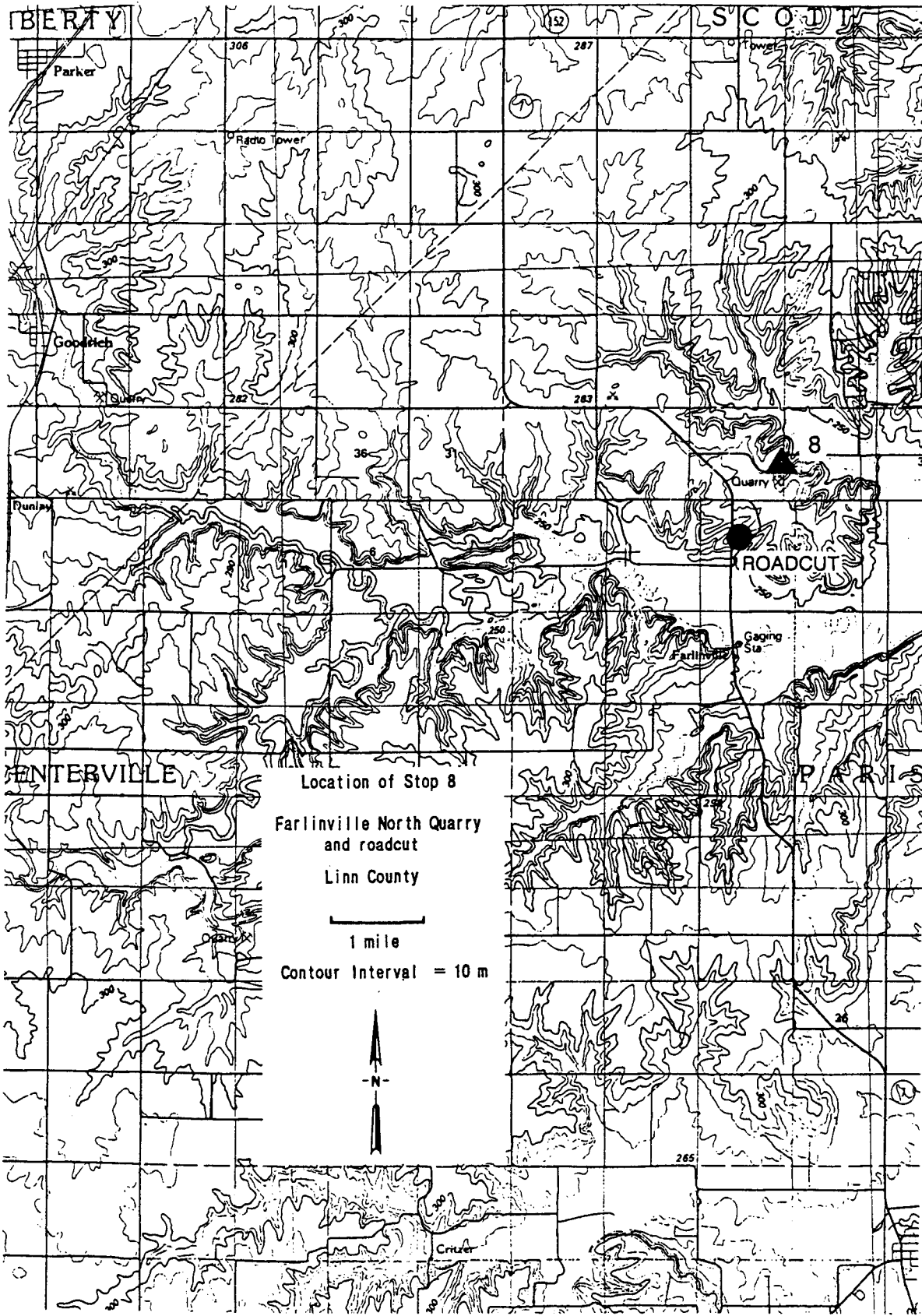


FIGURE 8-1—LOCATION MAP FOR STOP 8 (Farlinville North quarry) and Farlinville roadcut in Linn County, Kansas.

FARLINVILLE NORTH QUARRY

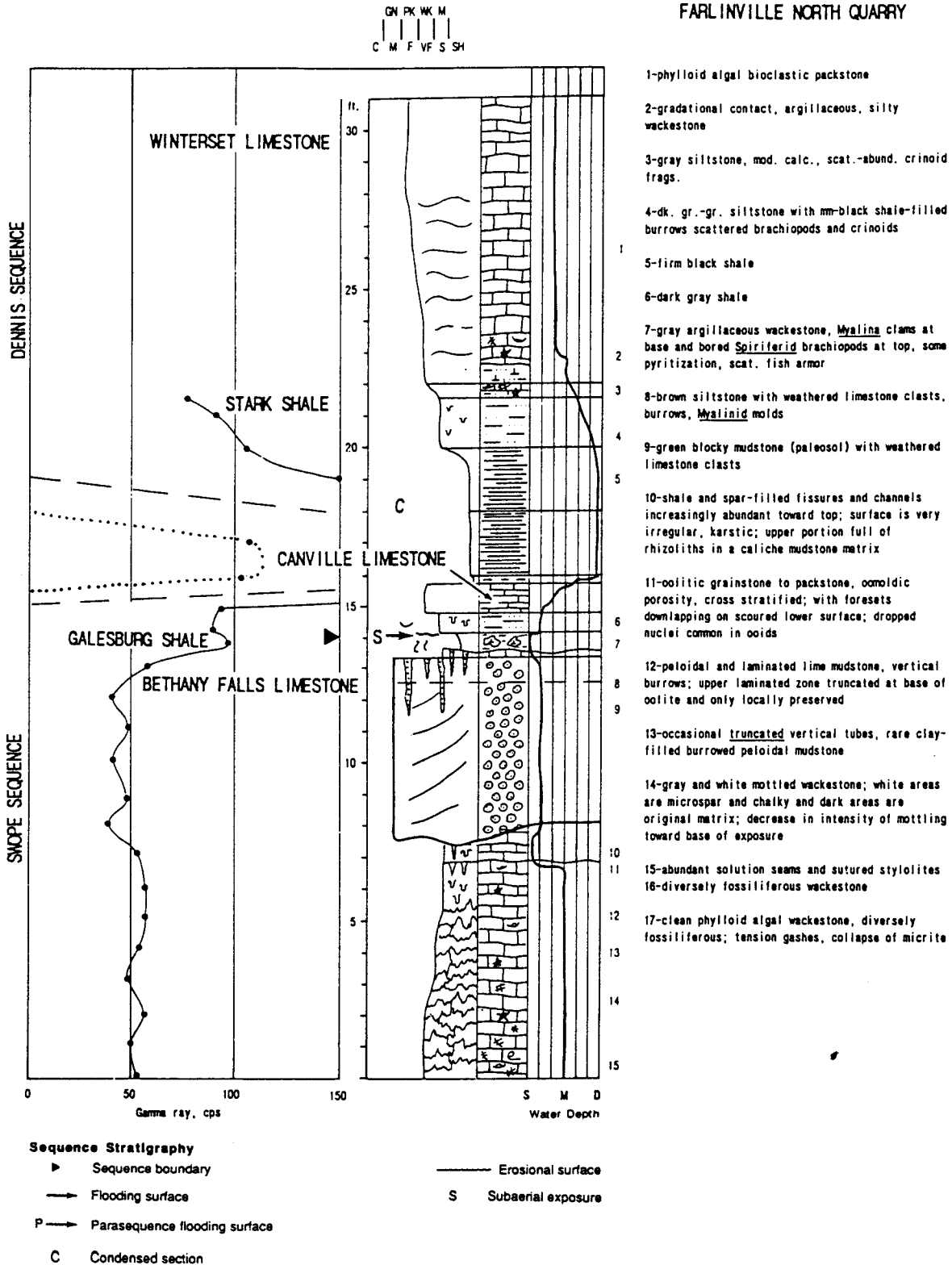
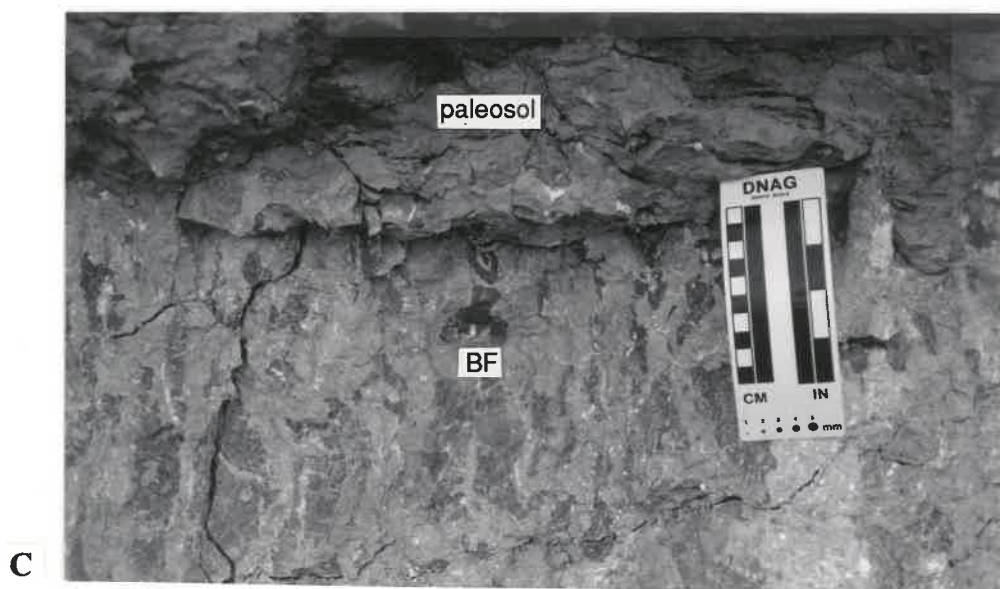
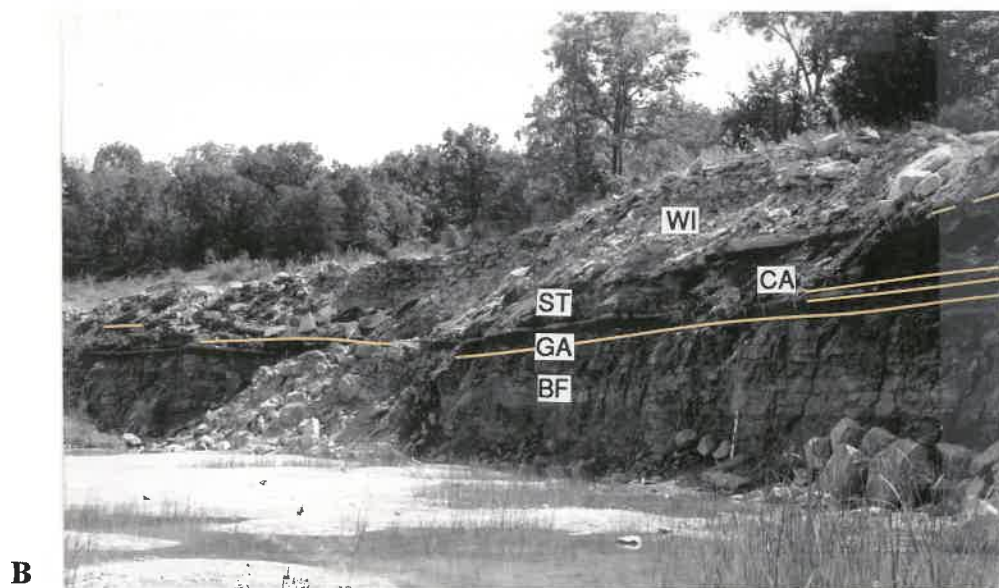


FIGURE 8-2. MEASURED SECTION OF FARLINVILLE NORTH QUARRY EXPOSURE AT STOP 8. Section includes gamma-ray profile and sequence-stratigraphic symbols. Bethany Falls Limestone Member of the Swope Limestone, Galesburg Shale, and Canville Limestone, Stark Shale, and lower portion of Winterset Limestone members of the Dennis Limestone are present along the walls of the quarry.

FIGURE 8-3 (A, B, and C)—WEST WALL OF FARLINVILLE NORTH QUARRY (A AND B). BETHANY FALLS LIMESTONE (BF), GALESBURG SHALE (GA), CANVILLE LIMESTONE (CA), STARK SHALE (ST), AND WINTERSSET LIMESTONE (WI) CAN BE TRACED AROUND QUARRY WALLS. C) Close-up of top of Pennsylvanian subaerially weathered Bethany Falls (BF) and paleosol in lower Galesburg Shale. This paleosol forms the sequence boundary between Swope and Dennis sequences.





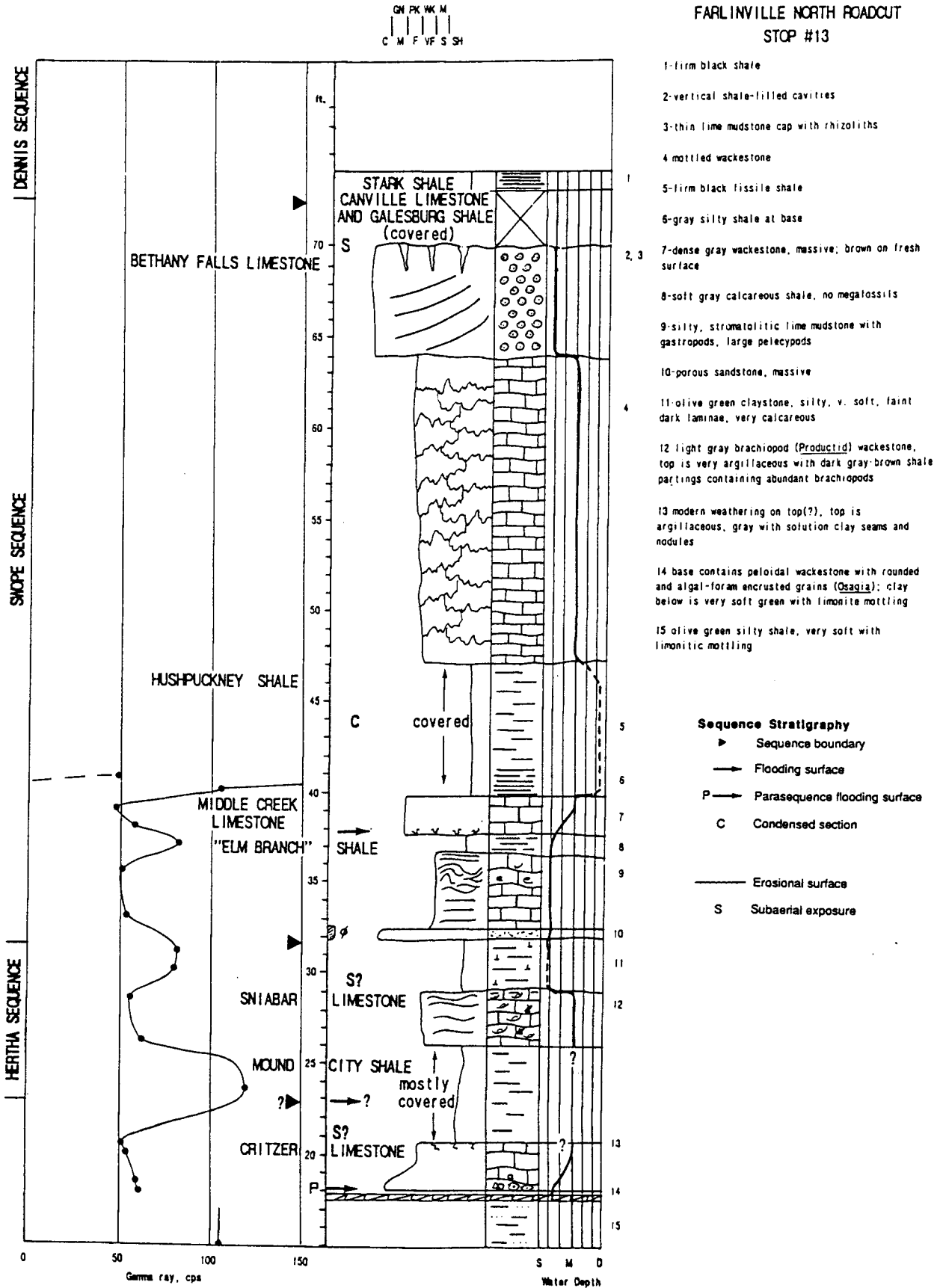


FIGURE 8-4—MEASURED SECTION OF FARLINVILLE NORTH ROADCUT (located in fig. 8-1).



# Stop 9 Xenia Northwest. Uppermost Pleasanton through Bethany Falls Limestone

Location: Center S/L SW sec. 23, T. 23 S., R. 22 E., Bourbon County, Kansas

Arrive: 9:50 AM

Leave: 10:10 AM

(10 minutes to Stop 10A)

Contributors: *Lynn Watney, Phil Heckel, and John French*

## Introduction

The outcrop exposed at Stop 9 contains the last set of shelf strata that will be seen on this trip, as later stops will be at slope or basinal positions. Significant stratal changes will be seen as we proceed through the last portion of this field trip.

Stops 9 and 10 will be handled differently from the other stops on the trip. First, Stop 9 will be very brief (20 minutes); we will examine only key features of shelf succession that will be useful in understanding correlations as we cross the shelf-slope-basin transition in the next series of stops. Stop 10 is composed of a series of three "drive-bys," where Philip Heckel will point out stratigraphic units that have been useful in his attempts at recognizing the shelf-slope-basin transition and in establishing correlations in the outcrop in order to understand the depositional history of these units. Exposure of the slope succession is generally poor, and those exposures that exist are few and isolated. It has only been over the last few years that Phil Heckel, Allan Bennison, and others have defined correlations in the outcrop along this slope setting.

Thinning of the Pleasanton Group revealed by the thickness of the interval from the Nuyaka Creek to Mound

City shales is on the order of 120 ft (37 m) in a distance of less than 5 mi (8 km; figs. 4 and 5). The overlying Hertha sequence thickens abruptly outboard of this slope break to form an algal-mound complex (figs. 4 and 6), a representative of which will be seen later at Stop 11 at Uniontown.

Stop 9 and the drive-bys associated with Stop 10 (a, b, and c) reveal abrupt lateral change in the stratigraphy of the upper portion of the Pleasanton in a slope setting. The depositional dip of these strata is southeastward from Stop 9. This is in contrast to a predominant southerly slope in the subsurface to the west (fig. 5). Therefore, the regional cross section near Stop 9 (fig. 4) is actually oriented along the strike of the shelf at the location of this stop.

A cross section based on surface exposures shown in fig. 9-2 links Stop 9, Xenia Northwest (XNW) with the drive-bys at Xenia Northeast (XNE; Stop 10a) and Mapleton Northwest (MNW; Stop 10b). The index map (fig. 9-1) shows our traverse which will be down the slope of the Pleasanton delta. After Stop 10b we will continue to Turkey Creek East (TCE; Stop 10c). TCE is also located on the slope. Stop 11 is located considerably down the slope from Stop 9.

## Stratigraphy

The measured section and gamma-ray profile for Stop 9 are included in fig. 9-3. The *Critzer Limestone* is about 9 ft (3 m) thick, making it thicker than its shelfal equivalent. Here it is interpreted to be in a shelf-margin setting. A flooding surface occurs at its base. This lower surface rests on a siltstone to very fine grained calcareous sandstone in the uppermost *Pleasanton Group*, which is interpreted as delta-front sandstone deposited during initial marine flooding. The shale and sandstone extend possibly 100 ft (30 m) down the slope of the hill. The shale below the Critzer Limestone is referred to here as the *middle Pleasanton shale*. Thicker sandstones of the Pleasanton Group, interpreted as delta-front deposits, crop out to the northeast near Mound City and Pleasanton. At this location the Critzer Limestone is a shallow-water limestone throughout. It contains snails filled

with blocky calcspar with large internal molds interpreted as an indication of meteoric diagenesis (Underwood, 1984).

The 7-ft (2.1-m)-thick *Mound City Shale* that overlies the Critzer Limestone is a complex unit. There is 0.5 ft (0.15 m) of green, very fossiliferous, conodont-rich claystone overlain by a thin limestone, 3 ft (1 m) above the base of the Mound City Shale. The thin green shale contains the three conodont genera that usually characterize black phosphatic shales. The shale and limestone combination are interpreted by Heckel (1985) as a "core" interval. Stop 9 is thought to lie above an anoxic layer that developed basinward during flooding and deepening associated with deposition of a condensed interval in the Mound City Shale. Inundation was apparently so rapid that a carbonate marine-flooding unit was not deposited. No elevated gamma radiation is noted in

this interval. The core shale or condensed section within the Mound City Shale is typically gray to dark-gray shale on the shelf north of Linn County, Kansas, all the way to Iowa. Basinward, the Mound City Shale grades to phosphatic black shale and forms an excellent subsurface marker bed (fig. 4).

The *Sniabar Limestone* is relatively thin at this stop. It is only 3.5 ft (1.1 m) thick, typical of its shelfward shallowing-upward equivalents. Although the upper surface of the *Sniabar Limestone* here shows no distinctive subaerial-exposure features, pitted carbonate lithoclasts occur at the base of the overlying *Elm Branch Shale*; these clasts are presumably erosional remnants related to an exposure event. Carbonate pebbles also fill cracks extending into the *Sniabar Limestone* at a location 10 mi (16 km) northeast of here.

The *Elm Branch Shale* contains a poorly developed paleosol at its base that is overlain by a dark-gray argillaceous siltstone containing abundant woody-plant debris and bivalve impressions. The base of this dark-gray siltstone is the lower boundary of the Swope sequence.

At 4 ft (1.2 m) thick, the *Middle Creek Limestone* is a relatively thick flooding unit of the Swope sequence com-

prising the upper portion of this surface exposure. The unit is rich in phylloid algae and contains a diverse fauna.

The *Hushpuckney Shale* is the prominent condensed section of the Swope sequence very similar to that seen at Stop 7. A burrowed siltstone above the black-shale facies similarly resembles the gray shale that is found above the black shale at Raytown. The black *Hushpuckney Shale* persists throughout most of the shelf and basin, becoming richly phosphatic in the basin. It is an excellent gamma ray-log marker bed (fig. 4).

The *Bethany Falls Limestone* is similar to that seen at Stop 8, composed of a mottled wackestone at the base and an oolitic grainstone in its upper part; the top of the unit is not exposed here. Most of the ooids have been leached, resulting in either oomoldic porosity or molds filled with calcite spar. The lower contact of the oolite with the wackestone is sharp, suggesting scouring prior to accumulation of the grainstone. The widespread oolite within the Swope sequence on the southern shelf suggests deposition on a ramp much like that inferred in southwestern Kansas around the margins of the Anadarko basin (Watney, 1985b).

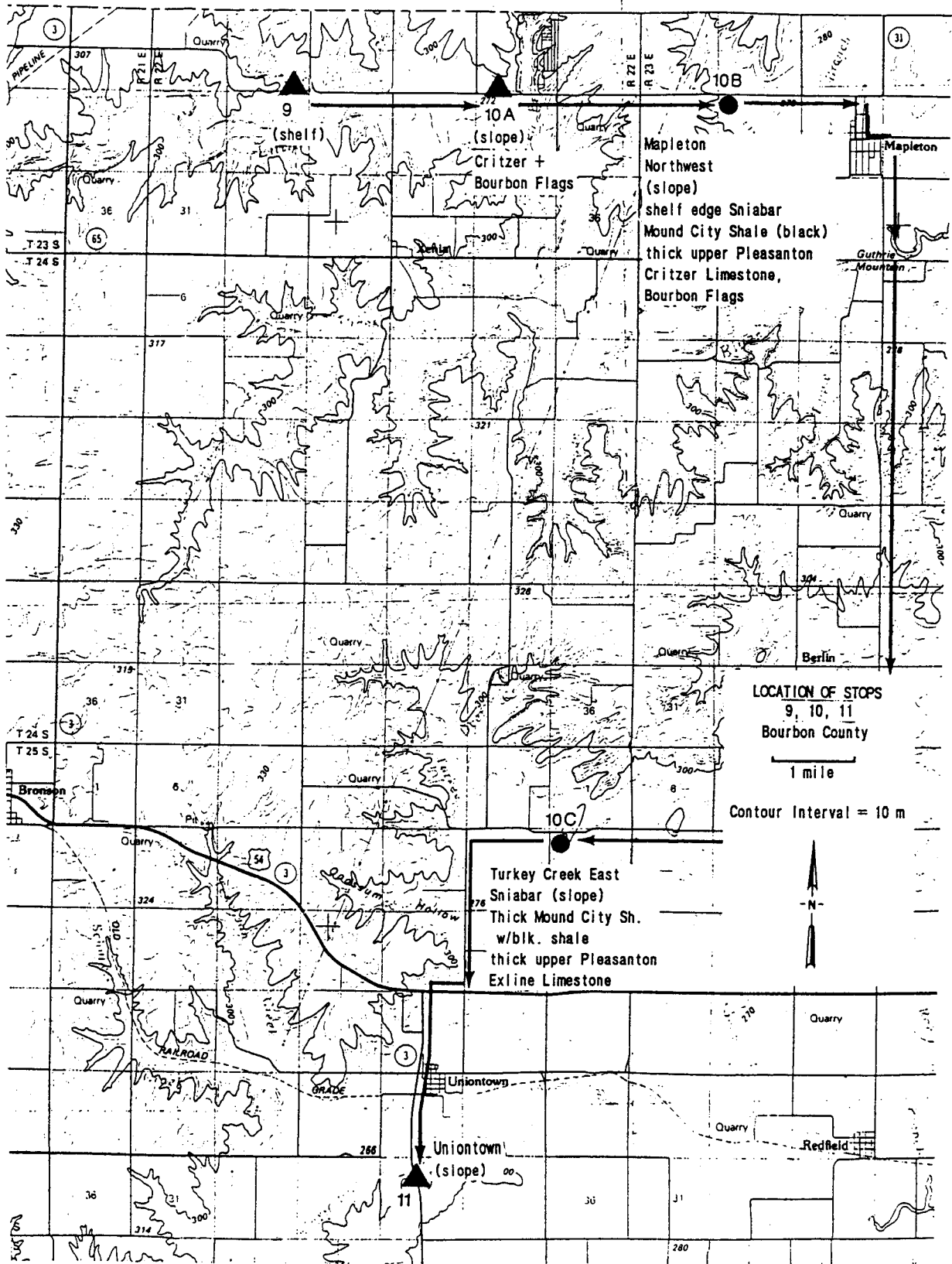


FIGURE 9-1. LOCATION MAP FOR STOP 9 (XENIA NORTHWEST) AND DRIVE-BYS OF 10A (XENIA NORTHEAST), 10B (MAPLETON NORTHWEST), AND 10C (TURKEY CREEK EAST). Drive-bys will consist of short pauses to point out marker horizons and stratigraphic changes associated with slope changes along the front of the Pleasanton delta.

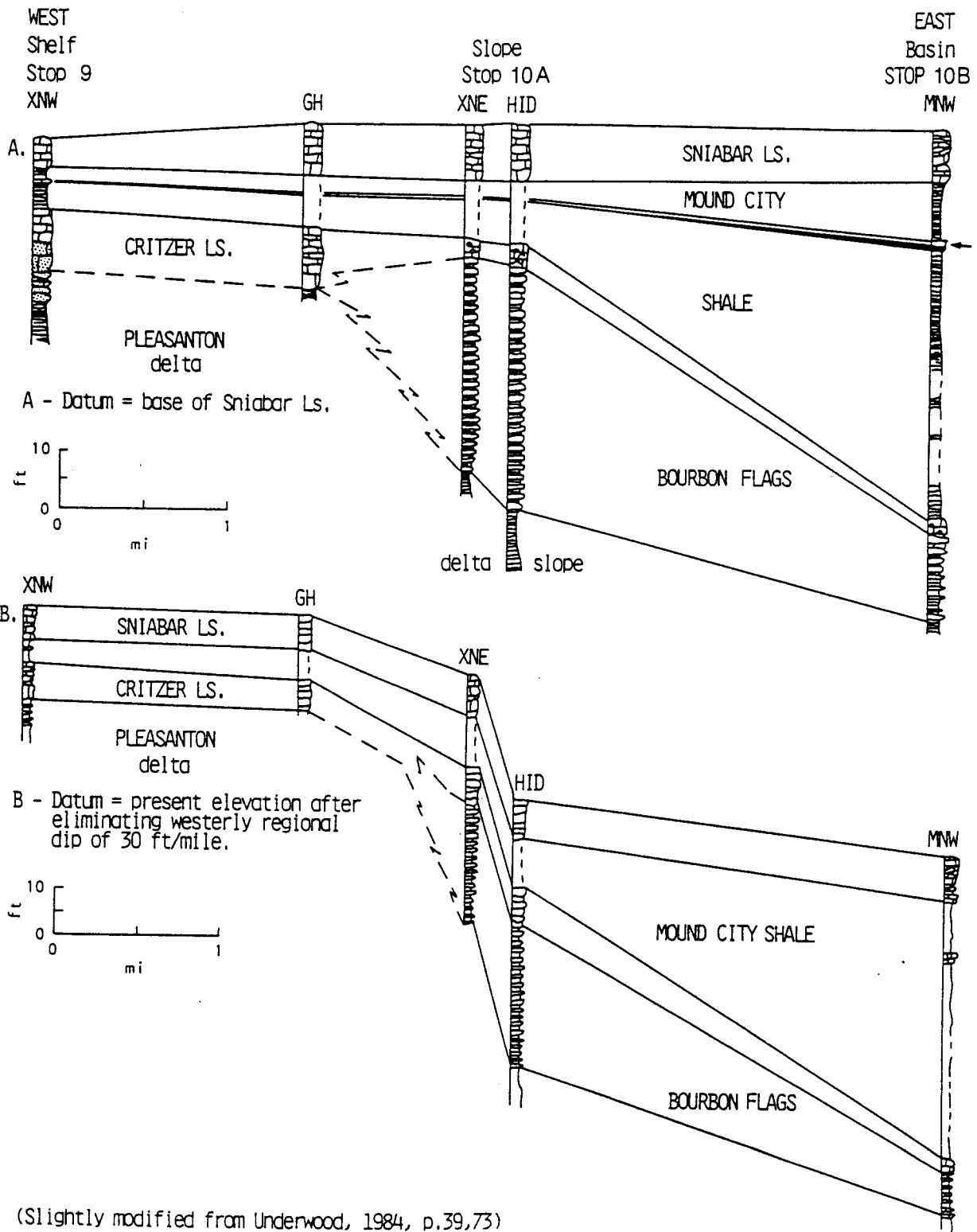


FIGURE 9-2—WEST-TO-EAST CROSS SECTION OF UPPER PLEASANTON GROUP AND HERTHA LIMESTONE BASED ON SURFACE EXPOSURES SEEN AT STOP 9 (XNW) and the first two drive-bys (10A, XNE) and (10B, MNW). Upper diagram is restored stratigraphic section and lower is a structural cross section. Note arrow on right margin of upper section identifying core or condensed section in the Mound City Shale.

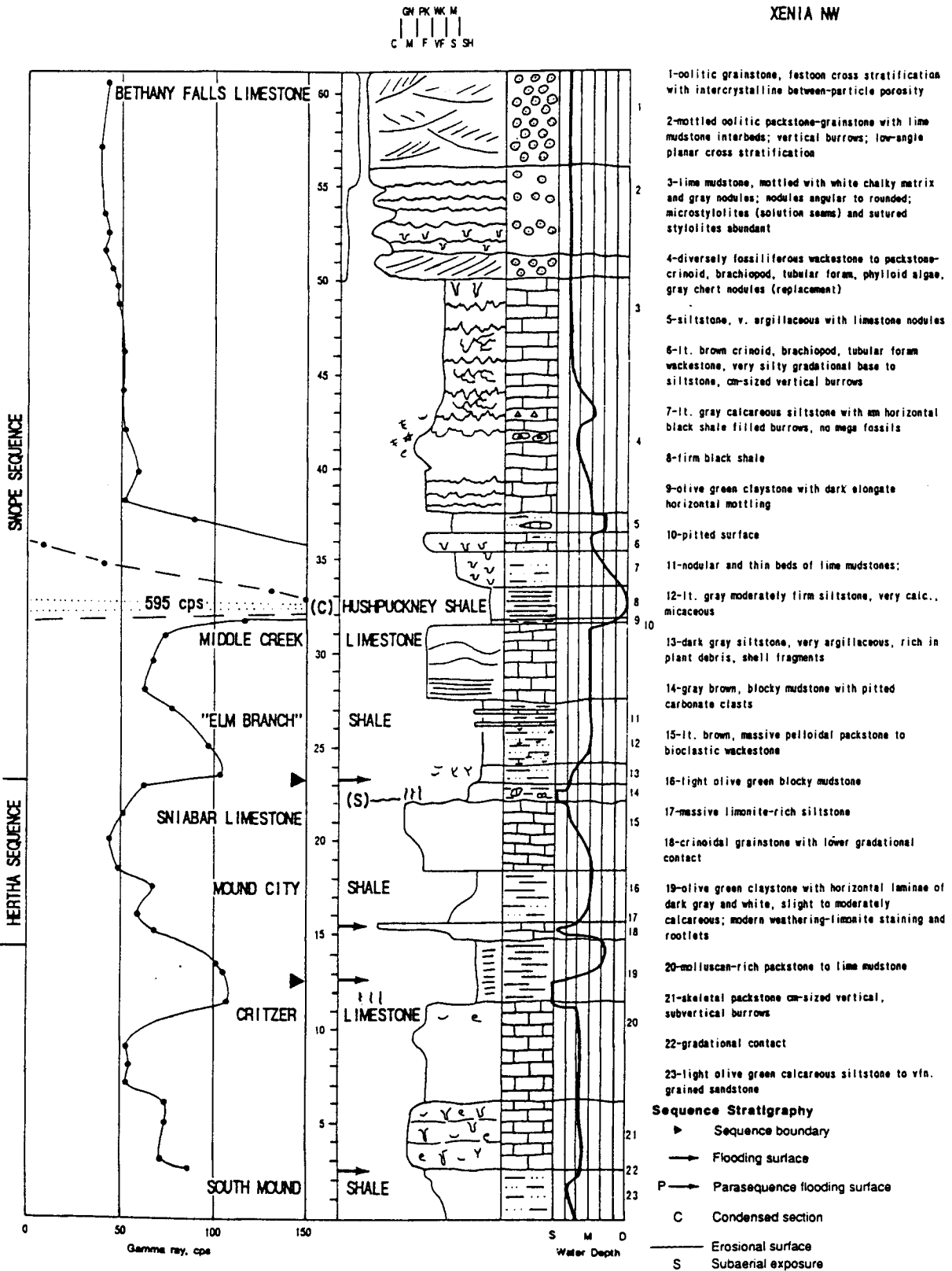


FIGURE 9-3—MEASURED SECTION AND GAMMA-RAY PROFILE OF STOP 9 (Xenia Northwest, XNW). A portion of this section is also shown on the cross section in fig. 9-2.



# Stop 10 "Drive-bys" of (a) Xenia Northeast (XNE): Critzer Limestone (Bourbon flags) on shelf slope, (b) Mapleton Northwest (MNW), and (c) Turkey Creek East (TCE)

Location: Stop 10A, S/2 SW sec. 23, T. 23 S., R. 22 E.  
 Stop 10B, NW NW NW sec. 29, T. 23 S., R. 23 E.  
 Stop 10C, NW NW NW sec. 7, T. 25 S., R. 23 E.  
 Bourbon County, Kansas

Arrive: 10:20 at Xenia NE (Stop 10a)

(Drive-bys on the way to Uniontown, Stop 11)

Contributors: Lynn Watney, Philip H. Heckel, and John French

## Introduction

Stop 10A is a drive-by of Xenia Northeast. Location is 2.5 mi (4 km) east of Stop 9 (fig. 9-1). Stop 10 is labeled XNE on cross section in fig. 9-2. It includes an exposure of the Bourbon flags, an alternating carbonate and siliciclastic package that is developed exclusively as a slope facies. The Pleasanton Group thins to the east-southeast at about 5 to 15 ft per mile (0.33–2.9 m/km; figs. 5 and 9-2). This thinning resulted in a slope that had a significant effect on the stratigraphy of the upper Pleasanton. In particular, abrupt changes occur in the interval from the Exline Limestone marker upward (fig. 10-2). One of these changes is the appearance of the Bourbon flags and attendant changes in the Critzer

Limestone, as well as the occurrence of a wedge of siliciclastics above the Critzer in the interval equivalent to the Mound City Shale on the shelf. Conodont biostratigraphy is presently being used to further resolve correlations from isolated exposures such as those shown in fig. 10-2.

Preliminary findings of French indicate while the basic correlations of the outcrop are verified, as seen in fig. 10-2, different stratal geometries exist in the subsurface to the west along the zone where the Pleasanton Group thins (fig. 4). The siliciclastic wedges observed above the Critzer Limestone apparently did not affect the western part of the Pleasanton delta (fig. 4).

## Stratigraphy

### Stratigraphy at Stop 10A, Xenia Northeast (XNE)

The Bourbon flags compose the lower two-thirds (35 ft [10.6 m]) of this exposure in Stop 10A (Xenia NE; fig. 10-1).

Middle Pleasanton shale present beneath the Bourbon flags is not exposed here, but is found in a spillway 0.5 mi (0.8 km) east of this locality. This middle Pleasanton shale consists of thin-bedded gray claystone and siltstone with intervals of abundant fossils, particularly crinoids. These strata reflect suspension sedimentation associated with Pleasanton delta progradation.

The *Bourbon flags* seen here in Stop 10A consist of a succession of alternating argillaceous and silty-lime mudstone and calcareous silty shale with very sparse marine fossils (brachiopods, crinoids, snails, conodonts—*Idiognathodus*) and well-preserved plant fragments. The Bourbon flags are thought to represent intermittent episodes of carbonate accumulation during generally rapid siliciclastic sedimentation, as evidenced by the paucity of fossils and good preser-

vation of plant fragments. The unit was deposited in a stable, open-marine environment, as indicated by the presence of stenohaline organisms such as crinoids and *Idiognathodus* (a conodont; Heckel, 1985). This unusual depositional motif took place along the slope of the Pleasanton delta during a time of marine flooding associated with the Critzer Limestone, identified here as a parasequence within the Pleasanton sequence (fig. 3).

The silty and calcareous layers of the Bourbon flags show little contrast in natural gamma radiation as measured at this exposure, 56 to 68 cps (counts per second) for siltstone and carbonate and 56 to 74 cps for the less resistant shaly intervals. Therefore, the detection of this slope facies is not likely with only a gamma-ray log. Rather, distinction of this facies would require a suite of logs sensitive to this variation in lithology such as neutron-density and possibly resistivity logs.

The base of the more typical *Critzer Limestone* occurs above the Bourbon flags. The contact is gradational, with limestone beds become thicker and more fossiliferous. A thin, abraded skeletal grainstone with a sharp, scoured base occurs near the base of the Critzer Limestone. This grain-

stone indicates either shoaling or deposition during an event such as a storm. This grainstone is overlain by a phylloid-algal wackestone that is succeeded upward by fossiliferous gray shale in the lower *Mound City Shale*. The lower portion of the Mound City Shale (below the thin Mound City condensed section) thickens farther down slope and is referred to by Heckel as the upper Pleasanton shale (figs. 9-2 and 10-2). While this shale is 5 ft (1.5 m) thick here, it is 15 ft (4.6 m) thick at the spillway 0.5 mi (0.8 km) east of here, in a basinward direction.

The *Sniabar Limestone* occurs as slump blocks on the hillside above this exposure.

### Stratigraphy Stop 10B at Mapleton Northwest (MNW)

This drive-by illustrates the abrupt change in stratigraphy in a lower-slope position 3 mi (4.8 km) east (basinward) of Stop 10A (fig. 9-1). The stratigraphic section seen at this stop is shown on the right side of the cross section in fig. 9-2, labeled MNW. The regional cross section based on surface exposures also identifies Mapleton NW (fig. 10-2).

The exposure includes the interval from the Bourbon flags at the base to the Sniabar Limestone at the top. The middle Pleasanton shale (interval below the Bourbon flags) is estimated to be 30 ft (9 m) thick here. The Critzer Limestone/Bourbon flags interval is approximately 13 ft (4 m) thick where exposed at the foot of the hill in the driveway on the south and along the creek bank to the north. The lithology is lime mudstone with scattered phylloid algae at the top. The *Critzer Limestone/Bourbon flags* is interpreted by Heckel to represent the toe of the slope.

The *upper Pleasanton shale* above the flags (and the shale beneath the condensed section of the Mound City Shale), mostly covered in this outcrop, is composed of 44 ft (13.4 m) of prodeltaic shale. This interval has thickened progressively from the Xenia NW where it was only 3 ft (1 m) thick. The condensed section (or core shale) of the Mound City Shale, found in the bank along the roadcut, consists of 2 ft (0.6 m) of black, conodont-rich shale and an overlying earthy, crinoidal limestone. This is the regional-marker horizon extending from shelf to basin recorded in both the surface exposures (figs. 10-2) and subsurface data (fig. 4). The shale in the upper Mound City Shale above the con-

densed section is composed of 13 ft (4 m) of gray prodeltaic shale. This shale thickens southward at our next drive-by at Turkey Creek East (Stop 10c).

The *Sniabar Limestone*, located at the top of the roadcut, contains 9 ft (2.7 m) of grainstone overlain by a skeletal wackestone. This lower grainstone is also present at Uniontown (Stop 11), where you will have a opportunity to examine it more closely.

### Stratigraphy Stop 10C at Turkey Creek East (TCE)

This drive-by at Stop 10C is located 9 mi (14.5 km) south of the previous stops at 9 and 10 A and B. Stop 10C lies parallel to the slope and slightly further down the slope from these previous stops. Turkey Creek East is identified in fig. 10-2.

The section includes the interval from the Exline Limestone to the Sniabar Limestone. The *Exline Limestone* is exposed along the bank of the road ditch near the road intersection. The Exline Limestone is composed of 1 ft (0.3 m) of skeletal wackestone, unlike the Bourbon flags lithology. Characteristic conodonts have permitted regional correlation of this thin limestone in the outcrop from Iowa to Oklahoma (fig. 10-2). The Exline Limestone is the marine-flooding horizon on which southward progradation and downlap of the Pleasanton delta occurred. The Exline Limestone is interpreted as a parasequence within the Pleasanton sequence (fig. 3b). This thin limestone is a good subsurface marker in many places and is clearly recognized in cores to the west. This horizon can be examined closely at Uniontown (Stop 11).

The *upper and middle Pleasanton shales* can not be distinguished here because the Bourbon flags and Critzer Limestone are not developed (fig. 10-2). The latter units have apparently downlapped onto the Exline Limestone horizon or have pinched out. The shale interval is 43 ft (13 m) thick. The *Mound City Shale* condensed section (core shale) is developed here as 4 ft (1.2 m) of black shale with abundant conodonts. This unit is seen low in the roadcut. Thirty feet (9 m) of prodeltaic shale with flaggy limestones are present in the hillside above. The *Sniabar Limestone* forms the top of the low hill to the northeast where it consists of approximately 8 ft (2.4 m) of basal grainstone overlain by phylloid-algal wackestone.

XENIA N.E. RDCUT (XNE) + ADJACENT SPILLWAY (HID-entire section)

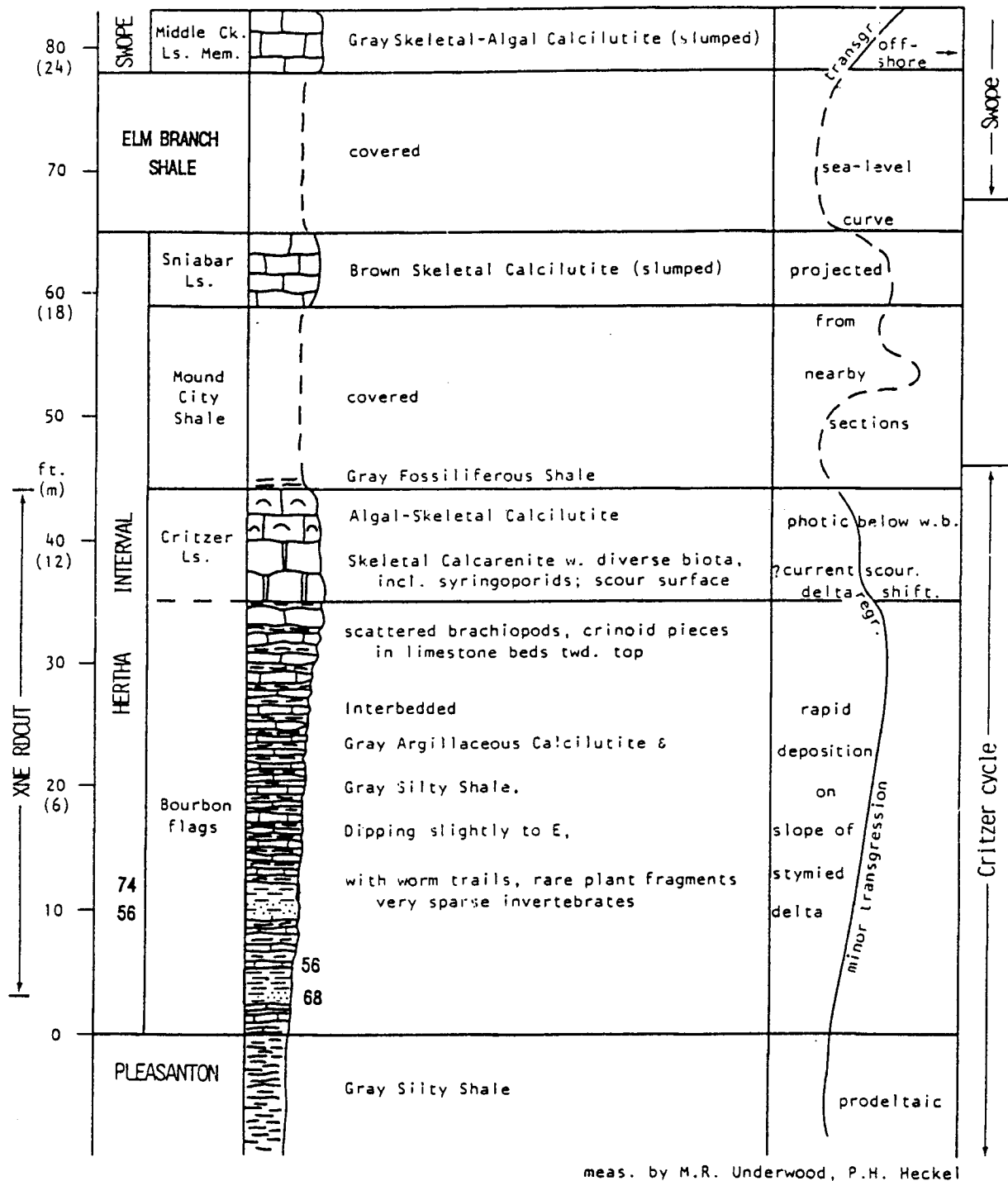
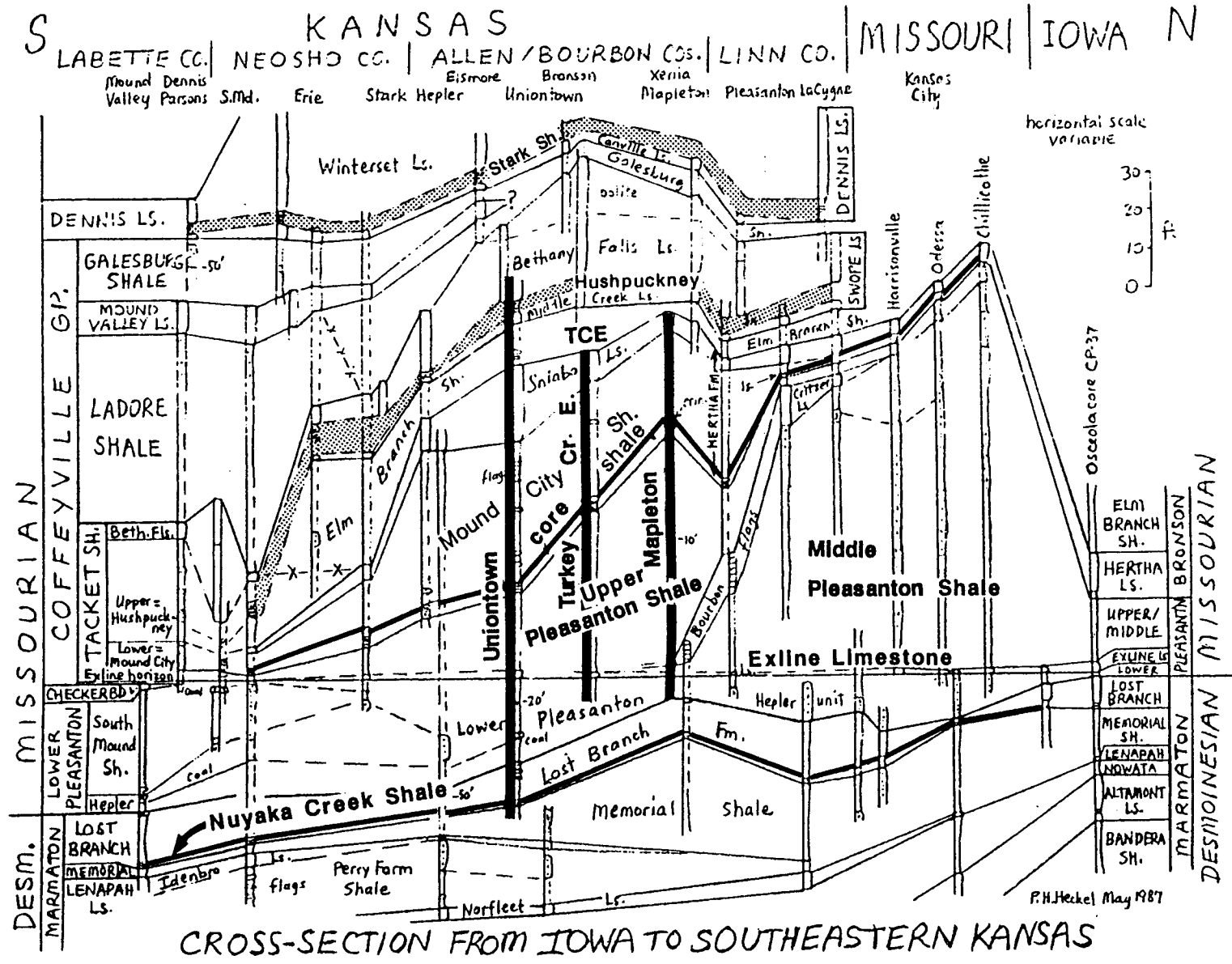


FIGURE 10-1—MEASURED SECTION OF DRIVE-BY 10A, XENIA NORTHEAST (XNE). This section is also shown on the cross section in fig. 9-2.



CROSS-SECTION FROM IOWA TO SOUTHEASTERN KANSAS

FIGURE 10-2.—REGIONAL SOUTH-TO-NORTH STRATIGRAPHIC CROSS SECTION OF UPPERMOST DESMOINESIAN AND LOWER MISSOURIAN STRATA BASED ON SURFACE EXPOSURES (Heckel, 1987). Measured sections of drive-by 10C (Turkey Creek East) and Stop 11 (Uniontown) are shown. Note Exline Limestone datum, a regional marker on top of which downlap of Pleasanton delta occurs.

# Stop 11 Uniontown: Pleasanton Group, Critzer Limestone, Mound City Shale, Sniabar Limestone

Location: Center N/2 sec. 34, T. 25 S., R. 22 E., Bourbon County, Kansas

Arrive: 11:05 AM

Leave: 12:15 PM

(lunch while in transit to next stop, 45 minutes)

Contributors: *Howard Feldman, Chris Maples, Lenore Tedesco, and Harold Wanless, Jr.*,  
with introduction by *Lynn Watney, Phil Heckel, John French, and Evan Franseen*

## Introduction

Fig. 10-2 relates the exposed section at Stop 11 (Uniontown) to the previous stops. The strata exposed at Uniontown were deposited farther downslope off the Pleas-

anton delta than at Turkey Creek East (Stop 10c; located 4.5 mi, 7.2 km north of Uniontown, fig. 9-1 and fig. 5).

## Stratigraphy

The interval exposed at Stop 11 extends from the lower Pleasanton shale up to the Elm Branch Shale and represents portions of the Pleasanton and Hertha sequences (figs. 3b, 11-1, 11-2, and 11-3). The 1-ft (0.3-m)-thick bed of *Exline Limestone*, the regionally traceable marine-flooding unit of the Pleasanton sequence, is present low in the Uniontown exposure on the east side of the road (fig. 11-1). It is the first widespread Missourian marine inundation. As indicated in the gamma-ray profile of fig. 11-1, the Exline Limestone is not associated with any elevated natural gamma radiation. The *lower Pleasanton shale* is exposed beneath the Exline Limestone marker. The section is mainly an alluvial to shallow marine deposit made up of siltstone and claystone with scattered marine fossils at the top. The Nuyaka Creek Shale, a black, radioactive regional marker (the condensed section at the base of the Pleasanton sequence, fig. 4) is exposed in a ravine west of this roadcut.

The *middle/upper Pleasanton shale* (above the Exline Limestone and below the black shale of the Mound City Shale, fig. 10-2) has thinned to approximately 20 ft (6.1 m). As indicated earlier, the Critzer Limestone/Bourbon flags interval apparently has downlapped onto the Exline Limestone north of this site or has pinched out (fig. 10-2). This shale interval was approximately 100 ft (30 m) thick at Xenia Northwest (Stop 9), 13 mi (21 km) north at the edge of the shelf.

The black-shale facies (condensed section and regional marker) of the *Mound City Shale* defines the upper contact of the middle/upper Pleasanton Shale (fig. 10-2). This black shale, 3 ft (1 m) thick, is poorly exposed near the culvert on the west side of the Uniontown exposure (present in lower covered interval in measured section in fig. 11-1).

The upper portion of the *Mound City Shale* above the black-shale marker is very thick, approximately 30 ft (9.2 m) here, as compared to the mapped area in the subsurface to the west (figs. 11-1 and 11-2). Thin beds of mudstone in gray to dark-gray shale present in this interval contain varying amounts of crinoids and brachiopods, some of which are bored, and trace fossils.

The *Sniabar Limestone* forms the prominent limestone in this exposure. It thickens noticeably southward across the Uniontown exposure from 6.5 ft (2 m) to over 20 ft (6 m; figs. 11-2, 11-3, and 11-4 A). A skeletal grainstone occurs at the base of the Sniabar Limestone. This grainstone unit is thickest where the base of the Sniabar Limestone is highest along the northern edge of this exposure. The grainstone is overlain by a phylloid-algal wackestone that contains abundant micrite and intervals of varying concentrations of broken algal blades. Upright, apparently in situ algal blades have also been found. Separate papers by Tedesco and Wanless and Feldman and Maples further describe the internal architecture and geometry of the Sniabar Limestone at Uniontown.

Feldman and Maples utilize the coral *Neosyringopora*, which encrusts depositional surfaces in the Sniabar Limestone, to estimate episodicity of sedimentation, depositional rates, and synoptic relief of the sediment surfaces within the algal facies. They conclude that 75% of the sediment of the Sniabar Limestone records unusual short-lived events. Average accumulation rates here are considerably less than these short-term, episodic events of lime-mud influx.

Tedesco and Wanless describe burrow-generated facies formed below the sediment surface that are similar to

those observed in modern mud banks and mounds. Specific textures are identified that resemble storm infilling of excavated burrow systems.

The upper surface of the Sniabar Limestone is irregular and has scattered but diagnostic evidence of Pennsylvanian subaerial exposure. A zone of calichification containing rhizoliths and large tubular-root systems like that seen in the Sniabar Limestone at Raytown (Stop 7) is present here. Preservation of the exposure features occurs in depressions along the upper surface of the Sniabar Limestone. Erosion has apparently removed exposure evidence in the topographically higher positions (fig. 11-4B and C).

A thin interval of *Elm Branch Shale* is exposed on the east side of the Uniontown roadcut in one of the depressions at the top of the Sniabar Limestone. The shale is a blocky mudstone similar to paleosols seen elsewhere. However, the shale is also part of a modern soil profile with notable oxidation and scattered live rootlets. This claystone resembles other blocky mudstones seen in core overlying subaerially exposed limestones. If this is the Elm Branch Shale, then the depression is not related to the Recent weath-

ering surface that immediately overlies the Sniabar Limestone.

The presence of subaerial exposure in this mid-slope position attests to a significant fall in sea level at the end of Sniabar Limestone deposition. Cores taken farther south and west in a more basinal position show no evidence of subaerial exposure at the top of the Sniabar Sequence.

The Sniabar is part of the Hertha sequence bounded by the condensed sections developed in the Mound City Shale at the base and the Hushpuckney Shale at the top (fig. 4). This exposure of the Sniabar Limestone is representative of a thick phylloid-algal-mound complex that forms an accretionary wedge that extends westward in the subsurface along the south-facing slope of the Pleasanton delta (figs. 4 and 7). The maximum thickness of the Hertha sequence exceeds 100 ft (30 m) along this shelf-to-basin transition. The slope associated with the region of maximum is in places greater than 80 ft/mi (16 m/km). The maximum width of the phylloid-algal-bank complex is approximately 20 mi (32 km). A discussion of the preliminary interpretation of this bank margin is found in the Introduction.

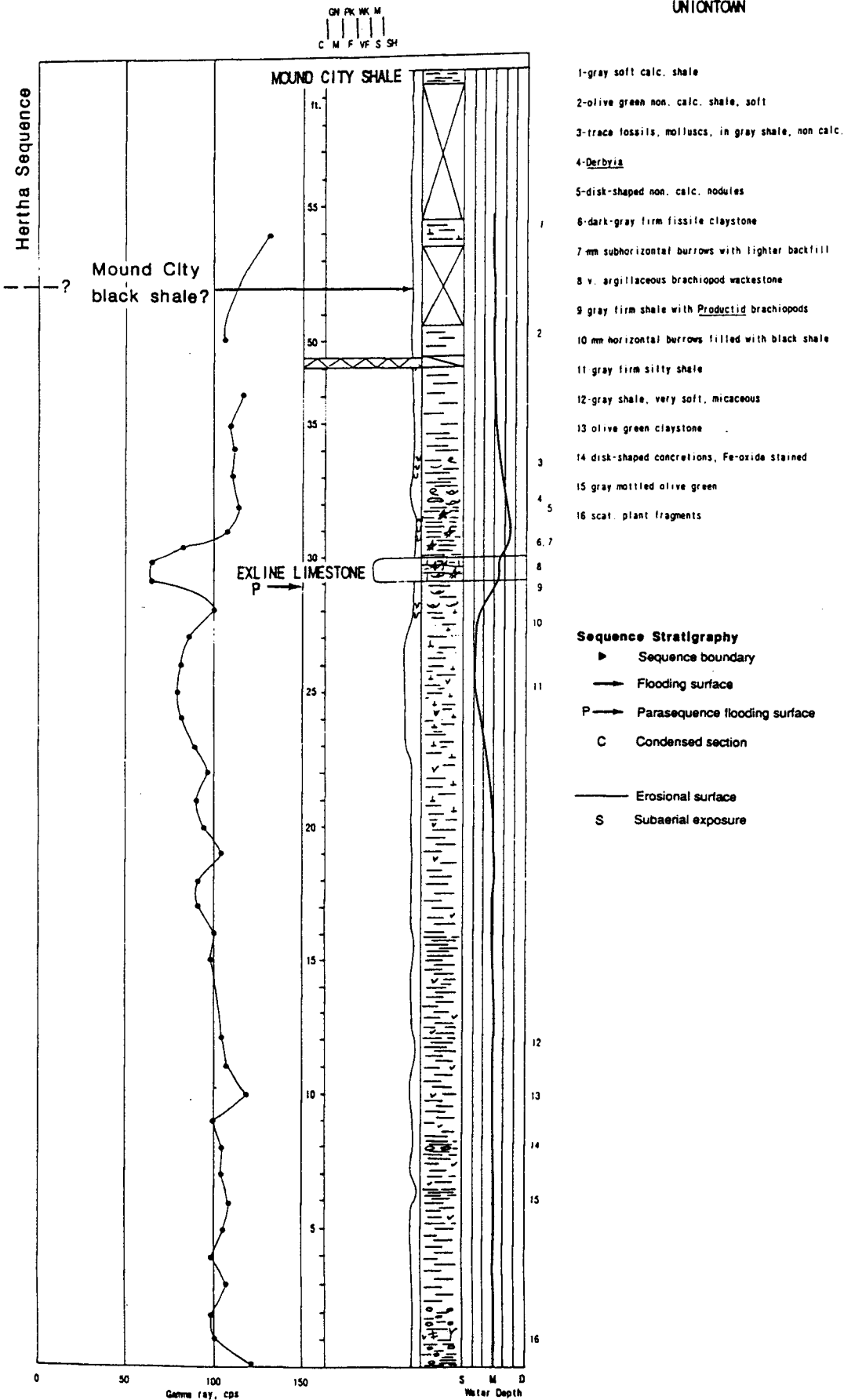


FIGURE 11-1—FIRST (LOWEST) OF THREE MEASURED SECTIONS WITH GAMMA-RAY PROFILES AND SEQUENCE-STRATIGRAPHIC SYMBOLS FOR STOP 11 (UNIONTOWN). The Exline Limestone is a regional marker bed in the outcrops and forms the datum for the cross section shown in fig. 10-2. The Mound City black shale (the core shale or condensed interval of the Hertha Sequence) is found in the lowest of two covered intervals in this section.

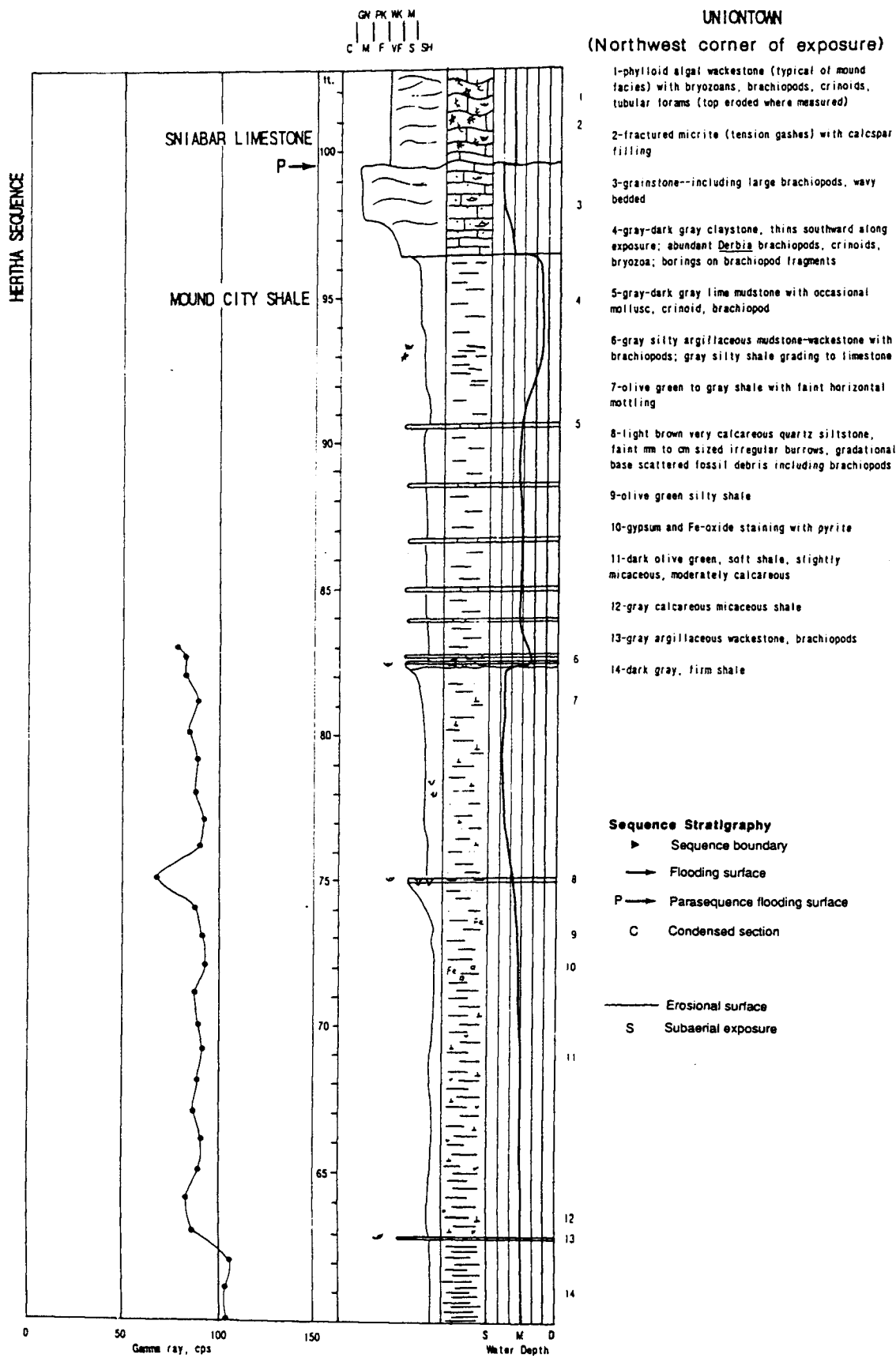


FIGURE 11-2—CONTINUATION OF MEASURED SECTION FOR STOP 11 (UNIONTOWN) OBTAINED FROM NORTHWEST CORNER OF EXPOSURE. The interval shown is all Hertha sequence including upper portion of Mound City Shale, above the black-shale horizon in fig. 11-1 (core shale, condensed section), and a thin Sniabar Limestone.

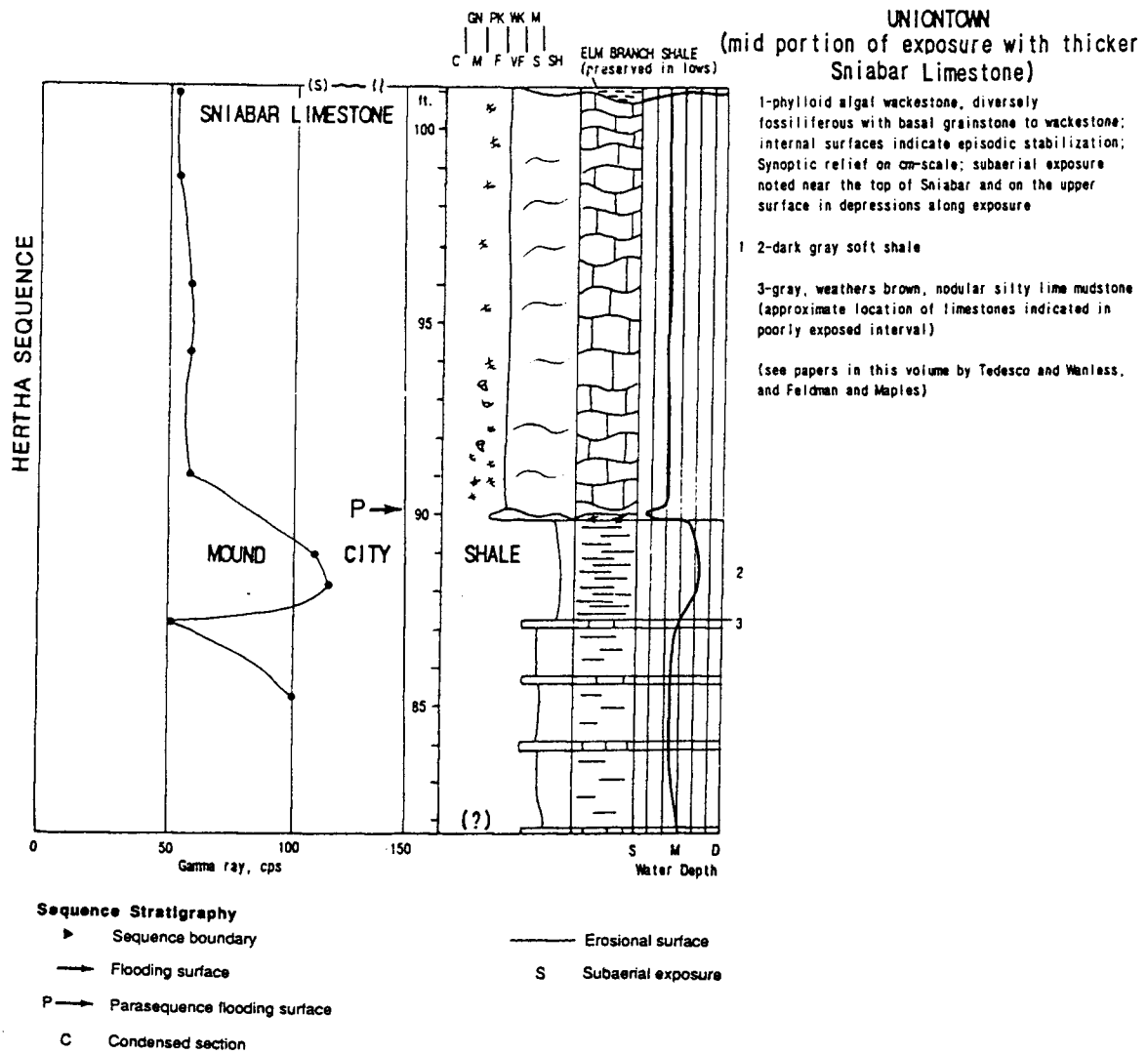


FIGURE 11-3—GENERALIZED MEASURED SECTION AND GAMMA-RAY PROFILE SHOWING SNIABAR LIMESTONE OF THE HERTHA SEQUENCE that is thicker than in fig. 11-2. Details are provided in following papers by Feldman and Maples and Tedesco and Wanless.

FIGURE 11-4 (A)—SNIABAR LIMESTONE (SNI) THICKENS SOUTHWARD (to the left), paralleling the thinning of the underlying Mound City Shale at Stop 11 (Uniontown). The staff resting against the Sniabar Limestone exposure, just left of center, is 5 ft (1.5 m) long.

FIGURE 11-4 (B and C)—IRREGULAR TOP OF THE SUBAERIALY EXPOSED PHYLLOID-ALGAL SNIABAR LIMESTONE (SNI) exposed on the east side of the roadcut at Stop 11 (Uniontown). Remnants of the Elm Branch Shale (EB), localized in swales on the irregular top surface of the Sniabar, resemble characteristics of paleosols seen in core. However, the shale is part of a modern weathering profile making interpretation indecisive, pending further study..





# Sedimentologic implications of encrusting organisms from the phylloid-algal mound in the Sniabar Limestone near Uniontown, Kansas

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## Colony development in the phylloid-algal mound

Encrusting, colonial organisms typically have variable colony shapes that respond to physical environmental parameters, and thus may be more a reflection of depositional conditions than taxonomic affinities. Such colonies may be employed to interpret aspects of sedimentation that may otherwise not be apparent. *Neosyringopora*, a colonial syringoporid coral, is common in the lowest 1 m (3.3 ft) of the phylloid-algal mound in the Sniabar Limestone at Uniontown, Kansas (see Tedesco and Wanless, this volume, for outcrop location). The colonies occur in a phylloid-algal-fragment-rich wackestone. Other fossils in the wackestone include primarily brachiopods (especially *Composita*, *Neospirifer*, and *Echinaria*) and gastropods. *Neosyringopora* occurs in thin sheets (under 5 mm) to thick (tens of cm), hemispherical masses, almost exclusively in life position. Rugose corals, also in life position, are commonly embedded in the colonies (see Tedesco and Wanless, this volume, fig. 7a). This lowest part of the phylloid-algal mound records the earliest stages of mound development. The *Neosyringopora* corals may be used to estimate episodicity of sedimentation, depositional rates, and the relief of the sediment surface. Depositional rates have previously been interpreted from favositid colony shapes (Philcox, 1971; Gibson and Broadhead, 1989), but to the best of our knowledge, this is the first attempt to use syringoporid colonies in this manner.

Early stages of corallum growth record rapid lateral expansion of the colony across the sediment surface. Small colonies are typically thin (less than 7 mm) throughout with little additional height in the central, older part of the colony. This suggests that early growth was directed laterally, not vertically. Individual corallites are oriented tangential to the sediment surface growing away from the point of colony origin within the lowest 2 to 3 mm of the colony (an *Aulopora*-like growth morphology), and are then directed vertically with subsequent growth. The lower surface of each colony thus records the topography of the sediment surface during early colony growth. Bedding planes otherwise are not easily discerned in the mound facies.

Sediment surfaces preserved by the corals generally are low and rounded (figs. FM1 and FM2). Some colonies are essentially flat-bottomed with as little as 10 cm (4 inches) of relief along a cross sectional diameter of 75 cm (30 inches). The steepest inclination observed was a thin colony inclined at about a 50° angle, with about 10 cm (4 inches) of relief over a horizontal distance of 10 cm (4 inches; fig. FM3). The

corallites in this colony are oriented vertically throughout the rolling topography of the colony indicating that the colony has not been rotated. Colonies oriented at high angles to the horizontal dip both to the north and south along the north-south roadcut, suggesting that at this stage of phylloid-mound growth the carbonate mud surface had a low, rolling topography with local depositional relief of 10's of centimeters and with positive topographic features a few 10's of centimeters in diameter. The steepest surface (50°) over which the corals grew is greater than the presumed angle of repose for loose sediment. Possible explanations include that the sediment was bound together by unpreserved organisms, or that the sediment was firm to hard and erosion produced the irregular surface.

The corals also apparently encrusted stromatactis-like vugs that are partially to completely filled with coarse, isopachous calcite spar (fig. FM2). These vugs are typically a few (up to about 10) centimeters (4 inches) wide and up to about 1 cm (0.4 inch) thick. The corals probably would not have grown bridgelike over depressions in the sediment surface, and even if they did, carbonate mud would have sifted through the open mesh of the coral skeleton filling in such pockets. The fact that the vugs lack any internal sediment and are apparently encrusted by the corals strongly suggests that they represent an unpreserved, soft-bodied organism.

## Implications for sedimentary modeling

### Episodic deposition

Coral colony morphology can also be used to interpret depositional rates and episodicity. Mud-dominated carbonates typically are interpreted as accumulating in low-energy environments. The micritic core facies of phylloid-algal mounds is usually interpreted as accumulating between algal fronds by the baffling activity of the algae (e.g., Coyle and Evans, 1987). Recent re-interpretation of many Paleozoic shales, also formerly interpreted as deposited slowly and continuously, has demonstrated that there are two distinct modes of shale deposition: slow background deposition and rapid episodic deposition (see Brett and Baird, 1986, and references therein). Background deposition occurred during normal conditions as mud slowly settled from suspension. The rapid-event deposition typically represents deposition of

mud below stem wave-base that was scoured from shallow-water settings. Coral colonies in the Sniabar record both rapid and slow depositional modes. All of the colonies in the Sniabar exposure at Uniontown are preserved as several stacked tiers of corallites separated by carbonate mud. Each tier records the early expansional and later vertical growth of the colony. Commonly, a few tall corallites from a lower tier can be observed to initiate a higher tier, mimicking the early astogeny of the colony (see Pandolfi, 1988). We interpret each tier as growing during periods of slow, background sedimentation. Modern corals, and probably most Paleozoic corals, are mud intolerant and would be killed by deposition of mud in excess of colony height. Thus in the Sniabar, corallum growth likely occurred in clear water, with little or no deposition of mud (at least deposition was less than the thickness of the tiers, which is commonly about 5 mm). Intervening mud layers represent rapidly deposited sediment that smothered the benthic fauna.

Other evidence of rapidly deposited mud includes in situ clumps of *Composita*. These clumps preserve brachiopods in life position at the same stratigraphic level as the corals. Taphonomic studies have indicated that articulated, in situ fossils nearly always are preserved by rapid deposition (Brett and Baird, 1986).

#### Rates of background deposition

The thickness of each coral tier is directly related to the length of time between rapid depositional events. Favositid corals commonly display growth banding (interpreted as annual) that indicates growth rates of up to about 2 cm (0.8 inch)/year (Philcox, 1971; Hill, 1981, p. F428). This estimate is reasonable compared with living-coral growth rates and is probably a reasonable estimate for syringoporidae corals. The thinnest tiers of *Neosyringopora* in the Sniabar are 2 to 3 mm thick, suggesting that successive rapid depositional events may have occurred within less than a year of each other (assuming that coral growth was initiated immediately after a rapid depositional event). Most of the corals observed at Uniontown have tiers less than 1 cm (0.4 inch) thick. The thickest tier observed is a hemispherical colony over 20 cm (8 inches) thick. However, the colony has several restrictions around its edges suggesting that the colony survived essentially unharmed through several depositional events.

If a few corallites were still exposed after a rapid depositional event, they re-established the colony giving rise to another tier. Thus, the distance between corallum tiers records the thickness of each event. Thicknesses between corallum tiers range from 4 to 90 mm with an average of 25 mm for 11 measurements. Upper colony tiers generally reflect the same surface characters as the lowest tier, or show subdued relief suggesting that the mud was deposited as a drape that covered the mound surface, with somewhat thicker accumulations in pockets.

Coral morphologies can also be used to estimate the ratio of sediment accumulated during normal times versus rapid events. Coral growth during periods of slow, back-

ground deposition must have at least kept pace with mud deposition or the colony would have been smothered and died. In fact, as shown earlier, corallum growth was probably much faster than background sedimentation, so that tier thickness is a maximum estimation of sedimentation between rapid events. Applying this reasoning to all typical colonies observed in this study (excepting the single large hemispherical colony which is difficult to interpret) the minimum limit of the ratio of rapidly versus slowly accumulated sediment is 3.0. The actual ratio is probably considerably higher. This translates to at least 75% of the sediment being deposited during short-lived events, and only 25%, or less, representing the normal day-to-day conditions during the early stage of mound growth.

#### Summary

We have presented just one example of how paleontological analysis can be used to evaluate depositional relief, episodicity, and rates in the absence of other sedimentological evidence. Certain organisms have the potential to preserve a record of the relative contributions of sudden-event deposition versus slow-background deposition over the scale of a few hours up to the life times of the organisms. This scale of observation is important because it represents the ultimate limit of resolution of the sedimentary record. Facies interpretations generally assume that most of the sedimentary fabrics record "normal" conditions for the facies. However, we have been able to document that even in the muddy phylloid-algal-mound facies, at most only 25% of the sediment records "normal" conditions (the vast majority of time) and at least 75% of the sediment records conditions during unusual, or at least short-lived and widely spaced (in time) events.

Average accumulation rates are commonly estimated in basin-scale studies and these rates are useful at such a large scale, but as modelers attempt to increase acuity and predictability, they will need to increase the resolution of depositional conditions in the rock record. Analysis of growth forms of fossils provides one useful, largely unexploited tool for increasing the resolution of depositional conditions in the rock record.

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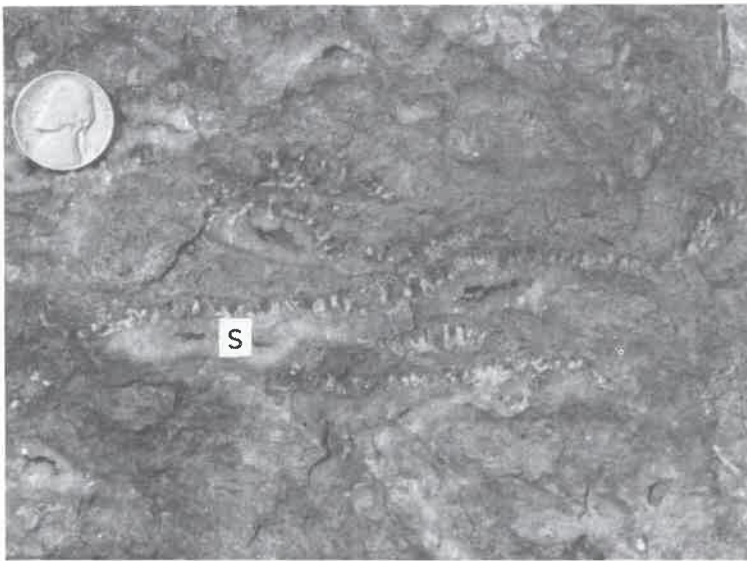
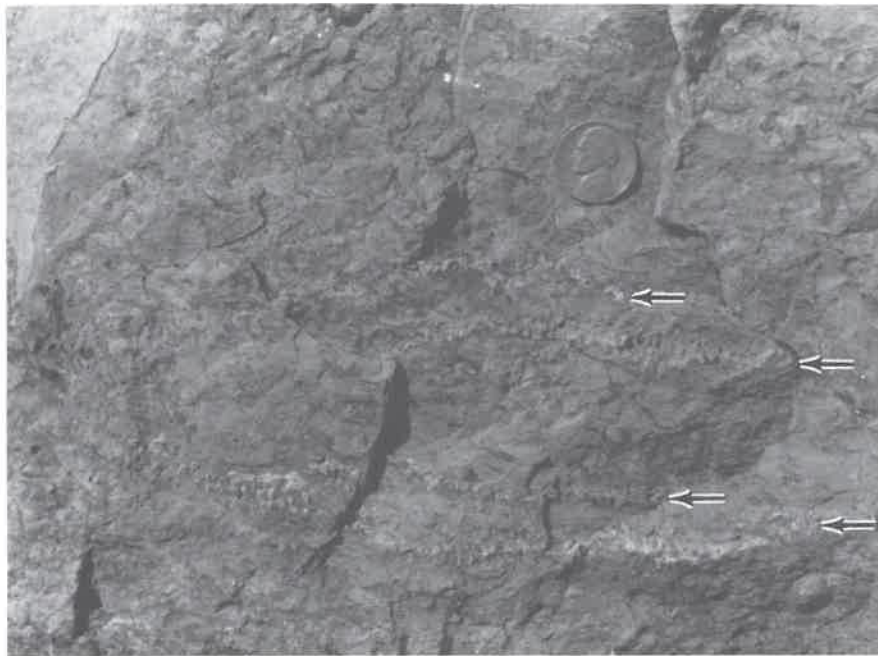
Pandolfi, J. M., 1988, Heterochrony in colonial marine animals; *in*, M. L. McKinney (ed.), Heterochrony in Evolution: Plenum Press, New York, p. 135-158

Philcox, M. E., 1971, Growth form and role of colonial coelenterates in reefs of the Gower Formation (Silurian), Iowa: *Journal of Paleontology*, v. 45, p. 338-346

FIGURE FM-1—TIERED COLONY OF *Neosyringopora* (arrows). Sediment between tiers is interpreted as having been deposited rapidly during depositional events. The scale in this and subsequent figures is a 2-cm (0.8-inch) nickel.

FIGURE FM-2—TIERED COLONY OF *Neosyringopora* ENCRUSTING STROMATACTIS-LIKE VOIDS (indicated by "s" on figure) that are partly filled with sparry calcite. This demonstrates that these voids were probably soft-bodied organisms that were encrusted by the coral but are no longer preserved.

FIGURE FM-3—A SINGLE TIER OF *Neosyringopora* (other higher tiers not shown in this view) that encrusted a steeply sloping surface. This bedding feature may not have been evident without the coral. Arrows indicate the ends of the coral tier.





# Role of burrow excavation and infilling in creating the preserved depositional fabric of Pennsylvanian phylloid mounds of southeastern Kansas

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Upper Pennsylvanian (Missourian) Mound City Shale and Sniabar Limestone members of the Hertha Formation Bourbon County, Kansas, Rt. 3, south of Uniontown

## Introduction

Deep burrowers create extensive open burrow networks that often penetrate to sediment depths in excess of 1 meter. Work in modern carbonate environments has shown that these subsurface chambers are catastrophically infilled with surficial sediment (Tedesco et al., 1986; Wanless et al., 1988). Repetitive excavation and infilling of subsurface chambers can 1) obliterate precursor facies (Wanless and Tagett, 1986; Wanless et al., 1989), 2) create subsurface depositional fabrics and facies (Wanless, et al., 1988; Wanless et al., 1989), and 3) influence subsequent diagenetic patterns (Wanless and Tedesco, 1987). Importantly, biogenically generated fabrics and facies are created in the subsurface and do not directly reflect surficial depositional conditions. Attempts to interpret these fabrics using traditional stratigraphic and sedimentologic methods may produce misleading results.

The fabrics, facies, and diagenesis of phylloid and other carbonate mud banks and mounds have continued to be difficult to interpret primarily because they contain characteristics that are equivocal with respect to paleoenvironmental reconstruction. For example, many mounds 1) contain unabraded but disarticulated skeletal material in a wackestone to packstone matrix, 2) lack pronounced or diagnostic stratification, and 3) possess an abundance of spar-cemented skeletal grainstone to packstone cavities. These features are also characteristic of modern mud banks and mounds whose facies, textures and fabrics have been produced by storm infilling of excavated burrow systems. In fact, modern burrow-generated facies, formed well below the sediment surface, are very similar to the fabrics and textures of ancient phylloid and other carbonate-mud banks and mounds.

## Purpose

We tested the role of burrow excavation and infilling in creating the preserved depositional fabric and influencing the diagenesis of some of the Pennsylvanian phylloid mounds of southeastern Kansas and found that these processes are responsible for generating the preserved fabrics of several important facies within the studied phylloid mounds. This paper will focus on outcrops of the Upper Pennsylvanian

(Missourian) Mound City Shale and Sniabar Limestone members of the Hertha Formation exposed in Bourbon County along Rt. 3, South of Uniontown.

## Outcrop description

The roadcut along Rt. 3 (figs. TW1 and TW2) exposes both the Mound City Shale and Sniabar Limestone members of the Hertha Formation.

### Mound City Shale

The Mound City Shale is exposed over the lower 10 m (33 ft) of outcrop and is a gray shale with interbedded limestone layers as well as distinct burrows infilled with molluscan-crinoidal grainstones to packstones. Vertical to subhorizontal burrow fills commonly weather out as individual limestone hand specimens 2–4 cm (0.8–1.6 inches) in diameter (fig. 3).

### Sniabar Limestone

**MOLLUSCAN-CRINOIDAL PACKSTONE FACIES**—The Sniabar Limestone member caps the Mound City Shale. The lower 60–70 cm (24–28 inches) of the Sniabar is a crossbedded to burrowed molluscan packstone to grainstone. Distinct unlined burrows, 2–4 cm (0.8–1.6 inches) in diameter, are infilled with crinoidal packstones to grainstones (fig. TW4).

**PHYLLOID FACIES**—The main body of the phylloid mound consists of nine lithofacies (fig. TW2), some of which are separated by argillaceous dolomitic seam zones (fig. TW1). Lithofacies include growth-fabric facies [in situ phylloid thalli framestone (fig. TW5) and in situ coral patches (fig. TW7a)]; layered facies (skeletal grainstone, phylloid packstone, phylloid wackestone, and skeletal wackestone); and phylloid packstones to wackestone with spar-cemented grainstone patches [brachiopod and coral fragment grainstone patches (fig. TW7a), phylloid-fragment grainstone patches (figs. TW6 and TW7b) and mud-clast grainstone patches]. Limestones with spar-cemented grainstone patches are a fundamental fabric style dominating the lower portion

of the mound (fig. TW2). Grainstone patches have a vertical to subhorizontal orientation and vary in size from 1-5 cm (0.4-2 inches).

## Evidence for burrow-infill fabrics

### Distinct burrow fills in associated facies

Both the Mound City Shale and the molluscan-crinoidal packstone facies of the Sniabar Limestone contain distinct burrow infills. These distinct burrow fills serve as a valuable guide to the size and morphology of the burrow structures present in other facies of these rocks.

### Distinct burrow fills in the phylloid facies

Within the main body of the phylloid mound at Uniontown, individual discrete burrows are exceedingly difficult to discern. However, both distinct and indistinct burrow infill fabrics are recognized within the mound.

In areas where there is a source of "exotic" sediment for infilling, distinct burrow-fill structures are evident in the limestone directly below the source. Exotic sediment types include *Neosyringopora* corals and brachiopods. These exotic sediment types can be seen infilling into phylloid-dominated packstones to wackestones (figs. TW7a and TW8a).

A particularly striking example of exotic sediment-filled tubes occurs at approximately 11 m (36 ft) in the measured section (figs. TW1 and TW2). In this interval, there are zones of abundant in situ *Neosyringopora* coral growth which initiated in brachiopod beds. Below this in situ coral growth, coral fragments and brachiopods form tube-shaped concentrations extending 20-30 cm (8-12 inches) into the underlying phylloid-dominated sediments. Importantly, these exotic sediment-filled tubes are markedly similar to the morphology of distinct burrows visible in the associated facies.

In addition to the tube-shaped forms, coral and brachiopod grainstones also occur as irregular zones and patches beneath the in situ coral growth. These exotic skeletal concentrations appear in outcrop as spar-cemented skeletal grainstones to mud-poor packstones and are a fundamental fabric type of the mound.

From these observations, we conclude that burrow excavation and infilling processes were operative during the growth and development of the phylloid mound. Where exotic sediment is available, burrow fills are recognizable both as distinct tubelike grainstone fillings of exotic sediment and as less distinct exotic-sediment grainstone patches.

### Indistinct burrow-fill fabrics

In addition to the distinct burrow fills and the exotic sediment patches recognized within the mound, there are also major zones of burrow-fill fabrics. These zones do not possess definable distinct burrow infills because individual

burrow fills are not clearly recognizable in most of the mound. However, irregularly shaped zones and patches of spar-cemented skeletal grainstone are abundant throughout the mound facies and are remarkably similar to the exotic sediment patches beneath the in situ coral growth.

The irregularly shaped spar-cemented grainstone patches throughout the mound contain various skeletal components. These components (when not phylloid-algae fragments) can be used as exotic sediments to trace sediment sources (fig. TW8b). Importantly, the composition of the fauna in skeletal-grainstone patches correlates extremely well with fauna contained in the overlying lithologies (figs. TW2 and TW8). The fauna in the overlying lithologies occurs within a mud matrix as host sediment and not as spar-cemented grainstones. Thus, there is a source of infilling sediments and evidence of sediment transport down into open voids which are similar in size to the more distinct burrows.

In addition to skeletal-grainstone patches, spar-cemented patches of mud-clast grainstones occur just below the in situ phylloid-thalli growth fabric at around 15 m (50 ft) in the measured section (figs. TW1 and TW2). The mud-clast grainstones appear to be fills from above and are indicative of processes of erosion and transport of cohesive (or lightly cemented) mud. This is expected as there seems to be an increase in physical processes as well as surface stabilization associated with the growth fabric (see next section).

The contained fauna within spar-cemented grainstone patches is highly variable and, in almost all cases, directly attributable to overlying faunal sources. Phylloid-algal fragments are the most abundant skeletal component within spar-cemented grainstone patches. It is reasonable that phylloid-algal fragments in spar-cemented grainstone patches are simply another indistinct burrow-generated fabric resulting from repetitive excavation and infilling (figs. TW6, TW7b and TW8c).

The abundance of spar-cemented grainstone patches can then be used as an indication of the minimum degree of fabric generation by burrow excavation and infilling processes. It is used as a minimum estimate because burrow-infill fabrics are not always skeletal grainstone patches. However, work in the Lower Cretaceous Glen Rose Formation (central Texas) indicates that skeletal grainstone to low-mud packstone burrow infills are a common burrow-fill type (Nagle, 1968; Wanless and Tedesco, 1987). In addition, modern burrow infills are porous and contain abundant skeletal fauna derived from the overlying sediments (Wanless et al., 1988), a conclusion also reached by Nagle (1968) for the Cretaceous.

## Vertical lithologic sequence

Lithologies are organized into a distinct and meaningful vertical sequence (fig. TW2). These lithologies may display some lateral variability but are traceable over long distances of outcrop exposure and across exposure gaps.

Some lithologies are separated by argillaceous dolomitic seam zones and therefore have sharp boundaries; others have gradational boundaries.

The vertical lithologic sequence within the mound indicates shallowing or growth into more turbulent waters. The lower portion of the mound is dominated by lithologies containing burrow-infill fabrics while the upper portion is dominated by high-energy growth and physically deposited skeletal grainstone fabrics.

For instance, the zone from 15-15.6 m (49.5-51.5 ft; fig. TW2) is dominated by in situ phylloid growth thalli suggestive of a higher energy "skeletal-bank crest" environment. Overlying this in situ growth lithology is either a layered phylloid-algal packstone or a washed skeletal grainstone composed of phylloid algae fragments, crinoids, brachiopods, and gastropods. These layered and/or sorted lithologies suggest sediment deposition under shallow, wave- or current-swept conditions and are somewhat reminiscent of a "skeletal-bank flat" style of deposition. Indeed, it has been suggested that the top of the Sniabar Limestone member contains evidence of exposure (Lynn Watney, personal communication, 1989).

The upward increase in physically influenced deposition is accompanied by a concomitant decrease in the dominance of distinct and indistinct burrow-generated fabrics. Therefore, there is the indication that the burrow-generated fabrics were restricted to the lower portion of the mound sequences because physical processes were diminished in that zone. Upward shallowing by bank growth and/

or sea-level change resulted in increased physical energy and conversion to physically deposited and biogenic growth fabrics.

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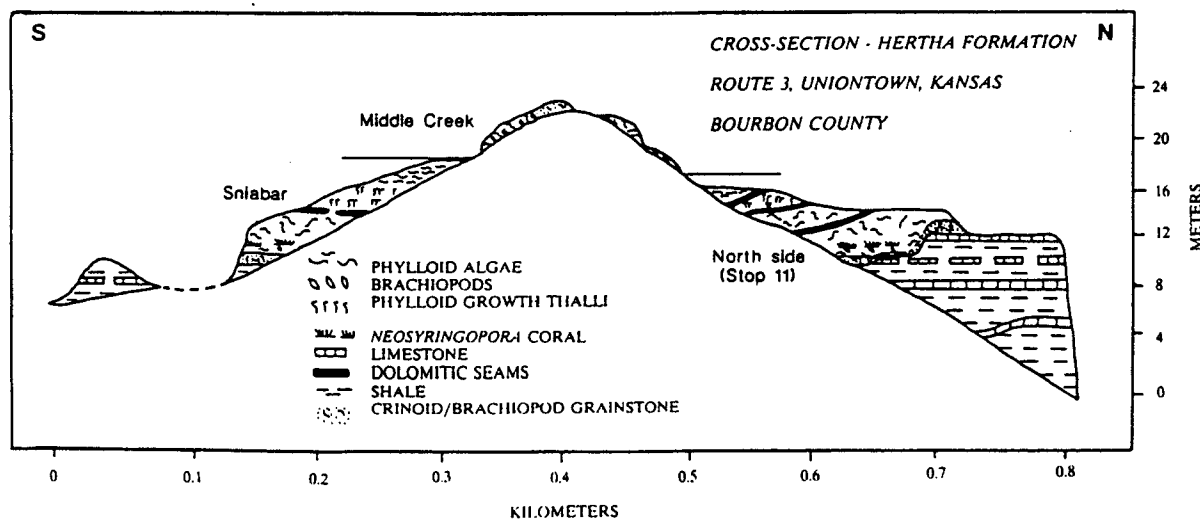


FIGURE TW-1—CROSS SECTION, HERTHA FORMATION, AT RT. 3, UNIONTOWN, BOURBON COUNTY, KANSAS.

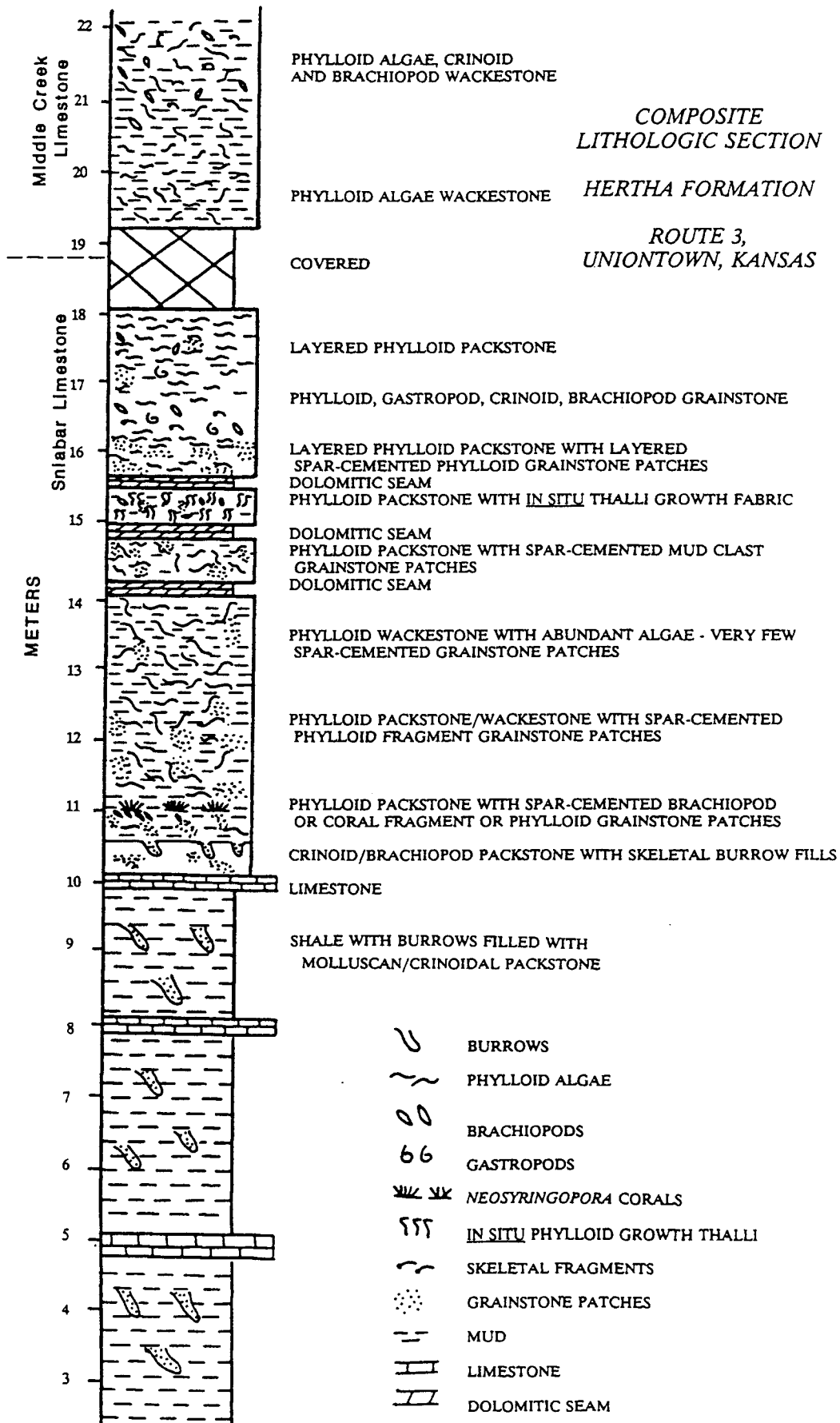


FIGURE TW-2—COMPOSITE LITHOLOGIC SECTION OF THE HERTHA FORMATION AT UNIONTOWN, KANSAS.



FIGURE TW-3—LIMESTONE BURROW FILLS FROM MOUND CITY SHALE. Stacked cylinders in upper left are filled vertical shafts segmented by shale compaction. Many burrows are infilled with a crinoidal-molluscan grainstone to packstone. Scale in centimeters.

FIGURE TW-4—DISTINCT AND INDISTINCT BURROW INFILLS IN THE LOWER PART OF SNIABAR LIMESTONE. Sample from crinoid-brachiopod packstone at approximately 10.5 m (35 ft) in the measured section (fig. TW-2). Scale in centimeters.

FIGURE TW-5—PHYLLOID-ALGAE FRAMESTONE COMPOSED OF STACKED THALLIE IN GROWTH POSITION. Stylolitic seams bound the sample. Specimen is from the Iola Limestone, near Chanute, but is similar to the fabric in the Sniabar at 15 m (50 ft) in measured section. Scale in centimeters.

FIGURE TW-6—PATCHES OF SPAR-CEMENTED PHYLLOID GRAINSTONE (DARKER) IN A PHYLLOID WACKESTONE. Fabric is interpreted to be burrow infill generated. Extensive pressure dissolution has further modified the fabric. Sniabar Limestone. Scale in centimeters.

FIGURE TW-7(a)—TOP OF PHOTO SHOWS BASE OF IN SITU SYRINGOPORA AND CUP CORAL-GROWTH PATCH. Spar-cemented coral-fragment grainstones below are burrow fills penetrating into underlying phylloid wackestone. Sniabar Limestone at 11 m (36 ft) on measured section. Scale in centimeters. TW-7(b) PATCHES OF SPAR-CEMENTED PHYLLOID GRAINSTONE IN A PHYLLOID WACKESTONE. Grainstone patches are interpreted as a replacive burrow-infill fabric. Sniabar Limestone. Scale in centimeters.

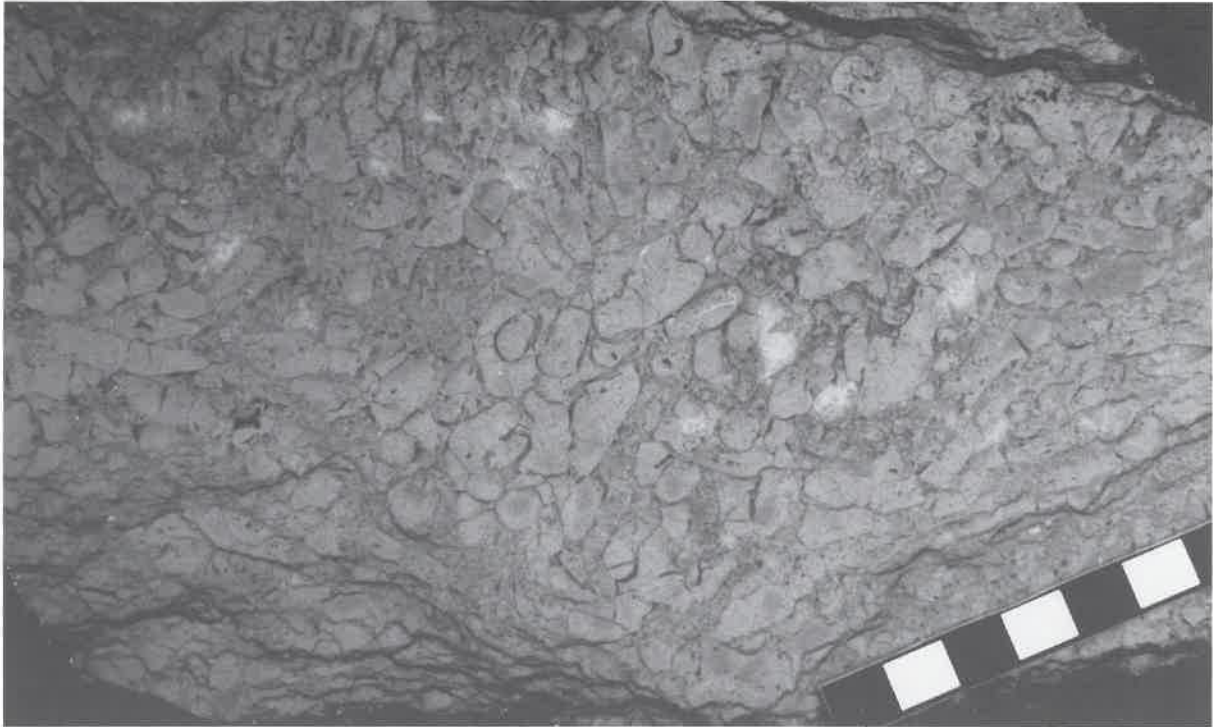


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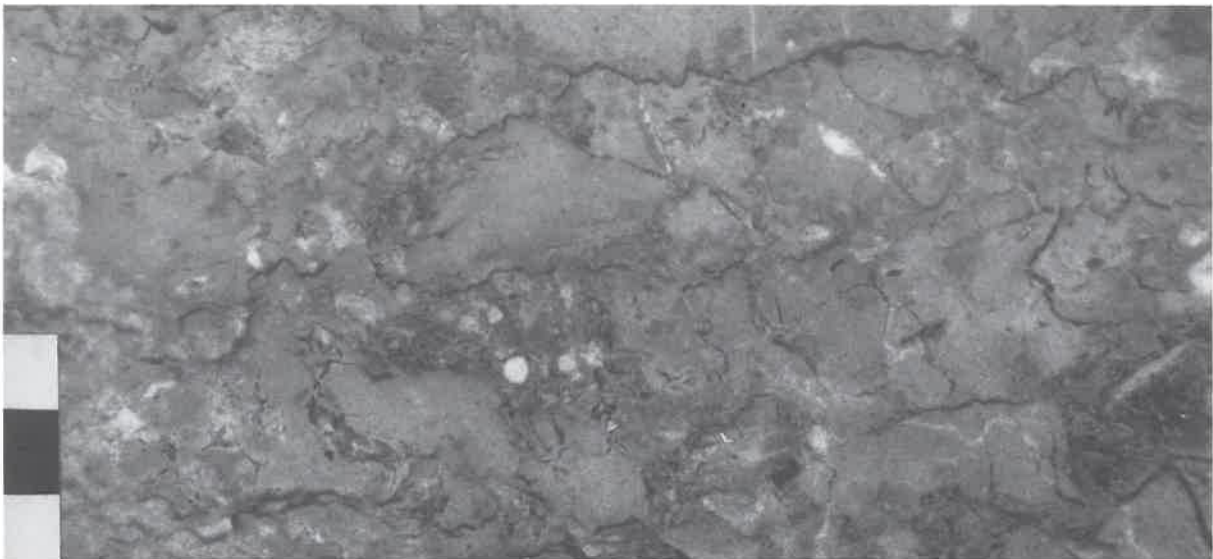


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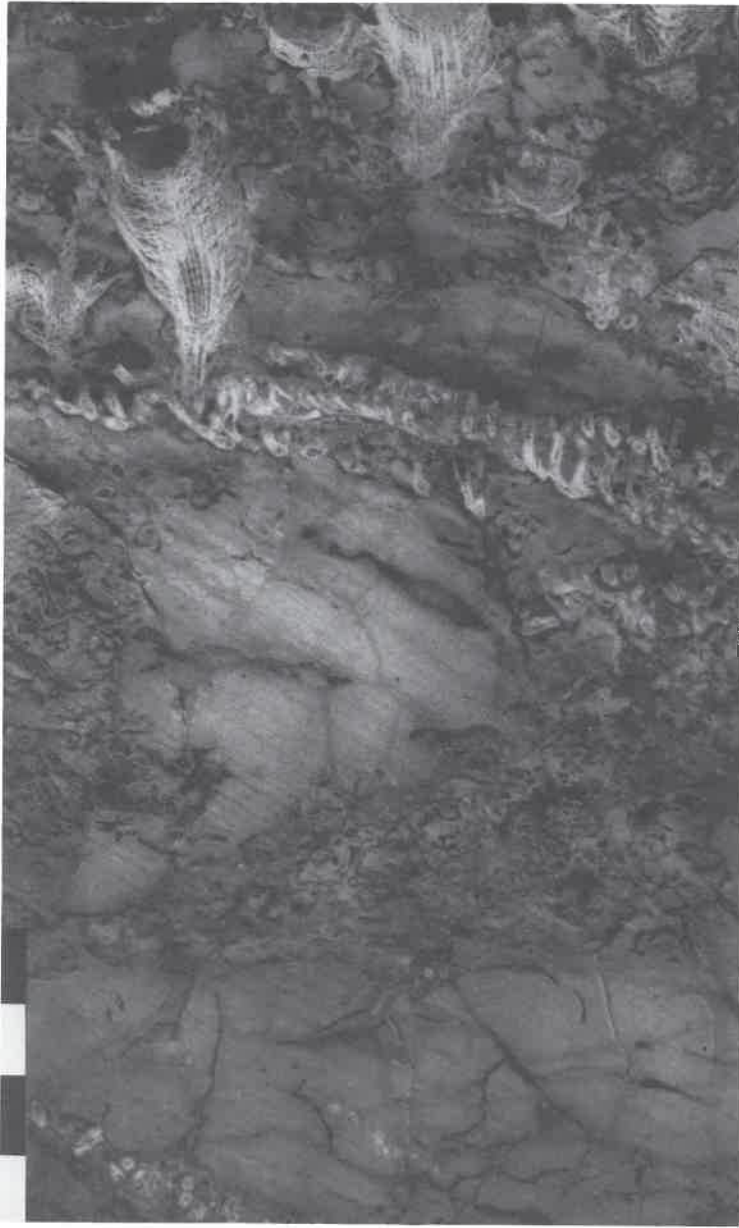


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6





7a



7b



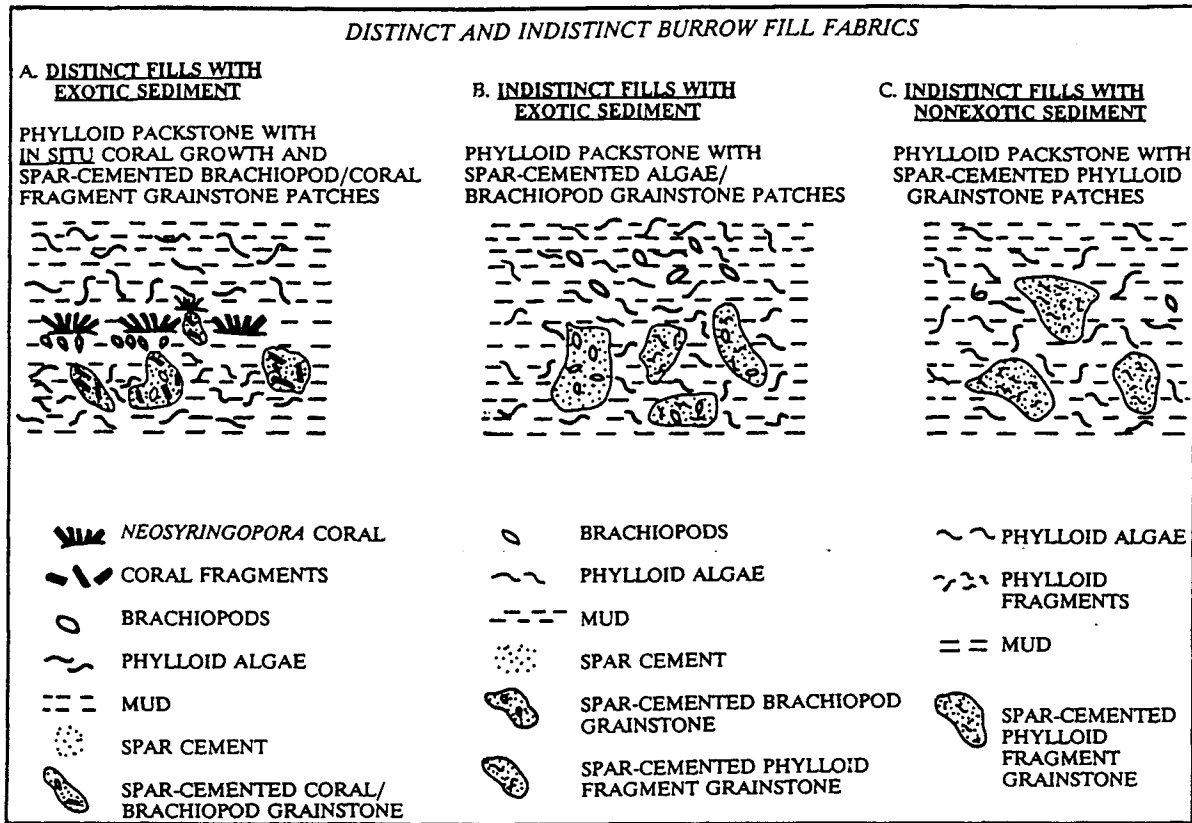


FIGURE TW-8—DISTINCT AND INDISTINCT BURROW-FILL FABRICS.

## Introduction to upper Swope sequence development in basinal setting prior to reaching Stop 12

The last two stops will focus on the Swope and Dennis sequences. On our way to Ogeese Creek (Stop 12) we will pass by Erie North, a locality 6 mi (9.7 km) north of Ogeese Creek (fig. 12-1). A measured section of Erie North is found in fig. 12-2. The heavy vegetation precludes stopping at this location. However, the rocks exposed at Erie North and the cores taken nearby, including the Heilman core shown in fig. 12-3, provide information important to understanding the nature of the Swope sequence.

Erie North and Ogeese Creek (Stop 12) are situated near the eastern end of the cross section shown in fig. 12-4. The index map for this section, an isopach of the Hertha sequence, is provided in fig. 12-5. The Pleasanton sequence and the Hertha bank margin have thinned substantially just west of Erie North (fig. 12-4).

The Swope sequence includes the uppermost portion of the Elm Branch Shale, the Middle Creek and Bethany Falls limestones, the Ladore Shale (present only in the basin), the Mound Valley Limestone (which laps out updip to the north of Erie North), and the lower portion of the Galesburg Shale (which has been observed on the upper shelf as a paleosol; figs. 7-11).

The measured section of Erie North (fig. 12-2) and the nearby Heilman core (fig. 12-3) indicate that on the lower shelf, more accommodation space provided room for a thicker and more complex Swope sequence. The Hushpuckney Shale (the condensed section) is continuous down the slope and into the basin (fig. 12-4). While clear evidence of subaerial exposure exists on the top of the Bethany Falls Limestone on the shelf (e.g., at Stop 8), no evidence for exposure is found in that unit in the Heilman core (fig. 12-3). The Bethany Falls Limestone thins basinward (toward Ogeese Creek, Stop 12), where it consists of only a few centimeters

of dark-gray, argillaceous, crinoid-brachiopod-encrusting foram wackestone. This latter facies is the focus of the stop at Ogeese Creek (Stop 12; fig. 8).

A wedge of shallow-marine Ladore Shale overlies the Bethany Falls Limestone in the slope-to-basin transition along the margin of the Hertha bank complex (fig. 12-4). The Ladore Shale is composed primarily of fine-grained clastics and represents a lowstand clastic wedge that thickens and coarsens basinward (fig. 9). Most of the clastic material was probably derived from the Ouachita Mountains to the south. The lower Ladore Shale is extremely rich in large plant fragments, including tree ferns (as will be seen at Stop 12 at Ogeese Creek). Turbidity associated with Ladore deposition probably contributed to the cessation of carbonate accumulation associated with the Bethany Falls Limestone in this basinal setting.

Marine flooding associated with Mound Valley Limestone deposition temporarily ended siliciclastic influx. The Mound Valley Limestone is interpreted as a parasequence within the Swope sequence (figs. 12-2 and 12-3). The Ladore-Mound Valley contact is gradational in most of the cores, leaving as an open question the mechanism of marine flooding. Local phylloid-algal mounds are developed in the Mound Valley Limestone in this basin-margin setting. The Mound Valley parasequence is restricted to the lower-shelf setting, lapping out updip (fig. 10). This parasequence terminates in subaerial exposure only in relatively updip positions (fig. 12-3). In the Heilman core, the subaerial-exposure surface at the top of the Mound Valley is also the Swope-Dennis sequence boundary. The overlying Galesburg Shale in this core is tentatively classified as a low-stand unit that was deposited during the initial base-level rise related to the Dennis sequence.

## Stop 12 Ogeese Creek, uppermost Bethany Falls and lowermost Ladore Shale

Location: S/2 S/2 SE sec., 7, T. 29 S., R. 20 E, Neosho County, Kansas

Arrive: 1:00 PM

Leave: 1:20 PM

(40 minutes to Stop 13)

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

Stop 12 at Ogeese Creek was in a basinal setting in front of the Hertha sequence shelf edge during deposition of the Swope sequence (fig. 12-1). The Bethany Falls Limestone thickens markedly west of Stop 12 (figs. 8 and 12-4).

At Ogeese Creek the upper surface of the Bethany Falls Limestone and basal beds of the Ladore Shale are exposed. Woody-plant debris is very abundant in the silty-lime mudstone to wackestone and overlying siltstone. This lithofacies is unlike any seen on the northern shelf. The cores seen the previous evening that were taken in a basinal setting

approximately 25 mi (40 km) west of this stop provide a succession of strata comparable to that thought to exist at this stop.

The plant-rich debris in the upper Bethany Falls Limestone was likely rafted into this basinal setting from distal deltas to the south. Plant fragments are also ubiquitous in the lower Ladore Shale, and similar plant-rich intervals occur in cores taken in equivalent basinal positions west of this stop. Increased turbidity associated with the influx of this suspended detritus led to the cessation of carbonate accumulation.

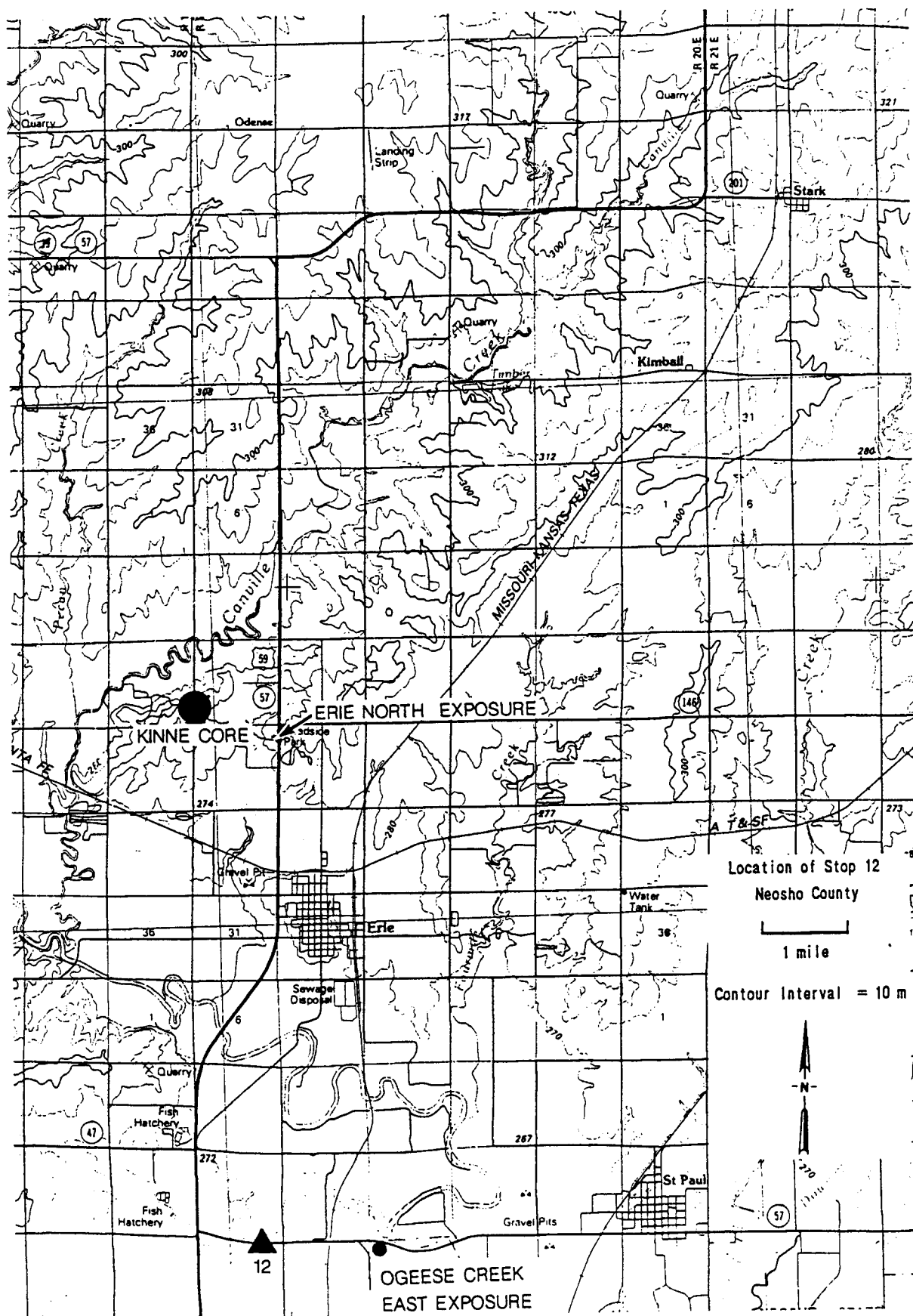


FIGURE 12-1—LOCATIONS OF STOP 12 (OGEESE CREEK), ERIE NORTH LOCALITY, AND KINNE CORE.

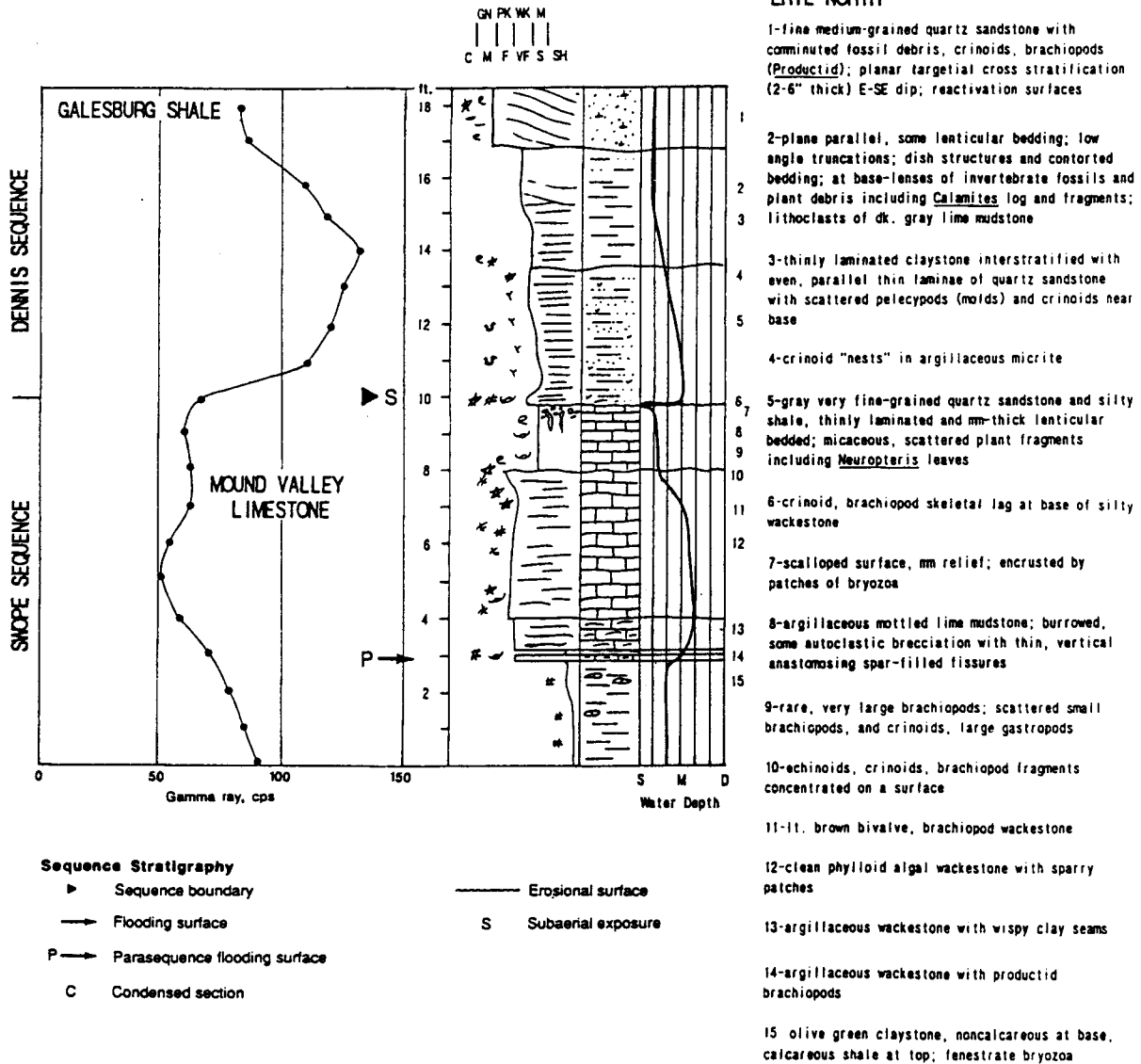


FIGURE 12-2—MEASURED SECTION AND GAMMA-RAY PROFILE OF ERIE NORTH EXPOSURE located in NW NW NW sec. 20, T. 28 S., R. 20 E., Neosho County, Kansas. Exposed section includes upper Ladore Shale, Mound Valley Limestone, and lower Galesburg Shale. Sequence-stratigraphic terminology is indicated on the left.

SWSESW 36 T28N R18W

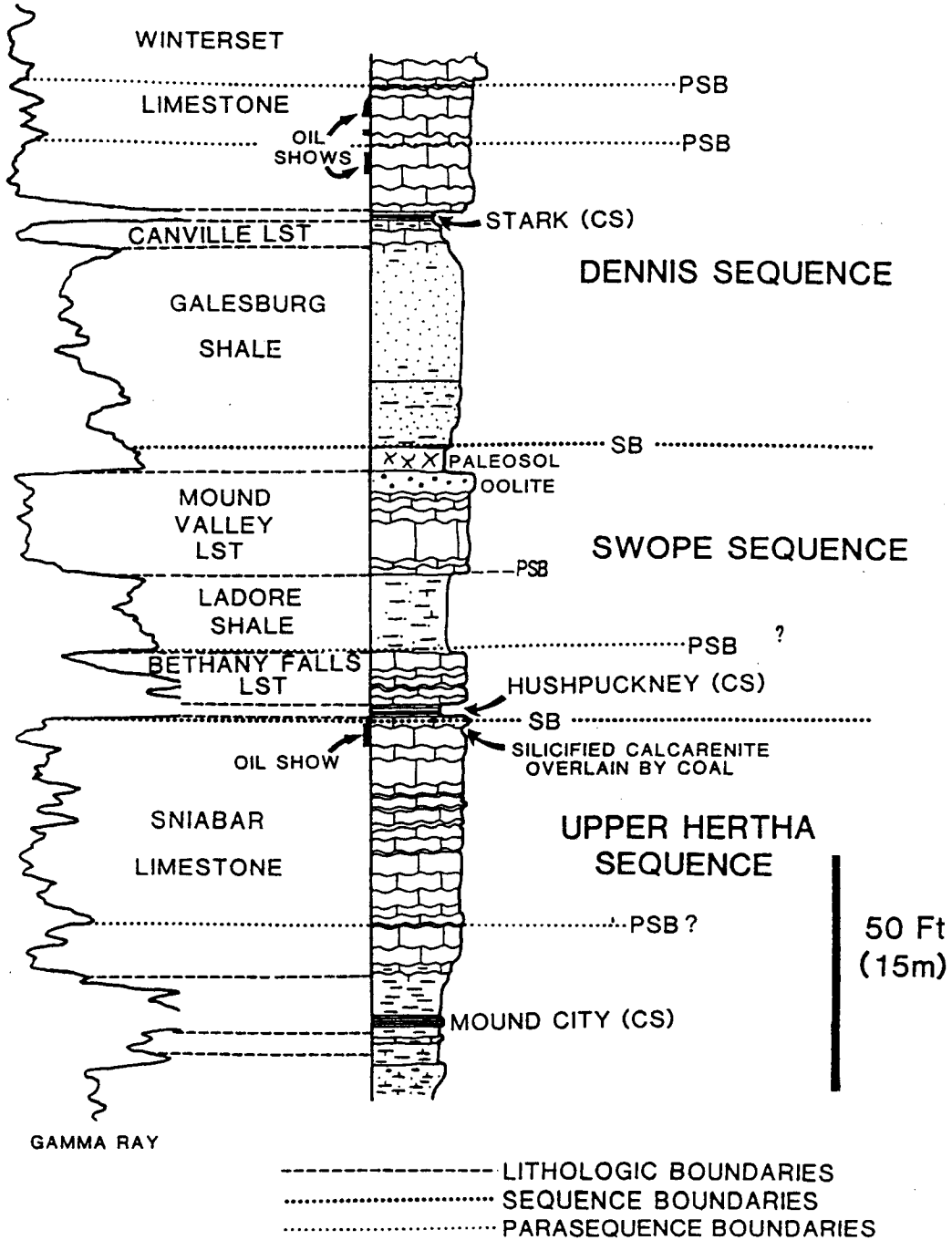


FIGURE 12-3—CORE DESCRIPTION OF HEILMAN CORE LOCATED 7 MI (11 KM) WEST OF ERIE NORTH. The Heilman core is used in cross section B-D in fig. 12-4 and in the regional cross section in fig. 4 (well J).

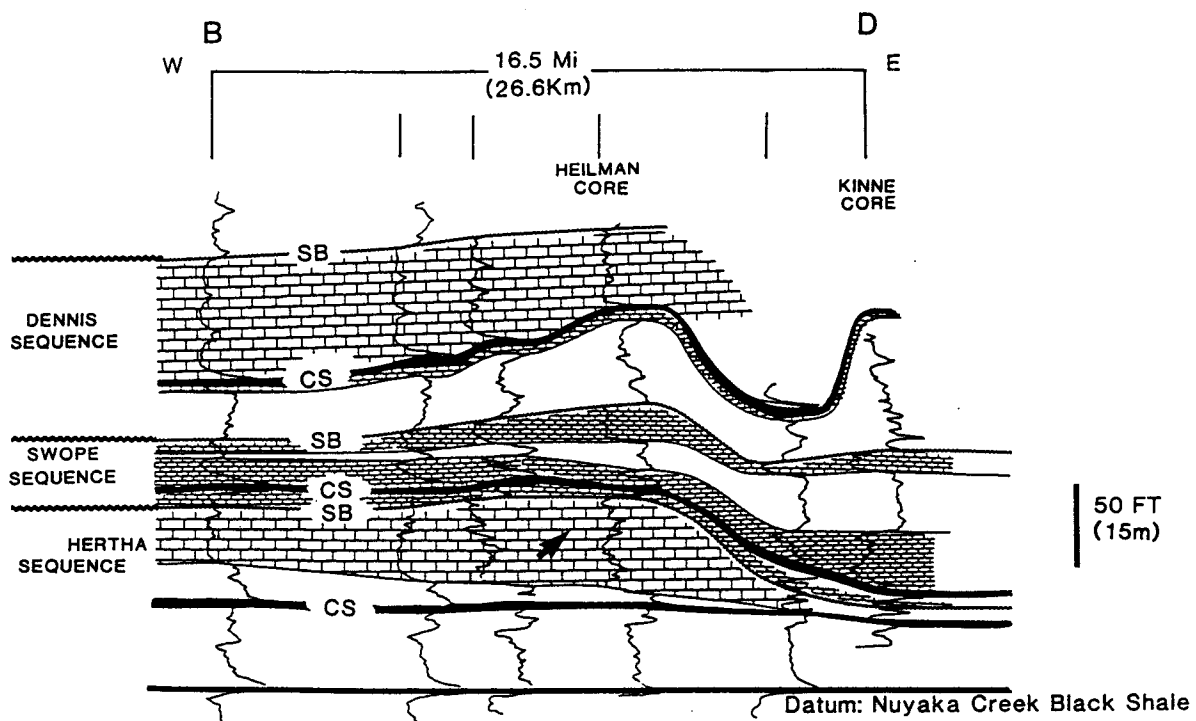


FIGURE 12-4—WEST-TO-EAST STRATIGRAPHIC CROSS SECTION ILLUSTRATING MAJOR CHANGES IN HERTHA, SWOPE, AND DENNIS SEQUENCES in response to thinning to the west off of the Sniabar Limestone bank (arrow). Condensed sections from bottom to top include the Nuyaka Creek Shale (datum), Mound City Shale, Hushpuckney Shale, and the Stark Shale.

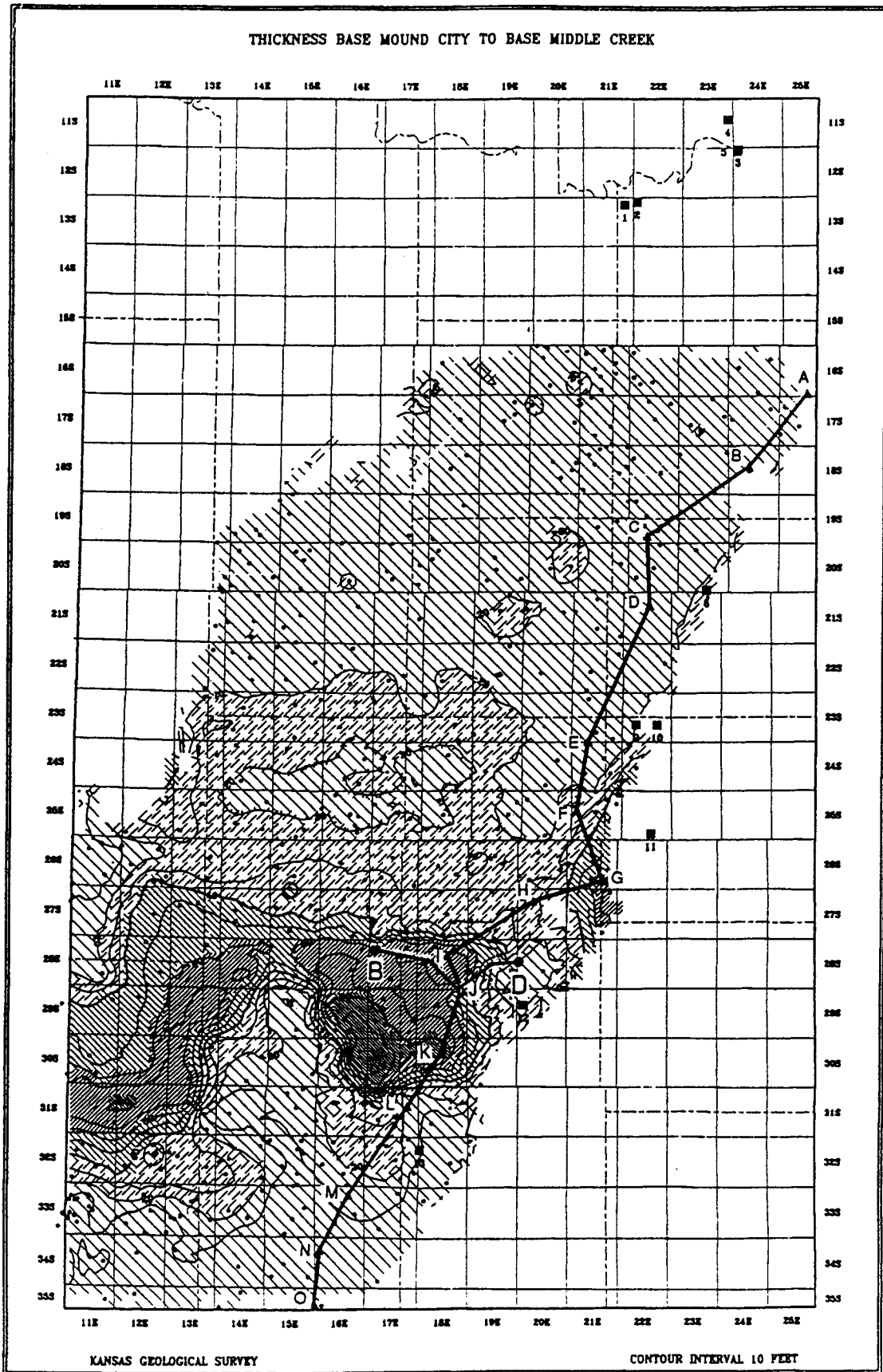


FIGURE 12-5—ISOPACH MAP OF THE HERTHA SEQUENCE SHOWING LOCATIONS OF WELLS USED IN THE CROSS SECTION SHOWN IN FIG. 12-4.

## Introduction on the way to Stop 13

The Galesburg Shale overlies the Mound Valley Limestone and is continuous throughout the basin and shelf. However, on the shelf the Galesburg is a paleosol overlain by a thin initial flooding deposit (e.g., at Stop 8 at Farlinville North quarry). In a shelf-slope setting such as at the locations of the Heilman core and Erie North exposure, the Galesburg Shale has thickened to 50 ft (15 m; fig. 10-3). The Galesburg Shale continues to thicken southward, being more than 150 ft (46 m) thick along the Kansas–Oklahoma border where it has been mapped in the subsurface (fig. 11). Southward it becomes an even thicker package of fluvial-deltaic deposits (fig. 16).

We will examine a portion of the Galesburg Shale in Stop 13 at Big Hill Reservoir, the last stop of the field trip. Sandstones developed in the Ladore and Galesburg shales are referred to as the lower and upper Layton sandstones, respectively. They are major petroleum reservoirs in southern Kansas and northern Oklahoma. The Erie North exposure (fig. 12-2) also contains a section of Galesburg sandstone that occurs along the upper slope.

The basinal Galesburg Shale section is markedly coarser than the Ladore Shale. Following the pause in influx of siliciclastic material during marine flooding associated with Mound Valley Limestone deposition, siliciclastic sedimentation resumed, resulting in a coarsening-upward succession in the Galesburg Shale. These thick clastics essentially filled in much of the basinal areas and reduced the topographic relief from shelf to basin (fig. 51). A paleosol and widespread coal bed (A. Bennison, personal communication, 1988) that will be seen at Stop 13 reflect the termination of the Swope sequence in the upper-middle portion of the

Galesburg Shale and herald the initial marine flooding associated with the Dennis sequence. Subaerial exposure and paleosol development apparently occurred during maximum low stand. This exposure surface merges with that which caps the Mound Valley Limestone on the basin margin, and which merges with the exposure surface found on the top of the Bethany Falls Limestone in the most shelfward settings (figs. 4 and 12-3).

Big Hill Reservoir is located in a basinal setting on the extreme northern edge of the active Arkoma basin (figs. 2, 16, and 18). This stop is our most basinward location on the field trip (fig. 4). The clastic depocenter was around the area of Tulsa where Bennison (1985) describes thick fluvial-deltaic deposits that were prograding basinward during this time (fig. 16). Large clinofolds with a minimum of several hundred feet of relief are developed in the Tulsa area. The siliciclastic wedges shed off the Ouachita mountain front were prograding northward and westward, gradually filling the Arkoma and the eastern portion of the Anadarko basins. Both basins were also tectonically active and episodically subsiding at rates sufficiently high to preclude complete filling until the Pennsylvanian. In spite of the tectonism and the abruptly changing lithofacies within the siliciclastic succession to the south, the same condensed sections seen on this trip have been physically correlated by Bennison (1985 and fig. 16, this volume) and biostratigraphically by Boardman and Heckel (1989) into this siliciclastic pile. The extremely rapid marine inundations associated with continental glaciation overwhelmed the best that tectonism had to offer during the Late Pennsylvanian.

## Stop 13 Big Hill Reservoir, Galesburg Shale (Upper Layton Sandstones)

Location: NW NW SW sec. 7, T. 32 S., R. 18 E.

Arrive: 2:00 PM

Field trip ends 3:00 PM

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

### Introduction

The index map for Stop 13 (fig. 13-1) indicates its relationship to Parsons, Kansas, and highways 160 and 169 (northwest corner of the map). This will be useful for those who are driving separately from this stop at the conclusion of the trip.

The cross section in fig. 4 and the isopach of the Galesburg Shale in fig. 11 identify the geologic setting of

Stop 13. Fig. 13-2 is the measured section for Stop 13 along the north wall of the spillway at Big Hill Lake. The interval examined is the upper portion of the *Galesburg Shale* at the position of the boundary between the Swope and Dennis sequences (fig. 4). Another measured section is shown for South Pond (fig. 13-3). Its location is 0.75 mi (1.2 km) southwest of the spillway cut (fig. 13-1). The South Pond

exposure shows the contact of the Galesburg Shale with the underlying Mound Valley Limestone. We are only visiting

the spillway section (fig. 13-2). Fig. 13-4 provides photos of these sections.

## Stratigraphy

The total thickness of the Galesburg Shale near Stop 13 is estimated to be around 50 ft (15.2 m), with the unit thickening abruptly to the southwest to in excess of 150 ft (46 m) near Coffeyville, Kansas (fig. 13-4F). The deposit consists of mostly marine sandstone and siltstone. The base of the Galesburg Shale above the Mound Valley (fig. 13-3) is composed of claystone containing brachiopods and crinoids, grading upward to siltstone containing trace fossils. Higher in this particular exposure thin lenses of sandstone appear. The section is considered to represent distal, prodeltaic, to delta-front deposits.

Sandstones at the base of the measured section against the north wall of the spillway (fig. 13-2) and in the floor of the spillway are cross-stratified and contain interference ripples, parting lineations, starved ripples, convolute bedding (including dish structures), load casts, flute marks, and trace fossils. Deposition of most of these sandstones does not appear to have been confined to channels. This deposition of coarse clastics is attributed primarily to density flows from a southwesterly deltaic source, with local current reworking of the surfaces of these event beds.

The underclay below the coal seen in the spillway wall is a gleyed clay horizon containing rhizoliths. The coal forms a very continuous and uniform bed throughout the length of the spillway. The coal can be traced over consider-

able distances beyond this locality and may represent a regional deposit (Allan Bennison, personal communication, 1988). The sandstone and siltstone immediately underlying the underclay seen on either wall of the spillway contain small-scale channeling and may reflect fluvial conditions as sea level fell and accommodation was lost. Major sediment bypassing may have been to the southwest toward lower elevations along the eastern edge of the Anadarko basin (fig. 18).

We are tentatively placing a sequence boundary at the base of the coal. We interpret the coal to represent a flooding unit analogous to the limestones on the shelf. Marsh environments developed as the water table rose during the initial stages of base-level rise. Once water depths were sufficient, siliciclastic material reached this area of the basin, as evidenced by cross-stratified sandstone units overlying the coal. As the waters deepened, more suspended sediment was deposited, and a fining-upward package that can be observed in the upper portion of the spillway wall resulted. At this level burrowed, fine-grained, ripple cross-laminated sandstone and siltstones are present. Above these units the Canville Limestone and Stark Shale (not seen here) resulted from rapid marine flooding and inundation of both basin and shelf, and the Dennis sequence came into being.

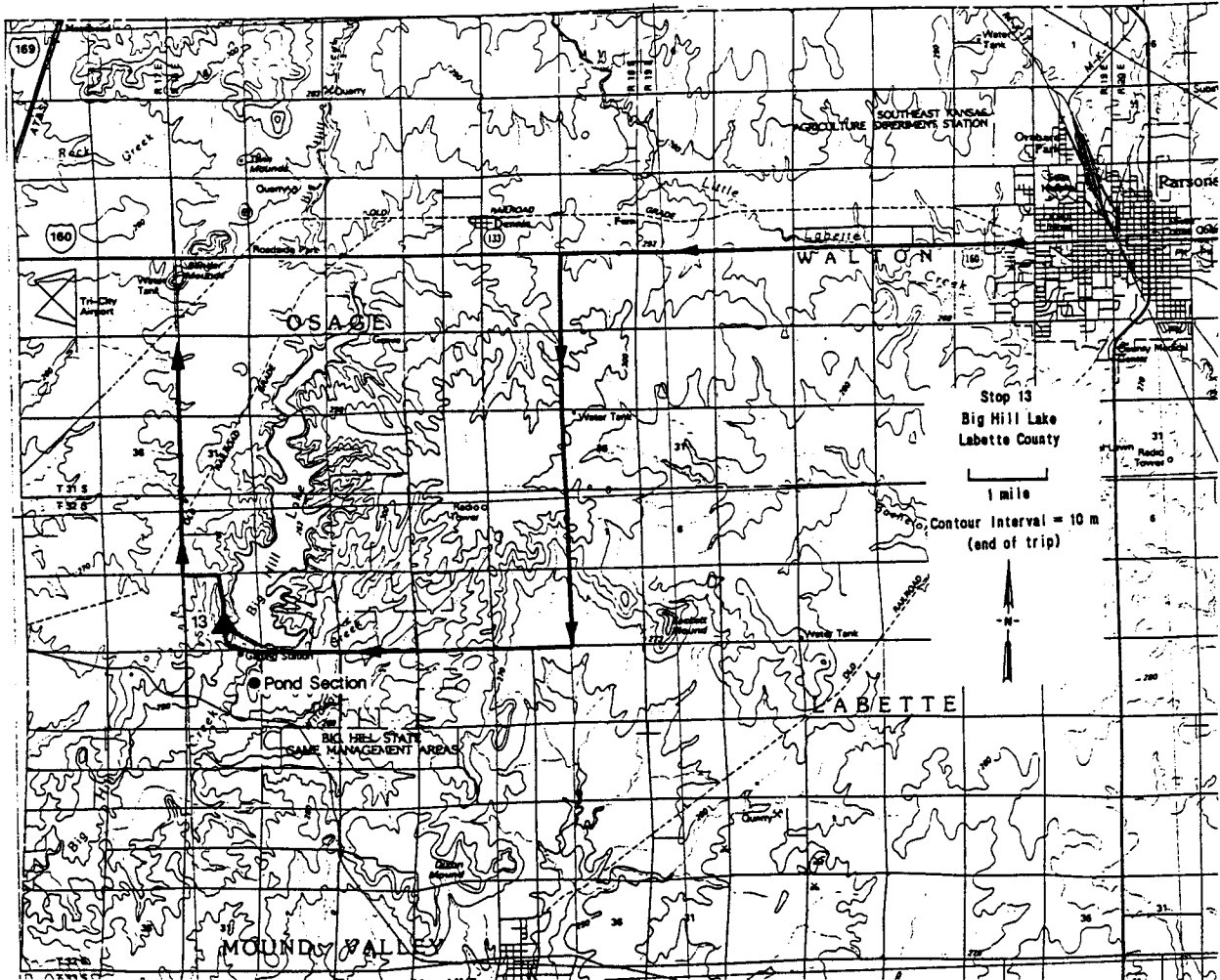
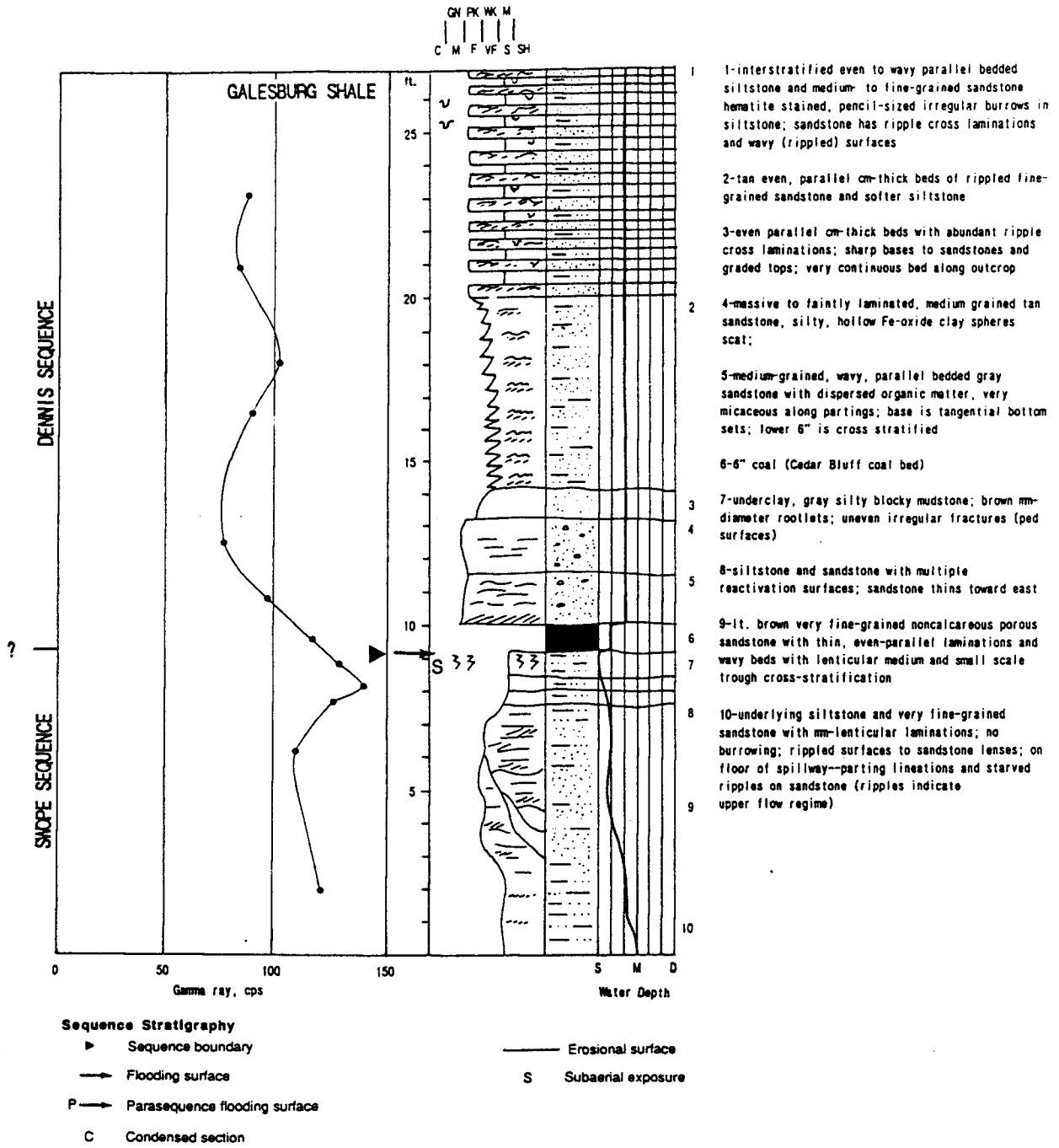


FIGURE 13-1—LOCATION MAP IN THE VICINITY OF STOP 13 (BIG HILL LAKE). Pond (south) section also shown. Highways 160, 169 (northwest corner of map), and city of Parsons are included for reference.

BIG HILL LAKE SPILLWAY



FFIGURE 13-2—MEASURED SECTION AND GAMMA-RAY PROFILE OF BIG HILL LAKE SPILLWAY (STOP 13). Sequence-stratigraphic terminology is indicated on left.

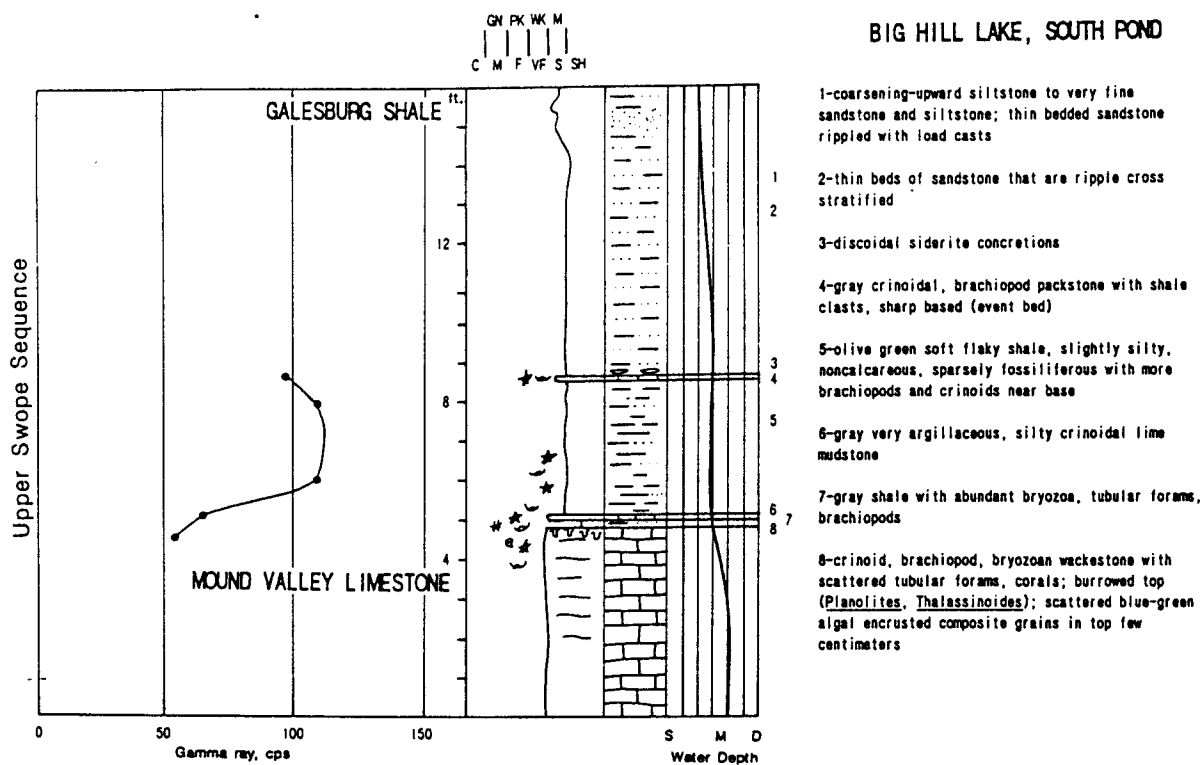


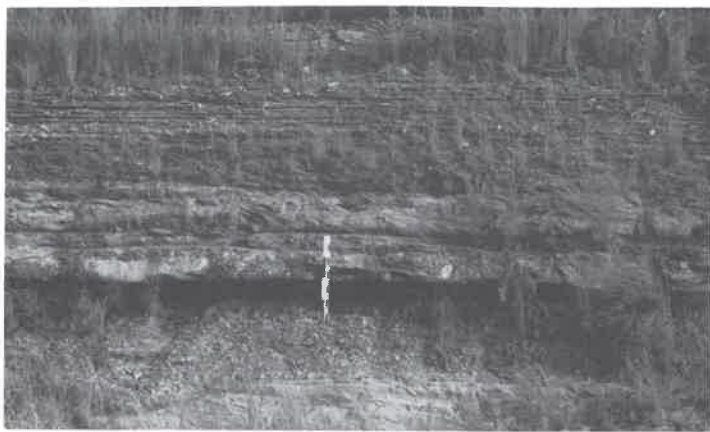
FIGURE 13-3—MEASURED SECTION AND GAMMA-RAY PROFILE OF SOUTH POND LOCATED SOUTHEAST OF SPILLWAY SECTION. Refer to map in fig. 13-1 for location.

FIGURE 13-4 (A and B)—THE GALESBURG SHALE (UPPER LAYTON SANDSTONE IN THE SUBSURFACE) ALONG THE NORTH WALL AND FLOOR OF THE BIG HILL LAKE SPILLWAY AT STOP 13. Vertical succession of sandstone and siltstone are interrupted by a continuous, regionally correlatable underclay (UC) and coal layer. The boundary between the underlying Swope sequence and the overlying Dennis sequence is tentatively placed at the base of the coal, the coal representing the flooding unit above a surface of a subaerially exposed horizon.

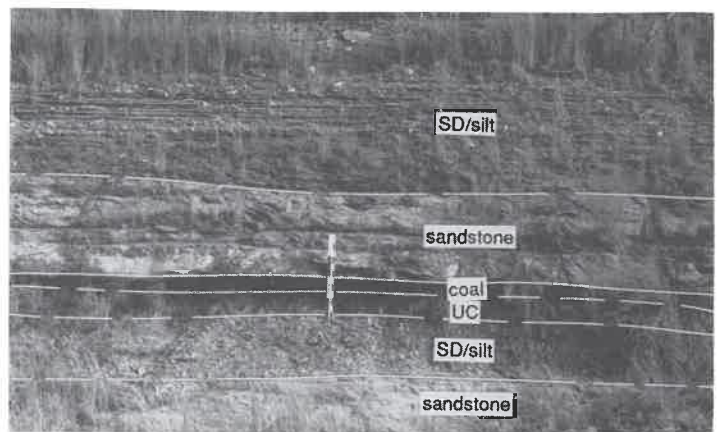
FIGURE 13-4 (C and D)—THE UPPER PORTION OF THE MOUND VALLEY LIMESTONE (MN) overlain by the basal GALESBURG SHALE (GA) AT THE SOUTH POND LOCALITY (see location in fig. 13-1). Fossiliferous claystone in the basal Galesburg grades upward to a sandy interval exposed near the top of the hill.

FIGURE 13-4 (E)—CUT-AND-FILL STRUCTURES AND REACTIVATION SURFACES IN SMALL CHANNEL FORMS IN THE SANDSTONE/SILTSTONE INTERVAL BELOW THE COAL AND UNDERCLAY ON THE WEST SIDE OF THE NORTH WALL OF SPILLWAY AT STOP 13.

FIGURE 13-4 (F)—UPPER GALESBURG SHALE IN A CLAY PIT ALONG THE VERDIGRIS RIVER ON THE NORTH SIDE OF COFFEYVILLE, KANSAS, 20 mi (32 km) southwest of Stop 13. A thick (150-ft [46-m]) section of clay that coarsens upward to predominately sandstone is displayed at this stop.



A



B



C



D



E



F

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