KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 88-41

I.O.C.C. FIELD TRIP
KANSAS CITY AREA
DECEMBER 5, 1988

MISSOURIAN (UPPER PENNSYLVANIAN) LANSING AND KANSAS CITY GROUPS IN THE KANSAS CITY AREA—MIXED CARBONATE-CLASTIC SEQUENCES

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INTRODUCTION

The major objectives of this trip are:

1) To establish why a refined understanding of these rocks is important. Some of the reasons include:

   * They include important oil and gas reservoir-bearing strata in Kansas and the Midcontinent;

   * The need for re-interpretation of depositional models in reservoir description; demonstrate utility of process-response modeling to integrate variables thought responsible for sedimentation;

2) To examine both typical and anomalous features of carbonate-dominated Upper Pennsylvanian cyclothems in the area from just east of Lawrence to Kansas City, including:

   * The succession of beds that typically comprise a cyclothem;

   * The facies present within the beds (phylloid algal buildups and grainstone shoals);

   * Aspects of correlation of cyclothems (including establishing stratal geometry by linking surface exposures with the subsurface);

   * Mechanisms that have been proposed to explain cyclicity;

3) To put these deposits in the context of the regional geologic setting, including:

   * The lateral variability that exists in a given vertical succession;

   * Correlation of these strata beyond the carbonate-dominated platform;

   * The nature and influence of tectonics (chiefly subsidence) in providing accommodation for sediments;

   * Evidence for eustatic sea level fluctuation, and the accommodation that it provided;

   * evidence for widespread paleosol development and significance in re-interpretation of cyclothems;

4) To demonstrate the applicability of sequence stratigraphic principles for improved interpretation of these cyclic lithologic successions. Some considerations of sequence stratigraphic analysis include:

* To examine as a means to provide more accurate and precise interpretations of these cyclothems;

* Use of approach in defining temporally equivalent depositional sequences that are based on areally extensive, correlable subaerial exposure surfaces and condensed sections;

* Examine feasibility in establishing the relationship between genetic units (and the above mentioned surfaces that separate them) and the processes that controlled their deposition (as opposed to strictly "typical" or "well developed" lithofacies successions);

OIL AND GAS RESOURCES IN MISSOURIAN ROCKS IN MIDCONTINENT

The Lansing and Kansas City groups have contributed a significant share of petroleum reserves and production in southwestern Nebraska, western and central Kansas, and the Panhandle areas of Texas and Oklahoma. The ultimate recovery from Pennsylvanian rocks in the Midcontinent is estimated to be nearly 9 billion barrels of oil (Rascoe and Adler, 1983). Non-associated natural gas produced from Pennsylvanian reservoir rocks from the Midcontinent now totals some 32 trillion cubic feet. Approximately 20 percent of this is attributed to Missourian reservoirs (Figure 1, distribution of oil and gas producing wells from Missourian strata of Kansas). An estimated one-fourth of the oil and 40 percent of the natural gas ultimately produced in this region will come from smaller Pennsylvanian fields. Nearly 30 percent of all new oil comes from Lansing and Kansas City reservoirs in Kansas.

Fields producing from the Lansing and Kansas City groups are commonly found on structures both large and small, since these have been the primary exploration targets. Studies have indicated that 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 (Ebanks and Watney, 1985; Watney, 1980, 1985; Watney and French, 1988; Watney and Stephens, in review).

Stacked pay zones are common on the larger structures. Also, lateral porosity variations in individual zones are the rule within a field, commonly compartmentalizing an 80 well field into 1 to 10 well elements (Watney and Stephens, in review). 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 these endeavors.

Primary recovery of OOIP in Lansing and Kansas City reservoirs in Kansas is typically low due to the predominance of solution gas drive in the fields in northern and central Kansas. Applications of secondary recovery methods typically doubles primary production, and can be as great as five times that of primary. The application of

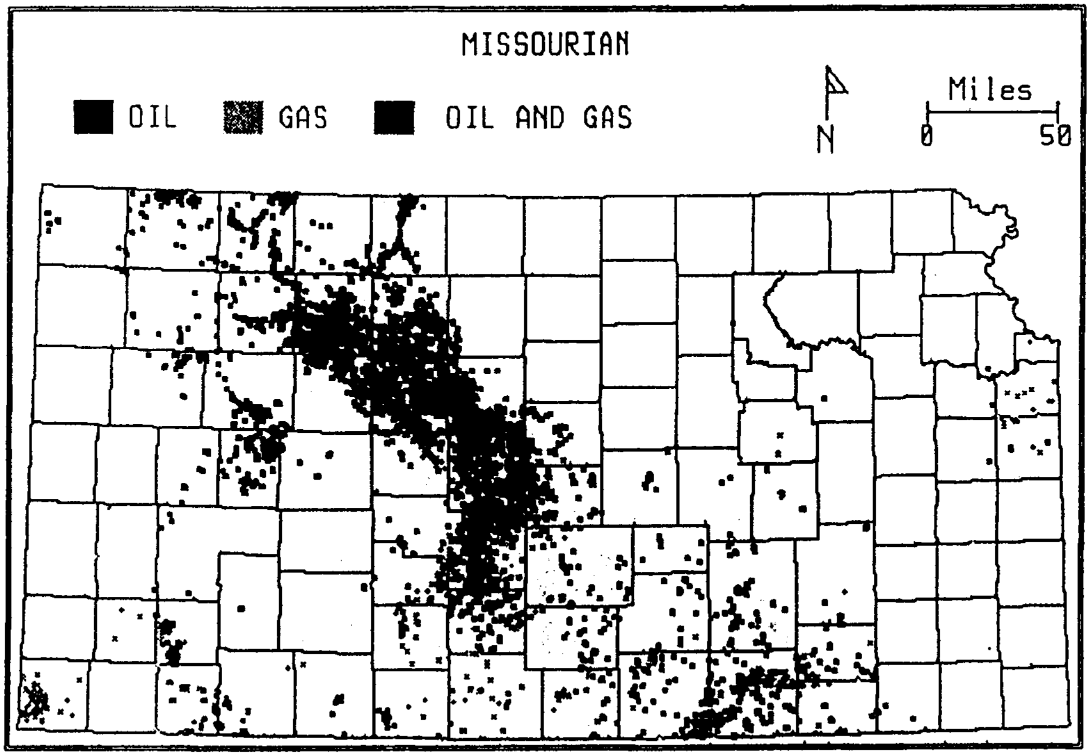


Figure 1. Distribution of oil and gas wells producing from Missourian-age reservoir rocks. Carbonate reservoirs are by far the dominant reservoirs in the western half of the state producing at depths ranging from 3000 to 6000 feet. Marine and non-marine quartz sandstone reservoirs of the Pleasanton and the Kansas City groups account for much of the production from eastern Kansas. These are shallow reservoirs ranging from depths of 200 to 2500 feet below the surface. Maps of the stratigraphic distribution and of production and productivity are found in Newell et al. (1987).

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. This success will require a team approach that incorporates improved geologic reservoir definition.

We believe the optimum approach will involve quantitative process modeling, which can simulate stratigraphic architecture and resultant reservoir compartmentalization and thereby assists in predicting porosity occurrence. Progressively more well-constrained models will be based on increasingly detailed observations and interpretations. The data will come initially from areas in which data can be obtained easily and economically, such as surface exposures and the near subsurface.

This field trip is a sampling of the approach that we are using to re-examine outcrops of the Lansing and Kansas City groups in eastern Kansas in order to develop quantitative processes-response models of sedimentation. These models will be tested to determine predictive capabilities. They will later be applied to improving our understanding of reservoir development in central and western Kansas (200 to 300 miles distant) in an concerted effort to assist industry in the optimization of the exploration and development strategies that are applied to these reservoirs.

The sedimentary models are 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). We believe that the information gained and models developed during these studies will be applicable to other situations, particularly those in which efforts at characterizing petroleum reservoirs include a need to understand the processes that have combined to produce complex stratigraphic packages.

CHARACTERISTICS AND PREVIOUS INTERPRETATIONS OF LANSING AND KANSAS CITY STRATA

Introduction

Raymond C. Moore (1931) first described cyclicity within the limestone and shale alternations of the Middle and Upper Pennsylvanian of Kansas (Figure 2). Wanless and Weller (1932) applied the name cyclothem to these deposits; this term was adapted by Moore (1936). The present stratigraphic nomenclature is derived from a classification scheme whereby formation names have been assigned to both carbonate-dominated marine intervals and to associated terrigenous-dominated marginal marine and non-marine strata (Figure 3, detailed formations and members of the Lansing and Kansas City groups).

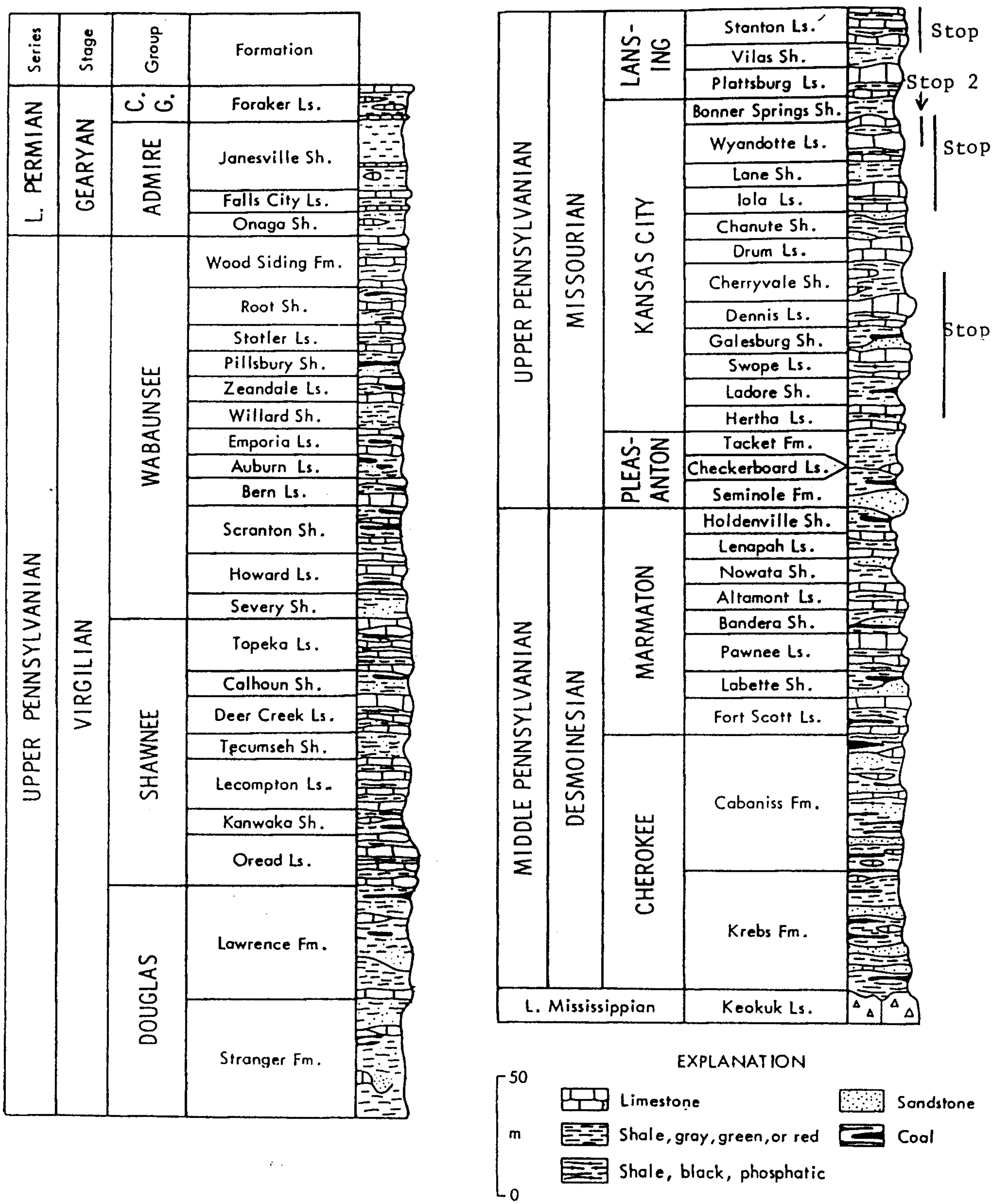


Figure 2. Columnar section of the formation nomenclature of the Middle and Upper Pennsylvanian Series of Kansas. Stratigraphic intervals examined at the four field trip stops are indicated as horizontal bars (adapted from Zeller et al., 1968).

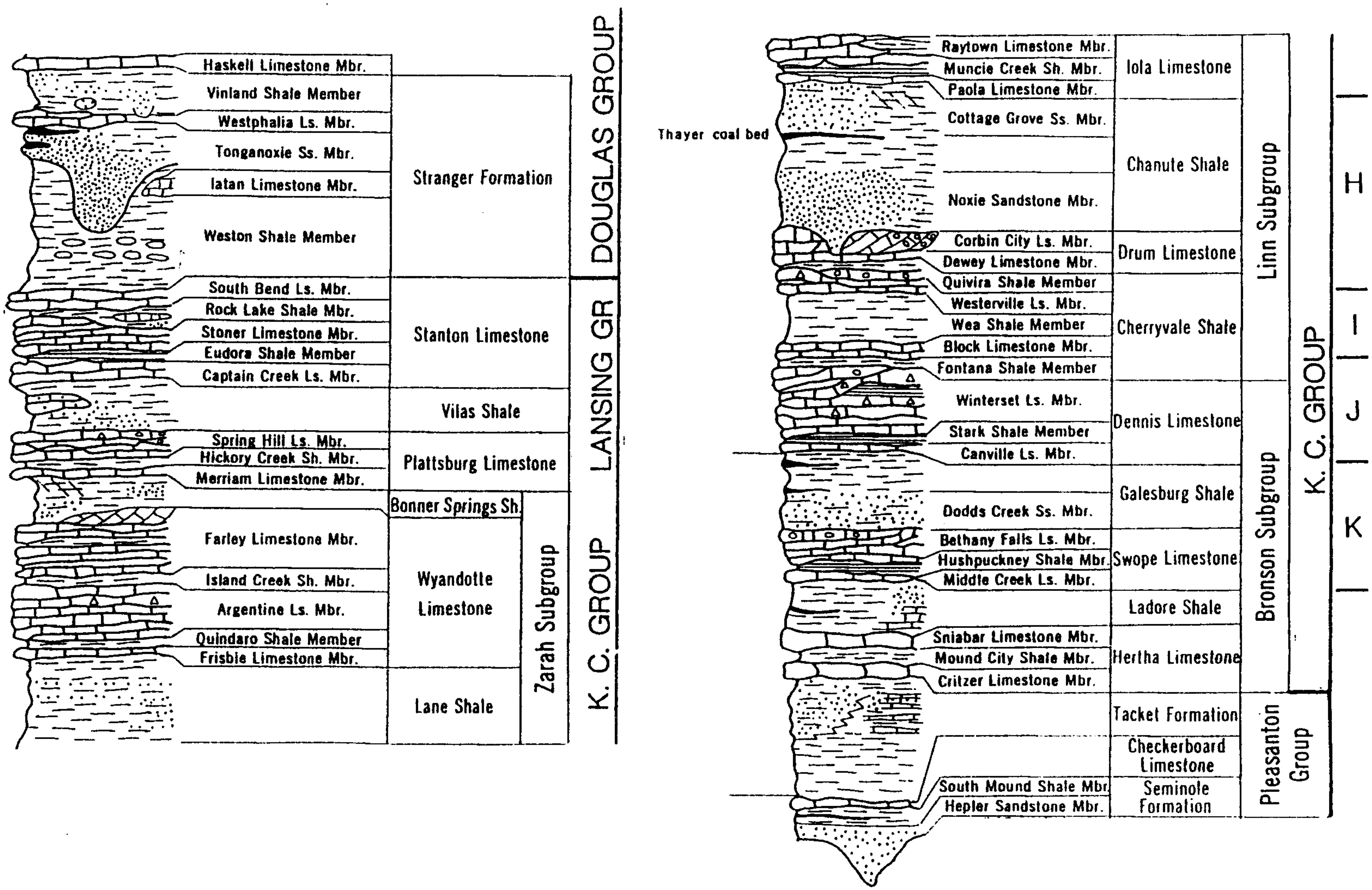


Figure 3. Stratigraphic chart of member and formation nomenclature of the Lansing and Kansas City groups (from Zeller et al., 1968).

The outcrop belt of the Lansing and Kansas City groups extends from Iowa to southern Kansas (Figure 4, outcrop map). The Missourian strata in this outcrop that extends over 350 miles are situated on a carbonate platform located north of a detrital dominated shelf and basinal area (Figure 5, paleogeographic map of Rascoe and Adler, 1983). In southern Kansas and northern Oklahoma the Missourian undergoes a major transition; carbonates dominate in the more northern areas, whereas siliciclastics are the most abundant lithologies proximal to the Arkoma Basin and Ouachita Mountain front (Figure 5). This area in southeastern Kansas is the focus of our current modeling efforts (data gathering -- coring, logging, shallow seismic, surface description and gamma ray profiling). This locus of activity will not be greatly emphasized on this trip, but it is our intention to flavor discussions with some of the preliminary results, which are most encouraging.

Geologic Setting and Tectonic Environment

The Arkoma Basin and Ouachita Mountains were very active tectonic elements during the Missourian, with clastic progradation episodically filling the Arkoma Basin and occasionally reaching onto the carbonate platform to the north. The Ouachita Mountains were an active thrust belt, and the Arkoma Basin was the associated foreland basin. It was nearly filled with detrital sediments by Missourian time due to diminished subsidence.

Western Kansas, the site of petroleum production from Lansing and Kansas City reservoirs (Figure 1, oil and gas map), was a westerly extension of the carbonate platform, and was situated immediately north of the actively subsiding Anadarko Basin (Figure 5). The Anadarko Basin in this area was sediment starved, possibly due to rapid subsidence in response to oblique thrusting in the Wichita Mountains. The Anadarko Basin is therefore considered to be a hybrid foreland basin.

The carbonate shelf in Western Kansas varied from a gently sloping ramp to a nearly flat platform during the deposition of Lower Missourian strata. The variation in elevation on this shelf resulted from crustal flexure induced by thrusting to the south (Watney, 1985a,b). The contiguous carbonate shelf that extended from eastern to western Kansas was linked to different tectonic regimes from east to west.

Terrigenous clastics episodically filled the eastern portion of the Arkoma Basin and prograded onto the carbonate shelf in southeastern Kansas. In contrast, the southern margin of the western shelf was never affected by similar clastic influx, but underwent episodic carbonate shelf margin progradation and retreat. The estimated water depth in the Anadarko Basin outboard of this shelf was 1100 feet (Kumar and Slatt, 1984).

The areal variation of average subsidence rates during the Missourian conforms to basin development in the southern Midcontinent (Figure 6,

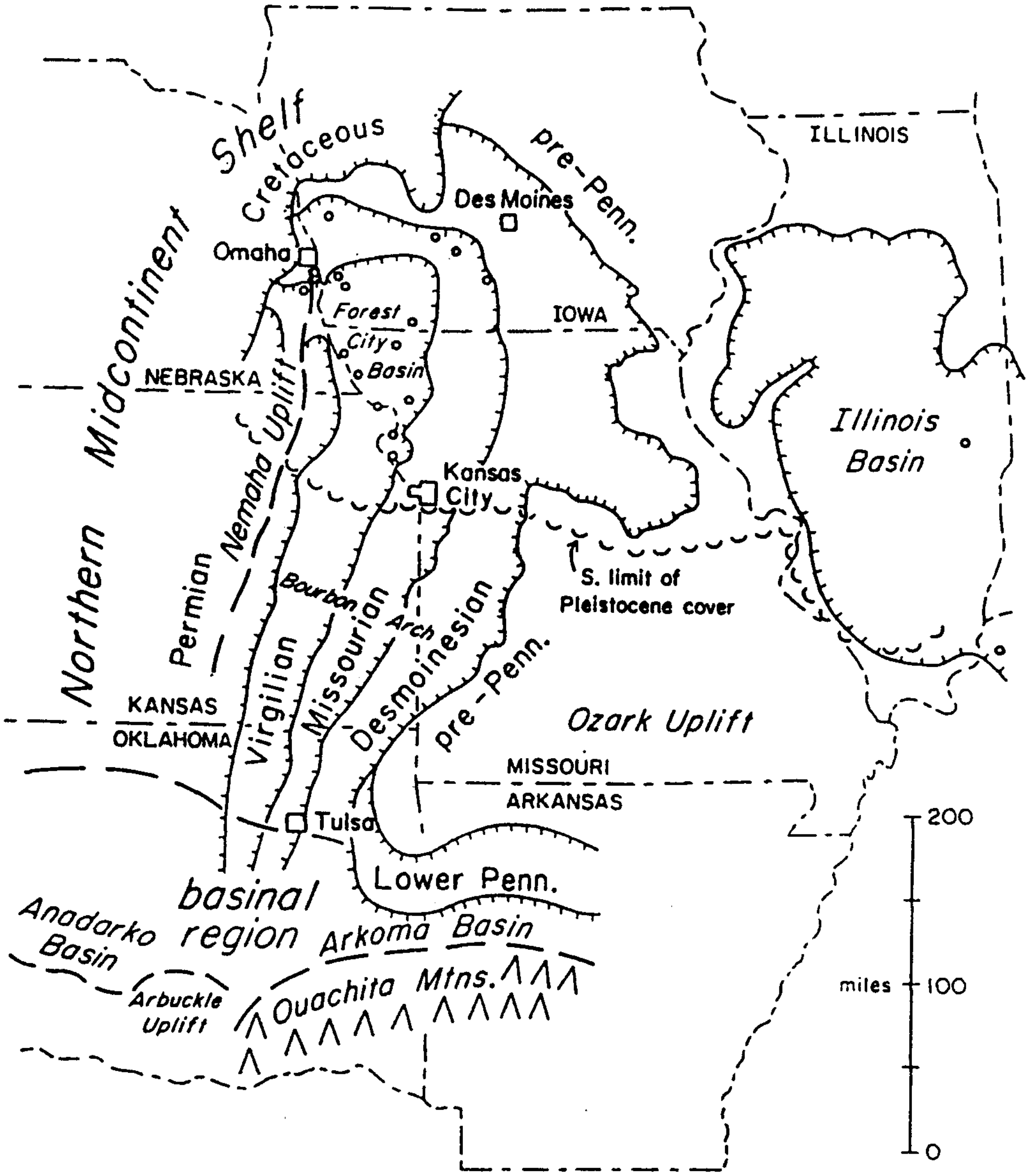


Figure 4. Map of Midcontinent Pennsylvanian outcrop belt. Hatures along the contact indicate dip direction. Strata in the Kansas and MIssouri area outcrop along the west flank of the Ozark Uplift. The Kansas City area is also situated on the southeastern flanks of the Forest City basin, a shallow cratonic basin with up to 4600 feet of Phanerozoic fill (from Heckel, 1985).

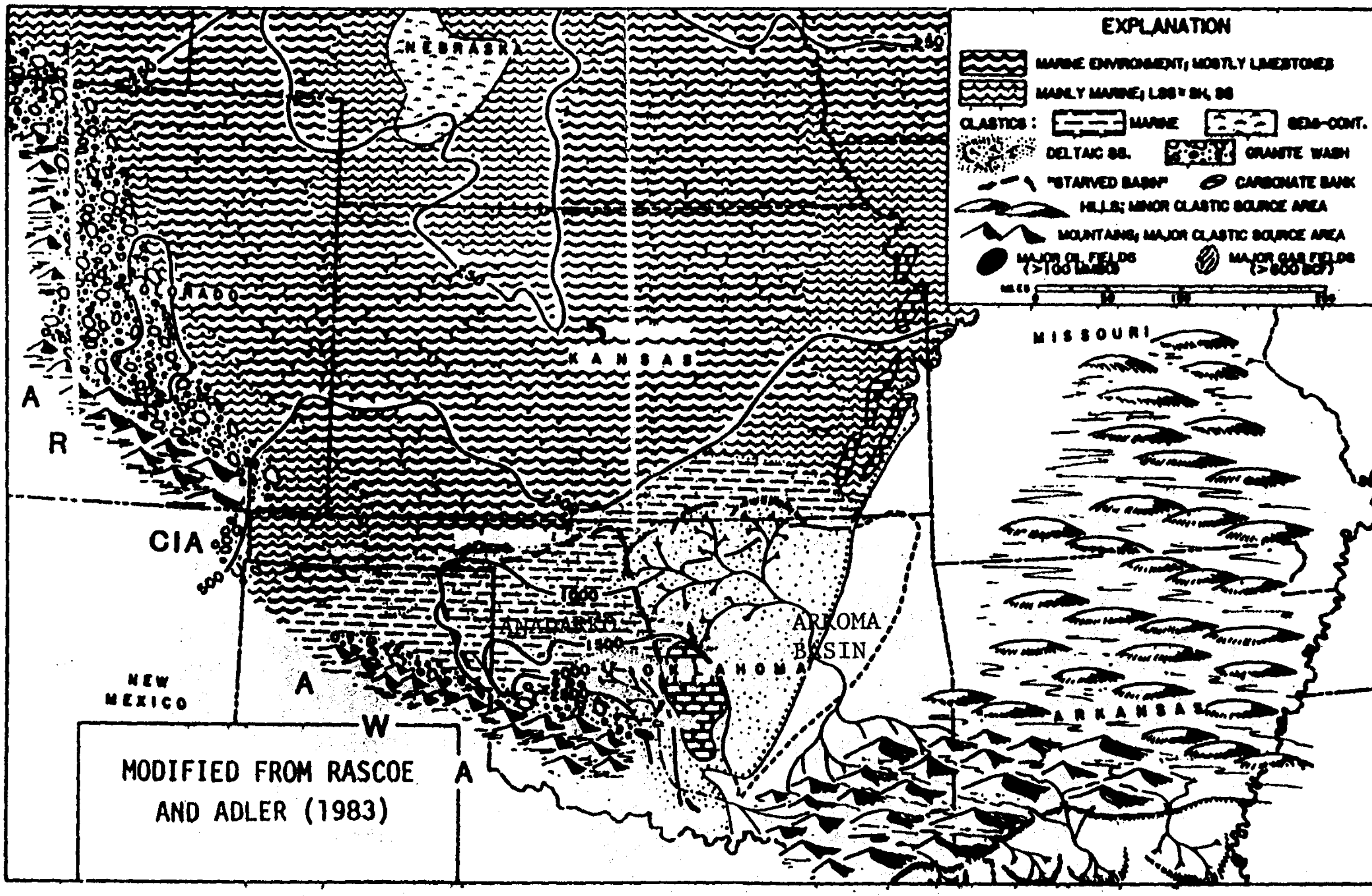


Figure 5. Generalized paleogeographic map of the western Midcontinent during the Missourian illustrating major depositional facies. The northern Midcontinent including the area of this field trip in mainly a carbonate-dominated marine shelf. This setting extends to the area of major petroleum production in central and western Kansas. Isopach lines on this map of the Missourian strata indicate thickening to the south into the Anadarko and Arkoma basins. AWA refers to the Amarillo-Wichita-Arbuckle Mountains, the positive and actually thrusted elements which led to substantial subsidence of the Anadarko basin. Sediment starved conditions were common during much of the Missourian in the region indicated by a dashed line. Sediment fill originated through episodic submarine fan deposition during lowstand sea level conditions and sediment bypassing of along the eastern margin (from Rascoe and Adler, 1983).

The mountainous area depicted in the extreme southeastern part of the map represents the thrust belt of the Ouachita Mountains also active during the Missourian. The Arkoma Basin in a foreland basin resulting from the thrust belt. It was generally filled with siliciclastic detritus shed off of the Ouachitas. Relief of the Ouachita mountain belt has been estimated to be around 15,000+ feet (Bethke et al., 1988).

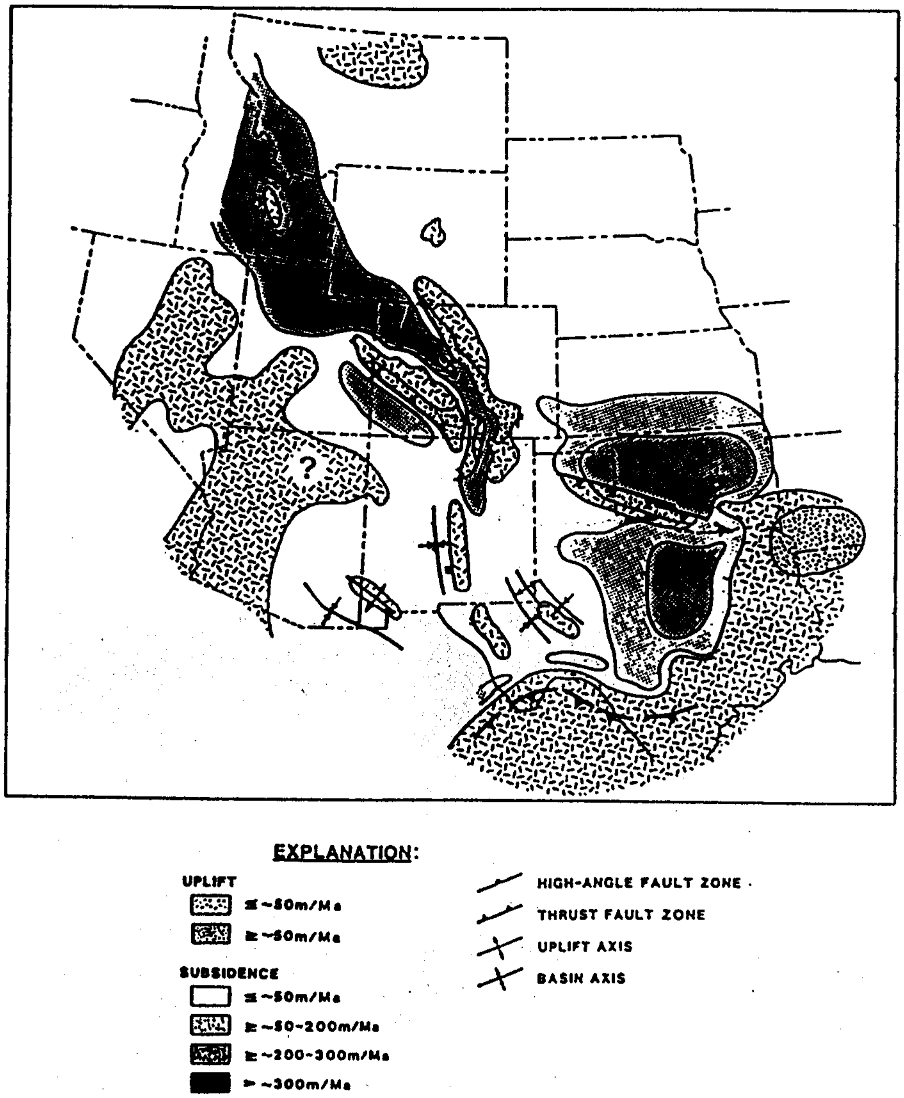


Figure 6. Map of average subsidence rates for the Missourian for the western U.S (Kluth, 1986). Note the progressively increasing rates of subsidence southward across Kansas into the Anadarko and Arkoma basins. Subsidence rates along southern Kansas were comparable to sediment accumulation rates resulting in thick sedimentary deposits. Subsidence rates in the basins commonly exceeded rates of sediment accumulation.

Kluth, 1986). The subsidence rates varied considerably from shelf to basin, ranging from over 0.3 m/ka in the basin to less than 0.05 m/ka on the northern shelf. Thrust-induced subsidence was episodic, with pulses of rapid downwarp followed by longer-term periods of slower subsidence. The precise duration of these episodes is not well known.

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.

Kansas Cyclothem Development

and the Role of Eustatic Sea Level Change

Introduction

Sea level change has been a critical process in the ongoing debates regarding the origins of Pennsylvanian cyclothems. We believe the problem of cyclothem origin is quite complex and certainly involves more than eustatic fluctuations alone; nevertheless, independent evidence points towards relatively high-amplitude and high frequency sea level oscillations during Missourian time.

The obvious and in many cases predictable alternations of shales and limestones, the general similarities in both lithology and thickness of the member beds from area to area, and the widespread correlability of both individual units and entire cyclothems, have led to a number of proposed causal mechanisms. The various options will not be described in detail here, but we would be more than happy to entertain questions and musings.

Kansas Cyclothem

Heckel (1977) presented a model that has been used extensively to describe and interpret the succession of beds within 'typical' cyclothems (Figure 7, Kansas Cyclothem, Heckel, 1977). Using the nomenclature of Heckel (1977), the lowermost bed of the cyclothem is the middle limestone. This nomenclature is a modification of R.C. Moore's the early descriptions of typical Virgilian megacyclothems. The lowermost limestone in the Missourian cycles is thought to correspond to Moore's middle limestone of his megacyclothem.

Middle Limestone. -- 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. Middle limestones in some units can be relatively thick, as is the case with the Captain Creek Limestone at Stop 1. The middle limestone may be very thin or absent, as is the case with the Canville Limestone at Stop 4. The Captain Creek is

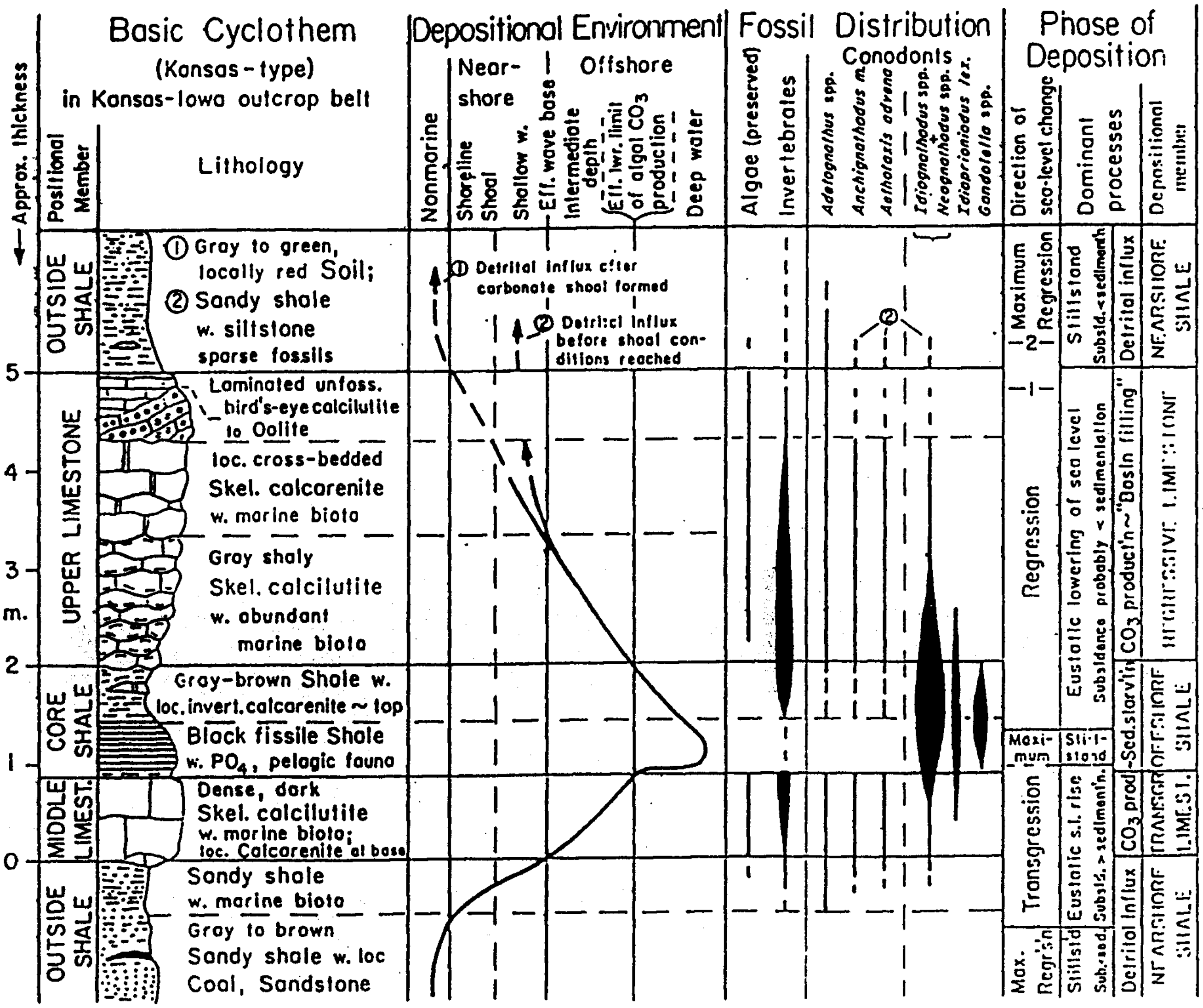


Figure 7. "Kansas Cyclothem" as described by Heckel (1977). This is an ideal cyclic lithologic succession developed in the Missourian in the upper Midcontinent.

locally in excess of 80 feet thick in southern Kansas, where it consists of phylloid algal buildups.

Core Shale. -- Overlying the middle limestone in the Kansas Cyclothem is the **core shale**, which is also typically thin, being around 1 to 3 feet thick. Like the middle limestones, core shales are areally extensive units. They commonly are black or dark gray shale and contain phosphate nodules. The black core shales are readily recognizable in surface exposures, and are excellent subsurface markers due to their high radioactivity.

Wanless (1964) used these black shales, which are common to a number of Middle Pennsylvanian cyclothems, to correlate siliciclastic-dominated cyclothems in Illinois with equivalent, marine-dominated successions in the western Midcontinent. A key idea stressed by Wanless was that a cyclothem could be distinguished regardless of the variation in the succession of sediments associated with the core shale.

The origin of these black core shales has been vigorously debated. Heckel (1977) reemphasized the significance of the regional correlability demonstrated by Wanless, and stressed that this lateral continuity, coupled with the faunal composition and phosphatic nature of these shales, made them the deepest water deposit of the cyclothem. In the western craton along the outcrop belt the indigenous fauna is composed primarily of conodonts, ammonoids, and fish debris. Minor elements such as uranium and various metals are also abundant in the black shale. Yet, workers like Zangerl and Richardson (1963), Merrill (1973), Maples (1985), and Coveney and Martin (1983) have demonstrated both paleontologic and inorganic and organic geochemical evidence for a shallow-water origin of black shales in the Illinois and Appalachian basins. This inconsistency is currently being addressed (Watney, Coveney, and Maples, in preparation).

A knowledge of the water depth represented by these core shales is critically important to our understanding of the changes in relative sea level that occurred during cycle deposition. The proper interpretation of relative sealevel changes is clearly of more than just an academic interest with regard to quantitative modeling. In sequence stratigraphic terminology, core shales are condensed sections. Although this genetic designation of the shale appears to hold in Kansas, the amount of time that they represent may vary considerably. Time and water depth are difficult variables to apply to this unit at this time.

Lateral variations are found in some black shales, such as the Eudora Shale in the Stanton Formation at Stop 1. The black Eudora in this area changes over distances of less than a mile to gray shale with totally different faunal composition. The lateral variations in organic content and the presence of a significant benthic fauna suggest at least some of the anoxic episodes involved the water column only near the sediment-water interface, and that variations in bottom topography may have been sufficient to eliminate anoxic conditions. Black shale formation is also thought to be a function of extent of vertical and lateral circulation in the water body, and of the levels of terrestrial and marine organic productivity.

Other widespread and easily distinguished black core shales are less variable laterally. The Hushpuckney and Stark shales, which are exposed at Stop 4, can be traced throughout the outcrop belt in eastern Kansas and southward into siliciclastic cycles proximal to the Arkoma Basin. They extend over 400 miles to the west into western Kansas and eastern Colorado where they can be identified both biostratigraphically and through their strong radioactive response on gamma ray logs (note scintillometer response of exposure at Stop 4). These black shales grade into gray fossiliferous shales along the Central Kansas Uplift, which is a positive element extending off of the Transcontinental Arch.

The effects of the Central Kansas Uplift on black shale development can be seen in a map of the maximum gamma radiation of the Hushpuckney Shale in western Kansas (Figure 8, maximum gamma radiation map of Hushpuckney Shale, from Watney, 1984). The radiation is low (less than 160 API units) where the shale is not black or too thin to be recorded properly on the wireline logs. The black facies of the Hushpuckney at Stop 4 has a gamma ray response that is one of the highest that we have recorded to date.

Recent biostratigraphic evidence (conodonts, ammonoids) has established interbasinal correlation of some of these marine core shales; this control is being used to verify physical stratigraphic correlations of terrigenous clastic depositional sequences in the Arkoma Basin. These sequences are correlable with those on the carbonate shelf in Kansas, but details have yet to be worked out. Biostratigraphic correlations have now linked Upper Pennsylvanian dark marine shales of the eastern shelf of the Midland Basin to those that occur on the Midcontinent carbonate platform.

<u>Upper Limestone</u>. -- The **upper limestone** is commonly the thickest bed within cycles on the carbonate platform. This unit ranges from less than 10 feet to over 100 feet in thickness. The upper limestone contains the major petroleum reservoirs of the Lansing and Kansas City Groups. Reservoirs consist of grainstone buildups, algal mounds, and structural and diagenetic traps created by fracturing and dissolution.

Facies and early diagenesis of the upper limestones indicate a shallowing-upward succession in most cases. Although the Kansas cyclothem model of Heckel (1977) indicates a continuous gradual shallowing, observed facies successions indicate fluctuations in water depth with an <u>overall</u> shoaling trend. The relative importance of local (autogenic) controls versus regional (allogenic) controls on the deposition of these generally complex shallowing-upward successions is another topic of intense interest and discussion. We will explore some of this variation with you on the trip. In general, individual upper limestones can be recognized and traced

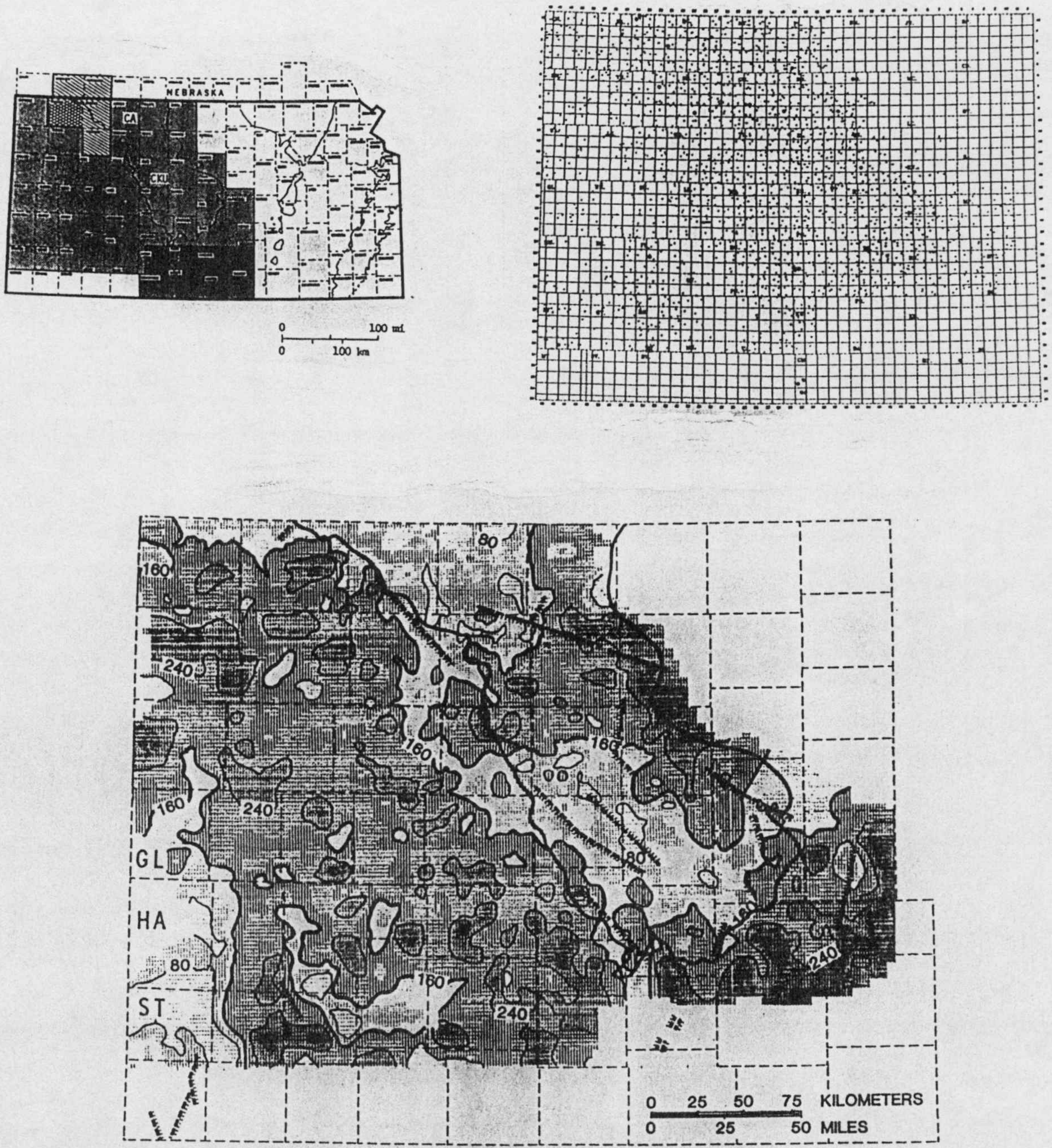


Figure 8. (a) Index map of area (stippled) where Missourian strata are mapped (thickness, porosity, stratigraphic information) in western Kansas (Watney, 1980, 1984). (b) The location of well control used in regional study (2300 wells). (c) Gray-level map of maximum gamma radiation in the Hushpuckney Shale (Swope Limestone) recorded by wireline logs. Areas mapped as having low gamma radiation (less than 160 API units) are inferred to have non-black shale facies or very thin shale accumulation as verified by core information. These areas are thought to have be slightly higher in elevation the immediate surrounding areas to account for the thinning or facies change.

Heavy black line along eastern part of map identify the edge of the Central Kansas Uplift, a broad, low-relief tectonic feature that was tectonically active some 20 million years before the Missourian strata were deposited. Later epeirogenic uplift (or area of less subsidence) is suggested to have proceeded concurrently with sedimentation by this map and others (isopach and facies) of the Swope Limestone and other cyclic units.

across large areas of the carbonate platform, and allogenic controls are believed to have dominated their development.

The individual episodes of abrupt deepening and gradual shallowing that characterize some upper limestones parallel overall cyclothem development, but are expressed on a smaller scale. The correlation and interpretation of these internal episodes (parasequences) is an important objective of our research.

Sedimentation unquestionably is episodic and incomplete. Some upper limestones exhibit more internal surfaces and episodes of deposition than others, e.g., the thin-bedded Winterset Limestone versus the more massively bedded Bethany Falls Limestone at Stop 4. Some of these internal units are event beds (e.g., storm deposits) with limited lateral extent, which are sharply bounded by distinct surfaces (e.g. the unit near the top of Winterset Limestone at Stop 4). Some facies are progradational in nature with prominent foreset bedding obvious from the surface exposures of units such as the upper Winterset and Westerville grainstones at Stop 4. Large-scale progradation is also suggested based on longer-distance correlations from the subsurface cores and wireline logs (Figure 9, North-South cross section along carbonate shelf margin, southeast Kansas) and surface exposures.

The cross sections and the color maps, which will be displayed at Stop 4, link this surface exposure with the subsurface and surface in east-central Kansas and western Missouri, and with the Arkoma basin margin in southeastern Kansas. This preliminary work illustrates some significant lateral changes in lithofacies and stratigraphy, particularly of the upper limestones. Increased rates of subsidence in platform margin, slope, and basinal areas greatly increase the likelihood of sediment preservation. Because of this differential subsidence, the southern shelf was an area of considerably more accommodation for sediment, which resulted in additional fidelity of the stratigraphic record.

Integrated surface and subsurface mapping also indicates that the well-known phylloid algal buildups and thick ooid shoals developed in an east-west direction along strike across the southern shelf. Algal buildups may thicken locally, or in some cases form regionally extensive bank complexes that can be three times the thickness of the entire cyclothem on the northern shelf. Some units wedge out toward the platform, exhibiting toplap and onlap geometries. Toplap relationships suggest that certain units, particularly siliciclastic ones, developed preferentially in lower shelf settings during relative sealevel lowstands due to sediment bypass higher on the shelf.

The idea of a widespread, layercake stratigraphy is seriously compromised when this data is considered. Moreover, it is the deciphering of these stratal packages in areas of high stratigraphic and sedimentologic resolution that will provide the means to identify and quantify the controlling processes. Certain areas in southeast Kansas had anomalously high depositional slopes, resulting in a

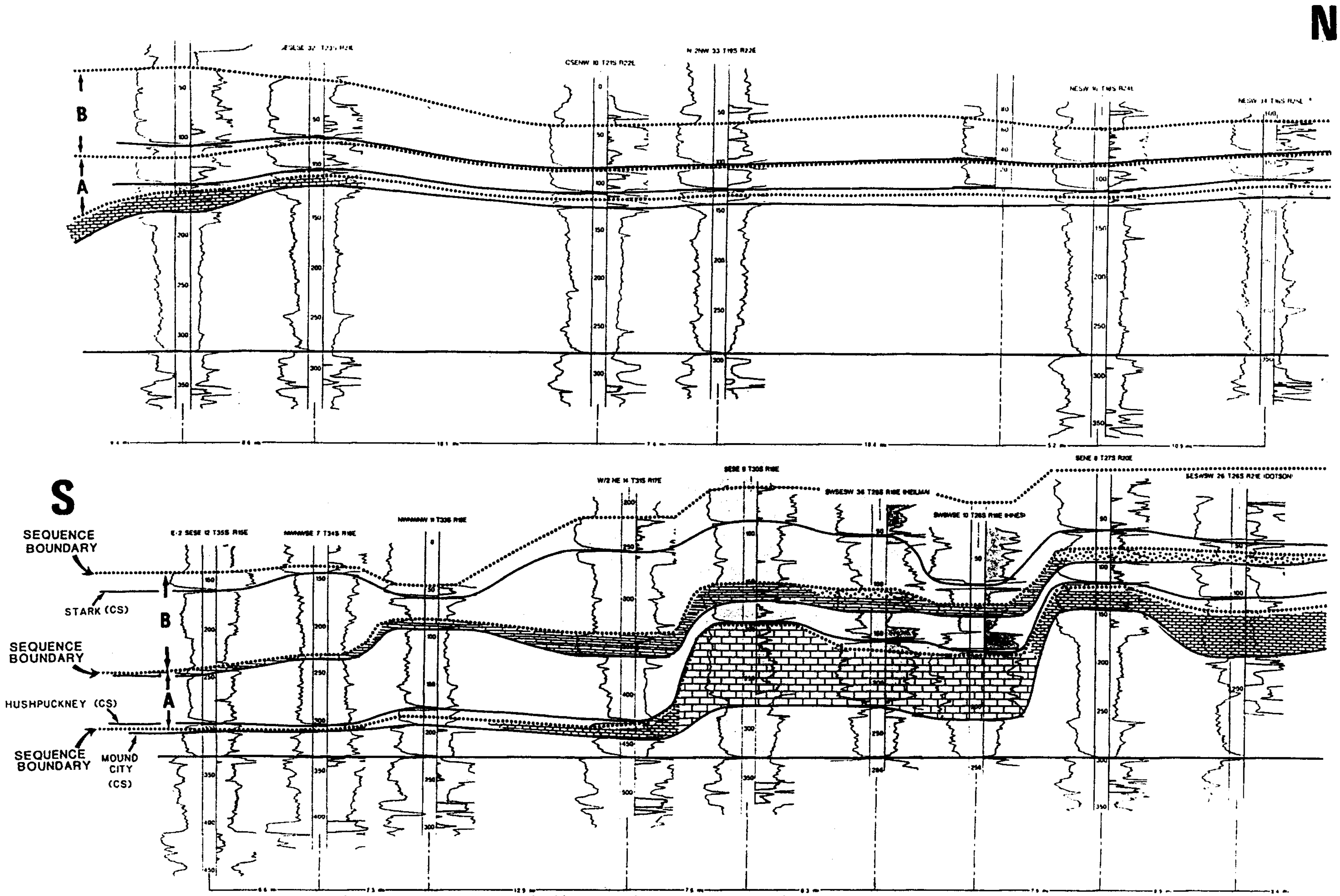


Figure 9. North-south, wireline stratigraphic cross section of lower Kansas City and Pleasanton groups in eastern Kansas extending from south of the Kansas City to near the Kansas-Oklahoma line. Section comprised of gamma ray and neutron logs parallels the outcrop. Lithologic assignments are based on near surface information and cored wells included on or near this section. Correlations are established primarily by the radioactive dark gray to black "core" shales (heavy line connecting wells). Dashed lines identify the bounding surfaces of the depositional sequences discussed in the text. These surfaces separate an underlying paleosol on the upper shelf from the overlying flooding unit heralding the succeeding sequence. Low shelf positions in southern Kansas

north-south compression of lithologies relative to the broad platform.

These areas will serve as the foundation for the refined interpretations and are the focus of initial modeling efforts, since we expect such areas to provide the greatest opportunities for success, and for application in other areas. The geometries and distribution of these stratal elements will be applied to our fundamental understanding of reservoir development.

Other units within certain upper limestones exhibit widespread lateral continuity on the carbonate platform, with correlations having been based on physical composition and wireline log character. Examples include some of the relatively thin units within the Winterset Limestone (Stop 4 and cross sections). The surfaces that separate these units are as critical to their recognition and correlation as are their facies. Their thinness and short accumulation times, however, pose problems in their correlation. Geochemical profiles appear to be very promising, and will be tested in an attempt to establish some sort of signature, which can be verified with allied data.

Outside Shale. -- The **outside shale**, the uppermost unit of the Kansas Cyclothem, exhibits considerable variability among cyclothems. These units range from only a fraction of a foot to tens of feet in thickness. The thicker packages of shale, sandstone, and siltstone such as the Lane Shale at Stop 3 represent deltaic clastic influx. These delta deposits contain invertebrate-rich horizons, thin limestones, channel sandstone, and paleosols. These platform deltaic deposits extend for tens of miles. The sediments that make up most of the outside shales in the Kansas City area were apparently derived from the east, with clastic debris likely shed from the then positive Ozark Uplift. In the interval examined, clastic influx did not become important until the deposition of the upper Kansas City Group. Outside shales of the lower Kansas City Group are notably thin, such as those seen in stop 4 (Elm Branch, Galesburg, and Fontana shales).

The margins of these areally limited deltaic units are abrupt in places, producing marked depositional topography that affected subsequent deposition. The Lane Shale at Stop 3 thins dramatically south and west from 43 feet in this exposure to less than 2 feet about 10 miles away. Such abrupt thinning of siliciclastic units provides accommodation space for superjacent units; in some places carbonate buildups occupy positions just outboard of the slope break in such situations (Stop 2). At Stop 2 the Wyandotte Limestone has begun to build up into a phylloid-algal bank in association with thinning of the underlying Lane Shale. A few miles to the west and northwest where the Lane Shale is virtually absent, the Wyandotte is over 80 feet thick (see illustrations in Stop 2).

The deltaic influx can take place when there is accommodation space for sediment accumulation. Deltaic influx occurs late in these sequences when water depth becomes sufficiently shallow to permit rapid progradation across the shelf. Clastic detritus in the upper

Kansas City and the Lansing Group reaches this area of the shelf prior to the subaerial exposure of the upper limestones. Continued fall in baselevel is suggested due to notable channeling of the deltaic wedges and occasional downcutting into the underlying limestones. Concurrent with the channeling and more widespread is the development of paleosols that are only now being recognized as major elements in these thicker deltaic shelf deposits. Evidence for subaerial exposure is much more apparent in outside shales without detrital influx. Nevertheless, closer examination of paleosol evidence is underway in the thicker outside shales.

Widespread subaerial exposure is clearly evident in most outside shales and on the tops of many of the upper limestones (Watney and Ebanks, 1978; Heckel and Schutter, 1984). In many cases the outside shale is essentially a paleosol that caps the carbonate. The paleosols seen at Stop 4 on top of the Sniabar and Bethany Falls limestones are splendid examples of ancient soils with diagnostic evidence for prolonged and intense weathering. These paleosols can be traced across the carbonate platform from eastern to southeastern Kansas, and are present in cores from western Kansas. In addition, soil development in each unit is distinct, making a particular subaerial horizon recognizable from locality to locality. Areas interpreted to be higher shelf locations generally exhibit evidence of more intense weathering (Watney and Ebanks, 1978; Watney, 1980; Heckel, 1983).

Current investigations in southern Kansas indicates that the subaerial surfaces can be traced to conformable surfaces that show no evidence of exposure. These lower shelf positions can provide a means to estimate the extent of sea level change.

SEQUENCE STRATIGRAPHY

The subaerial surfaces define a natural packaging of temporally equivalent genetic units. These are analogous to the depositional sequences described by Vail et al. (1977) and more recently by Haq et al. (1987) (Figure 10, Haq conceptual diagrams). The concepts and approaches of sequence stratigraphy are being applied and tested as a means of unravelling the stratal architecture and developmental history of these cyclothems. Rather than defining sequences by a certain lithofacies succession, we believe that the preferred approach is to identify genetic units and temporally significant surfaces such as condensed sections, paleosols and other surfaces of subaerial exposure, maximum flooding surfaces, and individual shallowing- or deepening-upward units. The recognition of these features is deemed essential to both the understanding of depositional processes and the correlation of stratigraphic units in disparate depositional settings.

As alluded to earlier, the information on processes will be applied to refining our understanding of reservoir framework and reservoir characterization. A promising area of related research is the use of very high resolution seismic profiling to define depositional

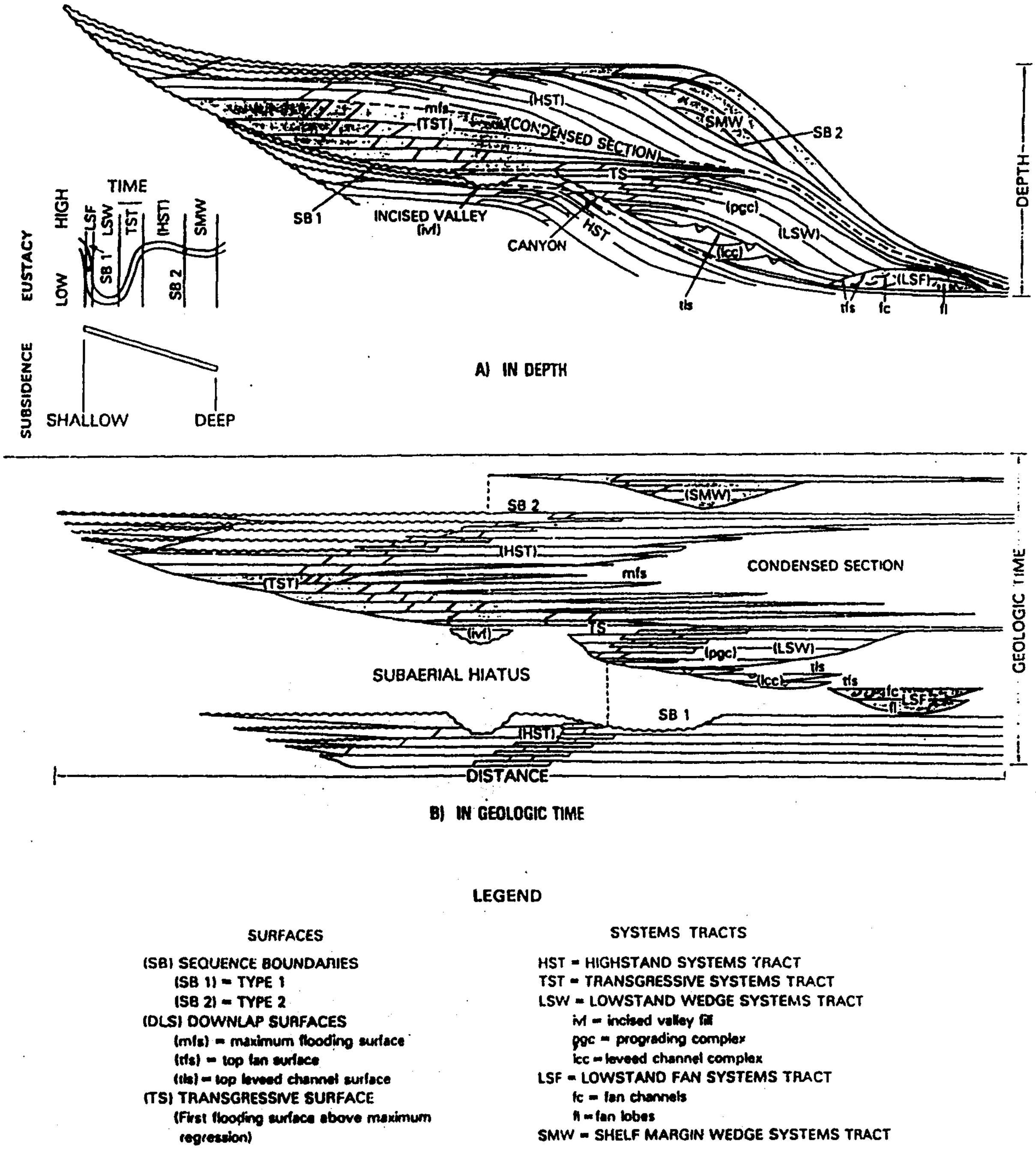


Figure 10. Conceptual model of a depositional sequence as presented by Haq et al. (1987). Model is being applied and tested to cratonic cyclothems. Objective of sequence stratigraphic analysis is to define temporally equivalent depositional units to define strata1 geometry and to distinguish facies and surfaces useful in developing quantitative sedimentary models to understand contributions of allogenic and autogenic processes.

sequences and bounding surfaces (Figure 11, backyard KGS seismic profile). Stratigraphic resolution using this method is about three feet down to a few hundred feet. Together with shallow coring and logging and outcrop examination, the database should help us understand complex geometries in critical areas on the shelf. This enhanced understanding of these rocks can provide keys as to the contributions of the myriad of potential causal mechanisms and processes associated with cyclothem development.

MODELING CYCLOTHEMIC SEDIMENTATION

The Role of Eustatic Fluctuations

Ross and Ross (1987) have recently published biostratigraphic evidence that major cyclothems are correlable among continents, which provides additional support for high frequency glacial-eustatic cycles during the period from the late Mississippian through the early Permian (Figure 12, Pennsylvanian sea-level and sequence chart). A major goal of this study is to refine such sea-level curves.

The rates, magnitudes, and duration of eustatic sea-level changes produced a major signature to these cyclothems. Yet, we do not know the absolute amount nor the relative contribution of this and the other mechanisms. Subsidence, pre-existing local depositional topography, and sediment accumulation and dispersal are also important factors that notably influence reservoir development. Some combinations of these processes produced a given cyclothem at a particular position on the shelf. An understanding of the relative importance of regional and local processes is sought in this study.

Forward Computer Modeling of Mechanisms and Processes

Concurrently with the sequence analysis we are developing computer models to incorporate information from the outcrops, cores, wireline logs, and seismic data. To date, the modeling has been simple, consisting of forward simulation of sedimentary sequences through application of sediment accumulation rates, subsidence rates, and sea-level fluctuation as might be anticipated for glacially induced eustacy (Figure 13, mid-shelf 1-D forward model). The sea-level curve shown in Figure 13 is obtained from an estimated sea-level curve of the Pleistocene based on the O-18 isotopic record from planktonic forams obtained from deep-sea sediment cores. The isotopic record is actually a function of ice volume, which is believed to be a close approximation of sea level history.

The period of cyclicity in the Pleistocene isotopic record is 100,000 years, roughly 4 times the average period of Pennsylvanian cyclicity. Accordingly, the Pleistocene time scale was multiplied by a factor of four to stretch the cycles in time to approximate the variability that may have occurred during the Pennsylvanian. The results include both a depth display and a time-stratigraphic display (Figure 13).

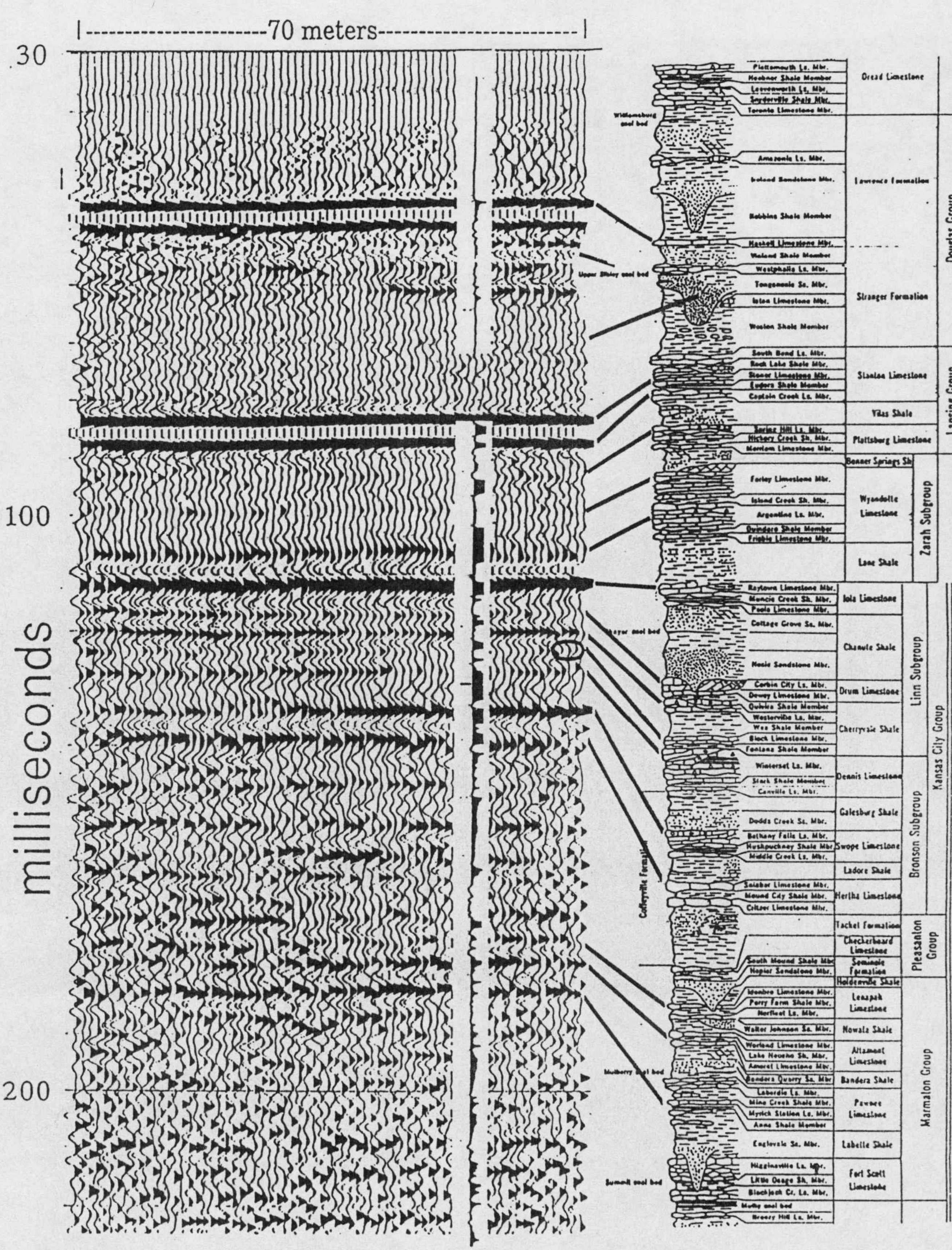


Figure 11. (a) Seventy-meter long seismic profile acquired with a 50-caliber gun as source along a line immediately south of Moore and Hambleton halls. Interval shown on the profile is the Lower Virgilian to upper Desmoinesian. Depth shown is approximately 1800 feet. Top of the Lansing Group is around 130 feet below the surface.

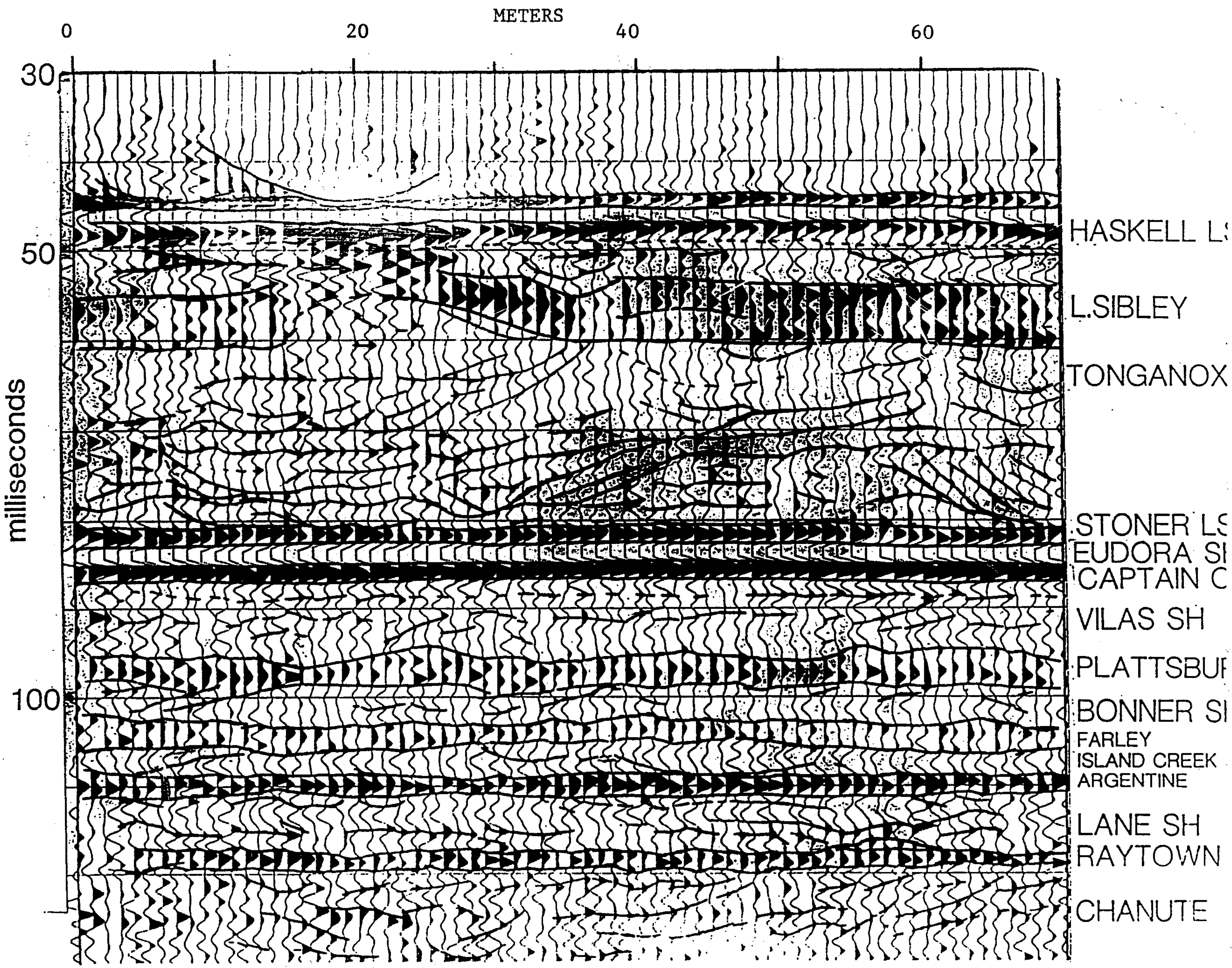


Fig. 11 (cont.)

(b) Detailed section of upper part of the seismic profile of (a). The refectors in the Tonganoxie Sandstone are large-scale bedforms as verified from nearby outcrops. Maximum resolution of this seismic source-detector arrangement is around 1 meter. Source frequency is over 500 hertz.

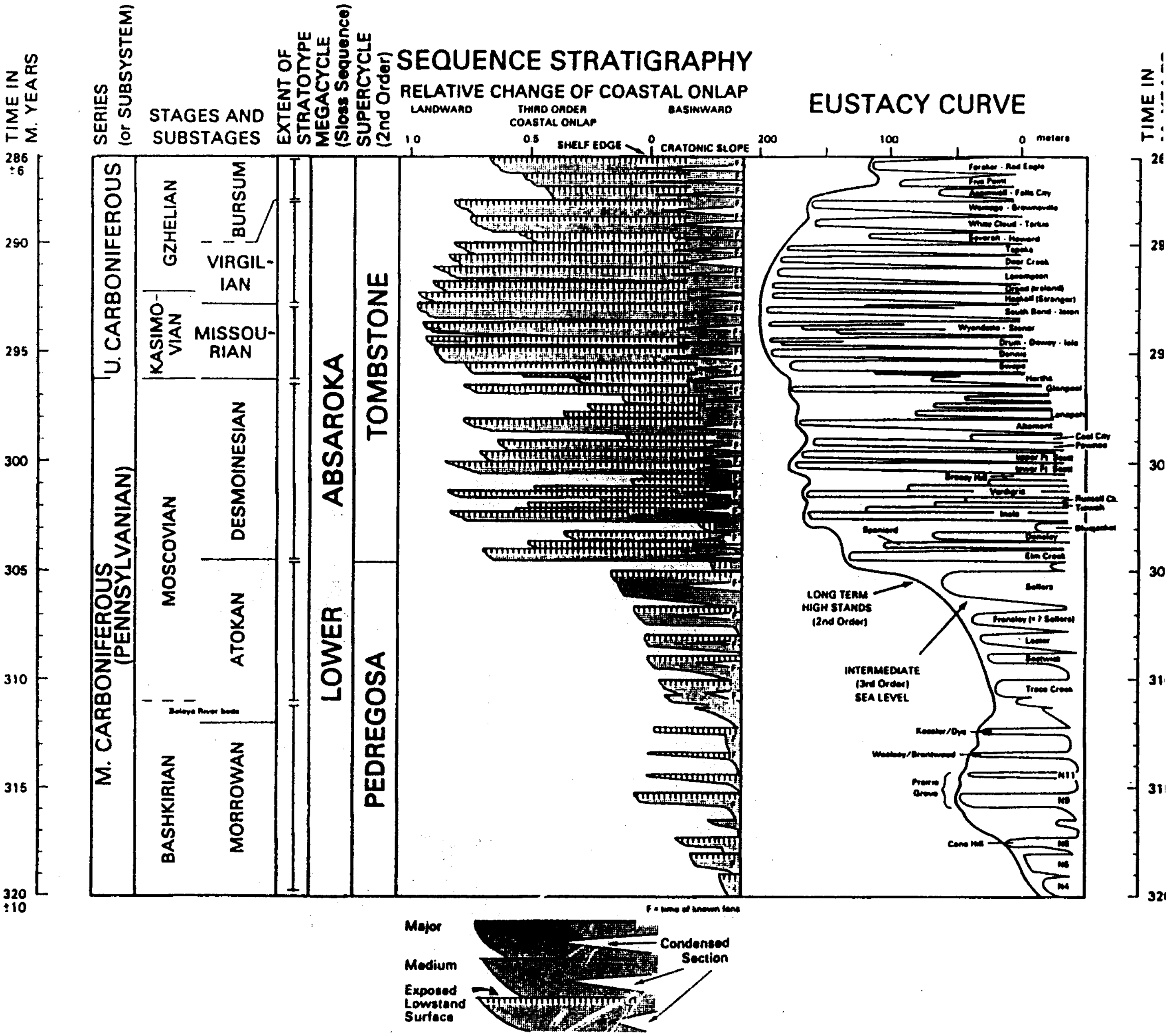


Figure 12. Estimated eustatic sea level fluctuations for the Pennsylvanian (Ross and Ross, 1987). Biostratigraphic data is providing worldwide correlation of individual, high frequency (approx. 300,000 to 500,000 year) marine cycles in strata ranging in age from Late Mississippian through the Lower Permian. Extensive evidence exists for Gondwanna continental glaciation as the driving force for these rapid oscillations of sea level.

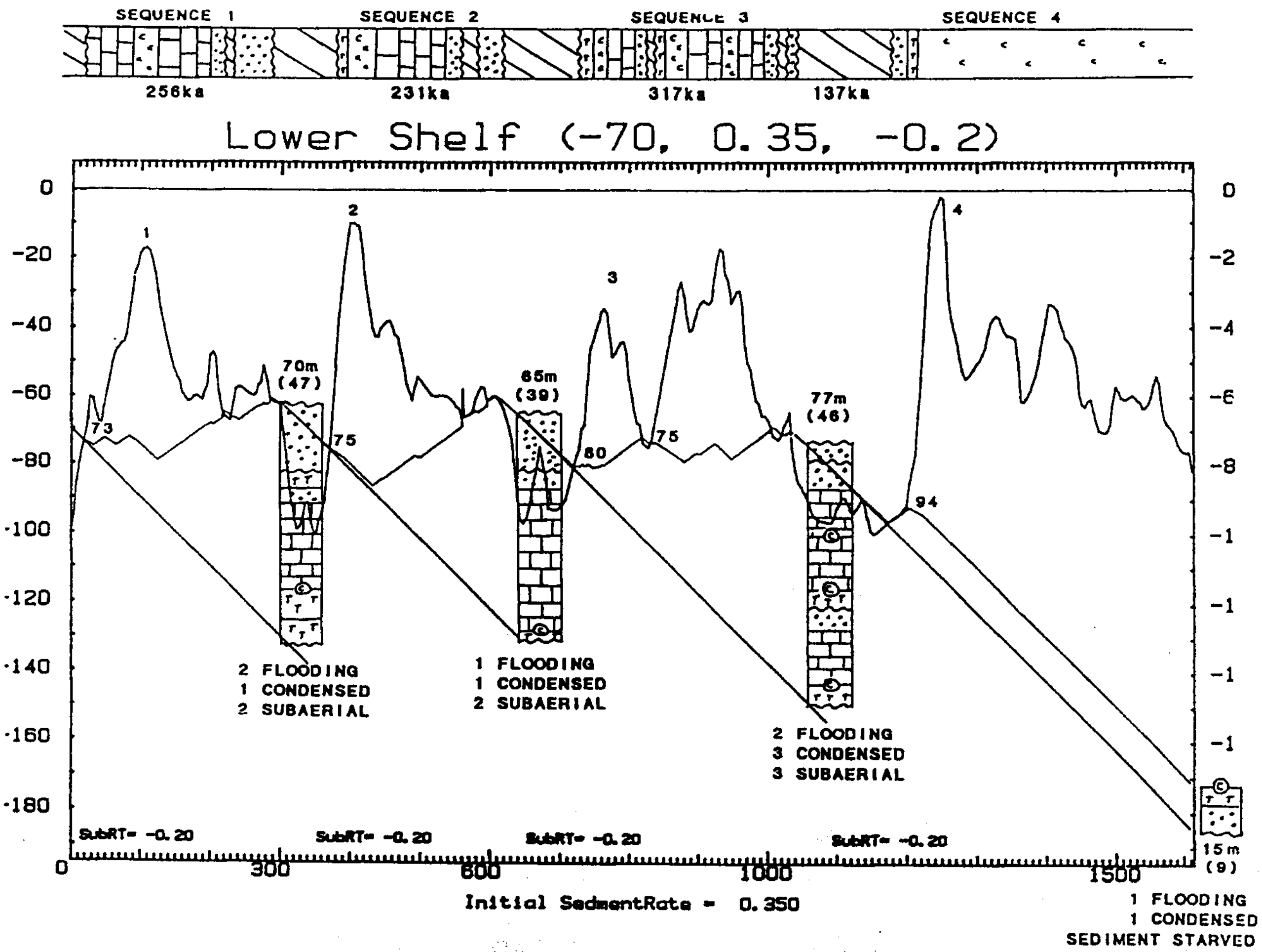
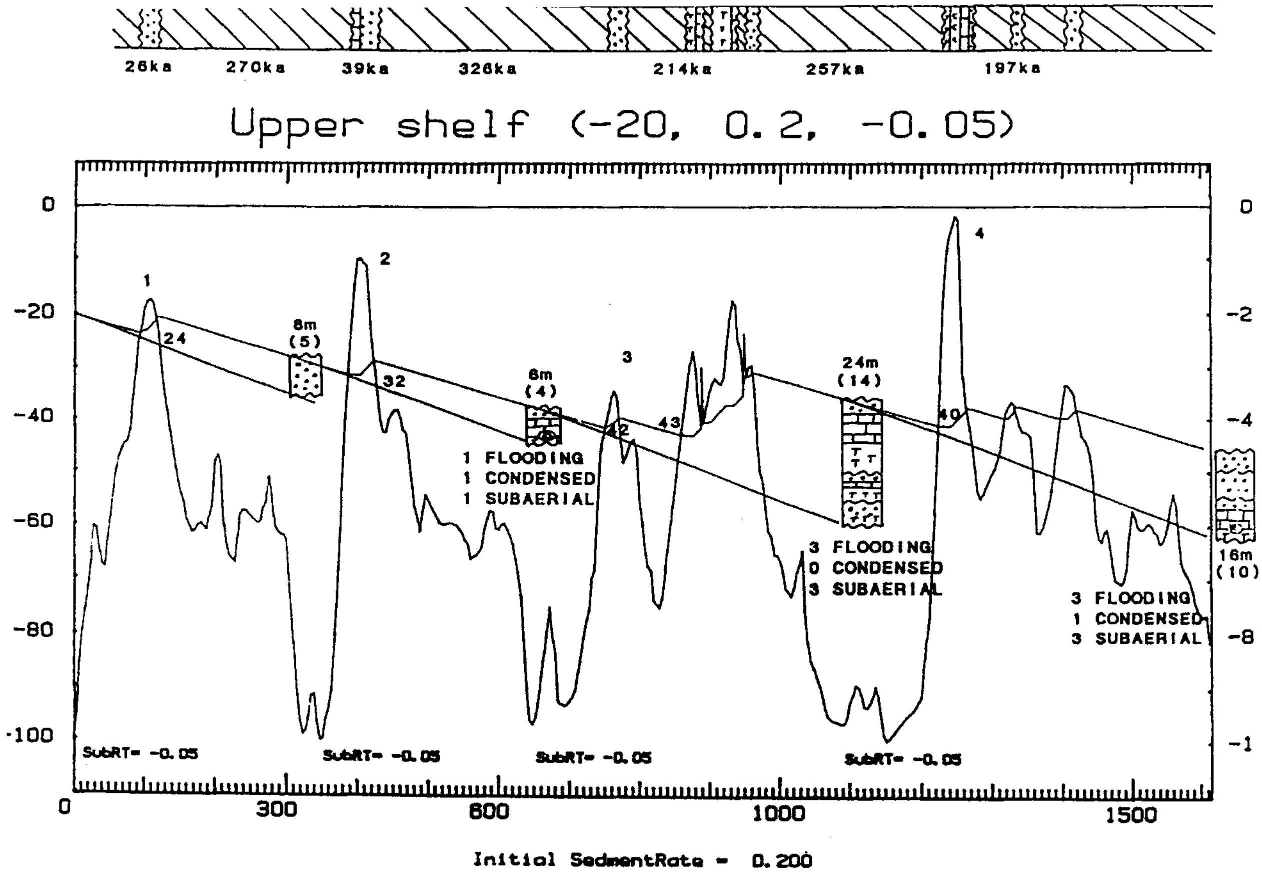


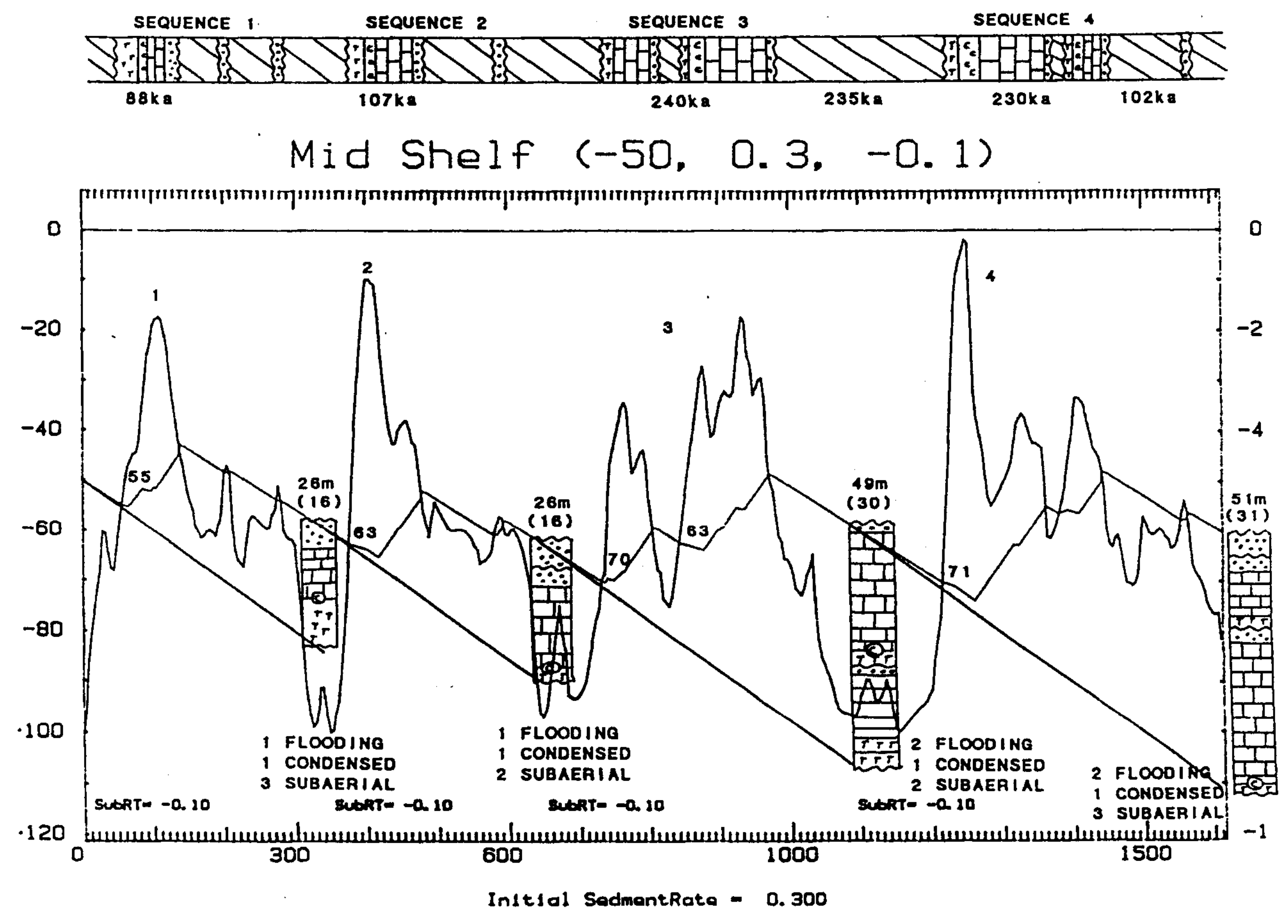
Figure 13. Forward computer model of cyclothemic sedimentation during the Pennsylvanian. Simulation of stratigraphic sequences consisting of shallow water deposits, <3 meters (dot pattern), below wavebase (brick), flooding units (T's), and condensed section (C). Sea level curve is hypothetical and derived from the following procedure. The oxygen isotopic variation in planktonic foraminifera obtained from deep sea cores provides an estimate of Pleistocene ice volume. This is turn a rough estimate of the sea level fluctuation. The 100,000-year Pleistocene glacio-eustatic cycles were expanded to 400,000 years and used in conjunction with varying subsidence and sediment surface elevations across a shelf to simulate a series of cyclothem (sequence 1 through 4). Presentation is both in depth (reference elevations in meters), vertical axis, and time, horizontal axis.

Models for upper, middle, and lower shelf, shown here vary in rates of sediment accumulation, initial sediment elevation, and subsidence rate resulting in substantial differences in cyclothem composition in spite of the same, but complex, sea level curve. Paper is in preparation (Watney and French) describing the model and the constraints on the variables used here. Note the development of substantial periods of subaerial exposure, particularly on the higher shelf. Process-response relations closely resemble what is observed and interpreted.

An inverse of this model is under development to: 1) analyze process/time data from the rocks to develop a tailored water depth curve; 2) to resolve the contributions of subsidence and eustatic sea level (allogenic); and 3) to access the local (autogenic) sedimentary response. Our goal is improved prediction of reservoir development at various shelf settings. As data becomes more precise and accurate (quantitative!), the models will become better constrained and suited for predicting increasing detail of reservoir development. We envision more sophisticated versions of the simulation models such as 2- and 3-D, based on depositional sequence analysis, will become our truly portable reservoir analogues.

Model is developed in Turbo Pascal and runs on an IBM compatible with menus for changing parameters. Data can be entered in digitized form or from the keyboard. Graphics are made on a HP plotter. Jan Chung Wong is the computer programmer.


26ka 270ka 39ka 326ka 214ka 257ka 197ka
Upper shelf (-20, 0.2, -0.05)
1
2
3
4
24
32
42
43
40
8m (5)
8m (4)
24m (14)
16m (10)
1 FLOODING
1 CONDENSED
1 SUBAERIAL
3 FLOODING
0 CONDENSED
3 SUBAERIAL
3 FLOODING
1 CONDENSED
3 SUBAERIAL
SubRT= -0.05
Initial SedmentRate = 0.200


SEQUENCE 1
SEQUENCE 2
SEQUENCE 3
SEQUENCE 4
88ka 107ka 240ka 235ka 230ka 102ka
Mid Shelf (-50, 0.3, -0.1)
1
2
3
4
55
63
70
63
71
26m (16)
26m (16)
49m (30)
51m (31)
1 FLOODING
1 CONDENSED
3 SUBAERIAL
1 FLOODING
1 CONDENSED
2 SUBAERIAL
2 FLOODING
1 CONDENSED
2 SUBAERIAL
2 FLOODING
1 CONDENSED
3 SUBAERIAL
SubRT= -0.10
Initial SedmentRate = 0.300

The 1-dimensional output (stratigraphic columns) can be combined to form cross sections such as the one shown in Figure 14, with columns of simulated cyclothemic sedimentation from upper, middle, and lower shelf positions.

Interpretations based on observations from the rocks studied will later be used to develop inverse models where variables such as water depth, sediment accumulation rate, duration of hiatal surfaces, and estimates of subsidence will be generated. These data, when compared for a number of areas, will hopefully distinguish regional patterns, and may allow for the determination of the relative importance of autogenic and allogenic processes.

The most prominent feature of quantitative sedimentary modeling at this juncture is that the model can be repeated and refined as more data becomes available. Furthermore, it allows one to test a number of scenarios. Interpretations can become better constrained with more accurate and precise data and corroborating evidence. Developing reservoir analogues and making predictions of reservoir development may some day be as sophisticated as predicting the weather. Hopefully, it will be a little more accurate.

CONCLUSION: NEED FOR QUANTITATIVE MODELING OF PETROLEUM RESERVOIRS

Figure 15 is qualitative stratigraphic model of one version of a "typical" depositional sequence developed in the Missourian shelf of western Kansas in the area of petroleum reservoir development. It is a picture of depth-distance stratal geometries for a hypothetical sequence, resembling the Missourian Dennis Sequence, a prolific reservoir unit. Establishing and verifying internal parasequence correlations is now in progress.

The qualitative model has limited value in prediction of facies development on the western Kansas shelf. It is certainly not a unique representation of the sequences present in this area of petroleum reservoir development. Processes responsible for the generation of such a pictorial rendition can only be inferred, but typically are not constrained. The dynamic interaction of processes is needed to develop tailored, constrained models for reservoir framework studies and potentially reservoir characterization. These are the ultimate objectives of our research.

ACKNOWLEDGEMENTS

Appreciation is extended to Lea Ann Davidson for handling the word processing, and copying of the manuscript. Thanks is given to Chris Maples for reviewing portions of the text. Mark Schoneweis and Jennifer Sims prepared Figure 9 and the cover, respectively. Thanks is given to them for applying their artistic talents to this endeavor.

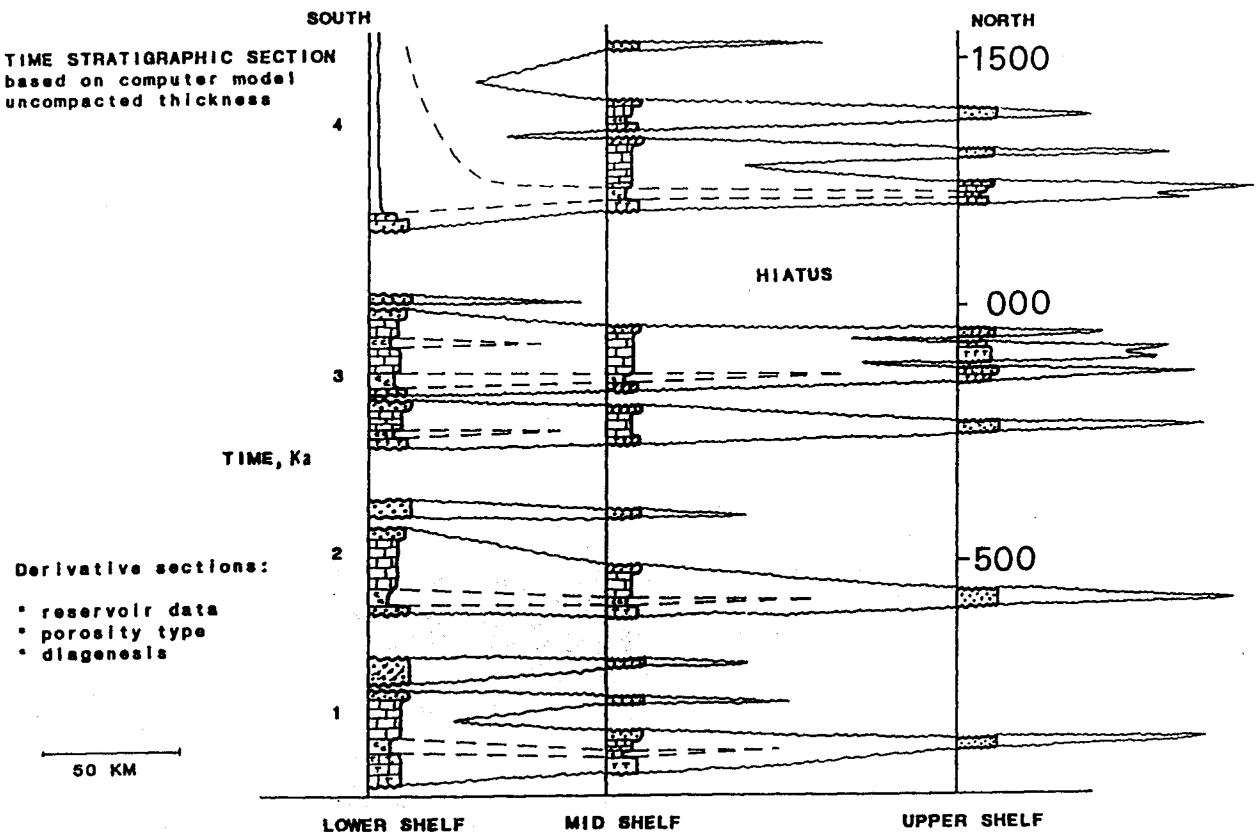


Figure 14. Two-dimensional time-stratigraphic distribution of four Pennsylvanian depositional sequences based on computer simulation at three dip-oriented shelf settings (upper, mid, and lower) with varying sediment surface elevation, subsidence rates, and sediment accumulation rates. Time-stratigraphic profiles are those generated along the time axis shown on the upper portions of plots in Figure 13.

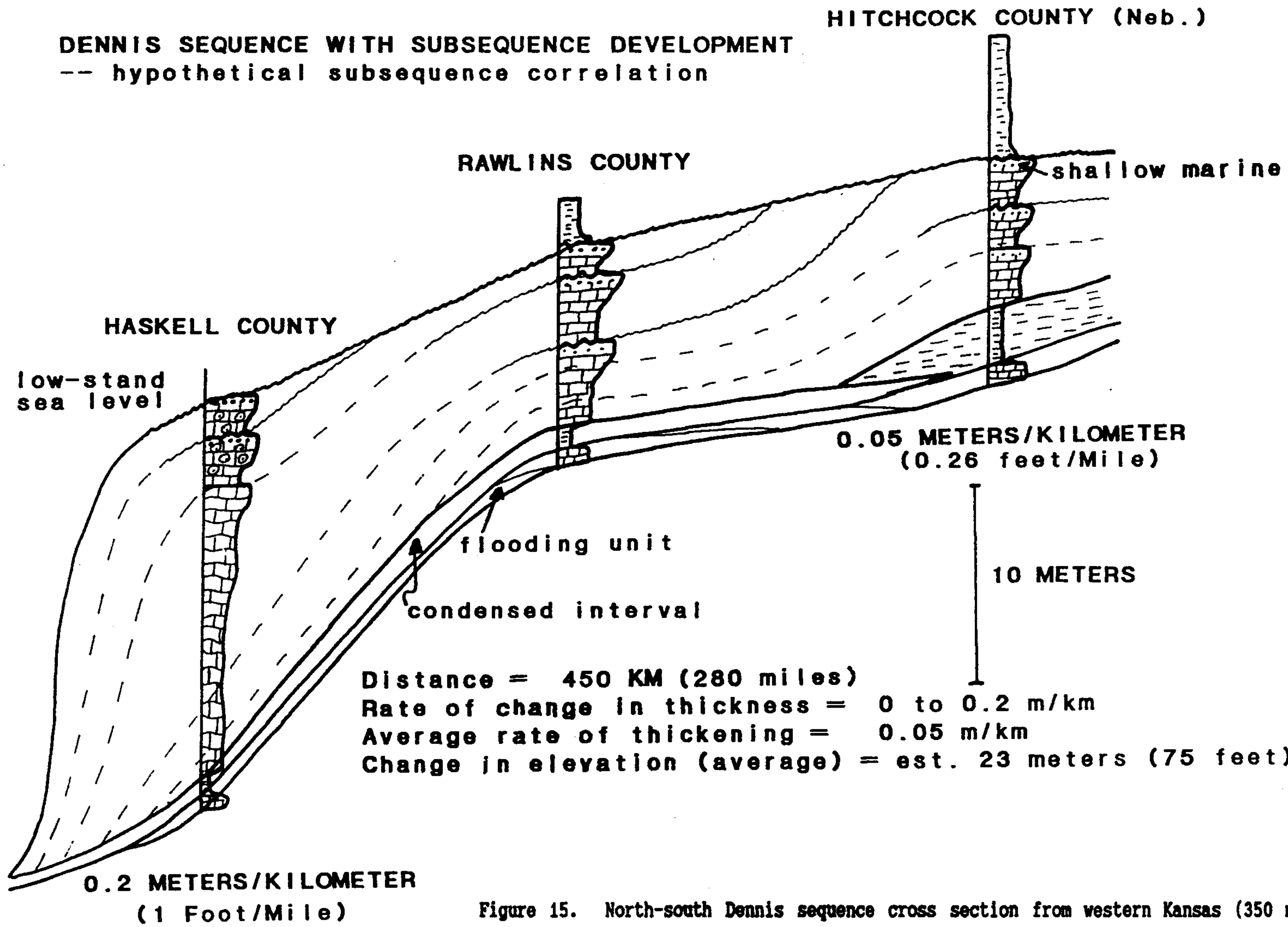


Figure 15. North-south Dennis sequence cross section from western Kansas (350 miles to west) across the carbonate shelf. Section extends nearly 300 miles along a dip section of the shelf extending from near the Transcontinental Arch on the north into the Anadarko Basin on the south. Possible internal correlations of parasequences are suggested within the sequence. Wavy lines reflect subaerial exposure surfaces that have been recognized. Dotted pattern is shallow-water carbonate facies. Shales topping sequence on north are red-brown siltstone with paleosols.

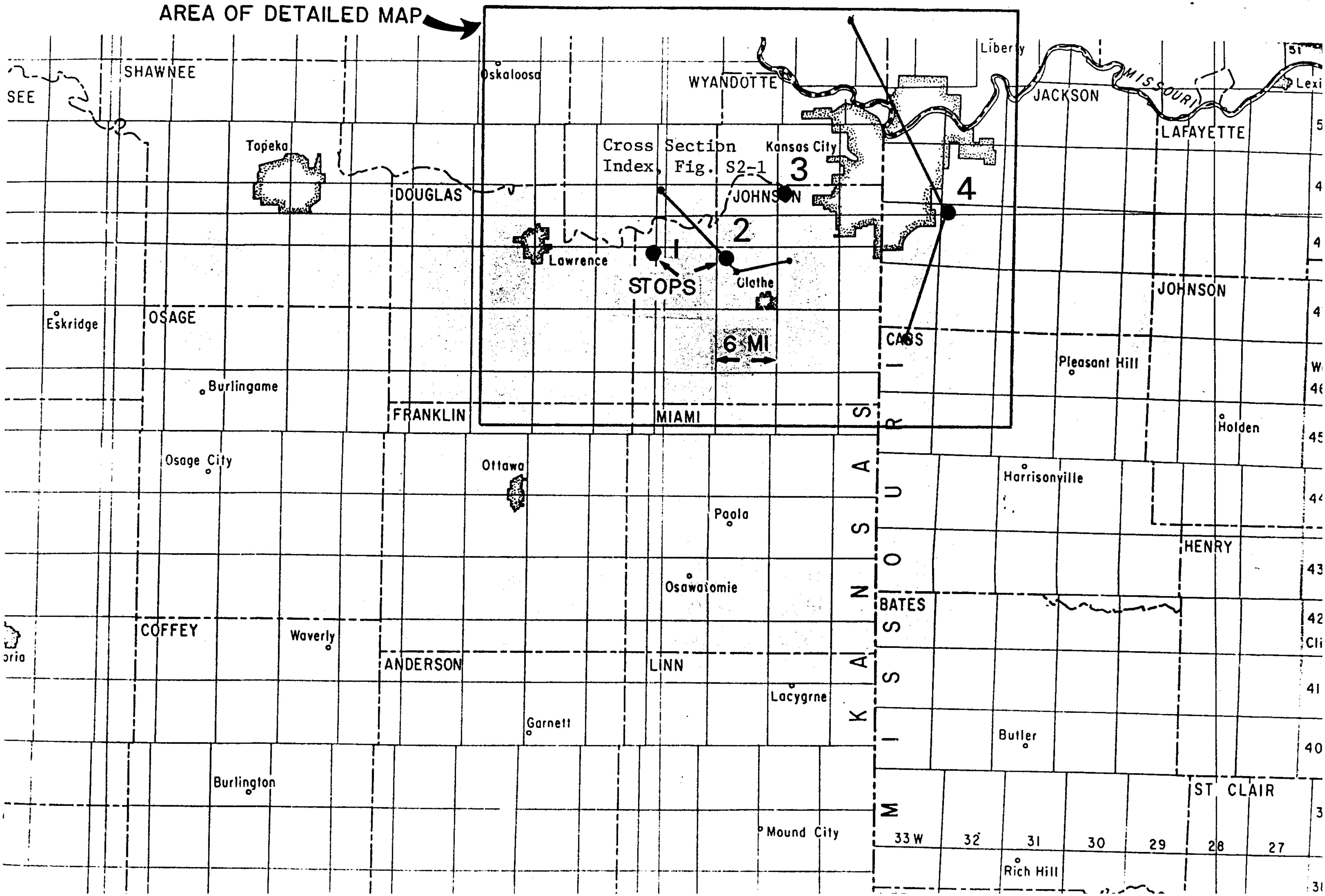
DESCRIPTION OF STOPS

The field trip consists of four stops beginning east of Lawrence and ending in the southeastern edge of Kansas City, Missouri (Figure 16, map of field trip area and Figure 17, detailed topographic map of field trip area). The stratigraphic intervals examined on the trip were identified in **Figure S2-1.**

Figures in the field stop section that follows are identified by stop number and order, e.g., S1-1. References in the field stop section are included in the section, REFERENCES CITED.

Figure 16

Cross Section Index
Figure S4-2



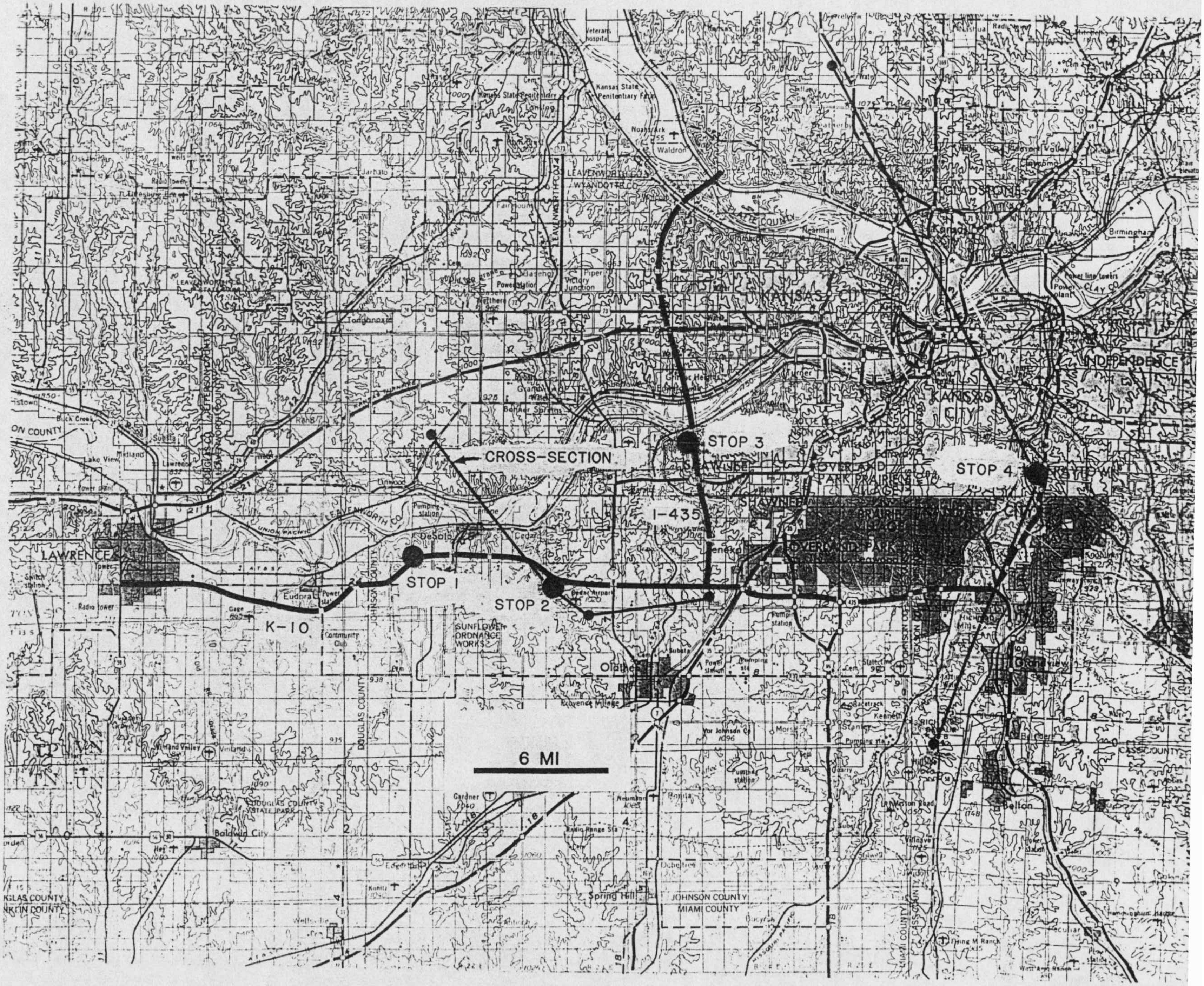

STOP 1
STOP 2
STOP 3
STOP 4
CROSS-SECTION
I-435
K-10
6 MI
LAWRENCE
KANSAS CITY
INDEPENDENCE
GLADSTONE
OVERLAND PARK
SHAWNEE
SUNFLOWER ORDNANCE WORKS
JOHNSON COUNTY
MIAMI COUNTY
DOUGLAS COUNTY

Figure 17

STOP 1: K-10 CUT EAST OF EUDORA: STANTON LIMESTONE

The Stanton Limestone is the uppermost Missourian formation. Measured section for Stop 1 is provided in Figure S1-1. At this location it is developed as a "typical" Kansas cyclothem, made up of the four basic members, in ascending order:

The **Vilas Shale** is a typical outside shale. It caps the underlying Plattsburg cycle, and represents deltaic sedimentation during lowered sea level.

The **Captain Creek Limestone** is a relatively thick middle limestone that represents the initiation of carbonate sedimentation during an inferred eustatic rise. At this location it is predominantly a normal-marine phylloid-algal wackestone. The unit locally thins markedly and contains mud-pebble conglomerates a few miles east of this locality. Farther east of this anomalous setting the Captain Creek Limestone returns to the more resistant limestone ledge.

The **Eudora Shale** at this location is a typical core shale that contains a well-developed platy, black, phosphatic facies. This unit is continuous over a wide area, and is interpreted to be a condensed section that originated during maximum rate of eustatic rise and/or in the deepest water associated with the Stanton inundation. The black facies grades locally to soft gray shale containing abundant benthic fauna.

The **Stoner Limestone** as it occurs at this location could be the archetypical upper limestone of a Missourian cyclothem. It consists of wavy bedded phylloid-algal calcilutite, and also contains a host of other normal-marine organisms. It shoals upward, and contains cryptic fenestral voids near the top; about 10 miles to the northeast the Stoner is capped by an abraded skeletal calcarenite. This unit most likely represents carbonate aggradation during relative sea-level stillstand and fall. It is usually capped by the Rock Lake Shale, which in places contains a mollusc-dominated fauna and a thin coal.

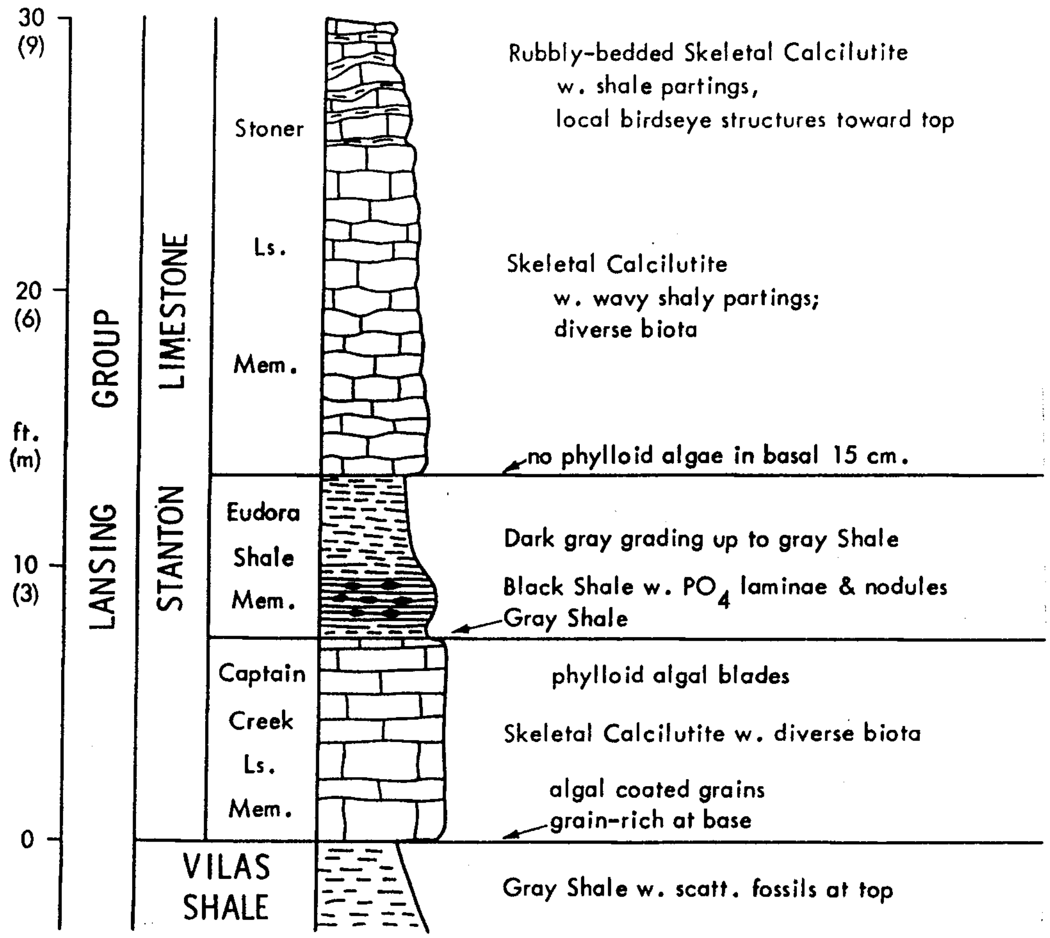


Figure S1-1. Measured section of Stop 1
from Heckel (1979).

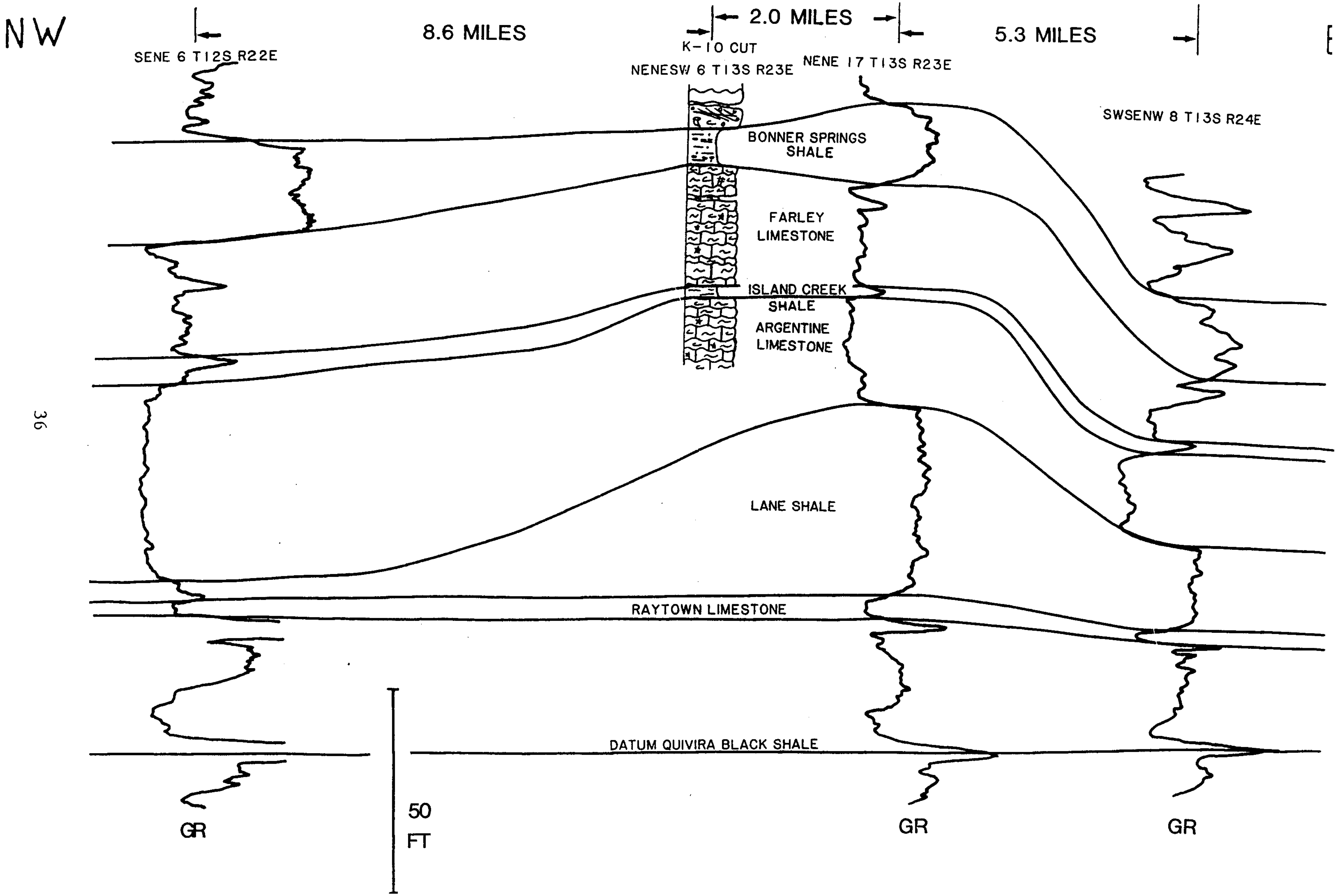
STOP 2: K-10 CUT 5 MILES EAST OF DESOTO EXIT: ALGAL BANK IN THE WYANDOTTE LIMESTONE

The Wyandotte Limestone at this stop consists almost entirely of phylloid-algal calcilutite. It represents a vertically stacked series of algal banks that developed across this area in response to the interplay between sea-level changes and the underlying depositional topography (Crowley, 1969).

A cross-sectional view from east of to northwest of this outcrop (**Figure S2-1**) shows the relationships between the underlying Lane Shale and the two main members of the Wyandotte, the Argentine and Farley limestones. The area to the east of this outcrop, where both the Lane and Wyandotte are thin, has been interpreted as a paleotopographically low area on the Lane deltaic platform, where circulation was presumably restricted Crowley, 1969). One area of Wyandotte bank development occurred on the northwest side of the underlying Lane platform, which is where this outcrop is situated (**Figure S2-2**). Index map for this cross section is found in **Figure 16**. The Wyandotte bank exploded off the northwest flank of the Lane delta, attaining thicknesses in excess of 80 feet (**Figure S2-3,4,5**). The combination of increased accommodation and normal marine circulation to the northwest is inferred to have promoted bank development in that direction.

Isopach maps of several of these units taken from Crowley (1969) have been included, as has a discussion of this stop from a 1985 field trip guidebook (Heckel, et al., 1985) including an accompanying illustration from this earlier work (**Figure S2-6**).

Figure S2-1. NW to E stratigraphic cross section constructed from gamma ray profiles from well logs near Stop 2. Stop 2's measured section is located in middle of this cross section. Index map to section is found on Figure 16.



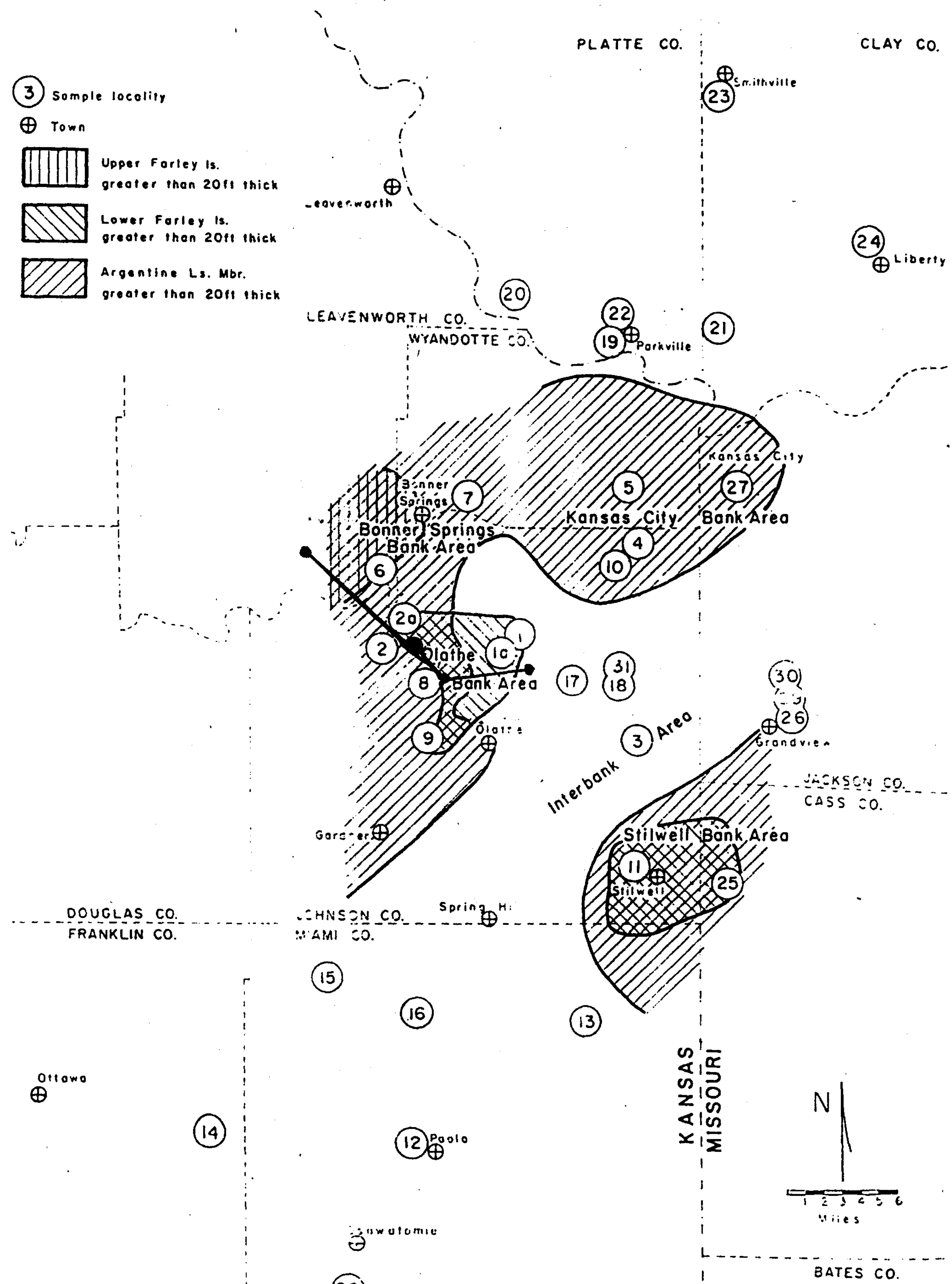


Figure S2-2.

FIGURE 2.—Carbonate bank development in limestone members of the Wyandotte Limestone. Banks tend to form over top of previous banks. Interbank area in southeastern Johnson County was a persistent feature throughout deposition of Wyandotte.

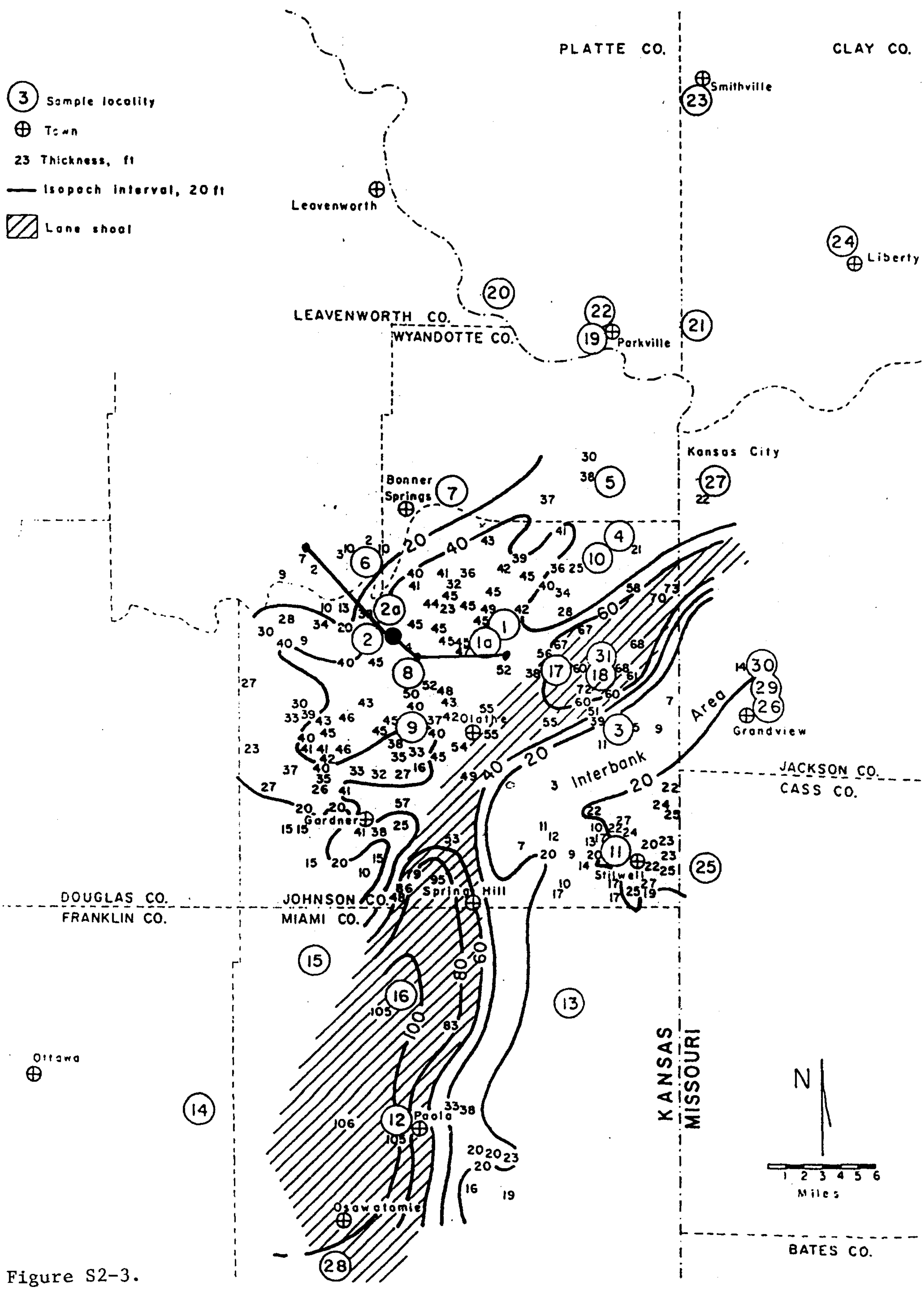


Figure S2-3.

FIGURE 4.—Isopach map of Lane Shale. Thickened part shaded and referred to in text as Lane shoal. Area northwest of shoal is Lane deltaic platform. Note abrupt thinning of shoal southeastward into interbank area. Data sources same as Figure 3.

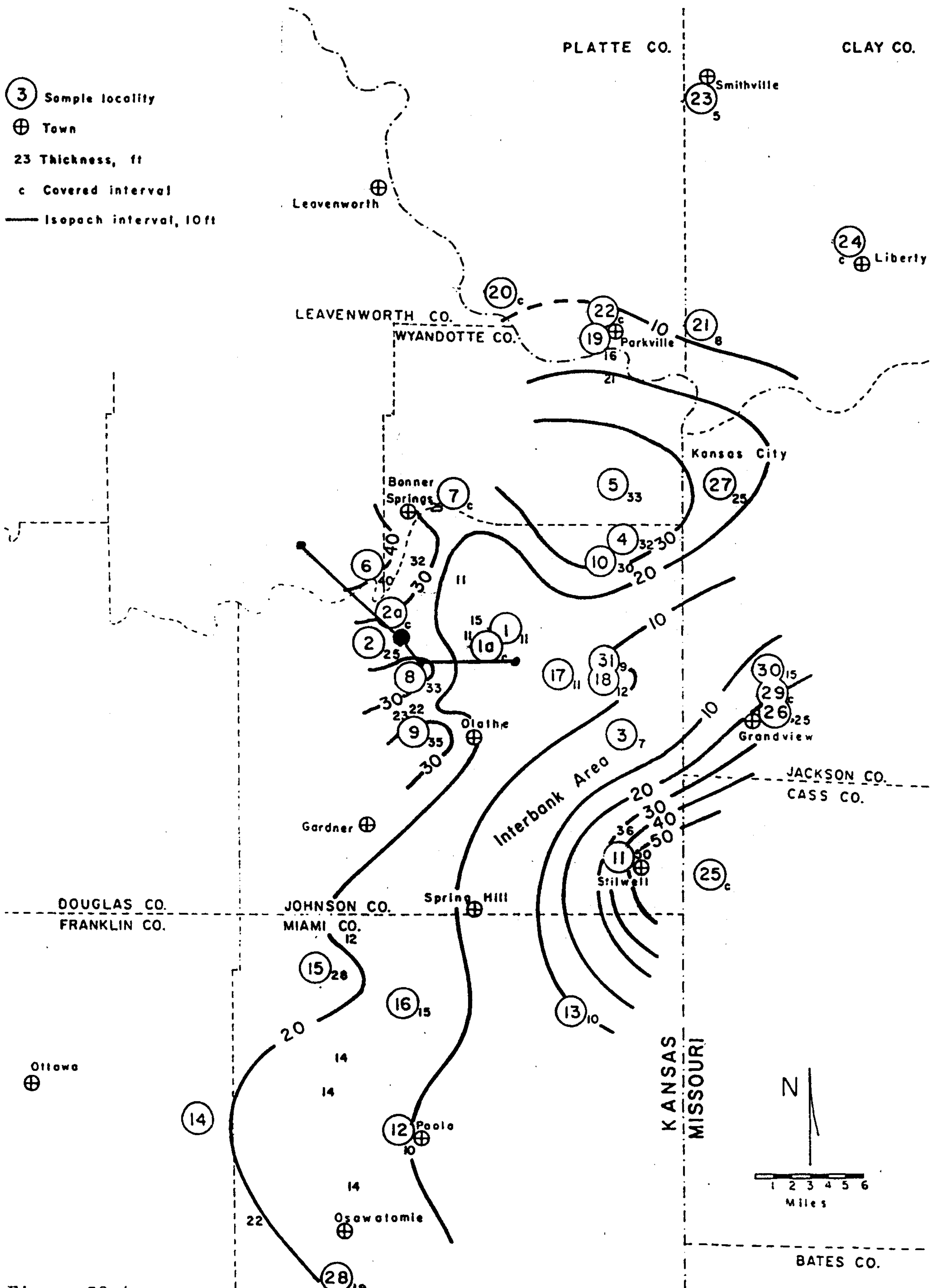


Figure S2-4.

FIGURE 8.—Isopach map of Argentine Limestone Member. Note thickened areas at Kansas City and Olathe-Bonner Springs separated from thickened area at Stilwell by thinner interbank area. Data from present study, Newell (1935), and Jewett and Newell (1935).

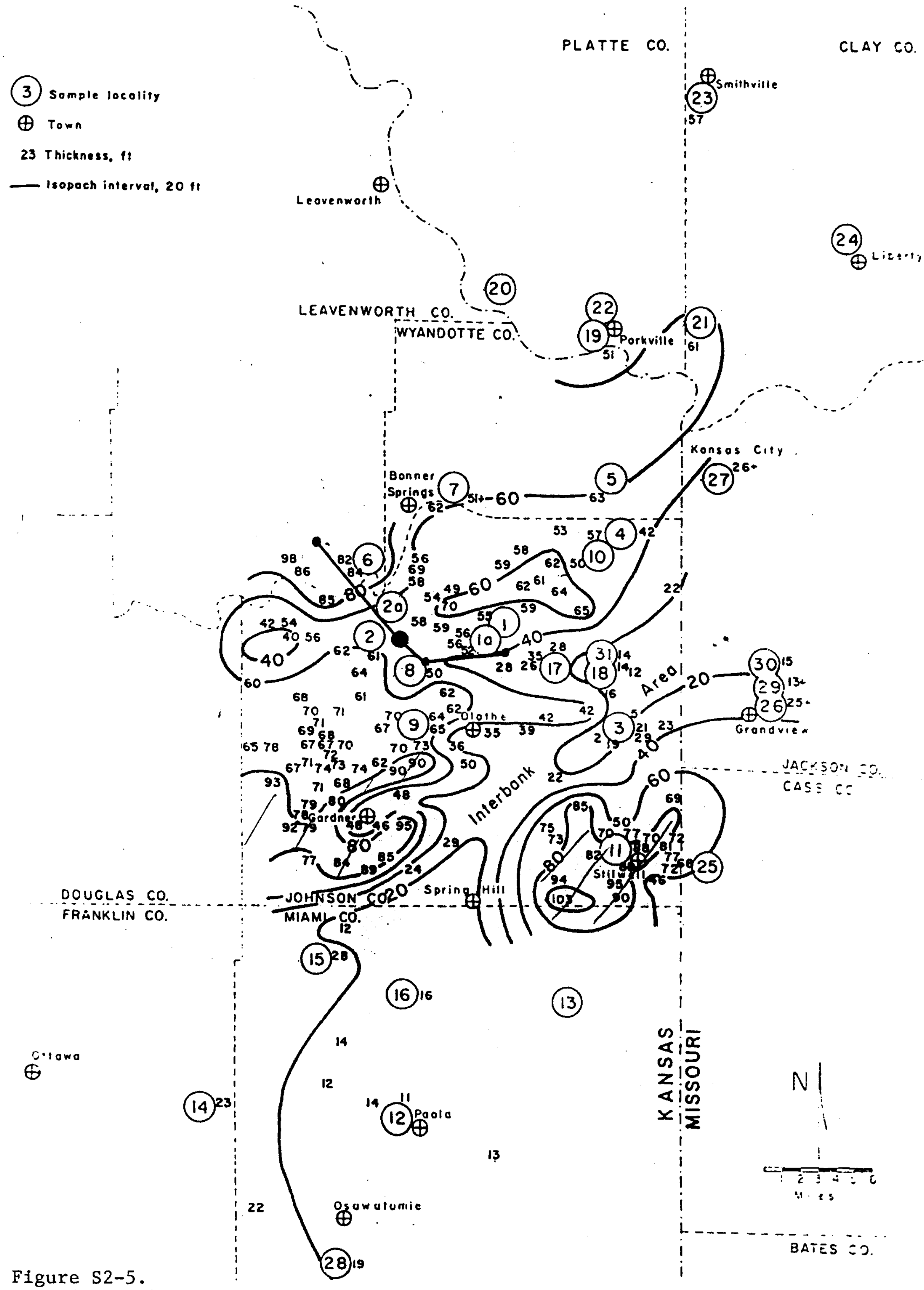


Figure S2-5.

FIGURE 3.—Isopach map of Wyandotte Limestone. Successive bank development has resulted in thickening of Wyandotte on either side of interbank area. Data for Johnson County from maps prepared for publication by H. G. O'Connor, State Geological Survey of Kansas. Outcrop and subsurface information on file at Kansas Geological Survey; other data from present study, Newell (1935), and Jewett and Newell (1935).

Commentary from Heckel et al. (1985), to accompany Stop 2.

STOP 2: ROADCUT AND ADJACENT QUARRY ON SOUTH SIDE OF K-10 HIGHWAY, 8 KM (5 MI) EAST OF THE DESOTO EXIT: FARLEY CARBONATE SEQUENCE (SE 6-13S-23E). Stop 4 is 13 km (8 1/4 mi) south of Stop 2, and 21 km (13 mi) southwest of Stops 3A and 3B. (20 min.)

Commentary by John Harris

The geologic section exposed in the roadcut and adjacent quarry includes units from the **Argentine Limestone (Wyandotte Formation)** to the Spring Hill **Limestone** of the Plattsburg Formation. At this stop, examination will be made of thin, wavy-bedded carbonates of the **lower Farley** interval that can be observed to grade laterally into shale, as well as the three-dimensional thinning and thickening relationships of the Bonner Springs Shale and the overlying Merriam Limestone.

At this locality the **Argentine Limestone** consists of approximately 5.2 m (17 ft) of thin, wavy-bedded phylloid-algal lime mudstone to wackestone with abundant brachiopods and crinoid fragments. Bedding in the Argentine is defined by numerous wavy, irregular yet laterally continuous, shale partings. The Argentine is thinner at this stop than at Stop 2, but the upper bed consists of a similar lime wackestone to packstone facies with terrigenous mud-filled burrows. The Argentine Limestone forms a continuous bed across the 21 km (13 mi) outcrop traverse.

Island Creek Shale is composed of 0.5 m (1.5 ft) of medium-gray, silty shale with nodular argillaceous carbonate. Abundant marine fossils are present in the unit.

Lower Farley Limestone consists of approximately 6.4 m (21 ft) of thin, wavy-bedded pelloidal and phylloid-algal lime mudstone to wackestone with abundant crinoids and brachiopods. Bedding in the lower Farley, as in the Argentine, is also defined by numerous through-going, argillaceous partings, many of which are associated with styolites. This type of styolitic development has been noted by some workers to explain the origin of argillaceous partings that are common to limestones throughout the world (Robin Bathurst, personal communication, 1985). However, after viewing the intimate association of shale and carbonate beds in the lower Farley-Island Creek interval at Stop 2, it is not hard to imagine the depositional origin of these wavy argillaceous partings, and the fact that these shale partings pre-date the styolites.

Middle Farley Shale, as recognized by Crowley (1969), reaches a maximum thickness of 0.24 m (0.8 ft). The middle Farley Shale can be thought of as a tongue of the **Island Creek Shale** and consists of a medium-gray, calcareous shale that is a laterally persistent stratigraphic marker across the outcrop.

Upper Farley Limestone consists of approximately 2.1 m (7 ft) of thin, wavy-bedded phylloid algal lime mudstone to wackestone with locally developed lenses of lime packstone. Brachiopods, bivalves, fenestrate bryozoans, and other normal marine fossils are common. Bedding characteristics of the upper Farley are similar to those of the Argentine and lower Farley limestones.

Thickness of the upper Farley unit ranges from approximately 2.1 m (7 ft) at Stop 4 to about 3 m (10 ft), 21 km (13 mi) northeast at Stop 3B. It forms a continuous stratigraphic marker between all three exposures. The Argentine Limestone ranges from 6.1 m (22 ft) thick at Stop 2 to about 5.2 m (17 ft) thick at Stop 4 and forms another laterally continuous bed across the 21 km (13 mi) traverse. The Island Creek Shale-lower Farley Limestone unit, or the interval between the top of the Argentine and base of the upper Farley limestones, ranges in thickness from 7 m (23 ft) at Stop 4 to 8 m (26 ft) at Stop 3B. Although this unit maintains a fairly constant thickness, the proportion of carbonate to shale changes drastically. Approximately 64 km (40 mi) to the southwest along the outcrop belt, all carbonate beds of the Wyandotte Formation disappear and the section consists of shale and sandstone of the Lane and Bonner Springs shales.

Bedding of the **Argentine Limestone**, **Island Creek Shale**, and lower and upper **Farley Limestones** appears to be horizontal, with some thin beds that can be correlated over the entire 21 km-long (13 mi) outcrop traverse. In view of the gradual thickness changes of mappable units involved, the horizontal and laterally continuous nature of bedding, and the intimate lateral association of carbonate and shale in the lower Farley-Island Creek interval, it appears that the phylloid algal bank or mound interpretation of Crowley (1969) and others, implying bathymetric relief and generally based on thickness changes of units involved, may be unjustified.

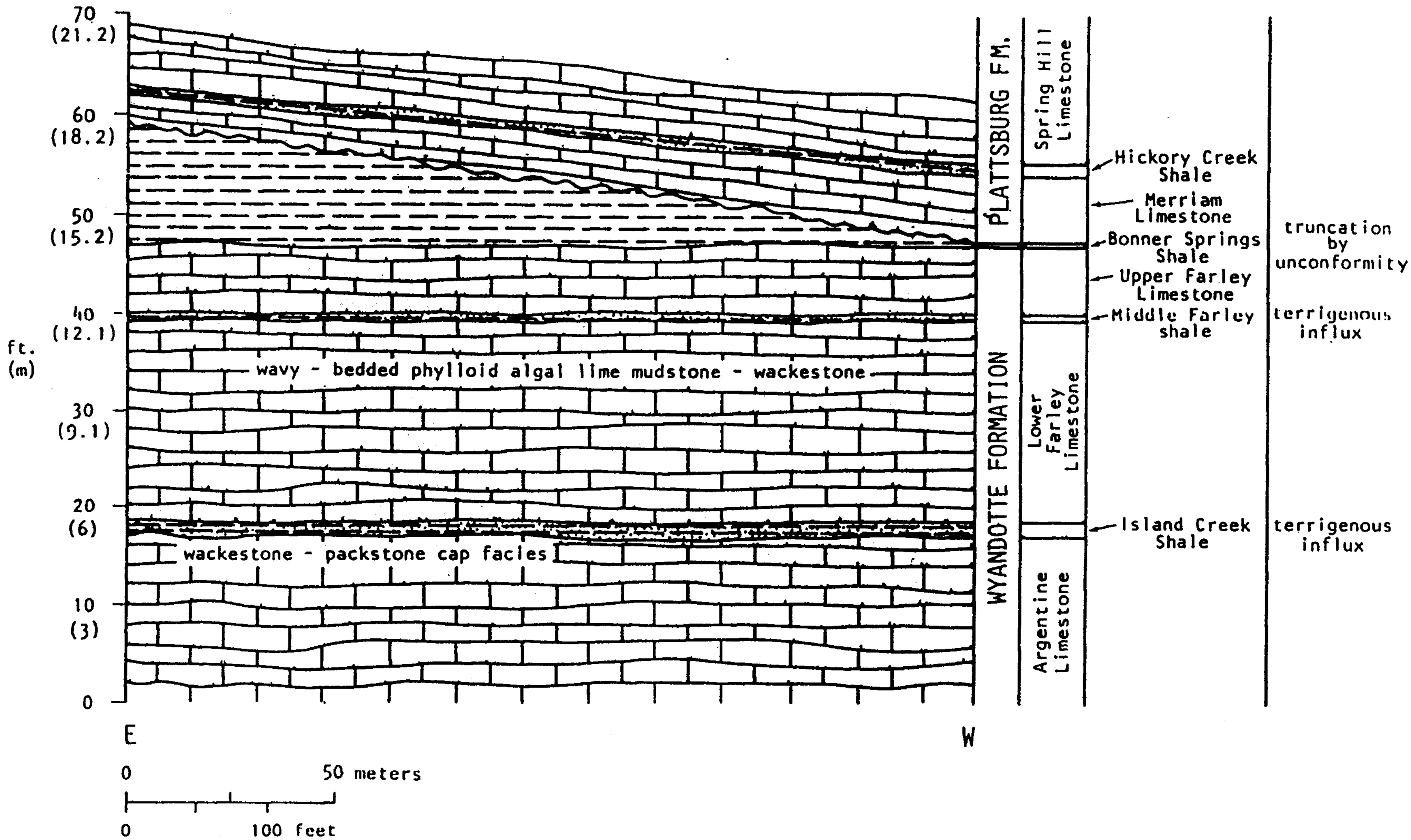
At this stop the **Bonner Springs Shale** ranges in thickness from 3.7 m (12 ft) at the roadcut to less than 0.3 m (1 ft) at the adjacent quarry. The pinchout of the Bonner Springs may be observed in a unique, three-dimensional view in the four quarry walls, with thinning towards the northwest. The Bonner Springs consists of a medium-gray, silty shale with numerous thin, laterally discontinuous lenses of mud-clast conglomerate. In the quarry face mud-cracks are present at the top of the Bonner Springs and bedding in the unit appears to be truncated by erosion.

Merriam Limestone of the Plattsburg Formation ranges in thickness from 1.8 m (6 ft) in the quarry at the thinnest location of the Bonner Springs to about 1 m (3.5 ft) in the road cut to the east. The Merriam at this stop as in earlier stops consists of low-angle cross-bedded lime grainstone to packstone with abundant corals, bivalves, brachiopods, Osagia-coated grains, and oolites. A 0.3 meter-thick (1 ft) bed of lime wackestone to packstone at the top of the Merriam forms a horizontal, laterally continuous marker across the outcrop. Thickness changes of the Merriam Limestone below this bed due to onlap onto paleotopographic highs expressed on the post-Bonner Springs unconformity.

The entire areal extent of the unconformity developed at the top of the Bonner Springs Shale is currently unknown. Similar Bonner Springs-Merriam relationships have been reported by Ball et al. (1963) in southern Franklin County [60 km (36 mi) south of Lawrence] so that the extent of the unconformity may exceed 88 km (55 mi) along outcrop. The above workers have also shown that the upper weathered, limonitic, or "wormy" surface of the Merriam is also present in Franklin County.

Hickory Creek Shale is represented at this exposure by about 0.3 m (1 ft) of medium-gray silty shale. The basal 1.8 m (6 ft) of the **Spring Hill Limestone** is exposed in the roadcut to the east.

Figure S2-6.
Stop 2 - Roadcut and adjacent quarry on south side of K-10 Highway, 5 miles east of Desoto exit (SE Sec. 6 - 13S - 23E), Johnson Co., Kansas. 8 1/4 mi. S of Stop 2, 13 mi. southwest of Stop 3A and 3B.



STOP 3: ROADCUTS ALONG I-435 NEAR HOLLIDAY ROAD EXIT: SECTION FROM CHANUTE SHALE TO STANTON LIMESTONE

This group of outcrops near Stop 3 identified by the letters A, B, C, and D in **Figure S3-1** is one of the best known continuous series of exposures of these Missourian cycles. A lack of 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 **Figure S3-1**). A composite measured section is found in **Figure S3-2**. A gamma ray-neutron log from a nearby well has been correlated to the lithologies of this exposure (**Figure S3-3**). The following discussion of the individual units has been modified from that of Heckel et al. (1985).

The **Chanute Shale** is a typical outside shale that records the influx of deltaic clastics. Approximately 40 miles to the south, The Chanute is a thicker shale that includes sandstones and coal.

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 example of a transgressive, or middle, limestone than is the Captain Creek Limestone that we saw at stop 1. It is a skeletal calcilutite containing a diverse biota, and represents a relatively rapid and widespread flooding of the Chanute delta.
>
> The **Muncie Creek Shale** is the core shale of the Iola cyclothem. The black, phosphatic facies of this unit is inferred to represent minimal sediment influx during a period of low bottom-water oxygenation during rapid eustatic rise, and is therefore interpreted to be a condensed section. It is one of only five black, phosphatic core shales that extend to the Iowa outcrop belt about 200 miles to the north.
>
> The **Raytown Limestone** is the upper Limestone of the Iola cyclothem. It is a skeletal and phylloid-algal calcilutite that was deposited in quiet water, probably below effective wave base. The thin, lenticular calcarenite 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.

The **Lane Shale** overlies the Iola Limestone. This unit is a typical outside shale that resulted from a northeasterly influx of siliciclastics. These accumulations of terrigenous detritus probably resulted from progradation during eustatic stillstand and fall, when clastic material was no longer ponded close to its source via the rapid glacial-eustatic rises. As was discussed at stop 2, the thickness of the Lane Shale varies across this area from over 70 feet about 10 miles southeast of this outcrop to a virtual pinchout only 7 miles to the west of here.

The **Wyandotte Limestone** overlies the Lane Shale. We will be able to examine the basal portion. In ascending order, the units we will see are:

The **Frisbie Limestone**, which is the transgressive, or middle, limestone of the Wyandotte cycle. This unit represents a regional marine incursion (flooding unit) that overstepped the Lane delta. Marine sedimentation extended beyond the Iowa outcrop belt some 200 miles to the north. At this location the Frisbie contains a number of discrete phylloid-algal buildups flanked by crinoidal calcarenites. The phylloids are unusually large, and may be in life position in places.

The **Quindaro Shale**, which is the core shale of the Wyandotte cycle. It is dark gray here (with low gamma radiation), but is 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 is another one that 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. Note that the shale can not be distinguished at the base of the Argentine Limestone on the gamma ray log from a well near this exposure (**Figure S3-3**).

The **Argentine Limestone** is the major upper limestone of the Wyandotte cycle. This location is in an area of thin Argentine associated with a thick Lane deltaic platform. This unit consists largely of skeletal lime mudstones at this locality, although it is topped by a calcarenite.

Figure S3-1.

1: Map showing locations of outcrops measured.

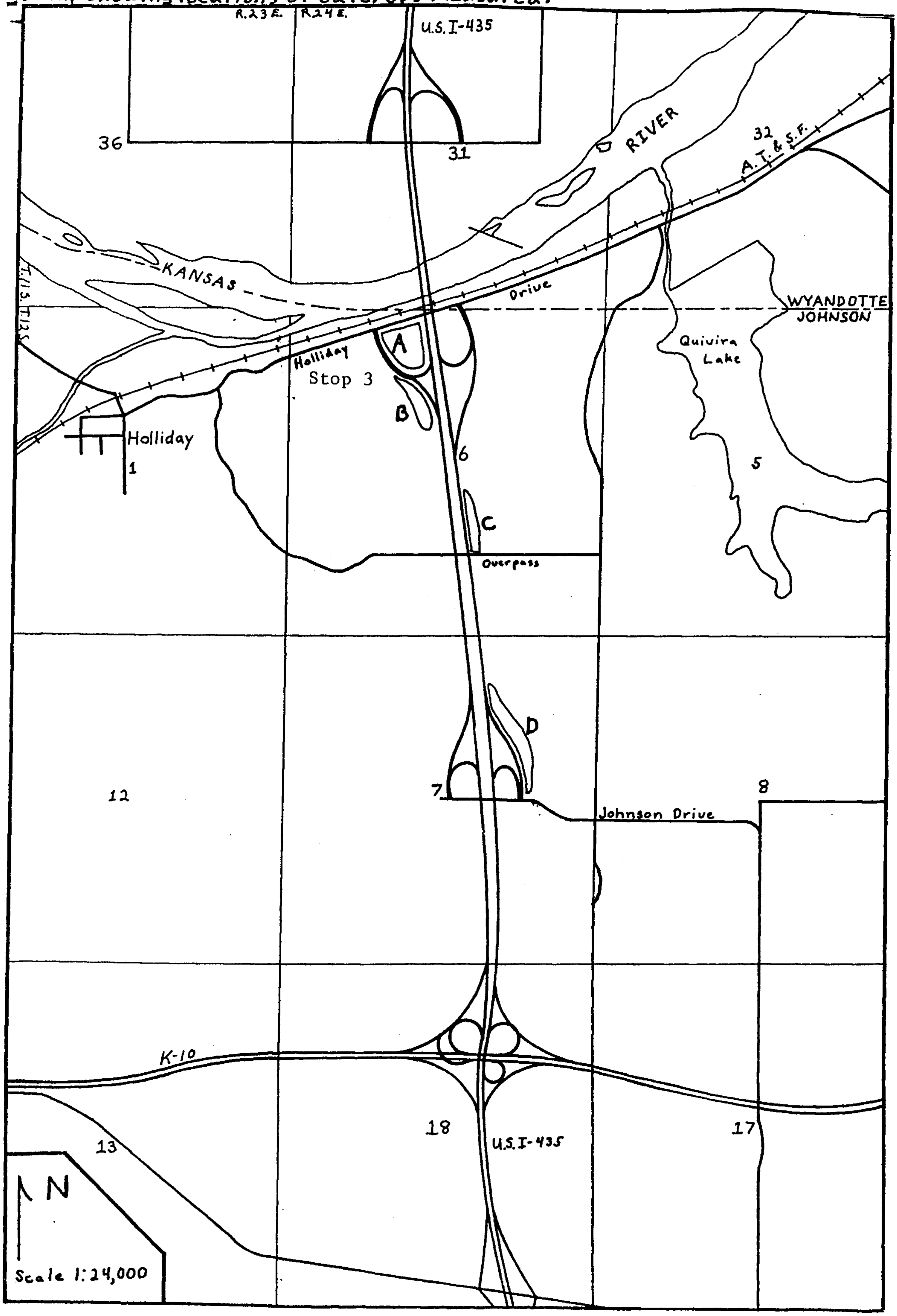


Figure S3-2 MEASURED SECTION ON I-435 AT THE JOHNSON DRIVE AND HOLLIDAY DRIVE INTERCHANGES, JOHNSON COUNTY, KANSAS

BY SCOTT JOHNSGARD, 1984

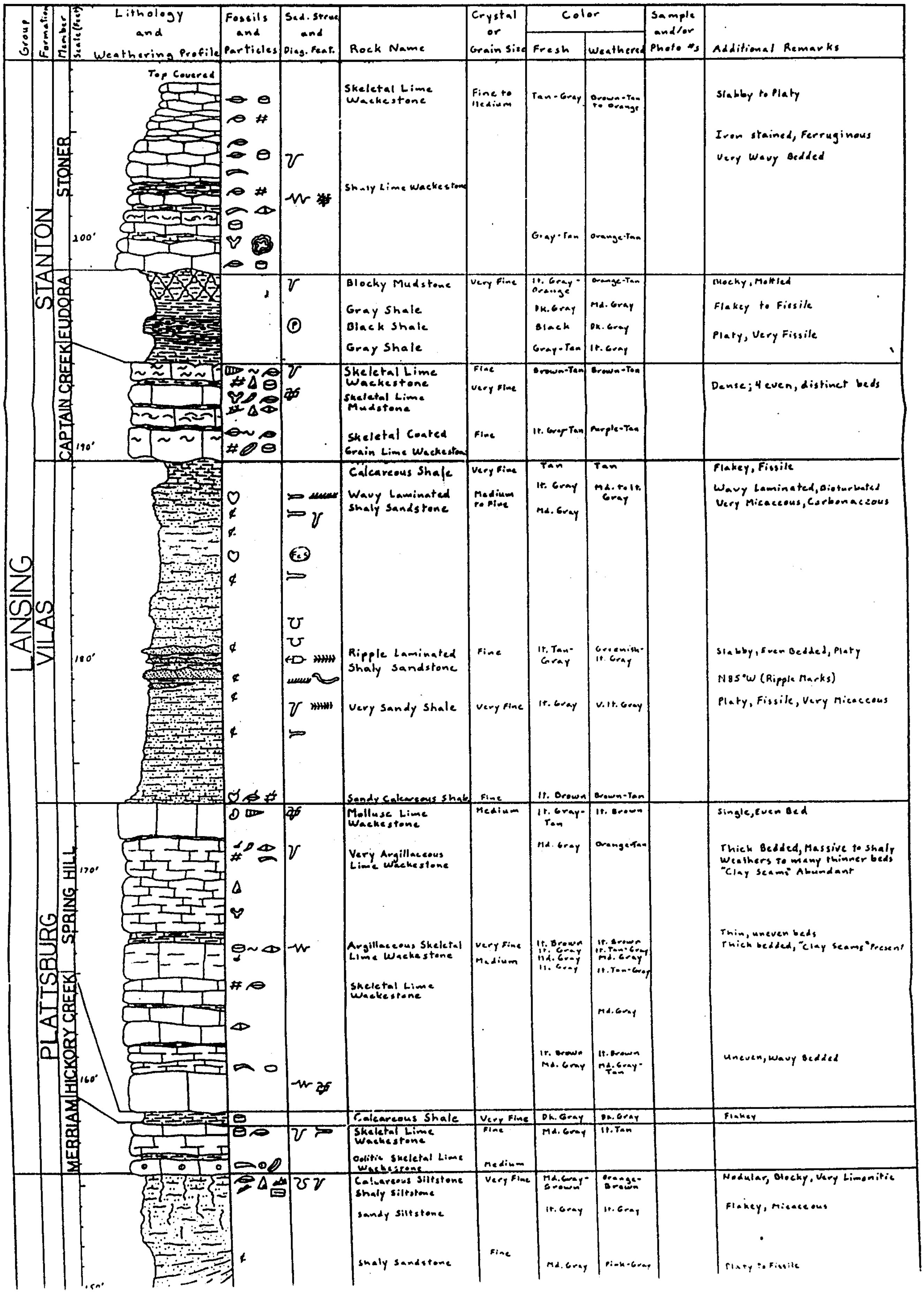
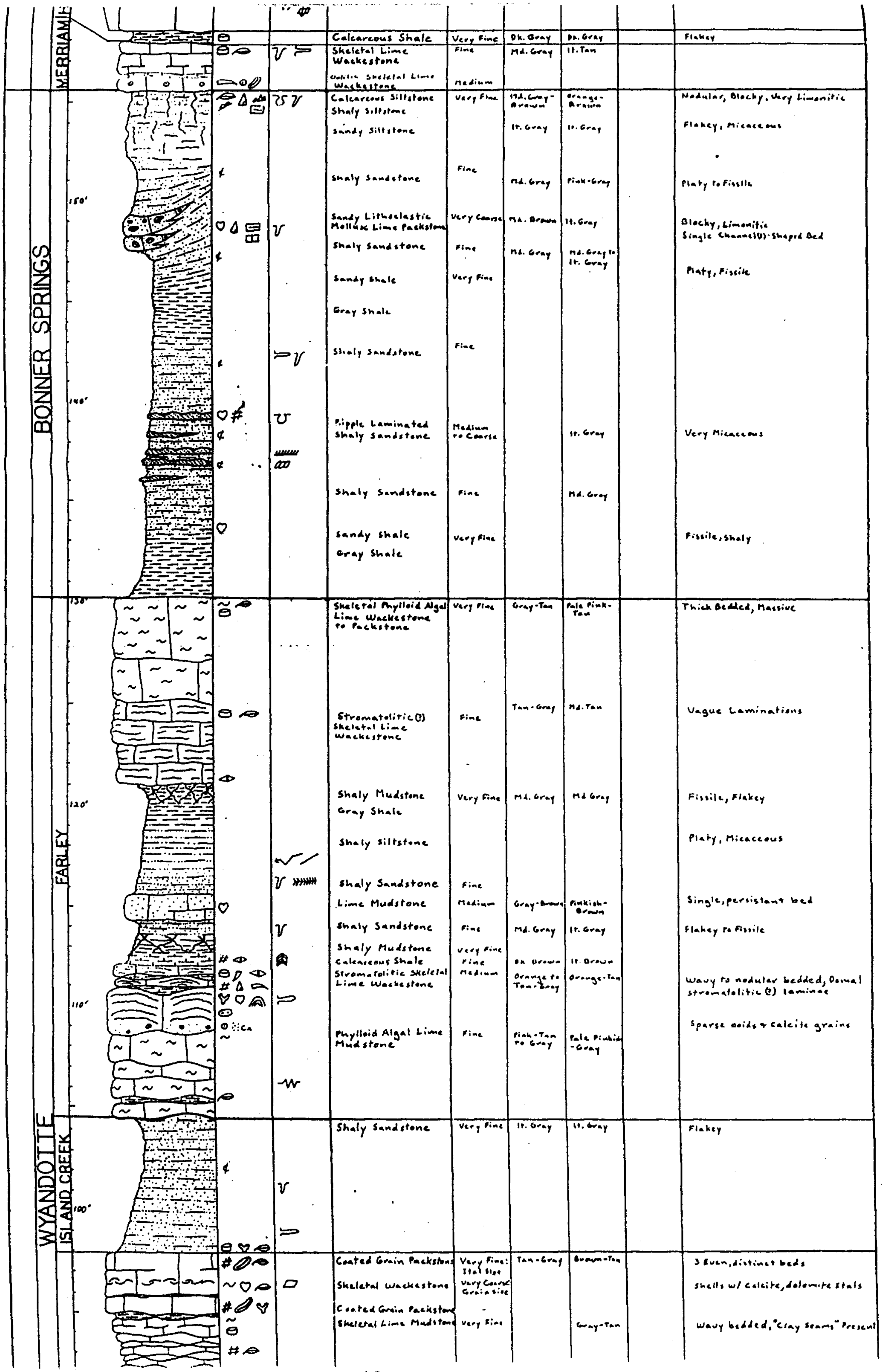


Fig. S3-2
(cont.)



MERRIAM
BONNER SPRINGS
FARLEY
WYANDOTTE
ISLAND CREEK
150'
140'
130'
120'
110'
100'
Calcareous Shale
Very Fine
Dk. Gray
Dk. Gray
Flakey
Skeletal Lime Wackestone
Fine
Md. Gray
Lt. Tan
Oolitic Skeletal Lime Wackestone
Medium
Calcareous Siltstone
Very Fine
Md. Gray-Brown
Orange-Brown
Nodular, Blocky, Very Limonitic
Shaly Siltstone
Sandy Siltstone
Lt. Gray
Lt. Gray
Flakey, Micaceous
Shaly Sandstone
Fine
Md. Gray
Pink-Gray
Platy to Fissile
Sandy Lithoclastic Mollusc Lime Packstone
Very Coarse
Md. Brown
Lt. Gray
Blocky, Limonitic
Single Channel(?)-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
Very Fine
Fissile, Shaly
Gray Shale
Skeletal Phylloid Algal Lime Wackestone to Packstone
Very Fine
Gray-Tan
Pale Pink-Tan
Thick Bedded, Massive
Stromatolitic(?) Skeletal Lime Wackestone
Fine
Tan-Gray
Md. Tan
Vague Laminations
Shaly Mudstone
Very Fine
Md. Gray
Md Gray
Fissile, Flakey
Gray Shale
Shaly Siltstone
Platy, Micaceous
Shaly Sandstone
Fine
Lime Mudstone
Medium
Gray-Brown
Pinkish-Brown
Single, persistant bed
Shaly Sandstone
Fine
Md. Gray
Lt. Gray
Flakey to Fissile
Shaly Mudstone
Very Fine
Calcareous Shale
Fine
Dk. Brown
Lt. Brown
Stromatolitic Skeletal Lime Wackestone
Medium
Orange to Tan-Gray
Orange-Tan
Wavy to nodular bedded, Dismal stromatolitic (?) laminae
Sparse ooids + calcite grains
Phylloid Algal Lime Mudstone
Fine
Pink-Tan to Gray
Pale Pinkish-Gray
Shaly Sandstone
Very Fine
Lt. Gray
Lt. Gray
Flakey
Coated Grain Packstone
Very Fine: Xtal Size
Tan-Gray
Brown-Tan
3 Even, distinct beds
Skeletal Wackestone
Very Coarse Grain Size
Shells w/ calcite, dolomite xtals
Coated Grain Packstone
Skeletal Lime Mudstone
Very Fine
Gray-Tan
Wavy bedded, "Clay Seams" Present

Fig. S3-2
(cont.)

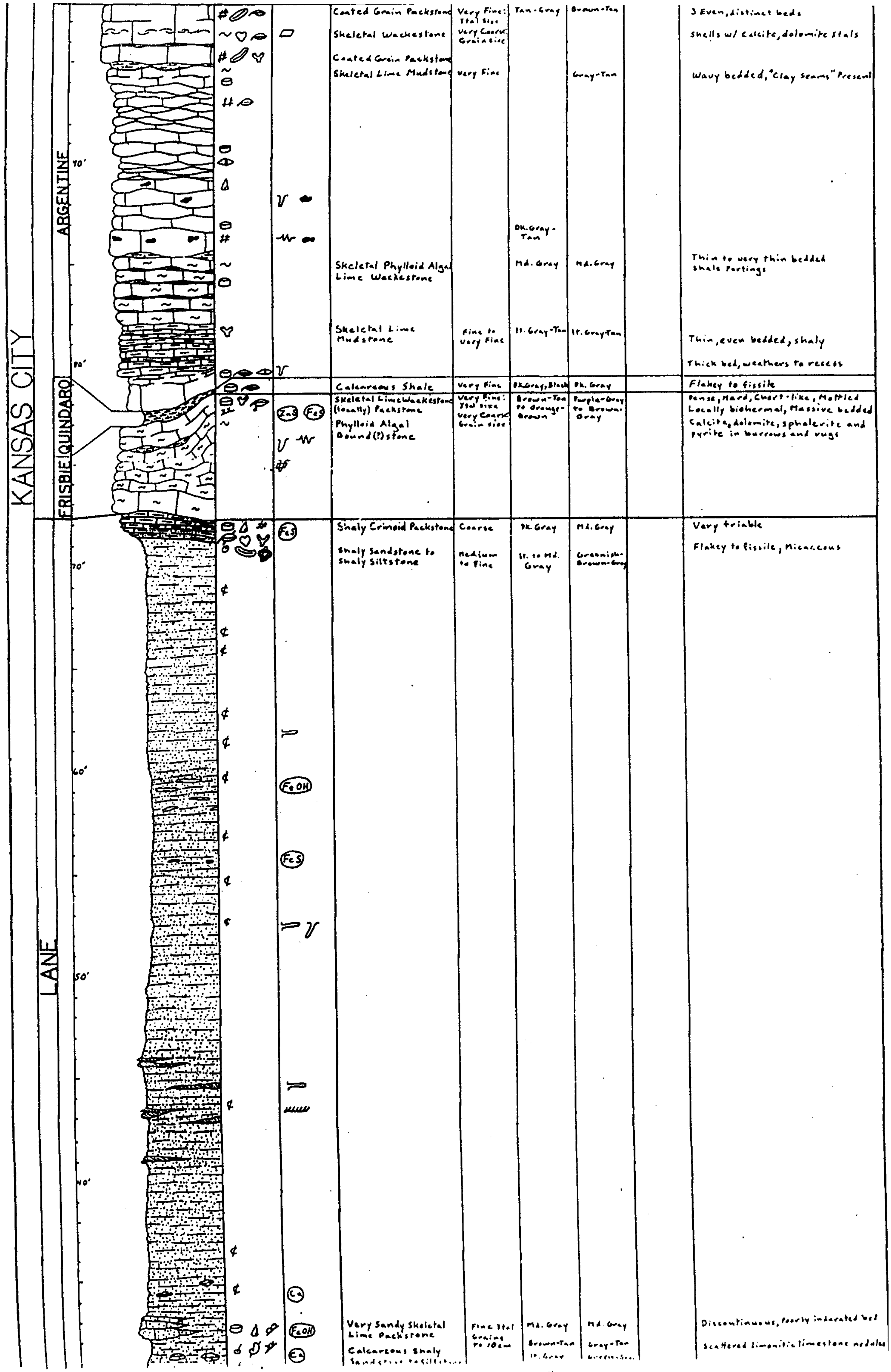

KANSAS CITY
LANE
ARGENTINE
FRISBIE
QUINDARO
90'
80'
70'
60'
50'
40'
Coated Grain Packstone
Very Fine: Xtal size
Tan-Gray
Brown-Tan
3 Even, distinct beds
Skeletal Wackestone
Very Coarse: Grain size
Shells w/ Calcite, dolomite Xtals
Coated Grain Packstone
Skeletal Lime Mudstone
Very Fine
Gray-Tan
Wavy bedded, "Clay Seams" Present
Dk. Gray-Tan
Skeletal Phylloid Algal Lime Wackestone
Md. Gray
Md. Gray
Thin to very thin bedded shale Partings
Skeletal Lime Mudstone
Fine to very Fine
lt. Gray-Tan
lt. Gray-Tan
Thin, even bedded, shaly
Thick bed, weathers to recess
Calcareous Shale
Very Fine
Dk. Gray, Black
Dk. Gray
Flakey to fissile
Skeletal Lime Wackestone (locally) Packstone
Phylloid Algal Bound(?)stone
Very Fine: Xtal size
Very Coarse Grain size
Brown-Tan to Orange-Brown
Purple-Gray to Brown-Gray
Dense, Hard, Chert-like, Mottled
Locally biohermal, Massive bedded
Calcite, dolomite, sphalerite and pyrite in burrows and vugs
ZnS
FeS
Shaly Crinoid Packstone
Coarse
Dk. Gray
Md. Gray
Very friable
Shaly Sandstone to Shaly Siltstone
Medium to Fine
lt. to Md. Gray
Greenish-Brown-Gray
Flakey to fissile, Micaceous
FeOH
FeS
Ca
Very Sandy Skeletal Lime Packstone
Fine Xtal Grains to 10cm
Md. Gray
Md. Gray
Discontinuous, Poorly indurated bed
Calcareous Shaly
Brown-Tan
Gray-Tan
Scattered limonitic limestone nodules

Fig. S3-2
(cont.)

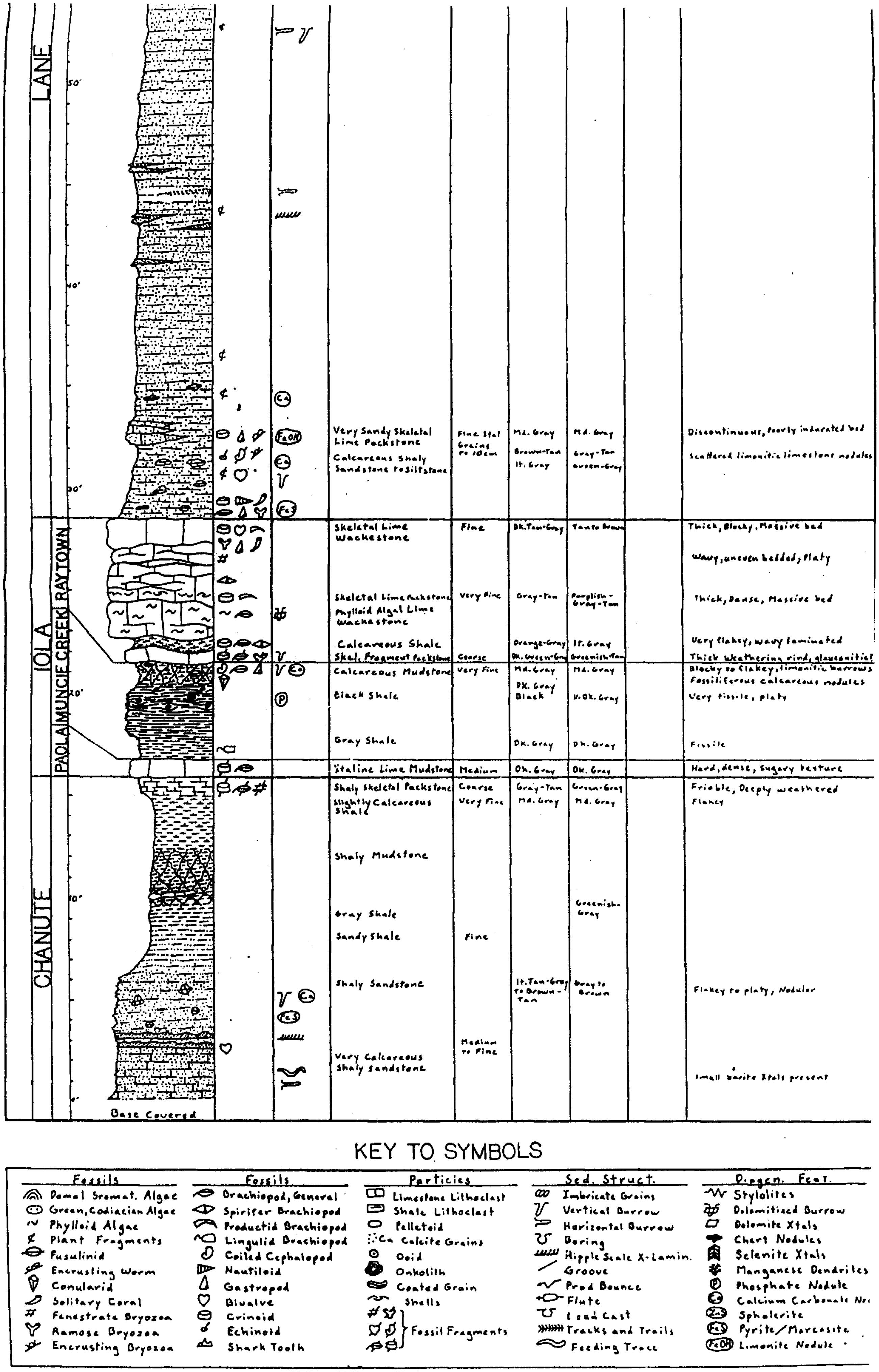
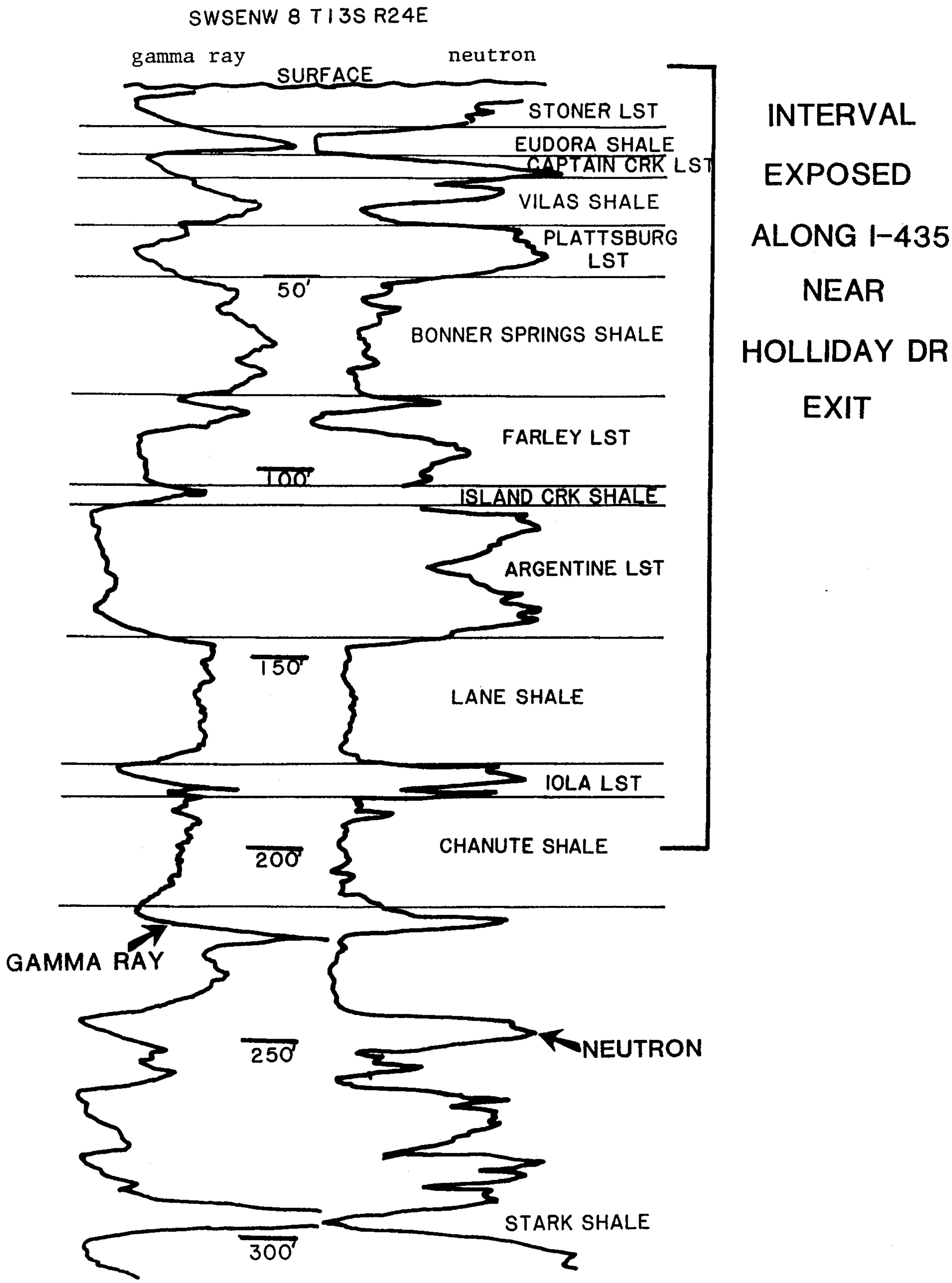

LANE
IOLA
RAYTOWN
MUNCIE CREEK
PAOLA
CHANUTE
50'
40'
30'
20'
10'
Very Sandy Skeletal Lime Packstone
Calcareous Shaly Sandstone to Siltstone
Skeletal Lime Wackestone
Skeletal Lime Packstone
Phylloid Algal Lime Wackestone
Calcareous Shale
Calcareous Mudstone
Black Shale
Gray Shale
Shaly Skeletal Packstone
Slightly Calcareous Shale
Shaly Mudstone
Gray Shale
Sandy Shale
Shaly Sandstone
Very Calcareous Shaly Sandstone
Base Covered
Discontinuous, Poorly indurated bed
Scattered limonitic limestone nodules
Thick, Blocky, Massive bed
Wavy, uneven bedded, platy
Thick, Dense, Massive bed
Very flakey, wavy laminated
Fossiliferous calcareous nodules
Very fissile, platy
Fissile
Hard, dense, sugary texture
Friable, Deeply weathered
Flakey
Flakey to platy, Nodular
Small barite Xtals present
KEY TO SYMBOLS
Fossils
Domal Stromat. Algae
Green, Codiacian Algae
Phylloid Algae
Plant Fragments
Fusulinid
Encrusting Worm
Conularid
Solitary Coral
Fenestrate Bryozoa
Ramose Bryozoa
Encrusting Bryozoa
Fossils
Brachiopod, General
Spirifer Brachiopod
Productid Brachiopod
Lingulid Brachiopod
Coiled Cephalopod
Nautiloid
Gastropod
Bivalve
Crinoid
Echinoid
Shark Tooth
Particles
Limestone Lithoclast
Shale Lithoclast
Pelletoid
Calcite Grains
Ooid
Onkolith
Coated Grain
Shells
Fossil Fragments
Sed. Struct.
Imbricate Grains
Vertical Burrow
Horizontal Burrow
Boring
Ripple Scale X-Lamin.
Groove
Prod Bounce
Flute
Load Cast
Tracks and Trails
Feeding Trace
Diagen. Feat.
Stylolites
Dolomitized Burrow
Dolomite Xtals
Chert Nodules
Selenite Xtals
Manganese Dendrites
Phosphate Nodule
Calcium Carbonate Nodule
Sphalerite
Pyrite/Marcasite
Limonite Nodule

Figure S3-3. Correlations of formations in Lansing and Kansas City groups on gamma ray-neutron log of well found near Stop 3 (Holiday Drive exit).



STOP 4: RAYTOWN SECTION ALONG I-435 JUST SOUTH OF 350 HIGHWAY: HERTHA, SWOPE, AND DENNIS CYCLES

This is a continuous, superbly exposed sequence of lower Missourian rocks that are currently a major focus of our investigations (**Figure S4-1**, a measured section; **Figure S4-2**, a Gamma ray log stratigraphic cross section that correlates the surface gamma scintillometer measurements to nearby wells). Cross section index for **Figure S4-2** is found in **Figure 16**. Due to these studies, we are familiar with the variability of these units throughout most of eastern Kansas and into the Kansas City area. Therefore, we can hopefully offer some insights regarding the lithologic manifestations of processes that have controlled deposition of these units.

The units exposed at this location will be described briefly in ascending order. For the sake of brevity, individual units will not be covered in great detail; rather, salient features will be noted, and these will hopefully serve as fodder for further discussion. The stratigraphic relationships and regional variations of these units can perhaps be better understood by reference to the measured section in **Figure S4-1** throughout this discourse.

The **Mound City Shale** is the lowermost unit exposed here. It can be viewed by hanging over the small waterfall and pool a few hundred feet downstream of the main outcrop. The Mound City is the condensed section within the Hertha sequence.

The **Sniabar Limestone** is the upper limestone unit within the Hertha depositional sequence. It is largely a phylloid-algal and skeletal wackestone. The Sniabar exhibits abundant evidence of subaerial exposure in the form of laminated crusts and a chalky, caliche-like rind along its upper surface. Centimeter-diameter root systems penetrate extensively through most of the Sniabar Limestone. Some beds within the Sniabar were more altered than others. Associated in situ breccias and micritization of the host carbonate rock is pervasive. Consequently, a fresh exposure of the Sniabar Limestone looks weathered. Although it is only 9 feet thick here, the Sniabar is a carbonate bank complex up to 90 feet thick roughly 120 miles to the southwest in Neosho, Wilson, and Elk Counties.

The **Elm Branch Shale** is about 2.5 feet thick and consists of an unfossiliferous gray mudstone succeeded upward by a coaly stringer, fossiliferous shale, and a thin carbonate. The Hertha-Swope sequence boundary is placed at the coaly stringer, marking the initial marine deposition.

The **Middle Creek Limestone** is just over a foot thick, and is a dark gray, dense, phylloid-algal wackestone. It is the regionally extensive marine flooding unit in the lower part of the Swope sequence.

The **Hushpuckney Shale** is the black, phosphatic, highly-radioactive condensed section within the Swope sequence. It can be correlated from here into Oklahoma, Iowa, and eastern Colorado. Uranium concentrations in this shale locally vary from 50 to 60 ppm (Coveney, 1985).

The **Bethany Falls Limestone** is the upper Swope carbonate here on the northern shelf. Although it is exclusively a lime wackestone to mudstone here, to the south it has an upper oolitic unit that forms an important hydrocarbon reservoir in central and western Kansas. The upper surface here is a rubbly, brecciated unit, that is heavily rooted (mm-sized, tubular rhizoliths) that records the effects of substantial subaerial exposure. This episode of exposure was quite significant. Southward two additional lithologic units are present between the Bethany Falls and the overlying Galesburg Shale. These units were not deposited and/or were weathered and eroded from this upper shelf location.

The **Galesburg Shale** at this location is a blocky mudstone that represents extended soil formation during the exposure event that terminated deposition of the Swope depositional sequence. To the south in Kansas this unit dramatically expands into a lithologically heterogeneous siliciclastic package that attains thicknesses of over 120 feet. These thick detrital units were derived primarily from the Ouachitas and probably some minor bypassed sediments from the northern shelf. Deltaic and submarine fans prograded across the Arkoma basin through eastern Oklahoma and unto the edge of the carbonate shelf in southeastern Kansas (see initial discussion 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 (the Layton sands).

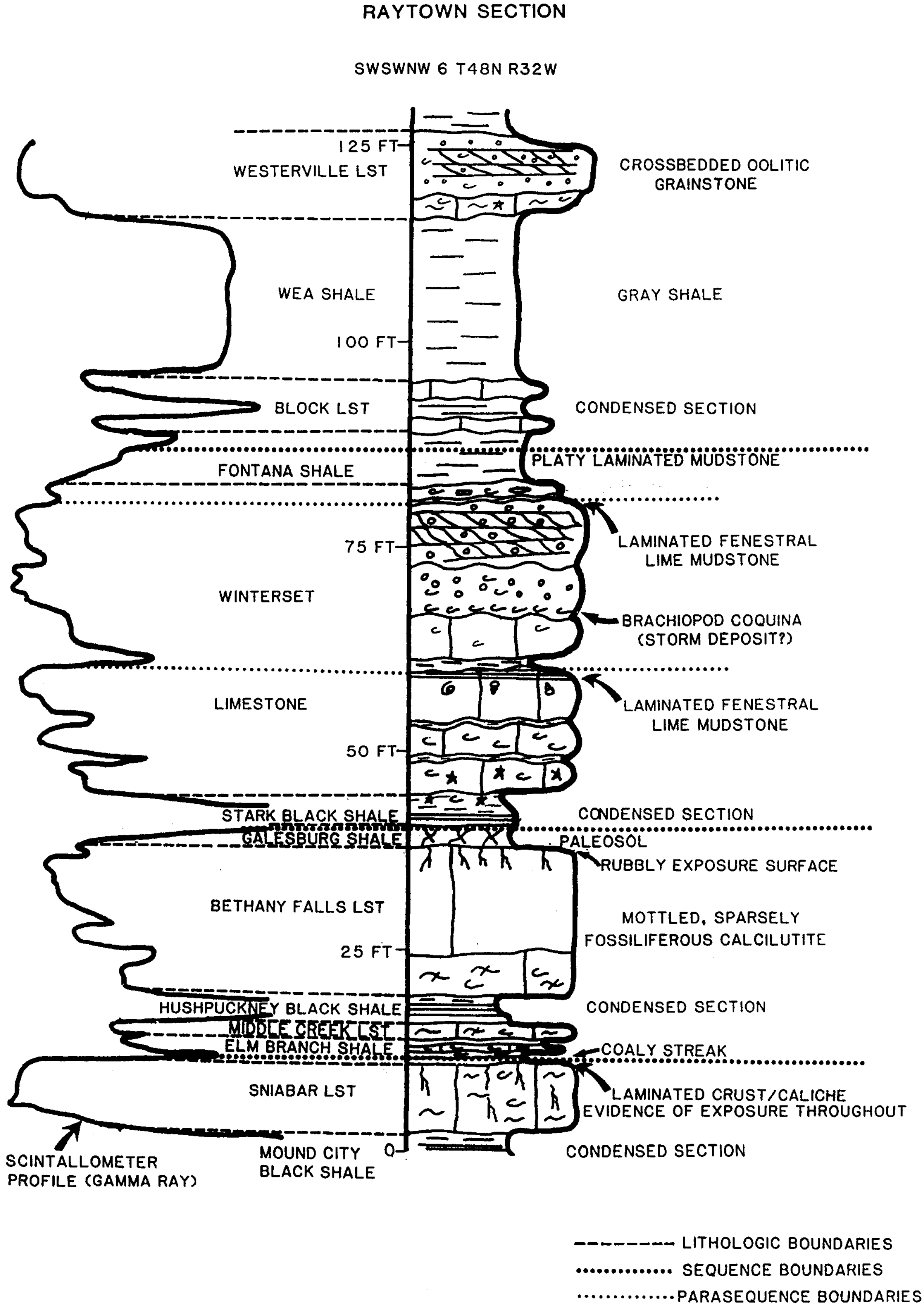
The **Stark Shale** is both the marine flooding unit and condensed section within the Dennis sequence at this position on the shelf. To the south the Canville Limestone intervenes. The Hushpuckney and Stark shales and associated lower flooding units are particularly widely correlable intervals that extend south into the detrital sedimentary pile in Oklahoma 300 miles distant and over 400 miles west across the carbonate shelf.

The **Winterset Limestone** is the internally complex upper Dennis carbonate unit. It has tentatively been divided into three parasequences (minor sequences) at this location; about 40 miles to the south by 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. Determination of the origins of these parasequences is an important goal of our investigation. Modeling by analogue with the Pleistocene glacio-eustatic curve anticipates that a complex packaging could be present due to rapid and very short term eustatic fluctuations (**Figure 13** in introductory text). The model in **Figure 15** is a working hypothesis that will be tested in ongoing research.

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** represents the transgressive phase of the Cherryvale sequence.

Figure S4-1. Measured section of Stop 4 (Raytown) accompanied by gamma scintilometer profile (recordings every one to two feet). Formations listed down middle of diagram. Note identification of boundaries.



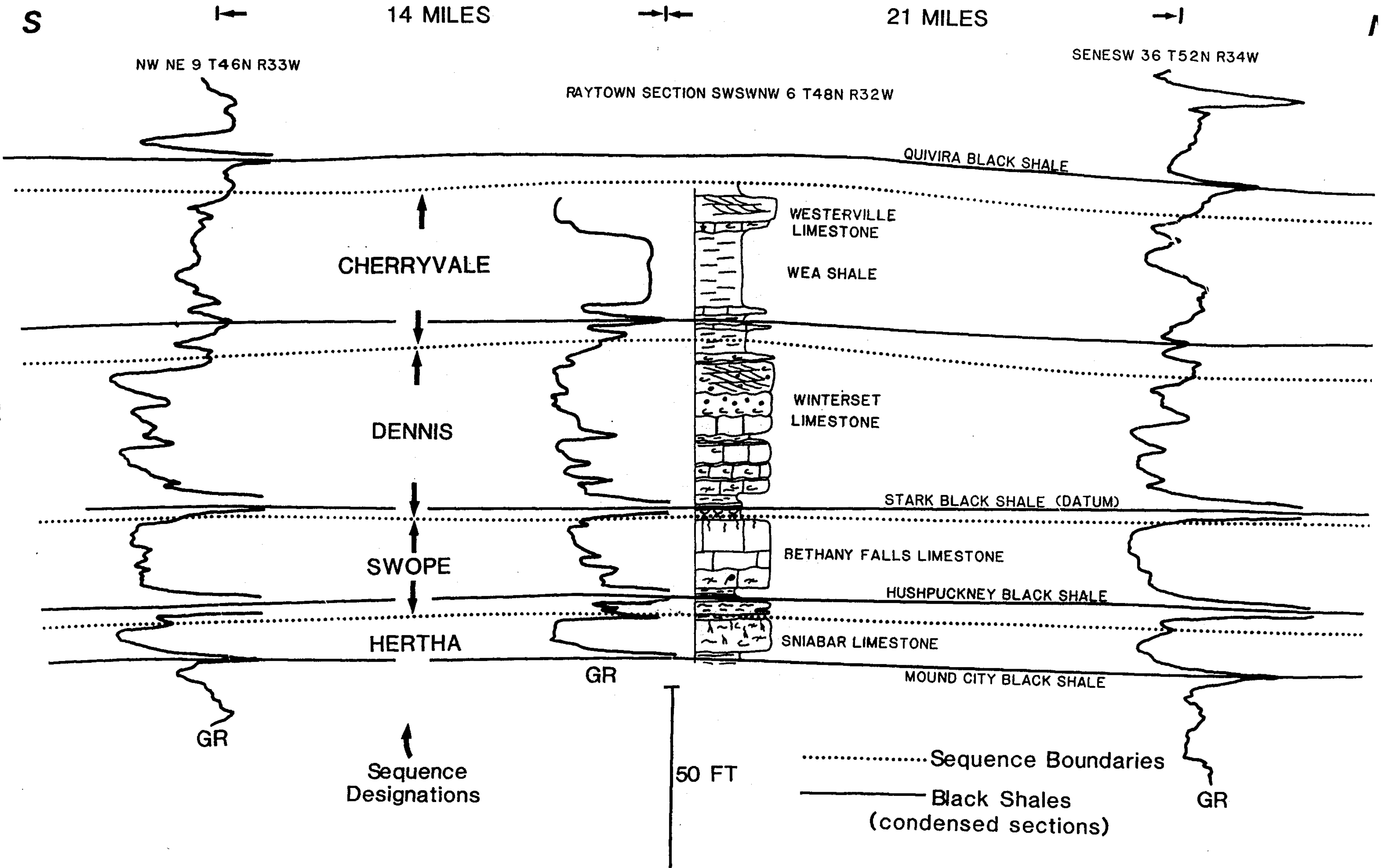


Figure S4-2. North-south stratigraphic gamma log cross section (Stark Shale datum) from wells in vicinity of Stop 4 and measured section and gamma scintillometer profile of Stop 4. Correlations based on gamma ray character of lithologic units. Sequence boundaries are established with

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