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Report of the U.S.–Germany Cooperative Research Project on Three-Dimensional Regionalization and Modeling for Sedimentary Basin Analysis, supported in part by NSF Grant INT-9111646

KANSAS GEOLOGICAL SURVEY
MATHEMATICAL GEOLOGY

## Kansas Geological Survey

Open File Report 95-32
December, 1995

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# MODELING OF SEDIMENT ACCOMMODATION REALMS USING REGIONALIZED CLASSIFICATION OF UPPER PENNSYLVANIAN STRATIGRAPHIC UNITS AND GENETIC SETS IN KANSAS

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*Using regionalized classification, six successive Upper Pennsylvanian stratigraphic intervals from an approximately 116,000-km$^2$ area in Kansas were analyzed. The objective was to model spatial patterns of variation in stratigraphic thickness entirely from information contained in the data rather than from subjective assumptions, and to infer the origins of these variations. The stratigraphic intervals studied are genetic stratigraphic units and genetic sets which are proxies for time-distinct depositional sequences. Isopach maps of genetic stratigraphic units or genetic sets provide time-distinct representations of coherent successions of sedimentation and sediment accommodation space on the Kansas Shelf and shelf margin. They depict an evolving configuration that represents the response to differential subsidence, shelf elevation, sea-level changes, and sediment supply. (If arbitrary stratigraphic intervals are used for isopach mapping, incremental depositional effects will be obscured and only general stratigraphic relationships will be shown.) Regionalized classification of the Kansas Shelf provides evidence that deposition was controlled in part by reactivation of preexisting basement structures during Pennsylvanian time.*

*Regionalized classification defines areas in which the genetic units are relatively uniform and correspond closely to basement blocks that have been identified previously, suggesting that reactivation of preexisting structures along the margins of these basement blocks was a primary cause of areal variation in deposition on the Kansas Shelf. Isopach maps and subsidence curves indicate that homogeneous processes affected sediment accommodation within each region. Zones between regions, perhaps the foci of fractures and structural flexures, may be important features for hydrocarbon traps and migration conduits, either of hydrocarbons or mineralized fluids.*

KEY WORDS: **Basin modeling, genetic stratigraphic unit (GSU), differential subsidence, basement structure, reactivation, geostatistics, regionalized classification.**

## INTRODUCTION

The geographic location of Kansas, in the center of the conterminous United States, coincides with the shelf margin of the Anadarko and Arkoma basins and the northern extension of the shelf. These basins were actively subsiding as the Gondwana-Larentia continental plate collision occurred during Pennsylvanian (Late Carboniferous) time. Episodic subsidence of the basins led to flexing of the adjoining shelf which was expressed as differential subsidence. This subsidence diminished gradually toward the north away from the basins. The position of the shelf margin in southern Kansas shifted repeatedly and abruptly northward as the lower shelf was exposed to episodes of sediment starvation; these episodes significantly changed local sedimentation patterns and affected

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sediment accommodation space. The resulting pattern of subsidence is recorded in the thicknesses of stratigraphic intervals that responded to changes in sediment accommodation space.

Sediment accommodation space is a critical parameter in interpreting sedimentary basin history. Subsidence, eustacy, and sediment supply control the sediment accommodation space and the elevation of the sediment surface. These processes operate at different rates, magnitudes, and duration. Local episodic sedimentation may occur at rates up to several meters per day (Enos, 1991) but persist only for a fleeting instant of geologic time. High frequency, high magnitude sea-level change, in the range of hundreds of meters and > 10 m/ka rates of change, characterizes glacio-eustacy (Schlager, 1981). Longer term subsidence may persist over millions of years. As a consequence, detailed, high-resolution, temporally distinct stratigraphy is needed on a regional basis in order to resolve cause-and-effect relationships that determine sediment accommodation space. Analyzing bundles of strata deposited during similar time frames provides a way to resolve changing sediment accommodation realms. This is necessary in order to develop a detailed model of a basin, either conceptual or quantitative. In this study, we examine a shelf-to-basin setting which is sufficiently large, both geographically and stratigraphically, to address the question of controls on sediment accommodation space.

Following introduction of the concept of time-distinct, unconformity-based stratigraphic units (Wheeler, 1959; Sloss, 1963), many refinements in genetic stratigraphy have been incorporated into geologic reconstruction and mapping (Ross, 1991). However, few regional studies of genetic units have been made because collecting the necessary data is labor-intensive. A high-resolution stratigraphic data set derived from petrophysical logs was used in this study to better characterize sediment accommodation space.

Once high-resolution maps of stratigraphic intervals have been prepared they must be compared objectively, preferably in a quantitative manner. However, maps usually are compared visually, by placing maps alongside one another or overlaying them manually or electronically. Color coding of map images and enhancement by statistical methods have been used to delineate features on maps for easier comparison. For example, the extraction of trend residuals was used on a preliminary study of a small portion of the western Kansas Shelf (Watney, 1985). Herzfeld and Merriam (1990) compared maps of stratigraphic intervals by computing weighted cross products of two map grids to map the resemblance between the two surfaces. In the present study, the method of regionalized classification is used to quantitatively resolve similarities in many maps simultaneously, subdividing the mapped area into regions that are homogeneous and distinct.

Sediment accommodation space is closely linked with subsidence, which has been a research topic for many years. In conventional subsidence analysis, geologic time usually is resolved to the level of geologic stages. Results from such studies are too coarse and lacking in detail to be used in the investigations of sediment accommodation space. The high-resolution, time-distinct stratigraphic intervals used in this current study can be used to address this problem.

Three-dimensional modeling may reveal the nature of local and regional controls on subsidence. However, such modeling studies also have been limited to large time intervals. A pseudo three-dimensional approach was used by Quinlan and Beaumont (1984) to estimate subsidence over regular grids of kilometer-sized squares. Although providing a general idea of spatial variation in sediment accommodation and subsidence, the spatial resolution of their study is too coarse to determine any correlation with basement features or to make inferences about possible reactivation of basement structures. In contrast, regionalized classification provides a consistent way to resolve time and can provide an empirical model that is sufficiently detailed to permit inferences about relationships with dominant spatial trends and patterns in the basement.

There are critical questions that must be addressed to assess the applicability of regionalized classification in the search for evidence of structural reactivation on the Pennsylvanian Kansas Shelf. Among these are:

1. Does regionalized classification delineate relatively homogeneous areas characterized by coherent changes in stratigraphic thickness; that is, areas of relatively constant sediment accommodation space?
2. If the answer to question (1) is yes, do these regions of more uniform stratigraphic thickness correspond to lithological, structural, and/or geophysical features of the basement?
3. Does the burial history, based on the average thicknesses in each region, follow rational, coherent trends? Can these trends be related to regional subsidence and basin and uplift development?
4. Are there areas of homogeneous changes that remain unexplained?

## REGIONALIZED CLASSIFICATION PROCEDURE

The concept of multivariate classification of "geological objects" developed by Voronin (1967) and extended by Rodionov (1981) has been combined with elements of regionalized variable theory by Harff and Davis (1990) to produce what is called "regionalized classification." The mathematical formalism will not be repeated here; instead, the computational aspects will be summarized and certain underlying assumptions highlighted. The objective of regionalized classification is to subdivide a two- or three-dimensional portion of the earth's crust into contiguous portions called regions that are as internally homogeneous as possible and as distinct as possible from adjacent regions. In this application, the area to be regionalized is part of the western Kansas Shelf, and the properties on which the regions are based are the thicknesses of selected stratigraphic intervals of Pennsylvanian age. The regions that are found had relatively uniform tectonic and depositional histories during the time of deposition, and were relatively distinct from one another. The boundary zones between regions are unusually narrow and abrupt, and can be interpreted as active lineaments separating stable blocks.

The initial step in regionalized classification is typification, in which the observations are subdivided into groups based on their mutual similarities. An unsupervised hierarchical clustering procedure such as Ward's algorithm, which uses a within-cluster minimum variance criterion, can be used to produce candidate groups (Bock, 1974). In common with other Q-mode procedures, there is no theoretical underpinning from which to estimate the appropriate number of groups or to evaluate their significance (Davis, 1986). External criteria may prove useful, and the degree of contiguity of cluster members also may be indicative. At the highest level of clustering, all observations belong to a single cluster and of necessity form a contiguous region. At the next lower level, the single cluster is split into two clusters whose members ideally occupy two distinct, separate regions. Because the spatial coordinates of the observations are not used in the clustering process, there is no guarantee that this will occur—it is possible that members of the two clusters will be spatially intermixed. In such a circumstance, we must conclude that regions either do not exist, or the variables chosen do not reflect the regionalization. Typically, when the number of clusters is limited, the cluster members will form a pattern consisting of approximately the same number of (or slightly more) discrete geographical regions as there are clusters. As the number of clusters increases, however, the spatial organization breaks down and the resulting map is a chaotic mixture of individual points. The level in the hierarchy at which this occurs provides a clue to the appropriate number of regions.

The hierarchical succession and maps of regions for each successive level of the classification were used to determine the optimum number of classes. When there are only a few classes, the regions define large geographic subdivisions that correspond closely with the "areas" described in a later section of this report. When the hierarchy includes more classes, the large areas are progressively subdivided into the smaller regions discussed below.

A regionalization containing 15 classes was selected as optimal. The regions generated at this level are clearly defined and the average size of the regions, approximately 10,000 $km^2$, provides a level of detail comparable with the geologic and geophysical data that are available for interpretation. Regionalization into 15 classes produces a pattern that has a remarkable correlation with geophysical and other available information.

For each cluster, the group centroid and within-group covariance matrix (actually, the matrix of sums of squares and cross products) are calculated, as is the between-group covariance matrix **H** (again, the matrix of sums of squares and cross products is used in practice). The individual within-group matrices are pooled to form matrix **E**. The eigenvectors of $\mathbf{E}^{-1}\mathbf{H}$ are linear discriminant functions, orthogonal axes onto which the observations can be projected (Fisher, 1936). To classify individual observations, it is necessary to calculate the similarity between each observation and the centroids of the groups to which it might be assigned. The similarity metric used is Mahalanobis' distance, $D^2$, which takes into account the relative inflation of the groups about their centroids. For classification purposes, these multivariate distances can be turned into a set of posterior probabilities that the observation belongs to each respective group. The observation is assigned to the group for which the probability of membership is the greatest (Tatsuoka, 1971).

A measurement such as the thickness of a stratigraphic interval in a well can be considered a regionalized variable modeled as a spatially varying stochastic random function whose spatial continuity can be expressed by its semivariogram (Journel and Huijbregts, 1978). Since discriminant functions are linear combinations, the discriminant scores based on isopach data also are regionalized variables, as are the Mahalanobis' distances and the group membership probabilities. At every sample locality, the probability that the observation is a member of group $k$ can be determined, and from these, a semivariogram describing the spatial continuity of the group $k$ probability function can be estimated. Using parameters from an appropriate model fitted to the semivariogram, kriging estimates of the probability of classification in group $k$ can be made at locations were no observations are available; for display purposes it is convenient to make such estimates at the nodes of a regular grid covering the study area (Deutsch and Journel, 1992). The process can be repeated for all $k$ groups, resulting in a series of probability surfaces that describe the likelihood of group membership at every grid location in the area. A specific grid node is assigned membership in the group for which the probability is the highest. (As a practical matter, no group assignment is made at grid cells where the highest probability is less than 0.5).

The final phase in regionalization is to produce a grid showing the maximum probability of assignment to any group; this distinguishes those locations that can be assigned to a region with reasonable certainty from locations whose classification is unclear. The latter mostly form boundaries between regions, but also may delineate areas which do not fit well into the system of classes that has been specified. A map showing the membership assignment at each grid node is the final expression of the regionalization. The regionalization map should be accompanied by a contour map of the maximum probability of assignment, because the contour map expresses the reliability of the regions.

## STRATIGRAPHY

Stratigraphic units used in this study include in the Upper Pennsylvanian Series, Missourian to early Virgilian Stages, Kansas City, Lansing, Douglas, and Shawnee groups (Fig. 1). In Kansas, these units are from 10 ft- to more than 150 ft- (3 to 50 m) thick successions (cyclothems) of alternating marine carbonates and nonmarine to shallow marine siliciclastics. Numerous mechanisms have been invoked to explain cyclothems, the most widely accepted being high magnitude (approx. 100 m) glacial-eustatic sea-level fluctuations (*e.g.*, Wanless and Shepard, 1936; Heckel, 1977; Watney, French, and Franseen, 1989; Watney and others, in press). Figure 2 shows a typical Kansas cyclothem composed of alternating limestones and shales. The boundaries of a depositional sequence and a genetic stratigraphic unit (GSU) also are shown. The depositional sequence is bounded by subaerial unconformities (Vail and others, 1977), while the GSU is bounded by thin flooding units and condensed sections (Galloway, 1989). Genetic stratigraphic units are described in more detail below.

The cyclothem, depositional sequence, and genetic stratigraphic unit are considered to be the thinnest regionally correlatable units. Biostratigraphic correlations based on ammonoids, conodonts,

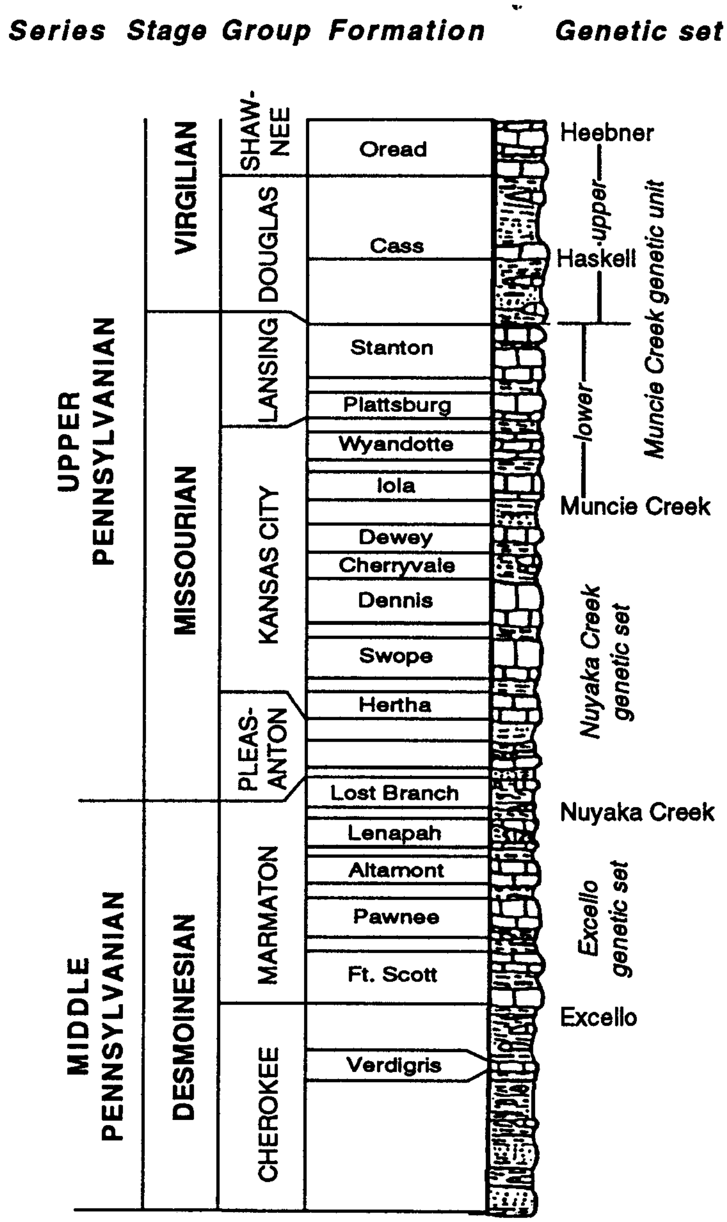


**Figure 1. Generalized stratigraphic column showing Pennsylvanian interval used in this study.**

fusulinids, foraminifera, and corals confirm the equivalence of 13 Virgilian and Missourian cyclothems in the northern Midcontinent and those of the eastern shelf of the Midland Basin in Texas (Boardman and Heckel, 1989). These correlations establish that marine inundations in both areas are synchronous. Because of this, eustacy is considered to have been an important, although not the only factor in creating sediment accommodation space on the continental shelf. Foraminifera, ammonoid, and conodont zones have also been used by Ross and Ross (1987) to extend correlations of similar Pennsylvanian marine inundations globally.

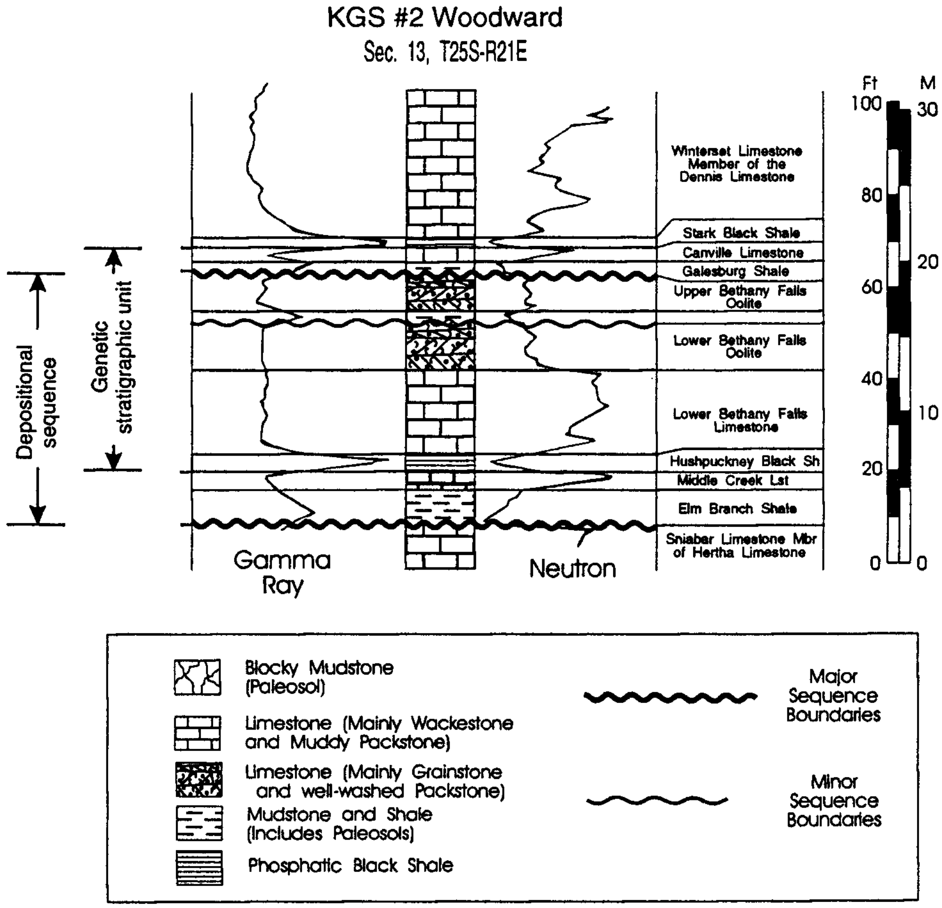


**Figure 2. Typical Kansas cyclothem, depositional sequence, and genetic stratigraphic unit interpreted from gamma ray and neutron well log traces.**

## GENETIC STRATIGRAPHIC UNITS

Genetic stratigraphic units represent distinct, mappable sedimentary intervals delimited by thin, prominent flooding units and condensed sections that can be regionally correlated (Galloway, 1989). Flooding units are thin limestones or, more rarely, thin, widespread coals; both have sharp basal contacts. The Upper Pennsylvanian condensed sections are thin, usually distinctive radioactive black marine shales. Each GSU consists of a thin flooding unit overlain by a condensed section, followed by a shallowing-upward carbonate or siliciclastic unit that is capped by a paleosol which represents a subaerial unconformity. These unconformities delimit time-distinct stratigraphic packages some of which are regionally extensive and meet all of the characteristics of depositional sequences (Vail and others, 1977; Youle, Watney, and Lambert, 1994). However, these unconformities and the corresponding depositional sequences are not nearly as easily correlated over long distances in the subsurface using well logs as are condensed sections. Because of this, it is necessary to correlate the genetic stratigraphic units that are bounded by definitive flooding units and condensed sections. GSUs serve as proxies for time-distinct depositional sequences because of the proximity of their boundaries over much of the shelf (Watney and others, in press). Thicknesses of the GSUs vary regionally, presumably in response to processes that affected sediment accommodation space such as subsidence, shelf elevation, sea-level history, and sediment supply. GSUs are designated by the

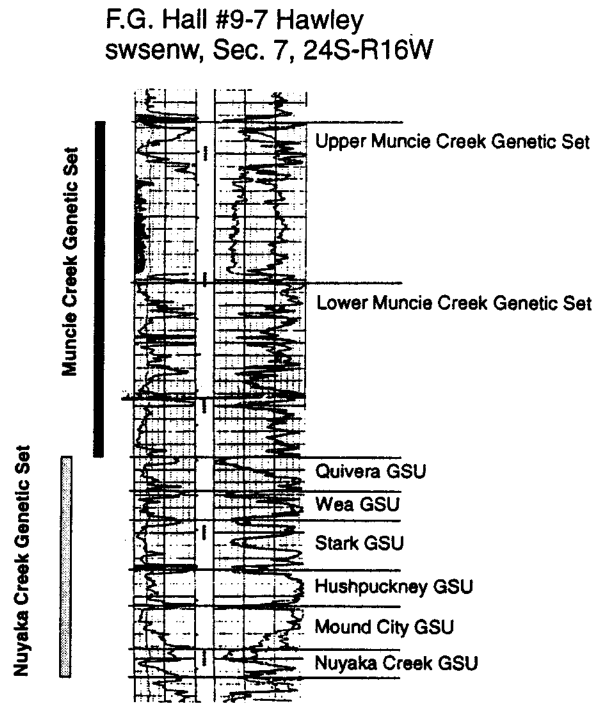


**Figure 3. Genetic stratigraphic units used in this study, with a typical suite of well logs.**

name of the associated condensed section, usually a member or bed in the formal stratigraphic nomenclature. This study considers the Hushpuckney GSU, Stark GSU, Wea GSU, and Quivira GSU presented in Watney and others (in press).

### Hushpuckney GSU

The Hushpuckney genetic stratigraphic unit is the third GSU from the base of the Nuyaka Creek genetic set (Fig. 3). The base of this genetic set corresponds to a time when the Kansas Shelf margin underwent prominent, abrupt backstepping or a sediment-starved event. The underlying two genetic stratigraphic units below the Hushpuckney GSU reflect the initiation of a period of lateral accretion and progradation of the basin margin to the south. The Hushpuckney GSU represents continued lateral accretion to the south into the Arkoma and Anadarko basins.

### Stark GSU

This GSU is part of the lateral accretion of the shelf margin, but the less extensive drowning event in the Stark GSU indicates a return of sediment-starved conditions on the lower shelf in southeastern Kansas. These relationships can be seen on the cross section in Figure 4.

### Wea and Quivira GSUs

These two genetic stratigraphic units were deposited during the last stages of the longer term Nuyaka Creek genetic set, concluding a long-term, shelf-wide episode of regression and basin margin filling.

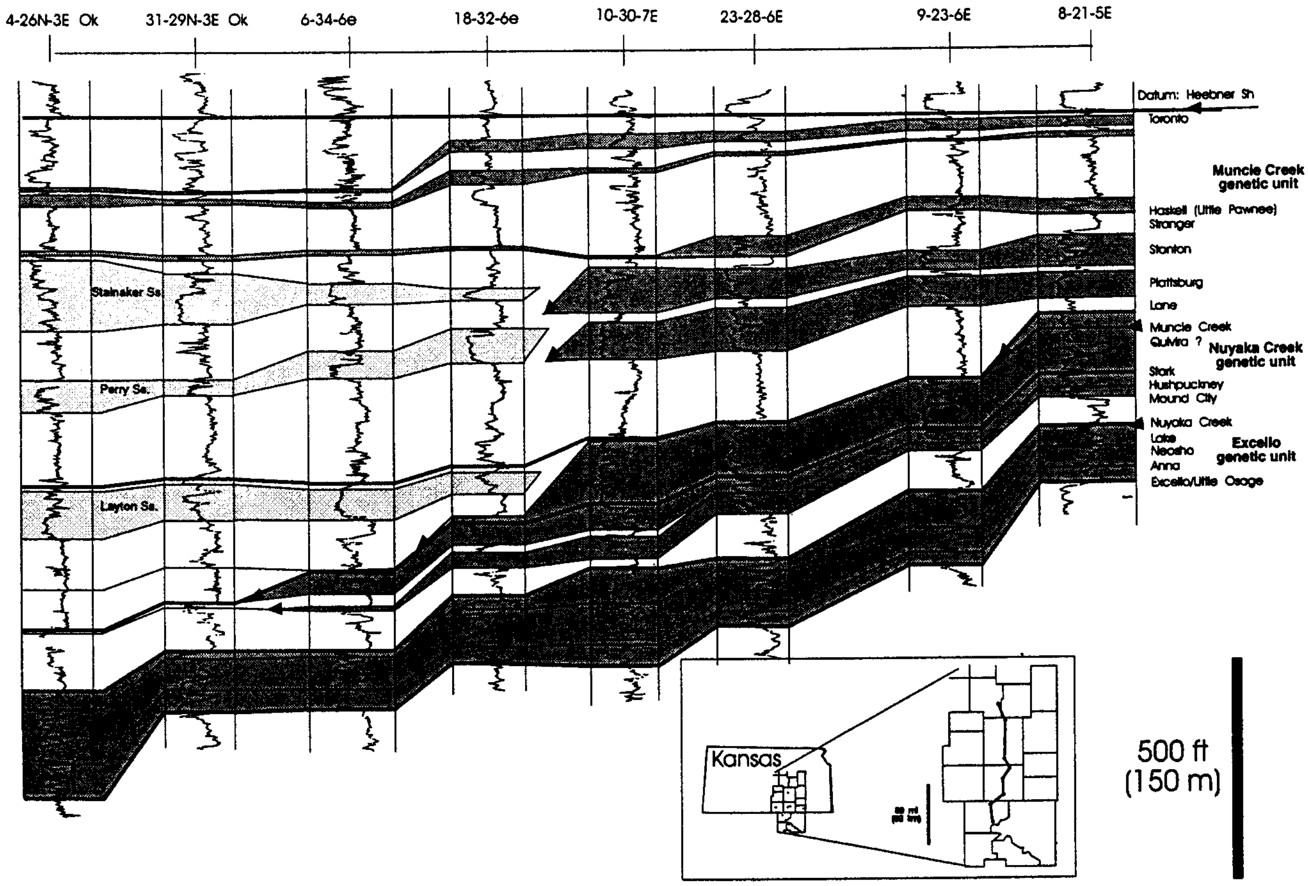


**Figure 4. North–south cross section from central Kansas to northern Oklahoma showing stratigraphic and structural relations in genetic stratigraphic units used in this study (from Watney and others, in press).**

Evidence for the loss of sediment accommodation space in the Wea genetic stratigraphic unit includes the lapout of the marine portion of this unit along the upper shelf, expressed as a zero isopach contour line in northwestern Kansas. The pinchout and amalgamation of paleosols within the Wea and Stark GSUs in northwest Kansas can be traced through cores and well logs. The absence of a distinctive condensed section in the Wea GSU (except locally on the extreme southern edge of the shelf) suggests that the sea was shallow during the maximum flooding associated with this genetic stratigraphic unit. Thick lobate accumulations of oolitic grainstone in the Wea GSU also are limited to the lower shelf, as in southeastern Kansas where a 12 m oolite bank is developed (Feldman and Franseen, 1991). The elevation and slope of the shelf apparently provided sediment accommodation space and permitted accumulation of oolites under shallow, energetic sea-level conditions.

## GENETIC SETS

Sets of genetic stratigraphic units are recognized in the Pennsylvanian of the U.S. Midcontinent. *Genetic sets* are defined as a succession of related GSUs that have similar regional patterns of lithology and thickness that are distinct from the characteristics of stratigraphic intervals above and below (Watney and others, in press). A genetic set is named for the lowest condensed section in the set. Genetic sets are well developed along the northern shelf margin bordering the Anadarko and Arkoma basins in southern Kansas and northern Oklahoma (Fig. 4). Each is approximately 330 ft (100 m) thick and contains from five to seven GSUs. Genetic sets may have different characteristics, and may include progradational, aggradational, or retrogradational stacking patterns (Youle, Watney, and Lambert, 1994). Like GSUs, genetic sets are time distinct but provide temporal views of changes on the shelf over a longer time. Since isopach maps of genetic sets represent longer intervals of time than do isopachs of individual genetic units, they reflect longer term tectonic processes in addition to eustatic processes. Therefore, genetic sets introduce additional influences into the mix of processes that are reflected in a regionalized classification.

Isopach intervals that consist of either genetic stratigraphic units or genetic sets are preferred to isopachs of arbitrary stratigraphic intervals because changes between GSU isopachs are time distinct and represent coherent successions of sedimentation. If intervals that cross unit boundaries or encompass multiple genetic units are used for isopaching, small-scale, incremental depositional effects will be removed or disassociated strata will be combined and only gross stratigraphic relationships will be revealed.

Recognizing and characterizing genetic stratigraphic units and genetic sets was initially done along the shelf margins of the Anadarko and Arkoma basins (Watney and others, in press). Here, large changes in local sediment surface elevation resulted from large, rapid changes in sediment accommodation space—as much as 100 m during much of the Missourian (Fig. 4). The shelf margin apparently was a dynamic system that shifted back and forth over distances of up to 80 km (Watney and others, in press). The present study includes this key region. The location and character of the shelf margin is inferred from the succession of isopachs and from facies interpretations based on cores and outcrops.

Stacking patterns associated with genetic stratigraphic units and genetic sets along the shelf margin are only vaguely expressed in the interior of the shelf in Kansas because the subdued local topography diminishes the vertical to horizontal aspect of the stratigraphic units. However, the genetic sets can be recognized by time-series analyses of thorium-to-uranium (Th:U) ratios in spectral gamma well logs (Watney and others, in press). Because the Th:U ratio is an index of redox conditions at the time of deposition, its variation correlates well with the level of marine inundation inferred from shelf margin stacking patterns. A series of profiles across the shelf suggests that patterns are persistent and correlatable with the more obvious stacking patterns observed along the shelf margin.

## Nuyaka Creek and Muncie Creek Genetic Sets

Genetic sets in the Upper Pennsylvanian are characterized by significant landward backstepping or drowning events. Drowning associated with the Nuyaka Creek genetic set resulted in a northward shift of the shelf margin of nearly 80 km. The Muncie Creek genetic set also began with a significant landward backstepping or drowning event, when the carbonate shelf margin moved about 70 km toward the north at the horizon of the Muncie Creek Shale, a prominent shelf-wide correlatable condensed section of radioactive black shale (Fig. 4). The Muncie Creek Shale is the condensed section of a genetic stratigraphic unit, but also heralds the onset of a significant, long-term stratigraphic reorganization of the shelf, as did the Nuyaka Creek Shale. The carbonate margin that previously existed near the present Oklahoma border abruptly retreated northward to central Kansas. This new carbonate margin formed during the Lower Muncie Creek genetic set and subsequently stepped southward forming a succession of genetic stratigraphic units similar to those in the underlying genetic set. Siliciclastics were deposited episodically and partially filled the drowned portion of the shelf on which succeeding carbonate cycles prograded, forming the Upper Muncie Creek Genetic Set.

Two episodes of coarse-grained siliciclastic sedimentation formed the Perry and Stalnaker Sandstones on the lower shelf during deposition of the Muncie Creek genetic set. The latter, more prominent sandstone-rich interval was deposited at the close of the Muncie Creek genetic set, at a position immediately below the Little Pawnee Shale (Fig. 4). The Little Pawnee Shale is a condensed section of dark marine shale associated with the Haskell Limestone. The next genetic set was initiated with the Little Pawnee Shale and continued slowly until deposition of the Heebner Shale, at which time the shelf was again drowned and reorganized. The upper boundary of the genetic set is placed at the Heebner Shale.

## DATA COLLECTION

The regionalized classification of Pennsylvanian sedimentary intervals on the Kansas Shelf found in this study is based on thicknesses of the six stratigraphic intervals listed in Table 1 and identified in Figure 3. The stratigraphic intervals utilized in this data set are selected genetic stratigraphic units and genetic sets that contain many significant oil and gas reservoirs in Kansas. These and other Pennsylvanian reservoirs are estimated to account for over 23 percent of the original oil-in-place (approx. 4 billion barrels) in Kansas (Watney, French, and Franseen, 1989). Also, the selected stratigraphic units have the potential to contribute additional traps and identifying locations that may have realized more significant hydrocarbon charging. Results of this study may assist in isolating these remaining prospective areas of hydrocarbon accumulation. Thicknesses of the intervals were measured on well logs from over 3000 wells in the study area. The initial GSU correlations were made using information from rocks obtained as well cores scattered throughout the mapped area and from outcrops. Gamma ray/neutron-density and other gamma ray/porosity well log combinations were used for measurements because condensed sections (usually radioactive shales) are clearly discernible on the gamma ray logs and lithologies are relatively easy to discriminate using these log combinations. Copies of the logs were made and incorporated into a series of sections that crossed the area. Log traces were correlated, concentrating on the recognition of condensed sections. In areas that proved particularly difficult to correlate, such as the southern shelf margin where thicknesses and lithologies vary rapidly within GSUs, the logs were laid out and correlated in a two-dimensional grid. Elevations of the boundaries of the GSUs were recorded in a computer database. Outcrop and subsurface studies, including biostratigraphic investigations, helped establish and confirm the correlations based on petrophysics (Watney, French, and Franseen, 1989; Boardman and Heckel, 1989). The data were collected in part with support from the U.S. Department of Energy under grant DOE/BC/1443-13.

The Nuyaka Creek Genetic Set consists of six GSUs. Upward from the base, these are the Nuyaka Creek, Mound City, Hushpuckney, Stark, Wea, and Quivira GSUs (Fig. 3). The lower two GSUs were not mapped throughout the region and are not included in this analysis.

## TECTONIC ACTIVITY AND PALEOGEOGRAPHIC SETTING OF THE MIDCONTINENT DURING LATE PENNSYLVANIAN

A generalized lithofacies and paleogeographic reconstruction of the Upper Midcontinent during Missourian (Upper Pennsylvanian) time is shown in Figure 5. The Kansas Shelf was dominated by carbonates in western Kansas and by mixed carbonates and siliciclastics in eastern Kansas. The Kansas Shelf bordered the active Anadarko and Arkoma foreland basins to the south. The Anadarko basin, which was responsible for subsidence along the western Kansas Shelf, was a hybrid foreland basin that owed at least some of its subsidence to the overthrusting of blocks of crust that are now exposed in the Wichita Mountains of western Oklahoma.

Uplift of the Amarillo–Wichita–Arbuckle mountains began in Early Pennsylvanian (Atokan) time, coincident with the onset of subsidence and definition of the Anadarko Basin (Brewer and others, 1983). At least 5 to 6 mi (8–9 km) of overthrusting in a northwesterly direction are indicated on deep reflection seismic profiles in the Wichita Mountains. The thrusting is believed to be the

TABLE 1. ISOPACH INTERVALS USED FOR REGIONALIZED CLASSIFICATION OF THE PENNSYLVANIAN KANSAS SHELF

| **Upper Datum** | **Lower Datum** |
|---|---|
| 1) Base Heebner Shale (Virgilian Shawnee Group) *(upper Muncie Creek genetic set)* | Top Stanton Limestone (Missourian Lansing Group) |
| 2) Top Stanton Limestone *(lower Muncie Creek genetic set)* | Base Iola Limestone (Missourian Kansas City Group) |
| 3) Base Iola Limestone *(Quivira GSU)* | Dewey Limestone |
| 4) Base Dewey Limestone *(Wea GSU)* | Base Cherryvale Shale |
| 5) Base Cherryvale Shale *(Stark GSU)* | Base Dennis Limestone |
| 6) Base Dennis Limestone *(Hushpuckney GSU)* | Base Swope Limestone |

result of a plate collision along the Ouachitas, and ultimately perhaps responsible for subsidence of the Arkoma Basin. Uplift along the mountain front is recorded as major episodes of conglomerate progradation into the Anadarko Basin along its southern margin (Ham and Wilson, 1967). These progradational episodes appear to have each lasted several million years and led to subsidence in the basin and adjoining shelves.

Sediment-starved conditions in the western Anadarko Basin immediately south of the western Kansas Shelf are recognized by Galloway, Yancey, and Whipple (1977), Kumar and Slatt (1984), and Rascoe and Adler (1983) as indicating a period of maximum subsidence. The eastern edge of the Anadarko Basin near the Ouachita Mountains was the site of reciprocally deposited clastic sediments similar to those of the Arkoma Basin. Relief across the shelf margin and the Anadarko Basin during the Late Pennsylvanian is estimated by Kumar and Slatt (1984) to have been as much as 1100 ft (335 m).

Subsidence of the Anadarko and Arkoma basins is believed to be a major cause of the creation of sediment accommodation space across the Kansas Shelf. The lateral variation of average subsidence rates on the northern shelf during the Missourian, including the Kansas Shelf, is conformable with basin development in the southern Midcontinent (Kluth, 1986). Average subsidence rates calculated by backstripping range from more than 1 ft (0.3 m)/ka in the sediment-starved, drowned basin to less than 0.17 ft (0.05 m)/ka on the northern shelf (Watney and others, in press). The average subsidence through the Missourian probably includes multiple episodes of thrust-induced subsidence, characterized by pulses of rapid downwarp followed by longer periods of gradually reduced subsidence (Beaumont, 1981). The precise duration of these episodes is not well known. Watney and others (in press) have concluded that the step-wise changes in sediment accommodation space on the Kansas Shelf that are recorded in the genetic sets were strongly influenced by this recurring tectonic deformation. Determining the spatial variation of this subsidence is one of the objectives in applying regionalized classification techniques to these data. Differential subsidence of the western

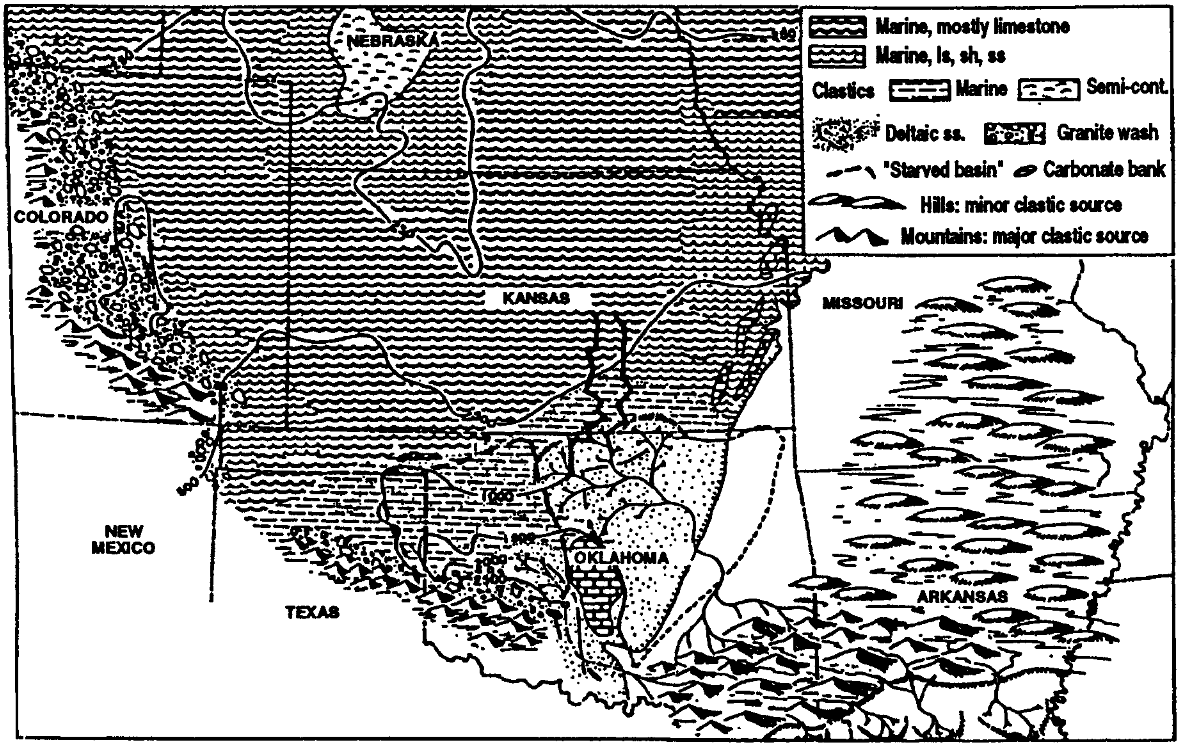


**Figure 5. Generalized paleogeographic reconstruction of the Upper Midcontinent during Missourian time (modified from Rascoe and Adler, 1983).**

Kansas Shelf is suggested by the patterns and trends apparent on the series of isopach maps of the genetic stratigraphic units and genetic sets (Watney and others, in press). An earlier regionalized classification of a more limited set of data from the Pennsylvanian and Permian in western Kansas suggested that large-scale, polygonal areas were present that represented regions of homogeneous thicknesses (Harff and others, 1989; Watney and others, 1994). The margins of these polygons seem to correspond to structural and compositional heterogeneities in the Precambrian basement, suggesting reactivation along lines of weakness. The present study expands the earlier region of investigation to include the shelf margin and additional geologic provinces.

## STRUCTURAL GEOLOGY IN THE STUDY AREA

The study includes data from 3096 wells located in an area that includes approximately 70 percent of the State of Kansas and extends from the western and southern borders of Kansas into the central and eastern portions of the state. Within the study area there are several major structural provinces (Baars and Watney, 1991), including the Central Kansas and Nemaha uplifts, the Hugoton Embayment, and the Sedgwick, southern Salina, and northern Cherokee basins (Fig. 6). Prominent fault zones are associated with the Central Kansas and Nemaha uplifts and the Pratt Anticline. The Humboldt Fault Zone clearly defines the Nemaha Uplift. The Central Kansas Uplift includes two conjugate sets of faults, one trending northwest and the other northeast.

### Structural Cross Sections

Three structural cross sections drawn on the stratigraphic intervals used in this study are shown in Figures 7 through 9. The cross sections were generated from numerical grids used to make

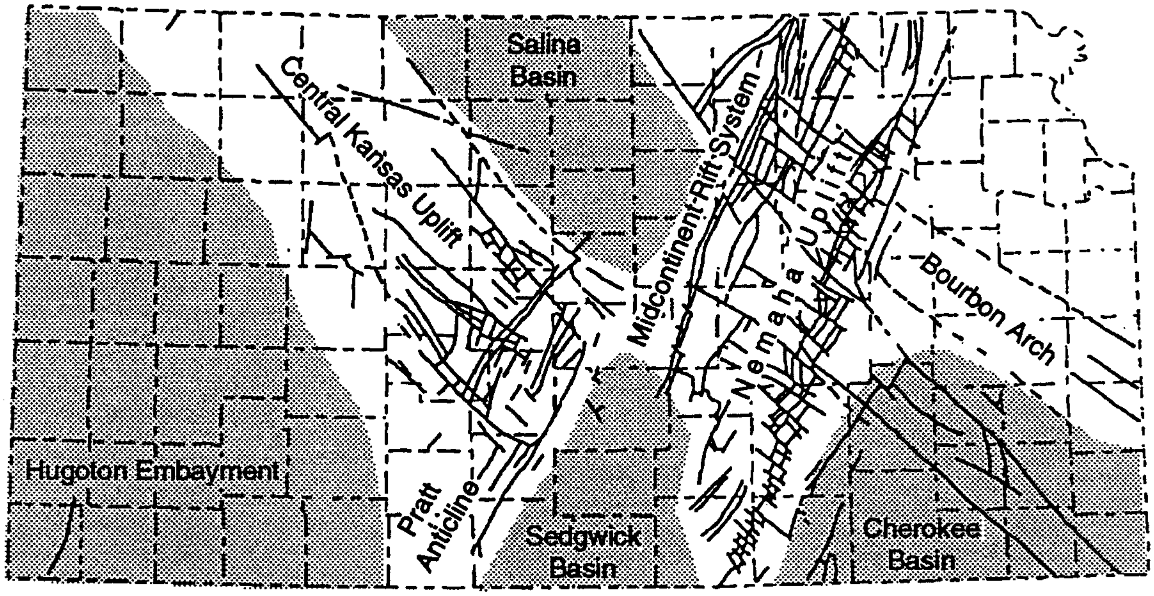


**Figure 6. Major structural elements and basins in Kansas.**

isopach maps. The interval from the Hushpuckney GSU to the base of the Pennsylvanian section is included on the cross sections. The base of the Pennsylvanian section in Kansas is an unconformity that coincides in time with the formation of many major structures, including the Central Kansas and Nemaha uplifts. A north–south section (Fig. 7) shows the gradual southward thickening of all of the Pennsylvanian intervals across the Kansas Shelf and the gradual structural slope into the Anadarko Basin. Figure 8 is an east–west cross section in southern Kansas, across the present regional structural low that comprises the southern part of the Central Kansas Uplift. The basal Pennsylvanian unconformity shows that there was substantially more topographic and structural relief at that time than during subsequent Pennsylvanian times. Figure 9 is a west–east cross section in central Kansas that crosses the more prominently developed Central Kansas and Nemaha uplifts. Here, as well as to the south, much of the topography existing at the beginning of the Pennsylvanian was substantially reduced by the time Upper Pennsylvanian strata were deposited.

## PRECAMBRIAN PROVINCES IN KANSAS

Assessing the possibility that Pennsylvanian depositional patterns on the Kansas Shelf reflect the reactivation of preexisting basement structures requires information about the nature of the Precambrian basement. The basement supports the relatively thin veneer of sedimentary rocks in Kansas and provides the crust with most of its strength. Three of five major Precambrian provinces recognized in the western Midcontinent are present in Kansas. The provinces are distinguished by their geologic histories and the resulting differences in composition and structure. The three provinces are shown in Figure 10 and include the southern Central Plains orogen (sCP), the southern granite–rhyolite province (SGR), and the Midcontinent Rift (MCR) (Van Schmus and others, 1993).

The southern Central Plains orogen is composed of metamorphosed igneous and sedimentary rocks that formed 1.70 to 1.60 Ga BP. The southern Central Plains includes the northern two-thirds of Kansas and is believed to represent a volcanic–plutonic suite, possibly an arc complex, that was intruded by a batholithic complex containing plutons as young as 1.62 Ga BP. It is interpreted to be part of the larger Inner Accretionary Belt and Outer Tectonic Belt of Van Schmus and others (1993). Age dates suggest that this crust formed upon older continental crust formed between 1.72

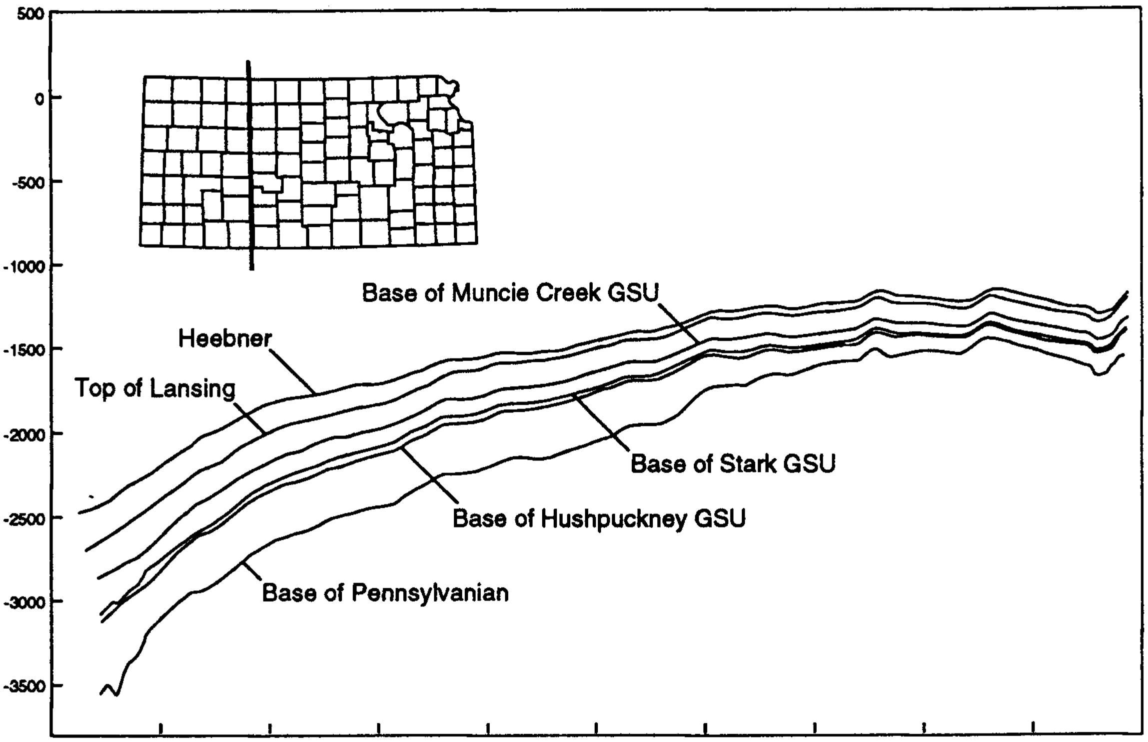


**Figure 7. North–south cross section across western Kansas showing structural and thickness variation in units used in this study. Vertical scale in feet below sea level. Horizontal ticks are spaced 20 mi apart.**

and 1.75 Ga BP. The present surface of this basement province is thought to represent erosion so deep that the cores of the batholithic complex were exposed.

The southern granite–rhyolite province (SGR) comprises a large area of southern Kansas and contains rhyolites and epizonal granites that formed between 1.40 to 1.30 Ga BP. Studies suggest that rocks in the province were derived by the partial melting of older crust, implying that the province must be a veneer of supracrustal and shallow plutonic rocks lying on an Early Proterozoic crust (Van Schmus and others, 1993). The older crust is most likely from the adjacent southern Central Plain orogen. Van Schmus and others (1987) report older epizonal granites within the SGR province that may be in a window through the cover of younger rocks. This suggests that the part of the basement responsible for the structural integrity of southern Kansas may be found below the SGR.

The Midcontinent rift system (MRS) is a failed extensional rift over 2000 km in length. The rift crosses various types of preexisting continental lithosphere, transecting structural patterns in some areas and following possibly reactivated structures in other areas. Sediments and volcanics in the rift are estimated to be up to 30 km thick in Minnesota and thinner to the south. The lava flows and magmas presumably came from sources in the asthenosphere and mantle plume (Cannon, 1992). The MRS contains volcanic, plutonic, and sedimentary units that originated about 1.10 Ga BP. The structure is a failed extensional rift system modified by compression and horst development, segmented by offsets that resemble the accommodation zones of the East African Rift system (Rosendahl, 1987; Berendsen and others, 1988). The offsets may be a response to preexisting crustal weaknesses. Magnetic and gravity maps have been useful in delimiting the rift in Kansas; the geophysical patterns suggest that dike and fracture systems associated with the rift continue at least to the southern border of Kansas (Yarger, 1985; Van Schmus and others, 1993).

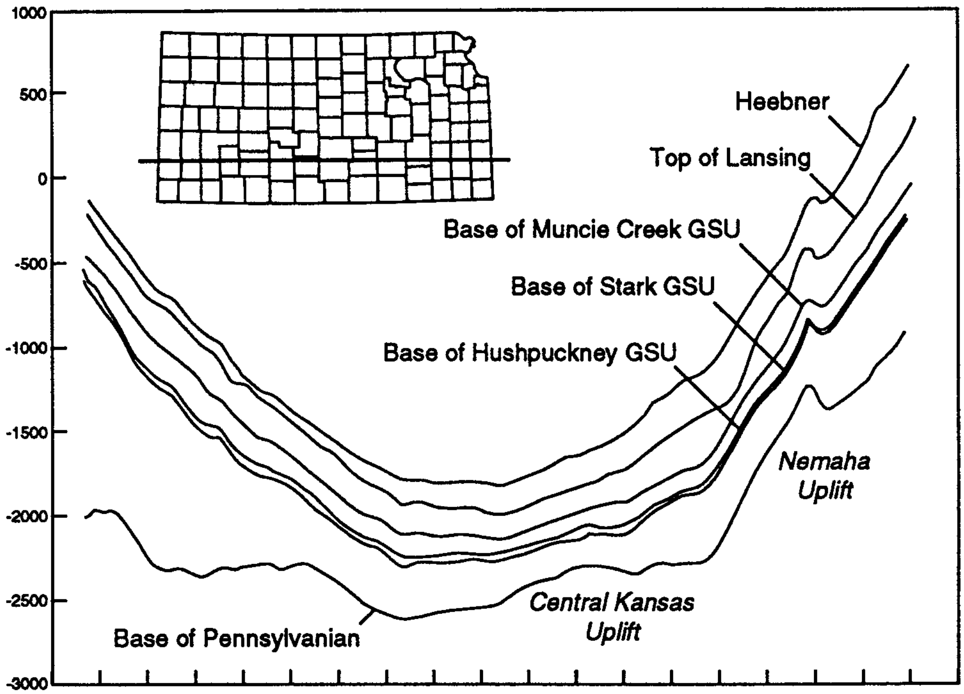


**Figure 8. East–west cross section across southern Kansas showing structural and thickness variation in units used in this study. Vertical scale in feet below sea level. Horizontal ticks are 20 mi apart.**

The Precambrian provinces can be divided into terranes that can be further subdivided into blocks. Subdivisions of the Precambrian provinces of Kansas also are recognized elsewhere in surface exposures. For example, the Mazatzal province of Arizona (Karlstrom and Bowring, 1988) is equivalent to the sCP of Kansas (Van Schmus and others, 1993). Unfortunately, the subdivisions cannot be well defined in the subsurface.

## POTENTIAL FIELDS GEOPHYSICS

Geophysical studies of potential fields have provided important perspectives on basement composition and heterogeneity in Kansas. None of the basement in Kansas is exposed and direct observations are limited to the approximately 3500 wells that penetrate the Precambrian. Interpretations of the geology, tectonics, and composition of the basement are greatly facilitated by geophysical information, especially that shown on state-wide gravity and magnetic derivative maps produced by Yarger (1985, 1989), Lam and Yarger (1989), and Xia, Miller, and Steeples (1995).

Gravity surveys include 31,000 observations, reliable to 0.1 mgal, covering the entire state (Lam and Yarger, 1989). Average spacing between stations in the north–south direction is 3.2 km in western Kansas and 6.4 km in northeastern Kansas. Average east–west spacing is 1.6 km for the whole state (Lam and Yarger, 1989).

Airborne magnetic data were acquired in Kansas in the late 1970's along 72,000 km of flight lines spaced 3.2 km apart in an east–west direction with tie lines spaced 32.2 km apart in the north–south direction. Yarger interpreted the Precambrian terranes of Kansas using spectrally filtered magnetic maps produced from these data, in conjunction with information from well samples (Yarger, 1989).

Second-order trend surface residual maps of the gravity and magnetic fields prepared by Xia, Miller, and Steeples (1995) were used in this study to identify features of the geophysical fields

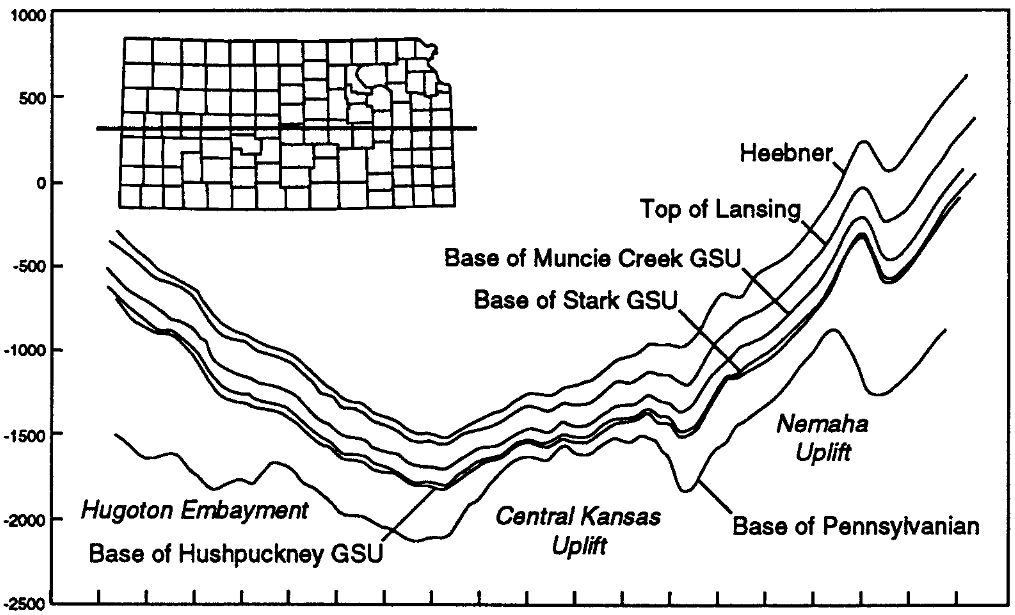


**Figure 9. East–west cross section across central Kansas showing structural and thickness variation in units used in this study. Vertical scale in feet below sea level. Horizontal ticks are 20 mi apart.**

that correspond with the regions found by regionalized classification. Figure 11 is a map of gravity residuals and Figure 12 is a map of magnetic residuals, rescaled for easier comparison to other maps in this report. The grids for these maps were taken from Kansas Geological Survey Maps M–41E and F (Xia, Miller, and Steeples, 1995). An unpublished map of the reduced-to-pole second vertical derivative of the total magnetic field intensity also was utilized in the comparison.

## REACTIVATION OF PREEXISTING BASEMENT STRUCTURES

For many years geologists have appealed to reactivation of preexisting structures to explain persistent tectonic and depositional features. For example, geologists have recognized the correspondence or coincidence of some elements of surface drainage and topography with underlying structures for nearly 100 years. The first giant oil field discovered in the United States was the El Dorado field in Kansas, detected by surface mapping of features that reflected a prominent subsurface structure (Fath, 1921). Since the 1920's, explorationists in Kansas have used shallow core drilling to detect or confirm shallow structures developed over more substantial deep-seated features. Although many of these structures were developed during a primary episode of major activity, repeated reactivation of some features is strongly indicated.

# RESULTS

## SHELF/BASIN DEVELOPMENT

Isopach maps utilized in this regionalized classification study are presented and summarized in Watney and others (in press), including the Hushpuckney GSU, Stark GSU, Wea GSU, and Quivira GSU. These, with the lower Muncie Creek genetic set and upper Muncie Creek genetic set, are shown in this report at a consistent scale. Brief summaries of features of these isopach intervals are

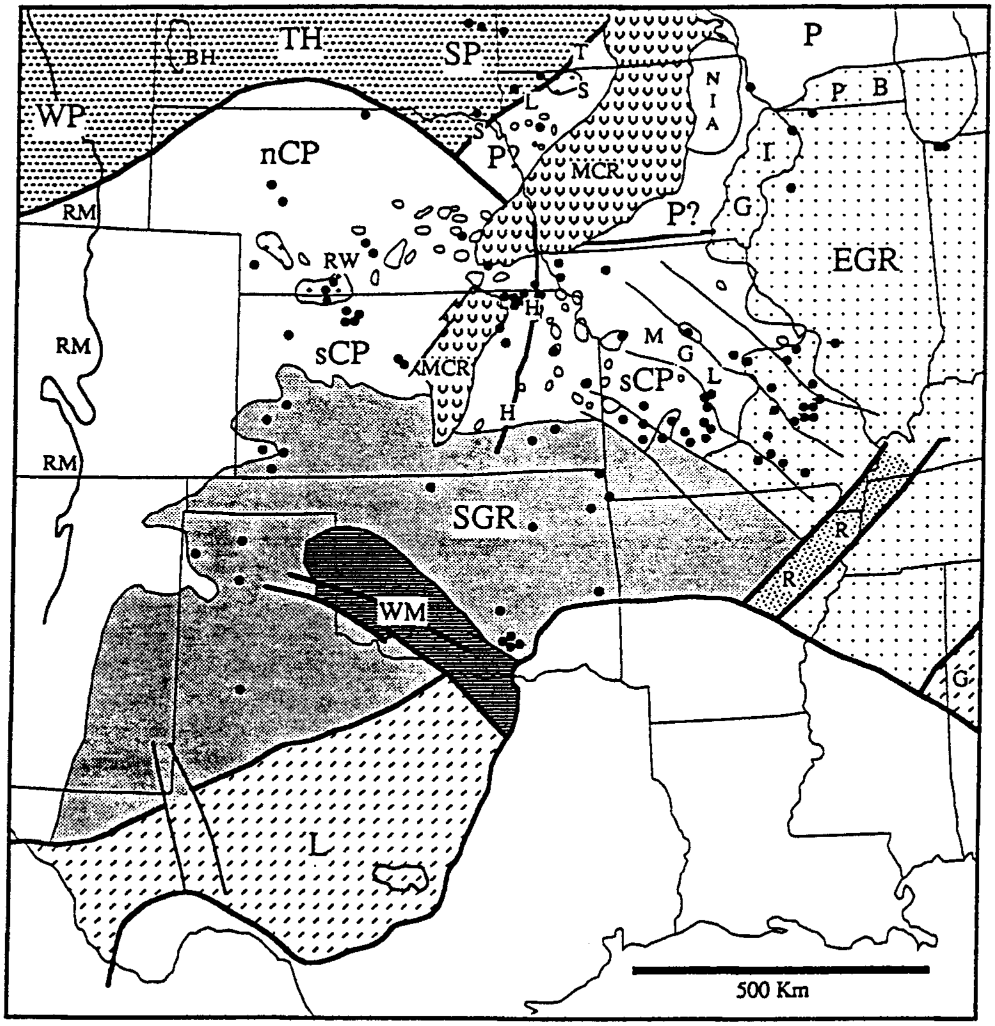


**Figure 10. Major Precambrian geologic features of the western Midcontinent region. Provinces in study area include the southern Central Plains orogen (sCP), Midcontinent Rift (MCR), and southern granite–rhyolite province (SGR). From Van Schmus and others (1993).**

presented below, but the reader is referred to Watney and others (in press) for more details.

### Hushpuckney Genetic Stratigraphic Unit

Local areas of thinning on the shelf are apparent over the Central Kansas Uplift. Thickening also is greater in areas of the shelf such as the southern Salina and Sedgwick basins. Trends in changes of thickness on the Kansas Shelf are oriented to the northwest in the western part of the state, to the north–northeast in the central part, and to the east–northeast in southeastern Kansas. Figure 13 is an isopach map of the Hushpuckney genetic stratigraphic unit.

Cores and samples indicate that thick oolitic grainstones accumulated in the Hushpuckney genetic stratigraphic unit in the Hugoton Embayment. These porous carbonate grainstones form northeast- and northwest-trending rectilinear lobes. Thicker oolitic grainstones are limited to the southern edge of the shelf in southeastern Kansas, where they form a narrow rim of porous carbonate

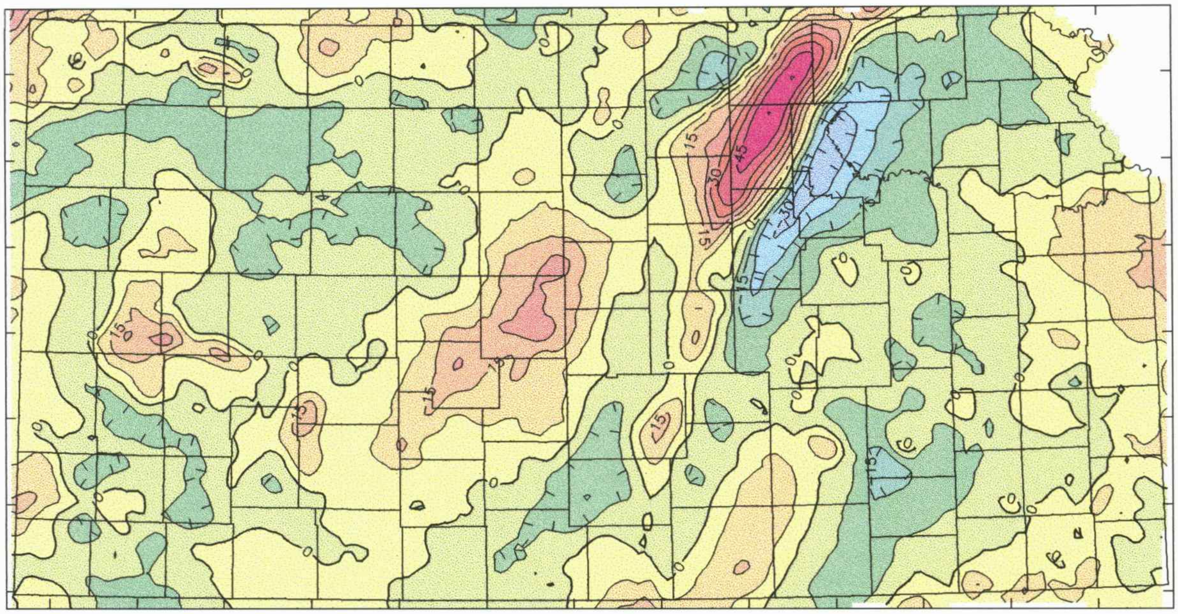

Figure 11. Residual Bouguer gravity map of Kansas, with second-order regional trend removed. Negative residuals are greens and blues, positive residuals are yellows and oranges. Contour interval is 7.5 milligals. After Xia and others (1995).

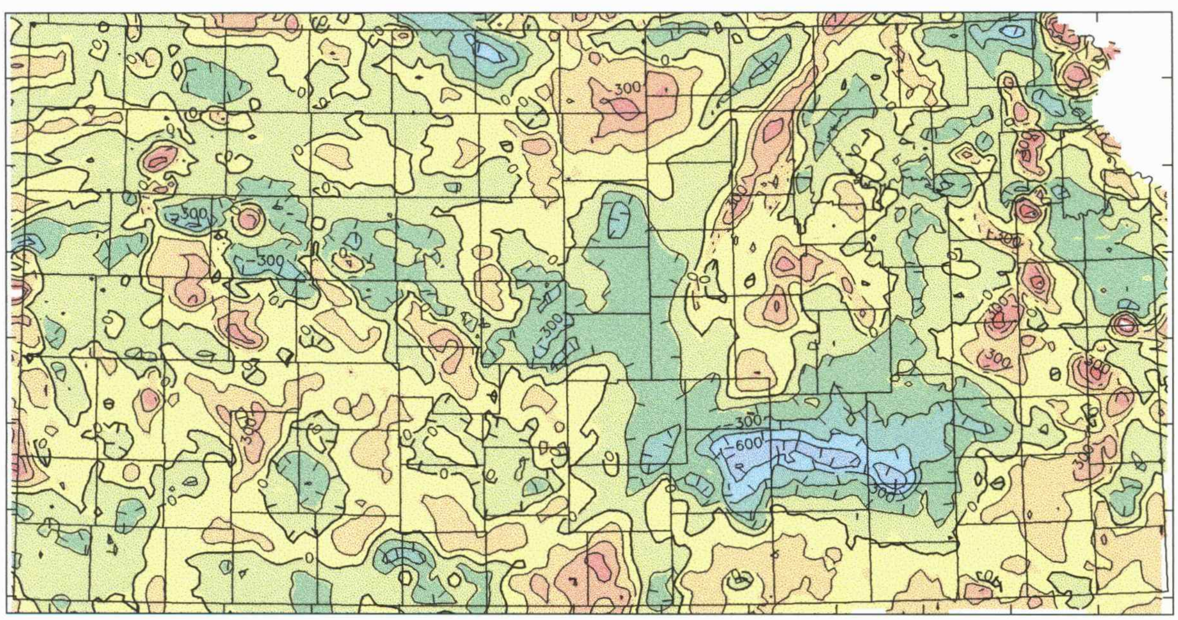

Figure 12. Residual aeromagnetic map of Kansas, with second-order regional trend removed. Negative residuals are greens and blues, positive residuals are yellows and oranges. Contour interval is 150 nanoteslas. After Xia and others (1995).

rock. Apparently, the shelf in southwestern Kansas was steep enough to sustain currents and waves which produced a thick, stacked succession of oolitic grainstone deposits.

The Hushpuckney genetic stratigraphic unit also is associated with an influx of clastics, the Ladore Shale, that partially filled the lower shelf in southeastern Kansas. The clastics probably were derived from the Ouachita Mountains as sediments overfilled the Arkoma Basin (Bennison, 1985). Siliciclastics entered the system from the east, probably terminating oolite deposition. To the west, the area was apparently too distant from the source for flooding by siliciclastics, so shallow-water oolite deposition and sediment accumulation persisted for a longer period. These shallow-water carbonate facies were very sensitive to changes in the slope and elevation of the shelf. Local studies indicate that the grainstones consist of separate stacked stratigraphic units that often are separated by subaerial exposure surfaces (French and Watney, 1993). The minor cycles defined by the exposure surfaces also punctuate the upper part of the Hushpuckney GSU in the area of mixed clastic/carbonate accumulation along the lower shelf in southeastern Kansas (Watney, French, and Franseen, 1989).

### Stark Genetic Stratigraphic Unit

The isopach map of the succeeding Stark genetic stratigraphic unit also reveals thickening toward the basin (Fig. 14). Areas of thinning are again apparent over the Central Kansas Uplift. Cores and samples indicate that thick carbonate buildups in the form of oolite and phylloid algal mudbanks developed along the southern shelf margin. This younger carbonate margin was displaced approximately 20 mi (32 km) northward (toward the land) compared to the underlying Hushpuckney GSU, suggesting a moderate backstepping or drowning event.

### Wea and Quivira Genetic Stratigraphic Units

Overlying the Stark genetic stratigraphic unit are the Wea and Quivira genetic stratigraphic units, the uppermost units of the Nuyaka Creek genetic set. Isopachs of these two genetic stratigraphic units (Figs. 15 and 16) reflect continued infilling of the lower shelf and the resulting loss of topographic relief along the shelf margin in Kansas. The thicknesses of these genetic stratigraphic units over much of the shelf are less than the thicknesses of underlying units, indicating loss of accommodation space because of infilling during earlier cycles of this genetic unit. Relative thinning in the Wea GSU is apparent over the Central Kansas Uplift, but the only area of substantial increase in thickness is in extreme southeastern Kansas near the Arkoma Basin. Apparently, significant sediment accommodation was limited to the southeastern area.

The Quivira genetic stratigraphic unit exhibits less than 20 percent of the variation in thickness of the underlying sequences, indicating a significant loss of sediment accommodation space across Kansas by this time. The genetic stratigraphic unit also exhibits a large, broad area of thinning that extends well eastward of the Central Kansas Uplift (Fig. 16). Thick grainstones also were restricted to the lowermost shelf during deposition of the Quivira GSU, producing a facies pattern resembling that of the preceding Wea GSU.

### Muncie Creek Genetic Set

The Muncie Creek genetic set is divided into two intervals, an upper, predominantly siliciclastic succession above the top of the Stanton Limestone and a lower carbonate-rich interval extending from the Stanton Limestone to the base of the Muncie Creek Shale.

The most prominent feature on the isopach of the lower Muncie Creek genetic set is a narrow band where the interval is unusually thick, adjacent to an abruptly thinning area associated with

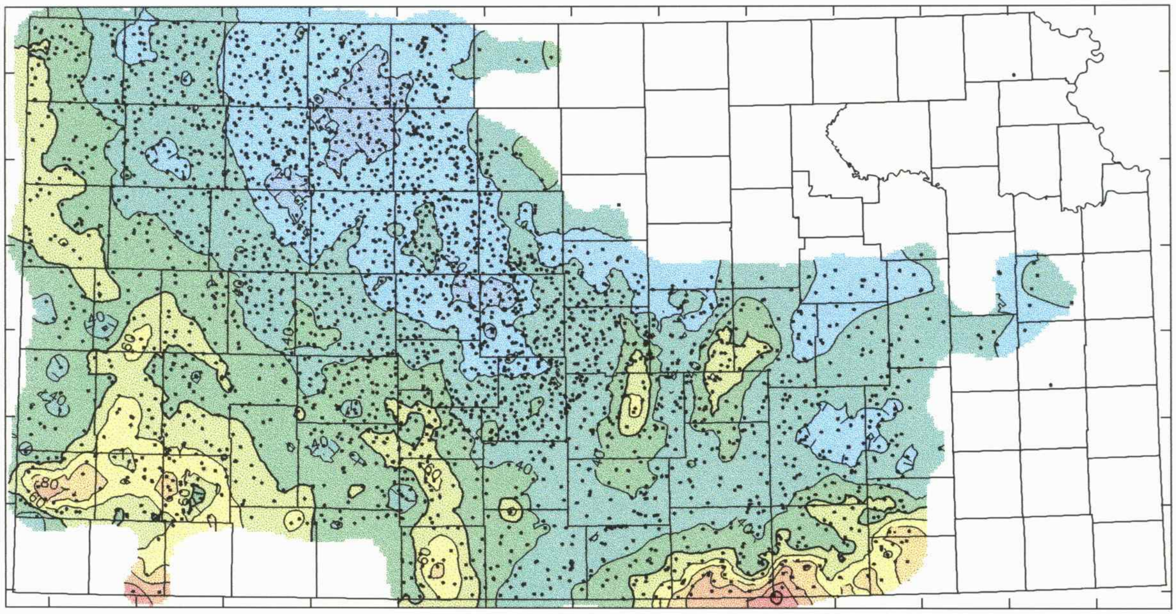

**Figure 13. Isopach map of the Hushpuckney genetic stratigraphic unit in Kansas. Contour interval is 10 feet. Isopach based on exponential semivariogram model with sill = 76.0, range = 92,756, and nugget = 13.0.**

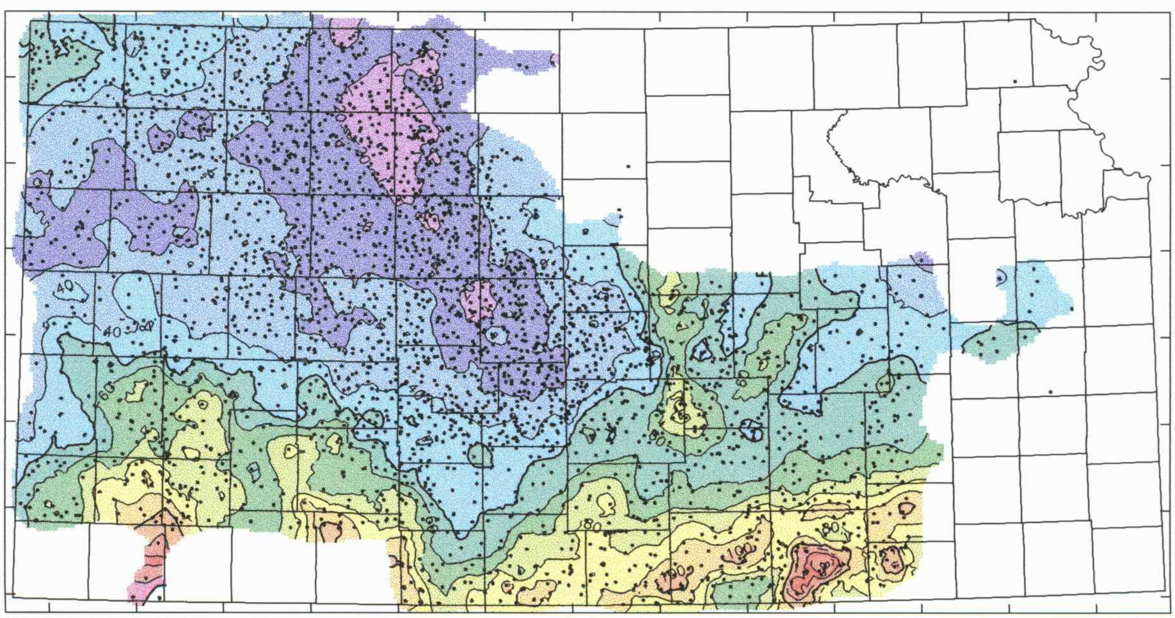

**Figure 14. Isopach map of the Stark genetic stratigraphic unit in Kansas. Contour interval is 10 feet. Isopach based on spherical semivariogram model with sill = 116.3, range = 69,252, and nugget = 23.2.**

the shelf margin (Fig. 17). This marks the "Lansing carbonate bank," which thickens at the shelf margin and thins rapidly into the basin to the south. The shelf margin is rhombic in shape, trending northeast on the western margin and northwest along the eastern portion. The northwest trend of this eastern bank margin is parallel to the Fall River tectonic zone but farther south (Berendsen and Blair, 1991). The drowned area is associated with the highest subsidence rate during the Upper Pennsylvanian (0.35 m/ka) identified in Kansas. The bank margin coincides closely with the current Sedgwick Basin. The interval abruptly thickens by half immediately east of the Nemaha Uplift, reflecting increased accommodation that was probably associated with increased subsidence in the Cherokee Basin.

Another prominent feature on the isopach map of the lower Muncie Creek genetic set is a northeastward trending lineament that bisects the Central Kansas Uplift in central Kansas. The southern portion of the Central Kansas Uplift forms a distinctive rhombic block of thinner interval whose edges trend northeast and northwest. This pattern is not seen on isopach maps of lower intervals. This "block" corresponds to an area of prominent northeast-trending faults that parallel the Midcontinent Rift System. Southwestern Kansas was a broad area of pronounced thickening toward the Anadarko Basin.

The interval from the Stanton Limestone to the base of the Heebner Shale is the upper siliciclastic-rich portion of the Muncie Creek genetic set; an isopach map is shown in Figure 18. This interval is marked by a prominent, uniform southeastward thickening across the southern Central Kansas Uplift and extending into southeastern Kansas. The upper Muncie Creek genetic set is uniformly thin to the northwest. The boundary between these two areas, which we refer to as a hinge line, corresponds with the northwestern edge of the rhombic positive block developed in the lower Muncie Creek genetic set. This positive block on the Central Kansas Uplift apparently tilted to the south.

North of the hinge line, siliciclastics of the Douglas Group are very thin and include thin carbonates (Iatan and Haskell limestones). Cores from wells in this broad, thin region in northwest Kansas indicate that rocks in portions of the Douglas Group are distinctly red. This suggests there was less sediment accommodation space in the northwest and more emergence leading to more pronounced oxidation; either the area was uplifted structurally or sea level fell. However, regional cross sections (Figs. 7 and 8) indicate lateral accretion of the shelf and infilling of the basin by siliciclastics during this time, suggesting that a lower sea-level stand was associated with the upper Muncie Creek genetic set. Redox profiles based on Th:U ratios from logs taken at various locations indicate more oxidizing conditions. This also suggests greater emergence during the later time of deposition of the Muncie Creek genetic set. The reduction in sediment accommodation space was at least shelf-wide in the study area. Dominantly clastic deposition in the upper Muncie Creek genetic set was restricted to southern and eastern Kansas, presumably to areas that were lower in elevation and closer to the sediment source.

## REGIONALIZATION OF THE KANSAS SHELF

The clustering phase of regionalization is illustrated in Figure 19, which shows the partial dendrogram produced using Ward's clustering algorithm applied to interval thicknesses from the 3096 wells used in the study. Clustering indicates that 15 clusters are appropriate, so only the final stages of 15 and fewer clusters are shown. The dendrogram indicates the relative similarities between clusters, and the approximate affinities between individual clusters and the larger groupings from which they emerged. At the lowest level of the dendrogram, the numbers correspond to those assigned to regions in the following discussion; colors on the diagram correspond to those used on the regionalization map.

The next step in the regionalization process is to map the probability of class membership at every location in the study area into each of the 15 classes. As an example, Figure 20 shows the

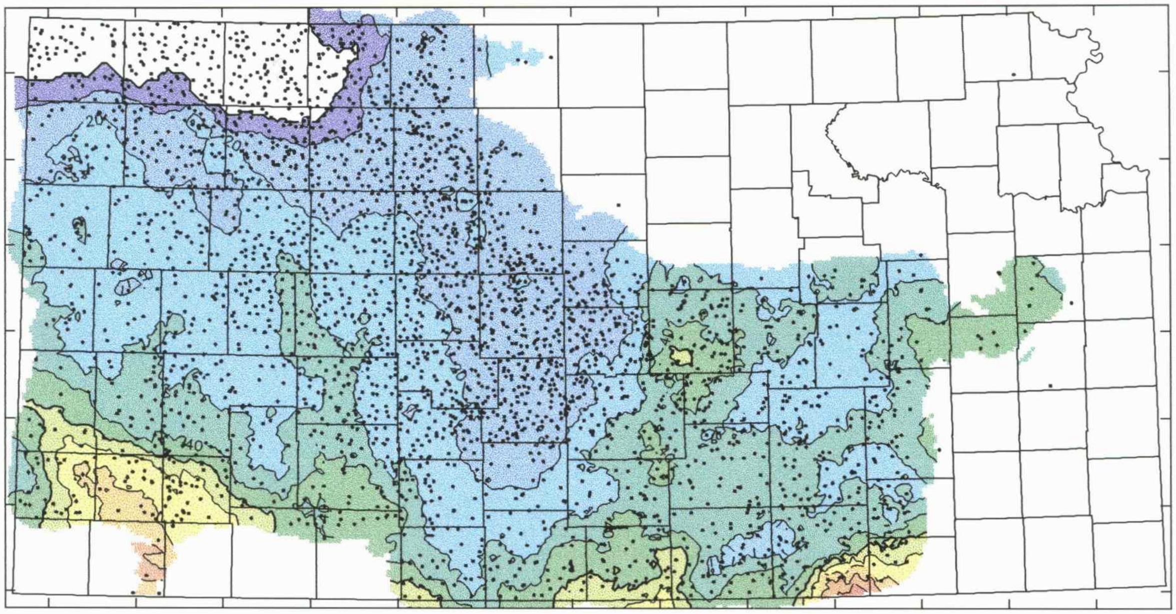

**Figure 15. Isopach map of the Wea genetic stratigraphic unit in Kansas. Contour interval is 10 feet. Isopach based on gaussian semivariogram model with sill = 96.9, range = 99,417, and nugget = 24.2.**

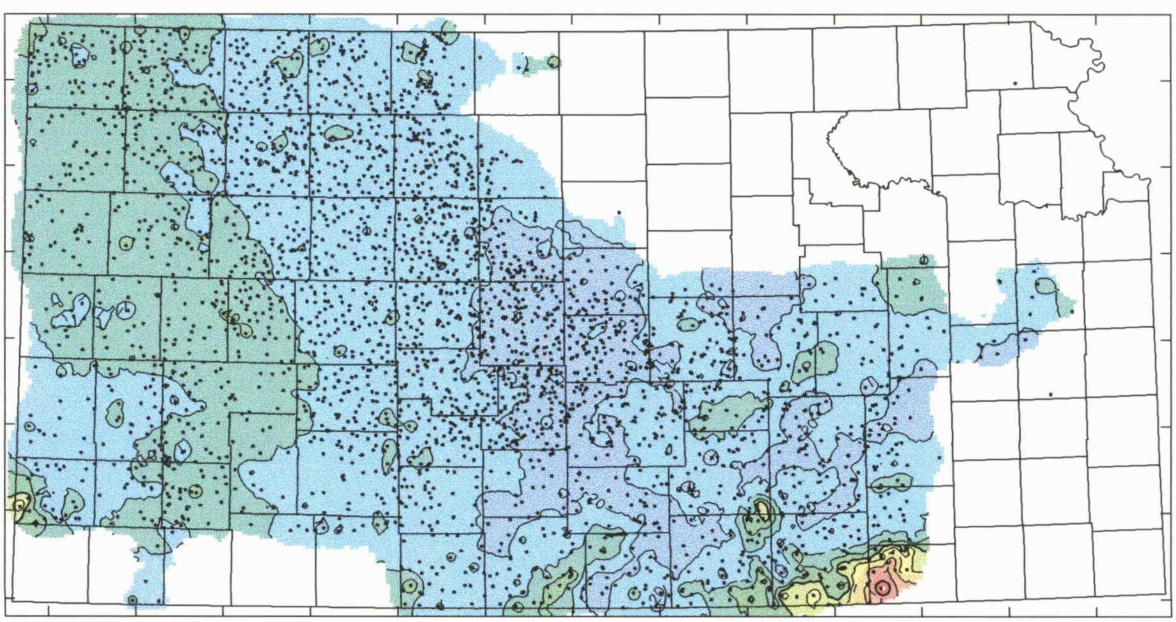

**Figure 16. Isopach map of the Quivira genetic stratigraphic unit in Kansas. Contour interval is 10 feet. Isopach based on nested semivariogram model with nugget of 1.7, gaussian model with sill = 24.2, range = 148,217, plus exponential model with sill = 18.0, range =12,352.**

probability of correctly classifying each well into class 4. The conditional probabilities are determined by a Bayesian transformation of the Mahalanobis' distances (similarities) between each well and the centroid of cluster 4. Spatial continuity of the probabilities can be estimated by computing an experimental semivariogram of the probability values. For cluster 4, an appropriate model is a nested spherical model: nugget = 0.0002 + spherical (sill = 0.018, range = 106,980) + spherical (sill = 0.031, range = 62,354), which indicates good spatial continuity of the probabilities. This model can then be used in kriging to estimate and map the probability of being correctly classified in cluster 4, forming the map shown in Figure 20. Within areas shown in shades of yellow to red, the probability of belonging to cluster 4 is very high; within areas that are shades of blue, the probability of belonging to cluster 4 is vanishingly low. Note that the high probabilities define a contiguous area, which is a region.

Equivalent maps can be made for the probability of correct classification as a member of each cluster; each map will be similar in appearance to Figure 20 but will define a region of high probability that occurs in a different location. Since the sum of the probabilities of membership at any point must sum to 1.0 (every well must belong to some cluster), locations of regions of high probability tend to be mutually exclusive across classes. However, there may be areas where class membership is ambiguous, and the probability of correct membership is relatively low (but not extremely low or 0.0) for all classes. Such areas can be identified by mapping the maximum probability of membership in any class, equivalent to the upper envelope that would enclose all of the surfaces in the 15 maps that are similar to Figure 20. Such a composite map of maximum probability of correct membership in some class is shown in Figure 21. Areas in shades of red define distinct regions; these are separated by narrow zones of ambiguous assignment shown in shades of yellow and green. In most instances stratigraphic intervals measured in wells located in these narrow zones have characteristics that are transitional between two adjacent regions. Elsewhere (especially near the edges of the study area) low maximum probabilities may indicate wells whose characteristics are not typical of any cluster, or they may be simply the result of extrapolation at the limits of well control (edge effects).

Figure 22 is the final regionalization, based on the probabilities of correct assignment to membership in one of the 15 clusters. The map is made by assigning a code value (graphically shown as a unique color) to every location in the map area, based on the maximum probability of correct assignment to a cluster at that location. The numbers (and the corresponding colors) assigned to each region are shown in the map legend, and correspond to numbers and colors used in the dendrogram of Figure 19. In the regionalized map, locations whose maximum probability of membership is below 0.5 are colored gray; at these locations, the probability of membership in the most likely cluster is less than the probability that the locality does not belong to the most likely cluster. These are areas of ambiguous assignment and are quite limited in extent.

The 15 regions form 4 distinctive mapped areas (Fig. 23). The first of these consists of several broad, northwest-trending regions (1, 2, 7, and 8) in the western part of Kansas. The second is a central area of elongate regions (3, 4, 5, 10, 12, and 13) that trend northeast–southwest. Third is an area of broad regions (11 and 14) in the east that are similar in shape to those in the first area in the west. A south-central collection of broad, elongate regions (6, 9, and 15) with very distinct subsidence implications constitutes the fourth area. The spatial distribution of these four areas closely accords with the Precambrian provinces—sCP, SGR, and MCR—that are shown in Figure 10. The present configuration of the major features of the basement (Fig. 6) closely coincides with the location of these four areas: the western area is located in the broad Hugoton Embayment and upper, northwestern reaches of the Central Kansas Uplift; the central area is located on northeast–southwest trending structures; the eastern area is mostly east of the Nemaha uplift; and the south-central area coincides with the Sedgwick Basin and southern Nemaha Uplift nearest the active Arkoma Basin.

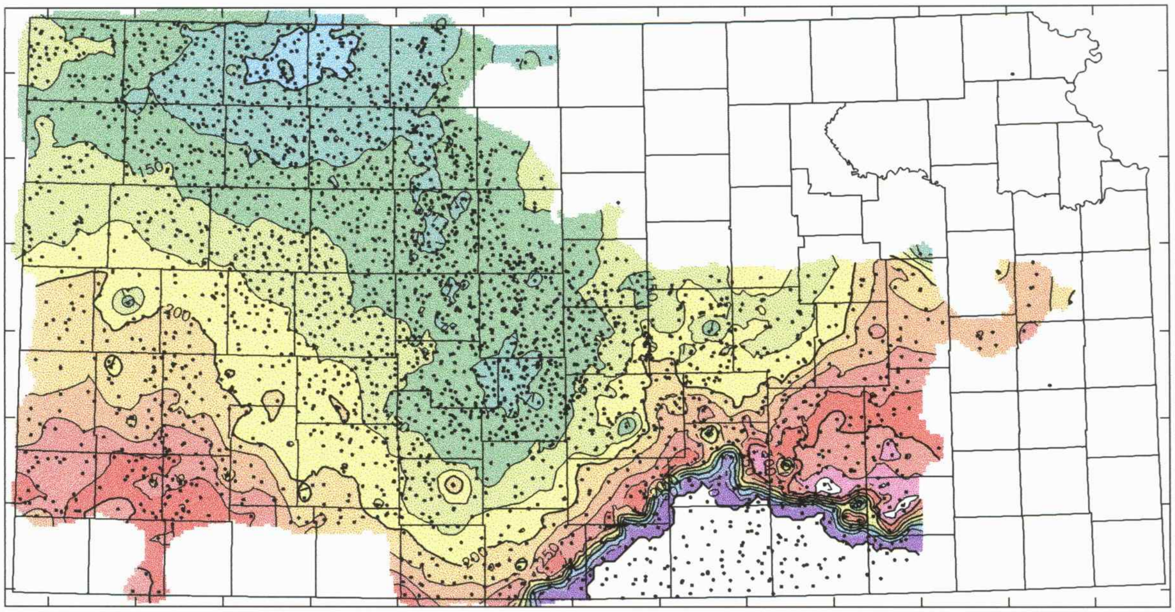


**Figure 17. Isopach map of the lower Muncie Creek genetic set in Kansas. Contour interval is 25 feet. Isopach based on spherical semivariogram model with sill = 2545.2, range = 107,450, and nugget = 133.9.**

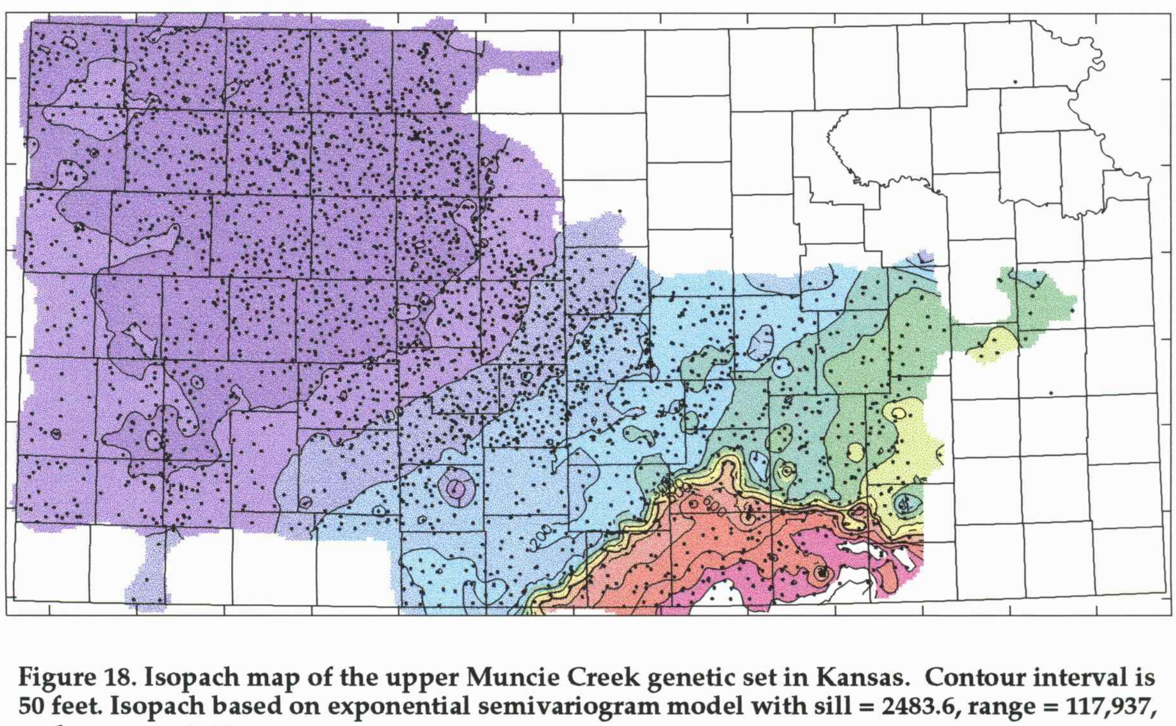


**Figure 18. Isopach map of the upper Muncie Creek genetic set in Kansas. Contour interval is 50 feet. Isopach based on exponential semivariogram model with sill = 2483.6, range = 117,937, and nugget = 57.3.**

### Western Area

Regions 1 and 2 in the western area correspond with the northwest Kansas Shelf, the northern reaches of the Hugoton Embayment, and the northwestern part of the Central Kansas Uplift (Fig. 6). Regions 1 and 2 also are part of the sCP Precambrian province (Fig. 10). Region 2 coincides with clearly defined lineaments on the second vertical derivative map of total magnetic field intensity (Fig. 11). The location of region 2 closely corresponds to the position of the boundary between Precambrian provinces sCP and SGR. This Precambrian province boundary, as interpreted by Xia and others (1995), is identified on Figure 24. Comparison of the province map in Figure 10 and the residual magnetic map in Figure 11 will show there are many similarities with the location and shape of region 2 on the regionalization map in Figure 22.

Mean thicknesses of stratigraphic units within each of the regions and estimated ages of these units were used to examine changes in sediment accommodation space within and between each of the regions. The comparisons are expressed in several diagrams: total mean thicknesses of each region (Fig. 25), mean thicknesses of GSUs and genetic sets (Fig. 26), and conventional subsidence diagrams of age *vs.* depth for mean thicknesses of each region (Fig. 27). Comparison of total mean thicknesses indicates that regions 1 and 2 are the thinnest (Fig. 25). Subsidence also is very low in these regions relative to other regions. The area is highest on the shelf and most distant from the foreland basins and may have undergone less subsidence than regions farther south (Fig. 28). Subsidence in region 2 is greater than in region 1, probably because region 2 is farther south and closer to the directed stresses of the active foreland basin.

Regions 7 and 8 are located in the southern part of the western area. These two regions lie south of the boundary between the sCP and SGR Precambrian provinces (Fig. 10) and conform with patterns in the gravity and magnetic residual maps (Figs. 11 and 12). Xia and others (1995) suggested that separate bodies of gabbro exist within these two regions (Fig. 24), implying that they represent discrete compositional entities. Both regions lie closer to the Anadarko Basin than do the more northern regions of the western area and are characterized by greater total thicknesses (Fig. 25), reflecting greater subsidence. Region 8 is thicker than region 7, particularly in the Nuyaka Creek genetic set, probably because region 8 is closer to the center of tectonism. There is an indication that region 8 also is distinguished from region 7 by deformation (Fig. 27).

### Central Area

The central area of regions coincides with the Midcontinent Rift (MCR) Precambrian province (Fig. 10). The gravity residual map (Fig. 11) shows strong trends that parallel the MCR and the margins of the regions. Class 3 is outlined by a prominent gravity high on this map; this feature is interpreted by Xia and others (1995) as indicating the presence of gabbro associated with the MCR. Other regions along the central area also are associated with gravity and magnetic anomalies (Figs. 11 and 12). In particular, strong northeast–southwest lineaments on the second vertical derivative map of total magnetic field (Fig. 28) coincide with the boundaries between regions formed by regions 3, 4, and 5. Region 10 is oriented and parallel to these regions without the substantial geophysical anomalies (Figs. 11 and 12). Earlier studies of similar lineaments farther north along the MCR, based on seismics, well logs, and rock cuttings, suggest the lineaments are the result of shallow gabbro or basalt brought near the surface of the Precambrian basement along fault blocks (Berendsen and others, 1988). The boundaries of the regions thus seem to correspond to compositional and structural anomalies in the shallow basement.

Subsidence plots of regions 3, 4, 10, and 5 show progressive increases in subsidence rates toward what were foreland basins in the southeast (Fig. 21). Apparently, the directed stress of the foreland basins propagated northward, but with decreasing intensities leading to reactivation of preexisting structures.

Region 12 is a southerly extension that split off from region 3 late in the classification procedure. The two regions exhibit very similar subsidence values, although those of region 12 are somewhat

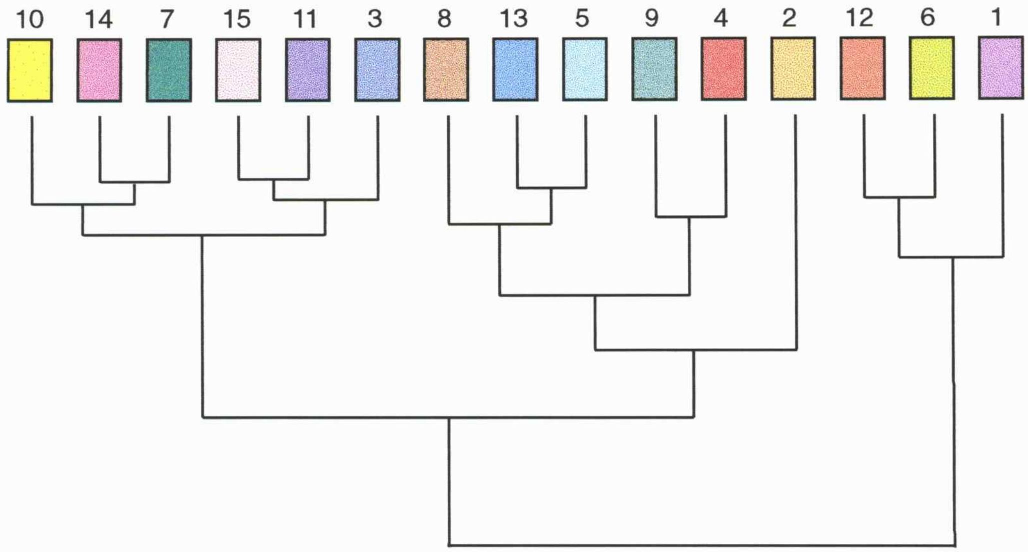


**Figure 19. Dendrogram showing order of clustering and approximate relationships between regions. Clusters are identified by number from 1 to 15; colors correspond to those on regionalized map shown in Figure 22.**

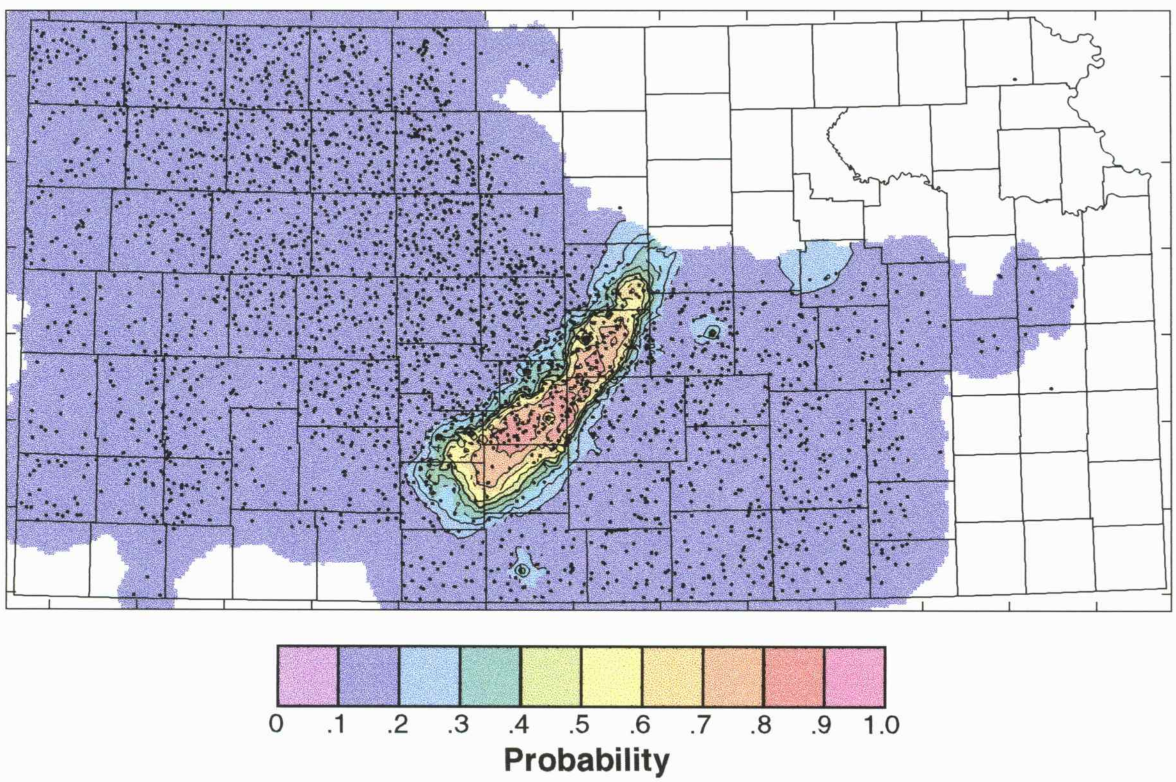


**Figure 20. Probability of correct classification as belonging to group 4, for a regionalization of the Upper Pennsylvanian of Kansas into 15 regions. Contour interval is p = 0.10.**

greater. Region 12 is a rhombic-shaped block that appears to be an extension of MCR trends, but lies south of the boundary between Precambrian provinces sCP and SGR (Fig. 10). Its greater rates of subsidence may be attributable to being part of the southern SGR province in closer proximity to the foreland basin. The intersecting Precambrian province boundaries appear to control the character of reactivated blocks of overlying sediment, judging from the distribution and associations of the regions. An analogous relationship between basement province boundaries probably has led to the shapes of region 5 and region 4 (Fig. 22).

### South-Central Area

Regions 6, 9, and 15 are south of and bordering the prominent magnetic low (Fig. 11) and the Precambrian province boundary between the sCP and SGR (Fig. 10). On the west side, the border of the area coincides with gravity and magnetic features associated with the MCR. The area seems to be beyond any significant influence by the MCR. These regions are characterized by the most subsidence of any region (Fig. 27). Within these regions, the early Muncie Creek genetic unit apparently accumulated during a period of sediment starvation. A pronounced carbonate shelf margin developed to the immediate west and north where carbonate sedimentation kept pace with subsidence, leading to the accumulation of thick carbonate intervals (Watney and others, in press). This was the site of increased early subsidence during the time of deposition of the Nuyaka Creek genetic set (Figs. 17 and 18). During the time of the upper Muncie Creek genetic set, sedimentation filled in the space created by earlier sediment starvation. This area has the shape of a rhombic block whose outline is closely related to basement heterogeneities, further evidence for reactivation.

### Eastern Area

Region 14 is coincident with a large magnetic low known as the "Wichita low." The region is situated at the southern edge of the sCP basement province and borders the Nemaha Uplift to the east and the MCR on the west; there is a strong correlation between basement features and the region. A large carbonate bank developed in the lower Muncie Creek genetic set. A line of apparent structural flexure borders this region on the south, beyond which the carbonate bank is lost because of sediment starvation (Watney and others, in press). There is an apparent cause-and-effect relationship between the location of the carbonate bank and the structurally controlled hinge line.

Region 11 is a large broad area residing on the east flank of the Nemaha Uplift. It overlies part of the sCP Precambrian basement province and is characterized by greater thicknesses of strata than immediately to the west.

## SUMMARY

Basement reactivation along structural and compositional weaknesses is clearly defined by regionalized classification. The key factors in deformation of the Kansas Shelf are proximity to active foreland basins with generally greater deformation closer to the Anadarko and Arkoma basins; position within the three basement provinces sCP, SGR, and MCR; and compositional and structural differences within the Precambrian provinces as expressed in gravity and magnetic derivative maps and reflected to some extent in present-day structures. Quantitative information supplied by regionalized classification provides useful perspectives that facilitate geologic interpretation. Although the number of classes for regionalization are chosen, once this is specified the boundaries between regions are determined automatically by the statistical model, using only information in the data.

Further characterization of the regions that have emerged from regionalized classification is warranted. It may be especially valuable to assess the development of stratigraphic traps along

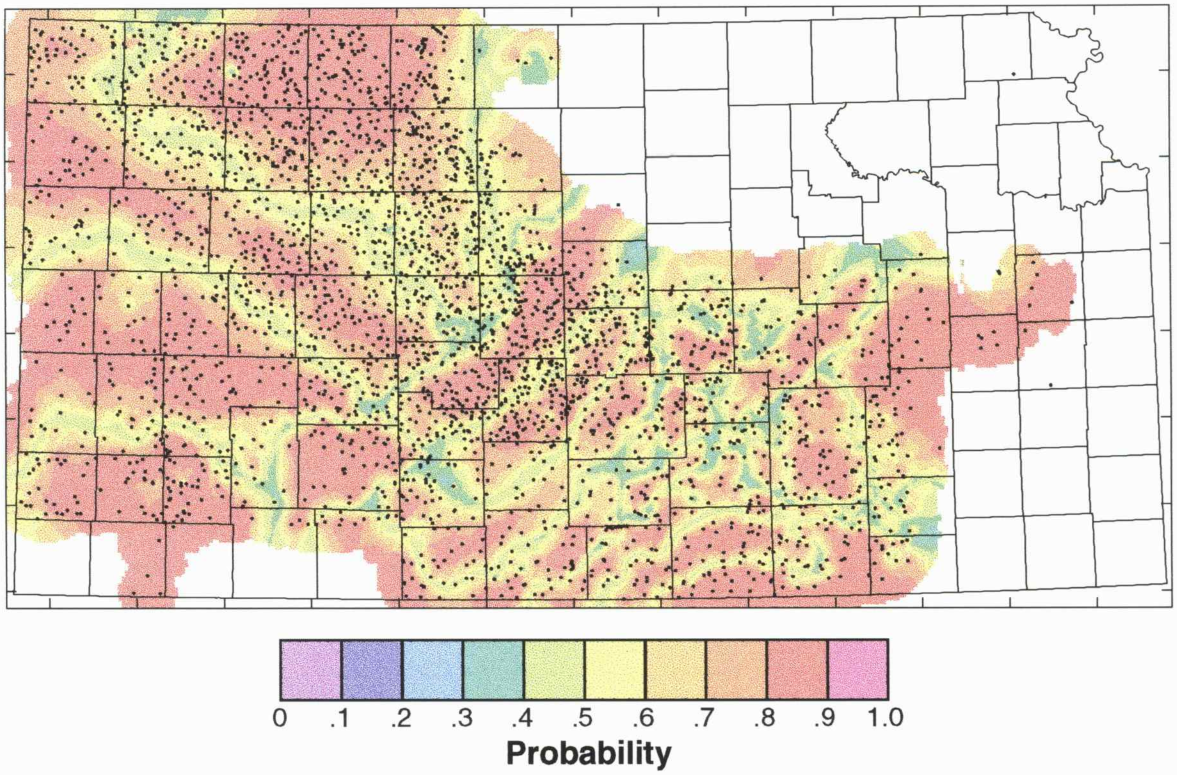


**Figure 21. Maximum probability of correct classification in the assigned group, for a regionalization of the Upper Pennsylvanian of Kansas into 15 regions. Contour interval is p = 0.10.**

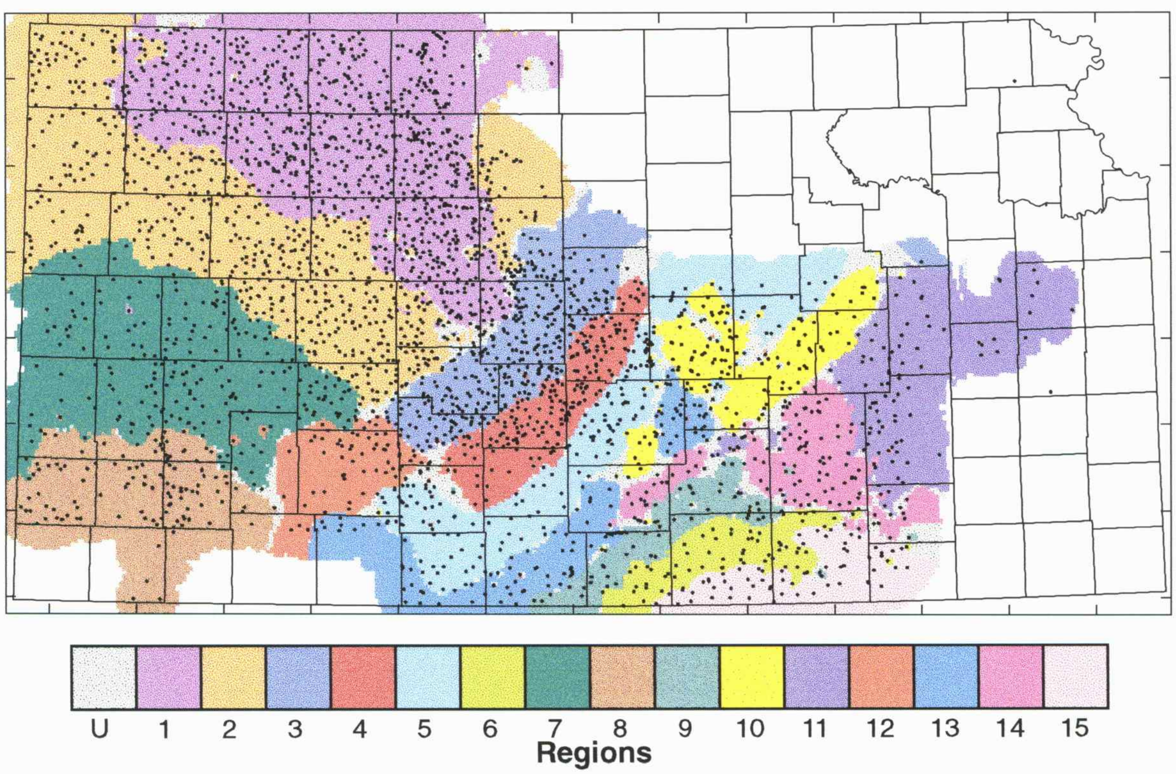


**Figure 22. Regionalized map based on Upper Pennsylvanian genetic stratigraphic units and genetic sets in Kansas. Regions are identified by number from 1 to 15 and are shown in colors. Areas in grey (identified as U) are unclassified because the probability of correct classification is less than p = 0.5.**

region boundaries and to test if regional boundaries coincide with conduits for fluid migration along unhealed fractures and possible fault systems.

### Sediment Accommodation Space

Large lateral variations in sediment accommodation space can be the result of differential subsidence. This study shows that differential subsidence on the Kansas Shelf is closely related to movement along basement blocks, in part driven by tectonism in the foreland basin. Such subsidence in the presence of directed stress fields leads to focused differential movement along boundaries between basement blocks; these blocks are reflected in the regions defined by regionalized classification. Sediment accommodation space apparently was amplified along block boundaries, such as the marked contrasts in sediment thickness of the carbonate bank complex in south-central Kansas that adjoined the time-equivalent, sediment-starved lower portion of the Muncie Creek genetic set. The carbonate bank developed on the southern edge of several less rapidly subsiding blocks, while more rapid subsidence occurred on blocks to the south. Frequent eustatic changes of high magnitude led to sediment starvation on the southern blocks as that portion of the shelf was drowned. In contrast, sufficient elevation was maintained to the north on adjacent, higher blocks that subsided less rapidly, leading to carbonate deposition and the growth of marine banks.

Our study confirms that the Upper Pennsylvanian geologic history of the study area is that of a sedimentary response along a basement structural hinge that was episodically active. Sea floor relief was exaggerated for a time until sediment filled the space or subsidence ceased. Each structural episode of subsidence did not necessarily result in the same response, depending on other controlling factors such as the sediment surface elevation, sea-level history, and sediment supply.

### Hydrocarbon Migration and Entrapment

Hydrocarbon migration and entrapment may be significantly affected by reactivated structural features in the basement. Flexures in strata overlying zones of basement reactivation may be gradual and of low magnitude. Brittle rocks such as dolomite and limestone may be more fractured than normal or the fractures may be more open within the zones marking boundaries of basement blocks where deformation is focused. Fluids may migrate upward and laterally along the pathways or conduits formed by such fracture systems. Episodic deformation suggests that fluid movement might be modulated as trapped hydrocarbons were released for remigration. The extent and orientation of fracturing may have changed significantly through time as stress fields changed and different basement blocks were reactivated. These factors suggest that stratigraphic and diagenetic hydrocarbon traps associated with structural reactivation may be identified using regionalized classification. GSUs and genetic units of different ages should be examined using regionalized classification to identify the loci of other potential stratigraphic traps.

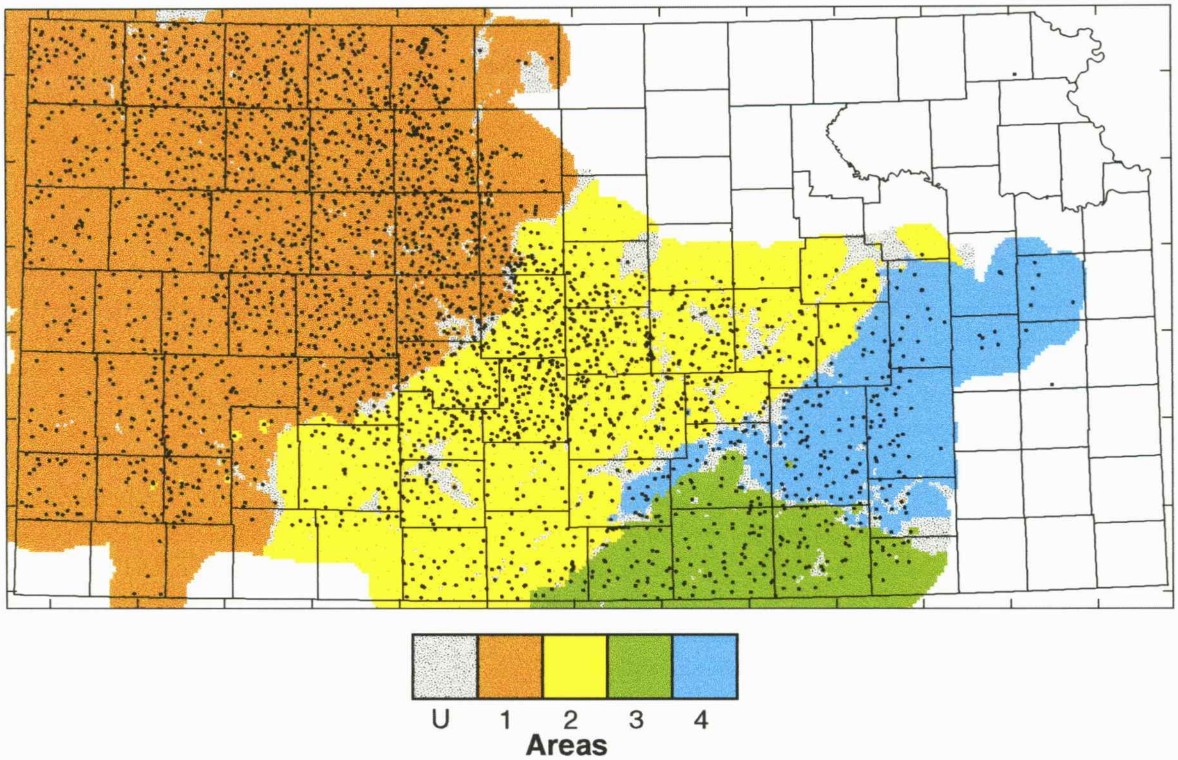


**Figure 23. Regions defined by regionalization and shown in Figure 22 combined into four areas on the Kansas Shelf. Western area (1) is composed of regions 1, 2, 7, and 8. Central area (2) is composed of regions 3, 4, 5, 10, 12, and 13. South-central area (3) is composed of regions 6, 9, and 15. Eastern area (4) is composed of regions 11 and 14. Areas in gray (identified as U) are unclassified because the probability of correct classification is less than p = .5.**

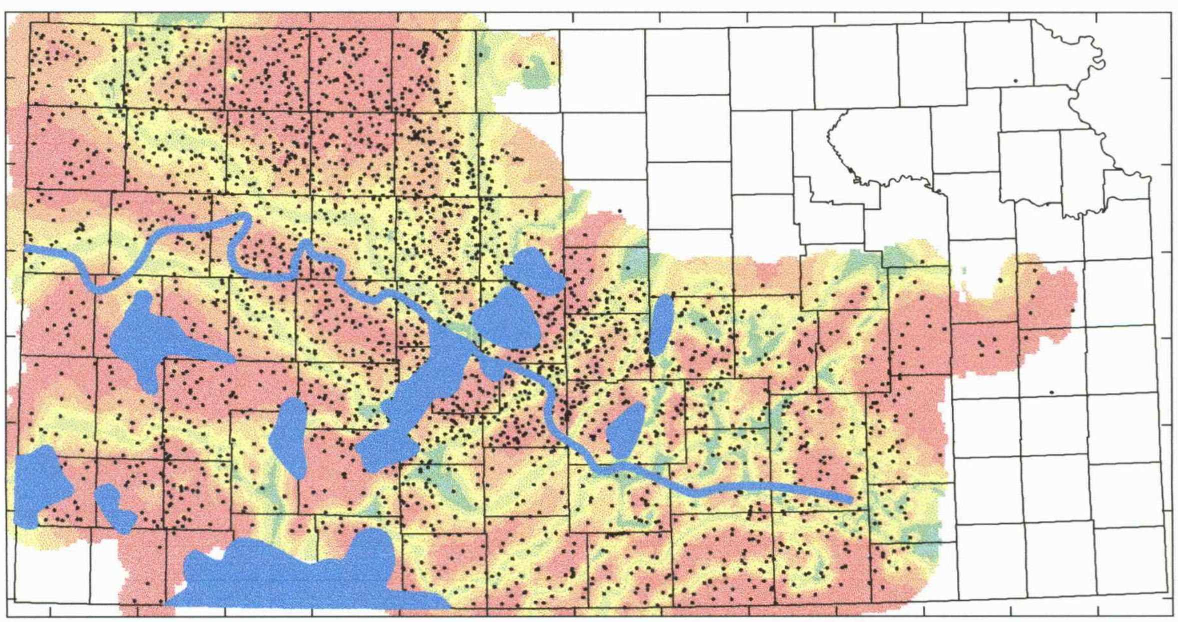

**Figure 24. Precambrian terrain boundary (heavy line) and areas of basalt or gabbro (blue) overlain on map of maximum probability of correct classification into regions (Fig. 21).**

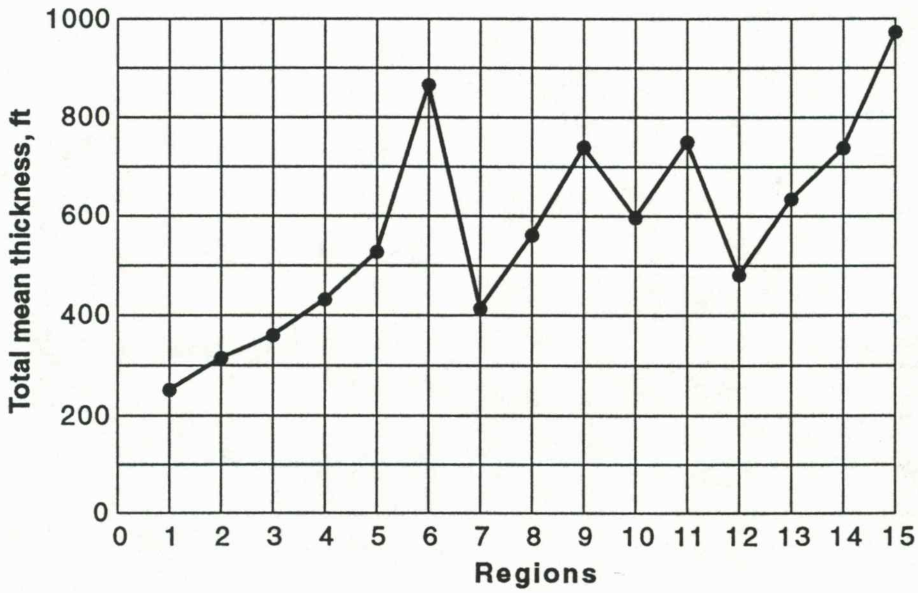


**Figure 25. Total of the average thicknesses of all stratigraphic intervals used within each of the 15 regions.**

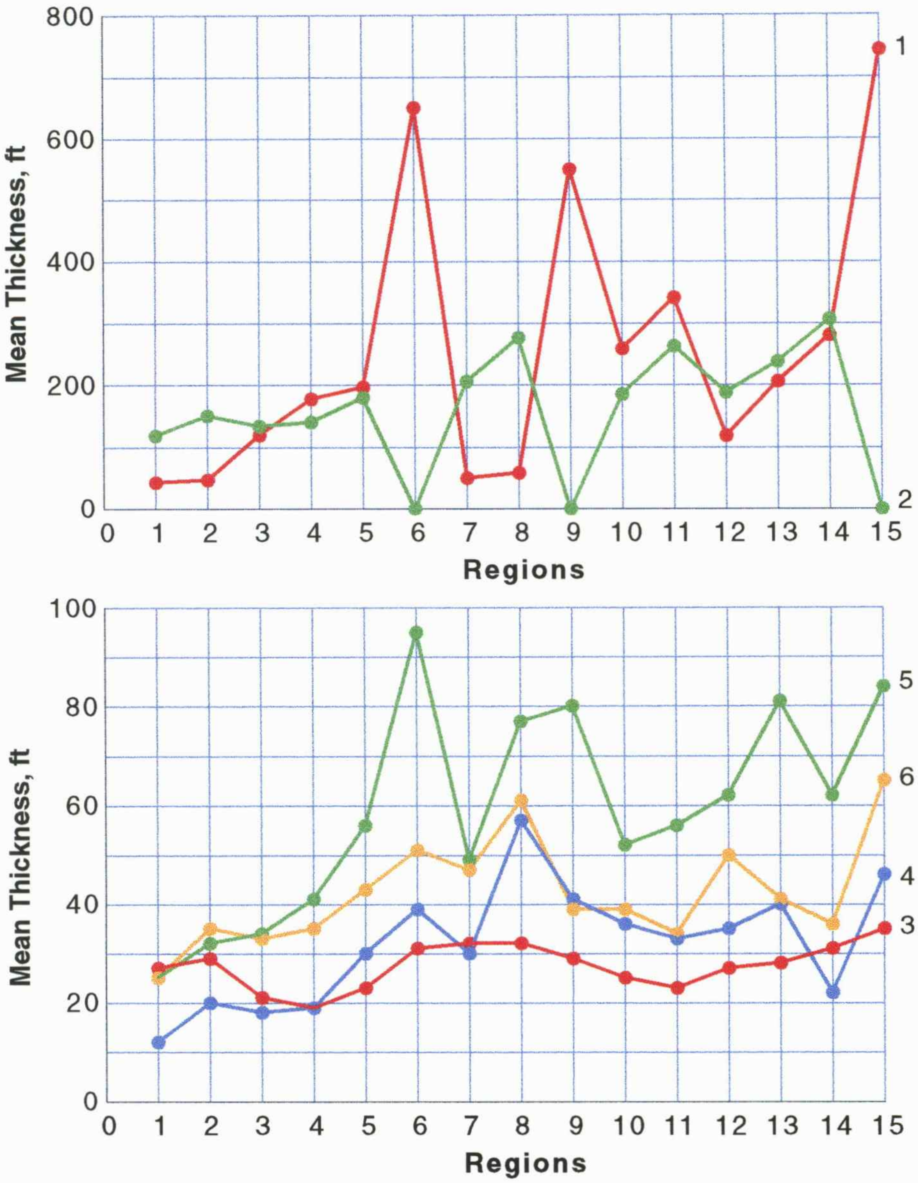


**Figure 26. Mean thicknesses of genetic stratigraphic units and genetic sets in 15 regions of Central Kansas Shelf. 1 = Upper Muncie Creek genetic set; 2 = Lower Muncie Creek genetic set; 3 = Quivira GSU; 4 = Wea GSU; 5 = Stark GSU; 6 = Hushpuckney GSU.**

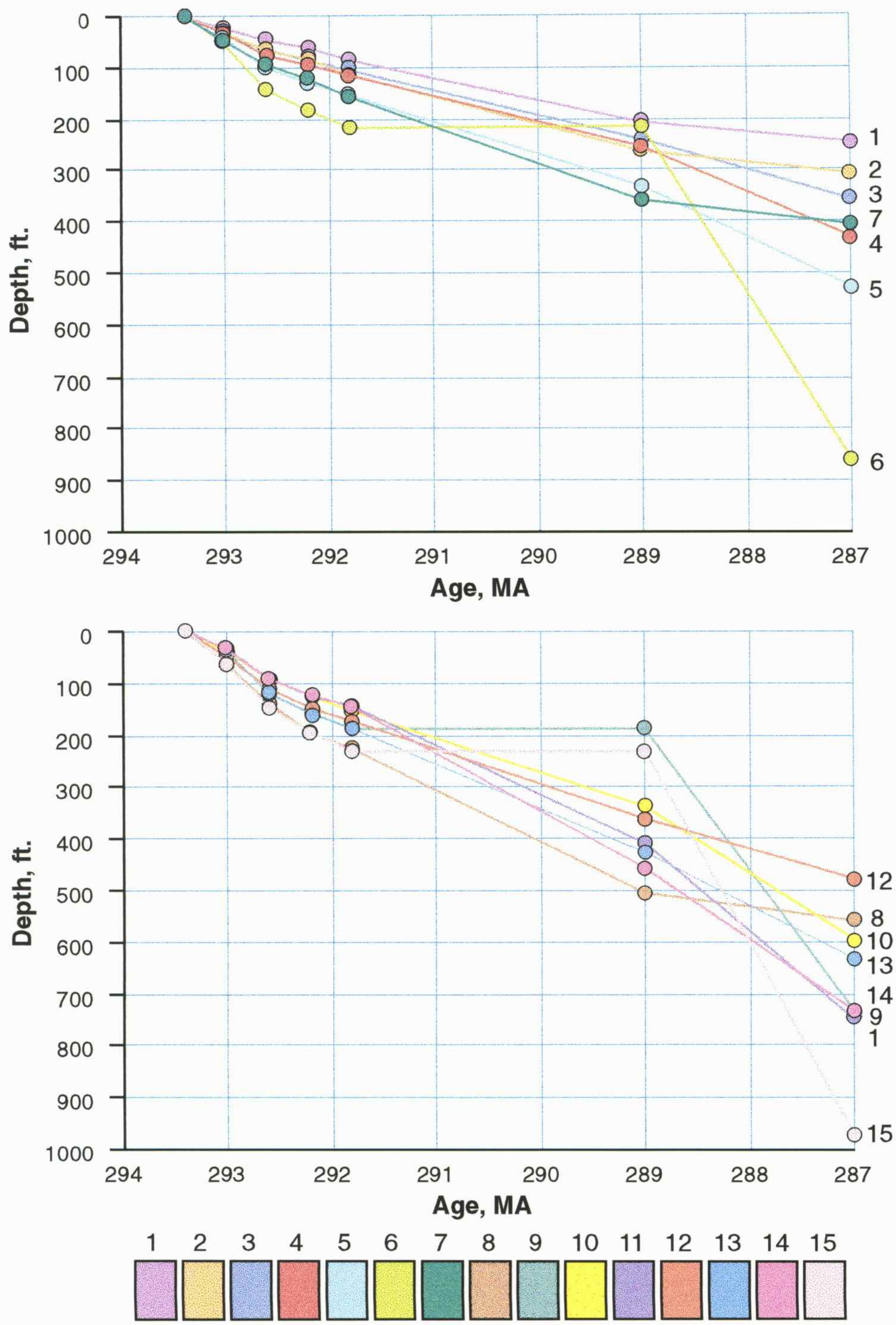


**Figure 27. Subsidence curves for regions on the Central Kansas Shelf. Numbers and colors correspond to regions shown on regionalization map (Fig. 22).**

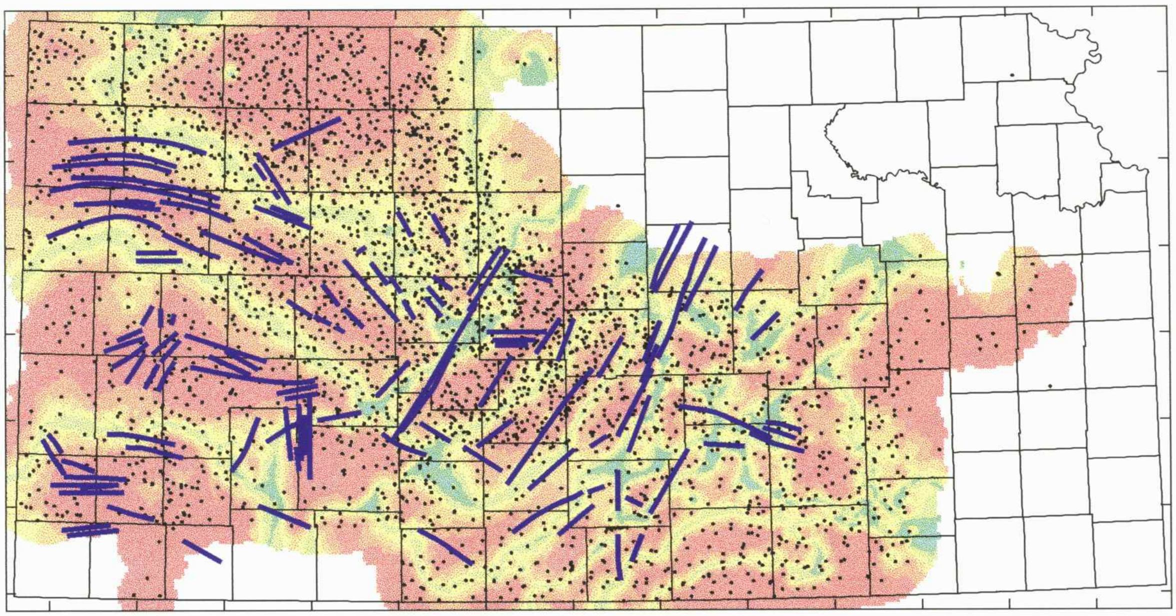

**Figure 28. Lineaments (blue lines) from the second vertical derivative map of total magnetic field intensity, overlain on map of maximum probability of correct classification into regions (Fig. 21).**

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