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# PATTERN RECOGNITION IN COMPUTER MAPPING AND TREND-SURFACE ANALYSIS USED TO DEFINE PETROLEUM-RESERVOIR DISTRIBUTION IN THE MIDCONTINENT, U.S.A.

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## ABSTRACT

*Thin widespread carbonate-dominated cyclothems of the Missourian Lansing and Kansas City groups were deposited across Kansas on a gently tilted 350+ km-wide shelf bordering the rapidly subsiding Anadarko basin. Similar cyclothemic deposits of Late Pennsylvanian age are found throughout the Midcontinent and in many parts of the world. The possible causes of this cyclothemic sedimentation are re-evaluated based upon a comparison of the depositional and early diagenesis that have affected four similar successive cyclothems in the Kansas City Group over a wide area (80,000 km$^2$) in the subsurface of western Kansas using cores, cuttings, and wireline logs. Patterns and trends of sedimentation recognized here are important in defining new areas of prospective reservoir development.*

*The shoreline advanced and retreated across the shelf during each cyclothem, depositing a veneer of shallow-water restricted-marine regressive carbonates and eventually exposing this carbonate to subaerial processes and meteoric freshwater diagenesis. A regressive shale capping the cycle is generally very thin or absent and commonly contains paleosols.*

*Analysis of the regional maps including trend-surface mapping of stratigraphic and structural data reveals that progressive, contemporaneous, epeirogenic deformation of the shelf significantly affected sedimentation and diagenesis in these cyclothems. These changes included first, variable but generally less subsidence over previously active uplifts such as the Central Kansas and Cambridge uplifts and along the shelf in areas most distant from the Anadarko basin resulting in condensation of lithofacies, loss of black marine shale, early onset of conditions depositing shallow-water facies, and more intense early freshwater diagenesis including fracturing and brecciation of carbonate rocks. Second, increased subsidence occurred along portions of the shelf closest to the Anadarko basin that was most active during deposition of the earliest two cyclothems. The increased subsidence resulted in a steepened depositional slope and a more favorable setting for extensive development of high-energy carbonate facies during late regression.*

*Widespread deposits of oolite cover much of the southern portion of this shelf and serve as important petroleum reservoirs. Distinctive wireline log signatures revealed by cross plotting facilitate identification and definition of this deposit. Epeirogenic adjustments which defined the shelf configuration and this facies tract, for example, were secondary in importance to a rapidly fluctuating sea level in controlling the formation of the cyclothems.*

## INTRODUCTION

The nature and distribution of four successive cyclothems in the Missourian (Gzelian) Upper Carboniferous Kansas City Group were examined in a four-year-long subsurface investigation using 37 cores, numerous sample cuttings, and 2300 wireline logs covering over 77,000 km$^2$ in western Kansas (Fig. 1). The study area provides a broad base that permitted an assessment of the effects of the configuration of the shelf and epeirogenic uplift on sedimentation with the major objective being to evaluate the mechanisms causing the cyclothems and to assess trends of favorable petroleum-reservoir development. Trend-surface modeling of marine-interval thickness in these cyclothems was instrumental in characterizing the evolution of depositional patterns between cyclothems.

This paper will first describe the general setting of the Upper Carboniferous shelf and the description and significance of the lithofacies and diagenesis of the four cyclothems. Constraints for assessing possible mechanisms that caused these cyclothems will be summarized.

The study area was part of a broad carbonate-dominated shelf extending from an abrupt, constructive shelf margin along the Anadarko basin in northwestern Oklahoma, to the Transcontinental arch in central Nebraska over a distance of 450 km. These strata completely covered the northwest-southeast-trending, Central Kansas uplift for the first time since its tectonic movement nearly 20 million years earlier during the Middle Carboniferous. The uplift crosses the northeastern portion of the mapped area. An objective was to contrast the area of the uplift with the broad shelf to the west.

The four successive cyclothems are identified by an informal subsurface nomenclature, H, I, J, and K zones in an alphabetic sequence where A represents the uppermost cyclothem in the Lansing Group and the M is the one in the Kansas City Group. Two widespread black shales in the J and K zones facilitate correlation of these strata to equivalent outcropping units.

Similar successions are found in many of the Permian-Carboniferous deposits from around the world in varying tectonic and depositional settings. For example, carbonate-dominated successions on the Russian platform are almost identical in character to the western Kansas Missourian cyclothems (Rauser-Chernovsova et al., 1979). These strata addressed here are part of a similar sequence of prolific reservoirs of Upper Carboniferous age. Major structures have been developed and more subtle stratigraphic traps remain. Means to characterize this shelf sedimentation should greatly assist in defining likely sites for reservoir development.

## COMPOSITION OF CYCLOTHEM

Each cyclothem comprises four lithofacies: the lower carbonate, lower shale, upper carbonate, and the upper shale (Fig 2). The lower carbonate is thin, commonly less than 1.5 meters (m) thick. It is a widespread marine carbonate with a length:thickness ratio of greater than 5 X $10^5$. The basal contact is sharp and with lithoclasts commonly in the lower interval. It is locally sandy and infrequently is underlain by a coarsening-upwards quartz sandstone. The fossil diversity increases upward as does the percentage of micrite. The depositional environment is interpreted to range from very shallow, commonly shoal water, restricted marine near its base to increasingly deeper and more open-marine conditions towards its top. It is commonly referred to as the transgressive carbonate.

The lower shale and lower carbonate are separated by a rapid transitional contact. The lower shale is generally less than two meters thick and varies from green or olive gray-green, massive, silty or clay-rich to gray or black, carbonaceous, fissile clay shale. The black shale is separated by several centimeters (cm) of gray shale from the adjoining facies. The green and gray shales contain open-marine, benthonic invertebrates like brachiopods, crinoids, and bryozoa. The black shales contain few benthic organisms but have abundant fish debris, conodonts, radiolarians, and organic matter and commonly contain phosphate nodules and pyrite. The black shale is typically hard in core but weathers to a distinctive brittle, fissile unit. The lower shale is also referred to as the marine shale.

Mapping of maximum gamma radiation of the marine shale from wireline logs allows the areas of black-shale accumulation to be identified (Watney, 1985a). Black shales generally are associated with gamma-ray readings exceeding 160 API units which is linked to the presence of abundant organic matter. Cores confirm the loss of black shales over positive shelf locations, areas with only tens of meters of relief at most as indicated by the regional isopach mapping. These sites may have been intermittently covered by a low-oxygen layer resulting in destruction of much of the organic matter. This low-oxygen layer apparently was only a thin bottom unit, insignificant in thickness in comparison to the total water column.

The marine shales are thin, but extensive, deposits and represent maximum transgression. The high gamma radiation permits some of the marine shales to serve as unusually good marker beds in the subsurface, particularly in association with other stratigraphic parameters.

The upper or regressive carbonate unit has the greatest diversity in thickness, depositional environments, and diagenesis. It is commonly a diversely fossiliferous, tan to gray, burrowed wackestone in the lower portion and commonly contains micritic carbonate buildups of phylloid algae similar to those in eastern Kansas (Watney, 1985c). The upper portion of the upper carbonate is generally lighter colored with lower fossil diversity. Micrites, commonly dolomitized, usually contain peloids, laminations, mudcracks, fenestral pores, and algal stromatolites in cores found throughout the study area. Skeletal grainstones and oolites are also common. The environments range from low-energy, open-marine conditions in the lower portion to shallow restricted-marine high- or low-energy conditions at the top.

The upper or regressive shale is generally less than one meter in thickness except in the extreme northwestern or southwestern portions of the study area where thicknesses can be up to nine meters. It is non-fossiliferous except for what appears to be lag concentrations of marine invertebrates found uncommonly at its base. Scattered plant fragments are common.

The regressive shale is composed of red-brown siltstone in the north and green and gray silty shale in the south. Paleosols are common in this shale and are recognized by the occurrence of root tubules lined by clay cutans, caliche nodules and rhizobreccias, shrinkage and circumgranular cracks, and general color-mottling and loss of primary depositional textures attributed to pedoturbation.

A continental environment prevailed during deposition of this shale on this shelf. The shale was deposited following carbonate accumulation over most of the shelf except on the extreme north where detrital influx began to occur locally in some cyclothems during shallow marine conditions. This shale then interfingers with the very uppermost portions of the upper carbonate.

The regressive carbonate unit was subaerially exposed prior to the accumulation of the upper shale in most areas in western Kansas. Laminar calcretes, alveolar, and chalky micritic calcification of the carbonate sediment including pendant and meniscus cements, insitu breccias, and conglomerates are found at and near the top of the upper carbonate in all parts of the shelf. Moreover, evidence of pervasive freshwater diagenesis, such as leaching of grains and matrix to form vugs and vertical fissures, is present, commonly followed on the northern shelf by the infiltration of silt and shale under vadose conditions (Watney, 1980; Ebanks and Watney, 1985).

The cores of these units now buried 1300-1700 m below the surface provided excellent preservation of fragile contacts and textures without the effects of modern weathering, aspects that were found to be very important in the interpretation of ancient subaerial exposure. Areas of exposure include the region along the southern portion of the shelf in southwestern Kansas near the northern margin of the Anadarko basin. Increased intensity, greater vertical penetration, and apparently longer duration of exposure, however, are indicated along a northward trend extending unto the upper shelf some 480 km distant from the shelf margin. On the upper shelf the carbonates are locally eroded by channels cutting down at least three meters (DuBois, 1985). This early freshwater diagenesis profoundly affected petroleum-reservoir development in these carbonates.

## MECHANISM FOR WIDESPREAD SHELF INUNDATION AND EMERGENCE

Episodic emergence along an inclined shelf is best accommodated by sea-level change that was independent of sediment progradation and aggradation. Sea level change would have also had to be sufficient to account for the marine shale which was deposited in water depths significantly exceeding the thickness of the sedimentary cycles.

The erosional (hiatal) upper surface of each cyclothem is essentially a formal boundary stratotype (Hedberg, 1976), a surface of nondeposition and limited erosion that developed during a restricted time interval that separates longer periods of deposition of the transgressive-regressive sequences. This would be representative of an event strata. The erosional surface is not dependent on the nature of the sediments that it separates.

The repetition or cyclicity is defined here by the recurrence of these four, widespread lithofacies examined here, each formed in four consecutive events with only minor variation. Subfacies composing these lithofacies and early diagenesis also follow a pattern created by repeated transgression and regression of the sea (Watney, 1980; Heckel, 1983). No direct link, however, is made with time. Similar thicknesses of the successions and proportion of lithofacies between these cyclothems suggest similar lengths of time for their development. The sea advanced onto the shelf and then fell, exposing the shelf each time during deposition of one of these cyclothems. A much more detailed description of the four cyclothems was given by Watney (1985c).

### Global Sea-Level Change

In developing a depositional model for reservoir assessment mechanisms of sea level change must be addressed. Considerations were given to both local epeirogenic and regional and global tectonics, sedimentation processes, and eustatic sea level change. Eustatic sea level change was concluded to be the primary cause of these cyclothems (Heckel, 1977; Watney, 1984, 1985c).

In assessing mechanisms of changing global sea level, Donovan and Jones (1979) concluded that the development and changes in the amount of ice in continental glaciers and changing volume of the ocean-ridge systems have provided the most significant changes in global sea level. During the past 700 years, the melting of glaciers accounted for a loss of 5000 $km^3$ of ice per year giving an average rate of change in sea level of 1 cm/yr, extremely fast in geologic time. Maximum lowering of sea level attributed to glaciation during the Pleistocene is 100 to 150 m.

An extensive, swollen ocean-ridge system resulting from fast seafloor spreading rates was responsible for raising sea level more than 300 m above the present levels during the Late Cretaceous (Hays and Pittman, 1973). The calculated rate of sea-level change during this time was 1 cm/1000 yrs, substantially lower than the rate due to glaciation. The estimated rates of change in sea level required by the Missourian cyclothems is closer to that of the glacial mechanism.

During the late Paleozoic the continents were reassembling rather than breaking up as they were during the early Paleozoic and the Cretaceous. The rate of sea-floor spreading was apparently not high, and mean sea level was falling to levels comparable to those of the present. Crowell (1978), Crowell and Frankes (1975), and others have documented extensive continental glaciation on Gondwana as this supercontinent migrated across the South Pole during the Permian-Carboniferous. This period of glaciation is considered to be closely analogous to the Pleistocene glacial epoch (Fisher, 1982). These periods of lowered sea level according to Fisher were times when climate was cooler, latitudinal temperature gradients were high in the oceans and atmosphere, and the continents near the polar regions were covered with ice. Fisher (1982) referred to these periods as O-states.

### Pleistocene Analogues of Sedimentary Sequences Developed During Glacial Episodes

The characteristics of Quaternary, continental-shelf, sedimentary sequences deposited during glaciation and fluctuating eustatic sea-level conditions on the U.S. Gulf and Atlantic coasts were summarized by Evans (1979). The areas he chose are those lacking significant terrigenous sediment influx. These successions are very similar to the Upper Carboniferous sequence in western Kansas. Evans found that 1) the shelves were rapidly inundated and the transgressive deposits consist of thin, reworked, shallow-water sediments; 2) followed by a condensed interval representing very slow sedimentation rates during high sea-level stand resulting commonly in a diastem or hardground and represented by the accumulation of glauconite, phosphorite, or carbonate debris depending on the level of stagnation; 3) followed by thicker, more rapidly deposited sediment heralding the onset of regressive coastal sedimentation; 4) a slow, staggered fall of sea level occurred during regression forming barrier bars and lagoonal and delta-plain deposits across the continental shelves of the Gulf and Atlantic coasts; and 5) followed by subaerial exposure and weathering terminates the sequences. Evans noted that even friable sediment were not eroded away during exposure and erosion during times of lowered sea level, but depositional relief is commonly preserved.

Glacial-eustatic sea-level change seems to be the primary cause of these cyclothems. Improved understanding of processes, rates, and frequencies of sea-level fluctuation recognized for the Pleistocene should prove useful in understanding the late Paleozoic cyclothems by using the better known Pleistocene as analogues. The regional geometry of these individual cyclothems will be a second-order variation related to the shelf configuration and, in turn, structural development. In particular, identifying local and regional patterns of sedimentation that can be attributed to subdued variations in epeirogenic deformation is desirable. The recognition of these event strata bounded by hiatal surfaces permit the evolution of the shelf setting to be examined in a time-lapse fashion. Trend-surface modeling was sought to aid in characterizing each cyclothem and facilitate in recognition of local and regional changes between cyclothems.

## STRUCTURAL FRAMEWORK

During the accumulation of these Upper Carboniferous strata, western Kansas was the shelfward extension of the Anadarko basin, a "hybrid" foreland basin, a reactivated, downdropped Late Precambrian-Early Cambrian aulacogen. The Anadarko and Arkoma basins are immediately north of a tectonic suture formed by collision of Laurasia, which the study area was a part, and the leading plate boundary of Gondwana (Fig. 3). Plate collision culminated along the Ouachita segment in the Early Carboniferous with thrusting and uplifting of the core region and downwarping of the foreland basins (Anadarko-Arkoma basins). Concurrent movement of intracratonic uplifts including the Central Kansas uplift and adjacent basins occurred during the onset of deformation of the plate margin in the Middle Carboniferous.

Kluth and Coney (1981) proposed that an evolving stress pattern in the interior of the craton developed as this orogenic system migrated to the southwest. Reactivation of the basement occurred on the craton during this time along pre-existing weaknesses. However, research on tectonism along convergent plate boundary indicates that even if tectonism were episodic, tectonic pulses would be too long in duration to have been the cause for cyclothem development. Tectonic episodes which are also generally non-periodic (Beaumont, 1981) are more commonly several m.y. long along convergent plate boundaries. Another component in the evaluation of structure of the area is the recurrence of subtle structural deformation and the effect of epeirogenic deformation on sedimentation.

A paleogeographic map of western Midcontinent for the Gzelian (Fig. 4) identifies a broad carbonate shelf in western Kansas on which the cyclothems were deposited. The Ghezian interval thins northwest in western Kansas into western Nebraska. Anadarko basin as stated above underwent rapid subsidence resulting in the development of an abrupt shelf margin. The northeastern shelf margin of the Anadarko basin was estimated to have presented up to 450 m (1200 ft.) relief (Kumar and Slatt, 1984) across which periodic influx of terrigenous detritus alternated with carbonate deposition. Anadarko basin was then a sediment trap, not a source of sediment, which blocked clastic influx from the southeast from the Ouachitas into western Kansas. An apron of coarse arkosic detritus was located adjacent to the Amarillo-Wichita-Arbuckle uplift and Ancestral Rockies, non of which affected the study area.

## Evidence for Recurrent Structural Activity in Western Kansas

The similarity in structure and isopach maps of many stratigraphic intervals of the late Paleozoic suggest that episodic movement of structures follows a template defined by underlying basement rocks. This is important in the appraisal of the geometry of the depositional shelf during Late Carboniferous.

Basement rocks in Midcontinent USA are primarily Precambrian igneous and metamorphic rocks that lie beneath Paleozoic strata. Weaknesses in the basement most susceptible for movement include faults, fractures, and discontinuities. Gravity and magnetic maps reflecting primarily this shallow basement define trends and patterns, some which have been related to discontinuities in the Precambrian crust.

Kansas is dominated by northwest and northeast structural trends. These also coincide with dominant joint trends. There are 3 distinct Precambrian terranes (Fig. 5). The two older orogenic terranes which dominate the southern Midcontinent probably formed by continental accretion paralleling the ancient Precambrian continental margin some 1625 m.y. and 1400 m.y. ago (Bickford et al., 1981). These are cut by younger narrow CNARS (Central North American Rift System) (1100 m.y.) which crosses the central part of Kansas. Geophysical patterns and lineaments observed in Figures 6 and 7 correlate very well with geology of Precambrian including some anomalies which correlate with present structural trends. In Figure 6 low frequency northwesterly lineaments probably represent the deep-seated structural grain of the Precambrian rocks (Yarger, 1983). Two prominent terranes are distinguished by a heavy line which is also shown in Figure 5. The filtering of the total magnetic field shown in Figure 7 enhances the short subparallel northeast-trending linears which is primarily associated with the shallow basement CNARS (Central North American Rift System). The basement heterogeneity is a significant component in understanding the evolving structural framework of this region. These geophysical maps provide important information for assessing the influence of basement structure and composition on patterns of Upper Carboniferous sedimentation and reservoir distribution.

## Distribution of Petroleum Production Related to Structure

Most wells producing from Lansing and Kansas City groups are on the Central Kansas uplift (CKU) (Figs. 8 and 9). Westward, beyond the CKU, in an area encompassed by this study (Fig. 9), fields are smaller and fewer and a stratigraphic component in traps becomes increasingly important (Watney, 1980). Well spacing in western Kansas is much less than in the CKU and together with recent successes has resulted in active petroleum exploration in the region.

Present structural setting in western Kansas is illustrated by subsea elevation of the top of the regressive carbonate of K zone (Fig. 9). CKU is expressed as a large northwest-southeast-trending anticline with relatively steep reversed dip on its northeast flank (see Cole, 1976). Major deformation associated with CKU preceded deposition of the K zone by some 20 m.y. at the end of the Mississippian Period during a time when Mississippian strata were eroded from the crest of this uplift. Structural configuration of K zone indicates in addition that longer term, but more subdued deformation, continued considerably after the main tectonic event but maintained a size and shape comparable to the earlier event; hence this prolonged deformation is of interest here since it was this movement that may have had a considerable effect on sedimentation. Deformation subsequent to deposition of this layer closely coincides with relief on the Precambrian surface.

A polynomial-trend surface and residuals are used to resolve and to illustrate similarities between the original deformation and later periods of differential uplift which may have been important during sedimentation. The main function of this statistical smoothing technique is to separate regional structure from local anomalies. In order to do this, a good match between the statistical model and structural surface is desired. This match is usually selected on an empirical basis. The choice made here is based on optimizing the fit of the model surface using the least-order polynomial equation.

A simple statistic based upon regression and total sum of square was chosen to establish fit of the polynomial-regression surface to the original data. The sum of squares due to regression is the variation in trend surface (Davis, 1973).

Sum of squares of residuals is composed of differences between original data and trend-surface values. Total variation in original data is the total sum of squares.

Ratio of sum of squares due to regression and total sum of squares is a measure of goodness-of-fit, expressed here as a percent.

$$R^2(\%) = (SS_R/SS_T) * 100$$

It is plotted versus order of trend surface (Fig. 10). A perfect fit to original data means that the regression surface explains 100% of variance, that is, no residuals. A large order of trend-surface equation eventually would provide a close match to an original surface, it it were not too complex. However, a map of deviation of trend surface from original data represented by residual surface may represent significant geological events that otherwise might be masked by a dominant regional trend. The function of trend-surface analysis here is to differentiate local from regional trends and patterns.

A third-order fit was chosen for presentation and analysis minimizing order but acquiring a good fit at the same time. This surface explains more than 90% of original variation. Greater order trends contribute additional fit, but only by smaller increments, which although adding to improved resolution of the fitting surface, do so at the expense of residuals. Therefore, residual maps from greater order surfaces are less meaningful geologically.

The trend surface of the structure top of the K zone is a simple broad south-plunging syncline, the Hugoton Embayment, with upturned edges extending over the CKU and over western Kansas along flanks of the Las Animas Arch. The difference between this smoothed surface and the original is the trend-surface residual (Fig. 11). Notice on the map of residuals that the CKU is more sharply defined than on the original structural map. The finer details of the residual map coincide closely with the Precambrian surface. In particular, note the local northwest-southeast-trending horst block called the Rush Rib (Merriam, 1963) on the Precambrian basement surface (Fig. 12). The feature is identified as a negative residual. This structure is also the site of a magnetic anomaly (Yarger, 1983) and may be the location of a weakness in the Precambrian basement (Watney, 1983). Note that the dominant trend of residuals is northwest-southeast in the western mapped area and northeast-southwest in the southeastern mapped area, coinciding closely with the geophysically defined lineaments in the basement rocks in Figures 6 and 7.

Outline of CKU is defined by a line which follows the truncated margin of upwarped Mississippian strata surrounding the CKU. The edge of the broad area of negative residuals on this map corresponds almost exactly to this earlier formed Mississippian truncation line, border of the CKU formed during the earlier uplift. Correlation of detailed structural anomalies between these two periods of deformation strongly suggests possible recurrent movement along weaknesses in the basement. These maps are compared now with others from individual cyclothems in order to assess effects of structural configuration of the shelf on the deposition of each cyclothem.

## ANALYSIS OF REGIONAL MAPPING OF CYCLOTHEMS WITH WIRELINE LOGS

A series of maps were prepared for each of four cyclothems using information from wireline logs and cores. Watney (1985c) describes the entire series of maps for the K zone and the integration with core data. These maps include marine-interval isopach, regressive-shale isopach, thickness of porous carbonate, maximum $\gamma$ ray recorded alongside marine shale, and ratio of thickness of cyclothem to composite thickness of the four cyclothems studied. Maps derived from wireline logs establish a set of relationships between lithofacies distribution in K zone. For example, exceptionally large porosity developed over the southern shelf correlates well with a broad region of maximum $\gamma$ radiation in marine shale. Regressive shale is thin in this area as compared to the northern (landward) shelf. The marine interval correlates and helps to identify (trace) occurrence of oolitic grainstone common to this area of the shelf. Oolitic grainstone accounts for buildups which develop along the southern shelf in K zone, distant from the northern source of terrigenous clastic influx and flanking positive regions of the shelf like the CKU. All considered, the marine-interval isopach is an acceptable means of summarizing changes in lithofacies that significantly affect measureable aspects on wireline logs.

### Characterizing Log Response

It was necessary to rely heavily on distinguishing lithofacies components of the cyclothems from the wireline-log response. However, log response is generally not unique to the detailed lithofacies because bulk composition of rock can vary considerably. Rather, wireline logs respond to change in lithology, pore volume, and composition of fluid in pores so only generalizations of lithofacies can be made with most available logging suites.

The best reservoir quality in these cyclothems is most commonly associated with rocks deposited originally in high-energy environments. Grain support provides a rigid architecture and network that assists in percolation of undersaturated waters and leaching of grains and mud. Porosity associated with this facies is commonly in the upper portion of the regressive carbonate. Moreover, thick mudbanks are also possible sites for early leaching by meteoric water as shelf becomes emergent or constrains flow of undersaturated subsurface waters. The secondary porosity produced is more varied and more difficult to predict and is found in any portion of the regressive carbonate.

A gamma ray-neutron cross plot of the K zone in the Hughes well in northwestern Kansas (Fig. 13) also illustrates the gamma ray frequency distribution. This distribution is broad including clean carbonate at low gamma radiation to marine shale at high gamma-ray levels. This is typical for the cyclothem on this northern shelf location. Marine shales at gamma radiation above 160 API units are dark gray to black shales and are distinctive on the cross plot and the depth traces of the GR log. Note the irregular but cyclic pattern of the lithofacies succession from transgression through regression on GR-N cross plot and the significant spread between the lithofacies. Thicker shales across the northern shelf also make the interval easy to correlate.

The southern shelf provides a contrasting depositional setting during the K zone which is reflected in the cross plot. The GR-N cross plot in Figure 14 is an oolitic bearing K zone on the southern shelf. The four basic components of the cyclothem can be distinguished on the wireline log. This oolitic rock typically is represented by high neutron porosity and low GR. This consistent response allows extrapolation of oolite from sample cuttings and core, which have led to the conclusion that oolite is pervasive across the southern shelf.

### Stratigraphic Mapping

Objective of the mapping includes defining the configuration of shelf, determining what effects that shelf configuration had on lithofacies distribution, and defining patterns and trends on maps to help interpolate very limited lithofacies data from cores and cuttings and relate to reservoir development. As previously mentioned, the marine-interval isopach is a useful summary map of each cycle.

Figure 15 is the marine-interval isopach of K zone. Thickness of marine (lower) shale is generally insignificant, compared to thickness of regressive (upper) carbonate. Therefore, the primary map represents thickness of the regressive carbonate. Exception to this is in extreme northwest and southwest mapped area where influx of terrigenous detritus occurred. Local carbonate buildups result from accumulation of grainstone (high energy), or mudbank consisting of lime mud trapped by organisms like phylloid algae (e.g., Watney, 1980; Ebanks and Watney, 1985).

The marine-interval isopach map illustrates regionally southward or basinward thickening and suggests that differential subsidence increased to south. Sedimentary facies and diagenesis do vary across shelf sympathetic to this trend and suggest differential relief during deposition of the cyclothem.

Features on the map of the marine interval of K zone (Fig. 15), the lowermost cycle studied, include: 1) thickening along an arcuate trend, concave to west; 32 km wide which runs 240 km from Wallace (WA) County to Stanton (ST) County; 2) thick lobate volume in Haskell (HS) County; 3) elongate multilobed area extending west-northwest to east-southeast; 4) narrow north-south-trending lobe in Rice (RC) and Reno (RN) counties; 5) northwest-southeast trend in west and northeast-southwest in southeastern mapped area; 6) generally a marked regional southward thickening south of 35-40 ft. (11.5-13 m) contours.

Note, all significant local anomalies occur in the southern region. The marine interval is thin over the northern shelf and along the CKU (outline).

Another map identified as particularly useful in interpreting the significance of the marine interval is thickness of porous regressive carbonate (Fig. 16). Data for this map were obtained from porosity wireline logs. Porosity in excess of 8% is generally permeable, with major exceptions being oomoldic porosity (not interconnected unless also fractured or vuggy) and fracture porosity (small porosity values can represent great permeability) (Watney, 1980). Thickness of porous rock is a good estimate of reservoir quality of that rock. Thicknesses are generally less than one meter across the northern shelf and over the CKU. On the southern shelf, thicknesses of porous carbonate locally exceed 18 m (60 ft.) (Watney, 1984).

The patterns on this map closely correspond with the marine-interval isopach map including lobate pattern in southwest 16-24 km wide, and a belt of multilobed porous carbonate development along a 240-km line extending from northwest to southeast. This line closely coincides with the location of the 35-foot isopach of marine-interval thickness. Substantial porosity development occurs in excess of 8 m in the southwestern mapped area. Area is immediately south of site of local thinning. Area of thinning on this map also is thin on marine-interval isopach map. Porosity and interval thickness in general vary closely across shelf; both are thin across northern (landward) shelf.

Cutting samples, cores, and a distinctive log signature reveal that the lobe-shaped porosity development on the southern shelf is oolitic grainstone. Whereas much of this porous carbonate rock is oomoldic and not reservoir quality, the map can be used to identify and to interpret distribution and in turn infer the origin of the thick porous oolitic grainstone. The thickness of porous rock is in an area that straddles what is interpreted as a northwest-trending zone of flexure in west-central Kansas previously identified by Watney (1984). A complex of widespread, thick porous carbonate rock (oolitic grainstone) is developed both along and south of the flexure.

The lithofacies evidence supports the interpretation that the regional change in thickness of the marine interval closely approximates the amount of paleoslope. Oolite banks formed along the flexure zone, interpreted here to represent a break in the slope on this generally gently south-dipping shelf. During basinward retreat of the shoreline and onset of shoal water conditions, the flexure zone became the focus of wind and waves.

## Trend-Surface Modeling of Marine-Interval Thickness

Trend-surface analysis of the marine-interval isopach map is used to determine the regional estimation of paleo-depositional slope and as a means to facilitate comparison of each cyclothem. Moreover, the mapped distribution of trend residuals could be more easily interpreted to define local trends, perhaps related to basement structure.

K and J zones, the bottom and next to lowest cyclothems studied, represent times of extensive oolite accumulation on the southern shelf, but younger I and H zones are notably different. I zone has only a limited oolite development on the extreme southwestern portion of the study area. H zone, in distinct contrast, was deposited on a shelf dominated by low-energy carbonate mudbanks with only local accumulations of grainstone.

Polynomial trend surfaces were computed for marine-interval thicknesses of each cyclothem to facilitate comparison. The trend model that was accepted represented a good statistical fit using a small-order trend. A plot of statistical fit versus order of polynomial surface (Fig. 17) for thickness of marine interval of H zone demonstrates a relatively poor fit of small-order trend surfaces, as well as a slower increase in fit with increasing order. Goodness-of-fit exceeds 80% for all orders of the trend of I, J, and K zones except the first order for K zone. However, goodness-of-fit values are all less than 50% for trend surfaces of H zone. This surface is more complex than others and consequently small-order polynomials do not provide an adequate fit. A plot of skewness of the frequency distribution of residuals versus order of trend-surface polynomial (Fig. 18) uses dimensionless skewness found by dividing the skewness by the square root of the cube of the second movement, or the variance (Davis, 1973).

Analysis of the fit is enlarged here to include the extent that skewness is minimized with increasing order of trend because information provided by skewness appears to have geological significance. In particular, the frequency distribution of both K and H zones are positively skewed.

The fourth-order trend surface of each marine-interval thickness was chosen to make comparisons. The major pattern on these maps is in all cases a primary northwest to southeast oriented thinning associated with the CKU. Constraints of smaller-order fitting polynomial surface enhanced the effect of this major structural feature. Exclusive use of the fourth-order essentially stabilizes the contribution of the CKU, that is, equalizing resolution of local anomalies for each trend surface. A larger-order fit might have been desired for adequate modeling of the more complex H zone, but if this trend were applied to simpler I, J, and K zones, it would have eliminated or downgraded many residuals with probable geologic significance. Choice of a single-trend order also was deemed important in order to minimize variation between residual maps.

## K Zone

The fourth-order trend-surface contour map of the K zone (Fig. 19) expectedly is much like the original surface. Yet, broad patterns necessary for comparison between maps are best observed using the trend-surface map. Thinning is pronounced over the CKU. The flexure zone is located along the 10.7-m (35-ft) trend contour line. Oolite development is south of this line. The map of residuals (Fig. 20) reveals an irregularly shaped positive anomaly in the southwest, south of the more organized arcuate-shaped porous oolite buildup that surrounds the southwest Kansas structurally positive area, active during deposition of K zone. A greater rate of dip off this feature apparently was an optimal site for formation of oolite. In particular, the pronounced buildup immediately south suggests an even greater slope on the southern seaward side, a location most suited for oolite proliferation. Farther east alongside the southwest flank of the CKU another strong positive anomaly is present which can be explained similarly as an oolite shoal.

The southwest structurally positive area (negative residual) and surrounding thick (positive residual) area are small-scale, greater-frequency anomalies. These features are not adequately fitted by small-order polynomial surfaces. The positive skewness of the K zone residuals is attributed to the more extensive northwest-southeast-trending positive elements in the southern mapped area that exceed the thick area defined by the 4th-order trend surface. In general, the most substantial positive residuals are flanking the most structurally positive (thin) areas. These may be favorable sites for prospective reservoir development and warrant more detailed investigations. The positive residuals on the southern shelf represent oolite shoals developed during the later portion of the cycle after wave base had intercepted the sea floor, but before exposure. Bending and subsidence of the shelf probably was strongly influenced by pronounced subsidence of the Anadarko Basin to the south during late Paleozoic. Relative relief over CKU, expressed by an extensive thinning, was also likely a result of differential subsidence, with surrounding areas subsiding more rapidly. Notably, the location of flexure parallels and in some cases coincide with the linear elements in the basement terrane as revealed by the geophysical maps. Local depositional elements in turn generally parallel the flexure approximately depositional strike. Further correlation of the basement anomalies and the stratigraphic maps would be of interest here in reservoir assessment.

The 480-km-long tract of marine shelf extending from southern Nebraska to northern Oklahoma during the K zone had a minimum estimated slope of nearly 0.1 m/km along the southern end of the shelf based on the trend-surface map of the marine isopach (Watney, 1985b). Some 48 m of relief was probably present across the shelf. Subsurface mapping including trend-surface modeling indicates that the regional slope is interrupted by many small flexures and local paleohighs. These local pertubations appear to have been very significant in regards to creation of isolated, high-energy, carbonate environments where grainstones were deposited during southward migration of the shoreline that eventually led to emergence of the shelf. These deposits now serve as modest petroleum reservoirs.

Table 1 summarizes the paleo-depositional slope estimated from the trend-surface maps of the marine interval for all four cyclothems.

| *Cyclothem* | *Slope (m/km) Northern shelf* | *Slope (m/km) Southern shelf* | *Dominant carbonate shallow-water lithofacies in south* |
|---|---|---|---|
| *H* | *.007* | *.007* | *micrite* |
| *I* | *.05* | *.10* | *limited oolite* |
| *J* | *.04* | *.17* | *oolite* |
| *K* | *.05* | *.07* | *oolite* |

*Table 1. Minimum estimates of depositional slope from trend-surface analysis of the marine interval isopachs (Watney, 1985c).*

The fourth-order trend surface of the marine-interval thickness of the H zone (Fig. 21) is characterized by 1) a marked change in the configuration of the shelf from the preceding cycles; with much less range in thickness [5.1 m (17 ft.) (up to 10 m thick) versus 15 to 24 m in other cycles]; 2) no southward thickening; 3) no significant oolitic facies in south; and 4) an unusual area of broad thickening in the west-central mapped area (160 km X 80 km) with up to 12 m of carbonate. The rate of thickening across upper shelf is 0.36 m/50 km = only 0.007 m/km. The rate of thickening of the lower shelf in the southwest is the same as the north which is essentially flat. The dominant northwest-southeast trend of the 4th-order trend-surface residual map (Fig. 22) is similar to other cycles in the western mapped area. Significantly thickened carbonate in the west-central area probably accounts for such poor fit of the polynomial trend surface in H zone. The thickened complex is micrite-dominated carbonate.

Southwest positive appears to have been active again after having no expression during the deposition of the J and K zones and perhaps provided a southern barrier to currents and waves generated in the south. The relatively level protected area northeast of the southwest positive became the site for a large complex of micrite-dominated carbonate buildups during mid-regression.

The very low slope and general stability of shelf seems to have produced a low-energy shelf setting, at least relative to the earlier cycles. Perhaps more rapid regression also occurred, limiting the time when shoreline could rework the shelf and deposit significant accumulations of grainstone.

An extensive area of pronounced thinning is also noted in the southeastern margin of the Central Kansas uplift extending southward off the mapped area. A progressive southeastward migration of the positive area associated with the Central Kansas uplift occurred through the time interval represented by these four cyclothems over approximately 4 million years. The most rapid change began during deposition of I zone.

The strategy for finding petroleum reservoirs in the H zone needs to be markedly different than for the K zone because of the change in lithofacies composition and distribution. Rather the emphasis should be on the search for local micritic carbonate buildups and secondary porosity development in the H zone (Ebanks and Watney, 1985).

The evolution of the shelf in western Kansas during deposition of the four successive cyclothems as revealed by the trend-surface modeling is summarized in Figures 23 and 24.

## SUMMARY

1) Differential structural movement of shelf occurred as it tilted and subsided in conjunction with downwarping of Anadarko basin.
2) Formation of 1st- and 2nd-order structural activity (uplifts and flexure lines) appear to be related to basement heterogeneity and weakness indicated by a) sites of ancestral uplift, b) faulting, c) geophysical anomalies. Isopach mapping is important to identify timing of structural activity with respect to sedimentation and oil migration.
3) Trend surface modeling has assisted in summarizing the regional shelf configuration and local anomalies, some of which are related to petroleum production.

Correlation studies of stratigraphic, lithofacies, and structure including basement anomalies should prove useful in future studies.

4) Precambrian is segmented into geologic terranes, each with varying physical strength, i.e., rigidity, encouraging propensity to operate independently. Some blocks are strong and unitized and generally positive while others are weak and possibly fractured or faulted.
5) Mechanical integrity, orientation and location, and sense and direction of forces define extent of movement of these basement blocks.
6) Evolution of a single tectonic event is associated with variation in stress and in turn extent of deformation.
7) Oscillation of the shelf is not demonstrated, i.e., did not cause the change in sea level needed to produce these marine cyclothems and subaerial surfaces. The shelf moreover was dominated by varying degrees of differential subsidence during successive cyclothems and, in turn, affect distribution of favorable reservoir rocks.
8) Western Kansas and the northern shelf of the Anadarko basin comprised a southward-tilted ramp during the Upper Carboniferous modified by local, resistant, positive elements. Subtle ridges, domes, and flexures significantly affected sedimentation and diagenesis. Porosity distribution is linked closely with grain-supported rocks which either provide the primary porosity or avenues for fluid migration to create secondary porosity.

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## LIST OF FIGURES

Figure 1. Map of the state of Kansas showing the area studied in this investigation (light dotted pattern in mapped area and heavier dotted pattern in area with core only) and that of Watney (1980) in western Kansas (double cross hatched in area mapped and cross hatured in areas studied with core only). The surface outcrop of the Lansing and Kansas City groups is identified in eastern Kansas. The Central Kansas uplift (CKU), Cambridge arch (CA), and the Nemaha uplift in eastern Kansas are recognized on this map as the outlined areas where the Mississippian strata are now missing due to erosional truncation along the edges of the uplifts (Merriam, 1963). After Watney (1984).

Figure 2. Facies comprising Gzelian (Upper Pennsylvanian) cyclothem in western Kansas.

Figure 3. Paleozoic basins in the interior of the U.S. (after Lidiak, 1982) showing the depth to the Precambrian basement in thousands of feet. During the late Paleozoic the interior of the craton was bordered on south by the Appalachian-Ouachita-Marathon orogenic systems defining the southern margin of the basins illustrated here and on the north by the Canadian

shield. To the west of the craton lie the Wyoming platform and the Ancestral Rocky Mountains.

Figure 4. Generalized paleogeographic map of the western Midcontinent during the Missourian illustrating major depositional facies and provenance areas for the siliciclastic sediments (from Rascoe and Adler, 1983). Contours shown represent thickness of Missourian strata in feet. Dominant terrigenous clastic source is the uplifted Ouachitas mountains (OM) in southeastern Oklahoma and Arkansas. Amarillo-Wichita-Arbuckle uplifts (A-W-A), Ancestral Rocky mountains (AR), and Cimmaron arch (CIA) provided coarse-grained terrigenous debris only locally. The only seaway permitting easy access of open marine waters onto the craton during the Late Pennsylvanian was the approximately 100-mile-(160 km) wide pass between the Amarillo-Wichita-Arbuckle uplifts and the Ancestral Rocky mountains (Rascoe and Adler, 1983; Heckel, 1977). Carbonate bank along southeastern Anadarko basin margin is Belle City Limestone.

Figure 5. Precambrian terranes in Kansas and immediate adjacent areas (after Yarger, 1983, modified from Bickford et al, 1981).

Figure 6. Filtered aeromagnetic map of western Kansas (modified from Yarger, 1983). Map is a pole correction of the total magnetic field. The distortion caused by the earth's inclined magnetic field is calculated and subtracted from the original map of the total magnetic field intensity. Yarger concluded that the low-frequency, generally northwesterly trending elements shown here probably represent deep-seated structure of the Precambrian. Yarger identified a prominent boundary between the two terranes of contrasting age shown on this map by the heavy line crossing the mapped area. CKU and CA with the basement faults are also shown on the map.

Figure 7. Filtered map of the total magnetic field intensity of Yarger (1983) depicting the second vertical derivative of the magnetic field. Dark shaded lineaments and patterns illustrate where the gradient in the magnetic field is greatest. The map identifies probable steep contacts between rocks of contrasting magnetization in the shallow basement such as might be produced by faulting or intrusion of mafic igneous rocks (Yarger, 1983). Filtering enhances the short, subparallel, northeasterly-trending magnetic pattern of the CNARS. Line segments likely represent graben and horst system intruded by gabbros. The area of attenuated magnetic signature outlined on this map denotes thick clastic sedimentary strata of the Precambrian Rice Formation, sedimentary rock which filled the rift feature.

Figure 8. Oil fields of western Kansas (see index map inset). Fields that are identified here as solid black areas produce oil from the Lansing and Kansas City groups. The heavy solid lines identify the area of study. Much of the production is from the northwest-trending CKU and more subtle subparallel trends in western Kansas. Northeasterly-trending narrow anticlines are sites of additional oil production from the Lansing and Kansas City groups in the southeastern area of the southern Salina and Sedgwick basins.

Figure 9. Structural contour map of the top of the K zone regressive (upper) carbonate. Sea level reference datum is used. Contour interval is 50 ft. (15 m). Heavy dashed lines are structural lineaments identified by visual interpretation of the contours. Black areas are selected large L-KC oil fields lying off of the CKU and along prominent positive structural features. They are identified as follows: C - Cahoj, J - Jennings, PP - Pleasant Prairie, E - Eubanks, VI - Victory, VO - Voshell, and B - Burrton. Counties are indicated with dashed lines and names are abbreviated. Townships are shown using light solid lines that are labeled along the perimeters of the mapped area.

Figure 10. Goodness of fit in percent versus trend order for top K zone.

Figure 11. Contour map of the third-order trend surface residual of top K zone. Contour interval is 50 ft. (15 m). County lines are dashed and the outline of the Central Kansas uplift is noted by the heaviest black line. The faults that offset the Precambrian basement are noted by the hachured dashed lines.

Figure 12. Contour map of configuration of the Precambrian surface for western Kansas from Cole (1976): southern portion of study area only crossing the Central Kansas uplift. Countour interval is 50 ft. (15m). Dots represent both estimated depths to Precambrian and actual penetrations. Southern corner of study area indicated by heavy line.

Figure 13. Gamma radiation (GR) plotted versus neutron porosity (ØN) for the Gulf #1 Hughes well located in SWSW Section 22-9s-29w found in the north-central portion of the study area. Points are plotted on one-foot increment. Points are identified by lithofacies in the legend. Vertical profiles of the GR and ØN signatures

are shown on the upper portion of the illustration. Normalized GR for the one-foot samples from the K zone are plotted in the upper left.

Figure 14. Gamma radiation (GR) in API units plotted versus neutron porosity (ØN) in percent for the Amoco #A-2 Lee well located in SWNW Section 4-26s-36w in the southwestern portion of the area of study. Points represent readings at one-foot increments over the K zone. The points are identified by lithofacies based on sample cuttings and nearby core:log combinations. Mudstone-wackestone is in the mid and lower regressive carbonate interval. Note the very low GR and relatively high ØN values for the oolitic facies. Vertical distribution of GR-ØN is shown on top of illustration with vertical scale in feet. Frequency of GR values sampled on a per foot basis is expressed as normalized percent for the K zone is shown as a small plot in the upper portion as well. GR values are predominately low values indicative of clean carbonate rock which comprise much of the cyclothem at this position on the shelf.

Figure 15. Thickness of the marine interval of the K zone in the study area of western Kansas including the top of the regressive carbonate to the base of the cycle. Interval of shading is 1.5 m (5 ft.) while the contour lines highlight only the 6.1 m (20 ft.) intervals. Black areas represent thicknesses in excess of 20 m (65 ft.). Selective counties are labeled for reference in text. Subcrop of the Mississippian strata surrounding the CKU and CA is indicated here by a heavy line. Major faults that offset the Precambrian basement are illustrated with heavy dashed hatured lines. Curved line segments identify trends in thickened marine interval described in the text. Counties are abbreviated as follows: WA - Wallace, WH - Wichita, ST - Stanton, SC - Scott, HS - Haskell, FI - Finney, HG - Hodgeman, EL - Ellis, ED - Edwards, KW - Kiowa, RC - Rice, and RN - Reno.

Figure 16. Thickness of porous carbonate rock in the K zone regressive carbonate. Shaded interval is 1.2 m (4 ft.) which is equal to the contour interval. The black area represents thickness in excess of 8 m (24 ft.). Wallace (WA) and Kiowa (KW) counties are identified.

Figure 17. Plot of the statistical goodness of fit of various orders of trend surfaces from 1st to 5th order for the thickness of the marine interval for the H, I, J, and K zones. The goodness of fit is defined as the ratio of the sum of squares due to regression to the total sum of squares. The result is expressed here in percent. The 1st- and 2nd-order fits are less than 40% for the H zone. The 4th- and 5th-order trend surfaces of the marine interval of the K zone are somewhat poorer fit to the original data than the I and J zones. The marine interval of the H zone is least well fit by all of these lower order trend surfaces suggesting a more complicated surface.

Figure 18. Plot of the skewness of the frequency distribution of the trend surface residuals of the marine intervals of the H, I, J, and K zones versus the order of the trend surfaces. The skewness is reduced appreciably for the I and J zones while the K zone shows an increase in skewness.

Figure 19. Shaded isopach map of the fourth-order trend surface of the marine interval thickness, K zone. Regional southward thickening occurs beyond zone of flexure identified in this figure. Note that the trend-surface contouring continues beyond the limits of the data on the northeastern and extreme southern portions of this map.

Figure 20. Shaded isopach map of the residuals of the trend surface for the marine interval thickness of the K zone. Positive residuals ring the southwest positive area noted here by broad negative anomaly (less than -4 ft.). Most prominent positive and negative anomalies in the southwestern mapped area trend northwest-southeast, all south of and paralleling the flexure zone defined in Figure 19. SWP area is also the location of patches of missing grid mapping elements. Note that mapped area for residuals does not project beyond limits of information as did trend surface map (Fig. 19).

Figure 21. Shaded isopach map of the fourth-order trend surface of the marine interval of the H zone. Contour interval equals 5 ft. Zone of flexure comparable to regions of increased thickening of the three earlier cyclothems is limited to extreme southeastern portion of map approximately along the 25-foot contour. Area in northeast that is rapidly thickening to northeast represents projection into area without data. Large isolated thick area in west is attributed to a buildup of the regressive carbonate. Pronounced thinning over southeastern portion of the CKU. Range of values mapped is 60 to 80 percent less than ranges in thickness for trend surfaces of K, J, and I zones, i.e., much less variable in thickness.

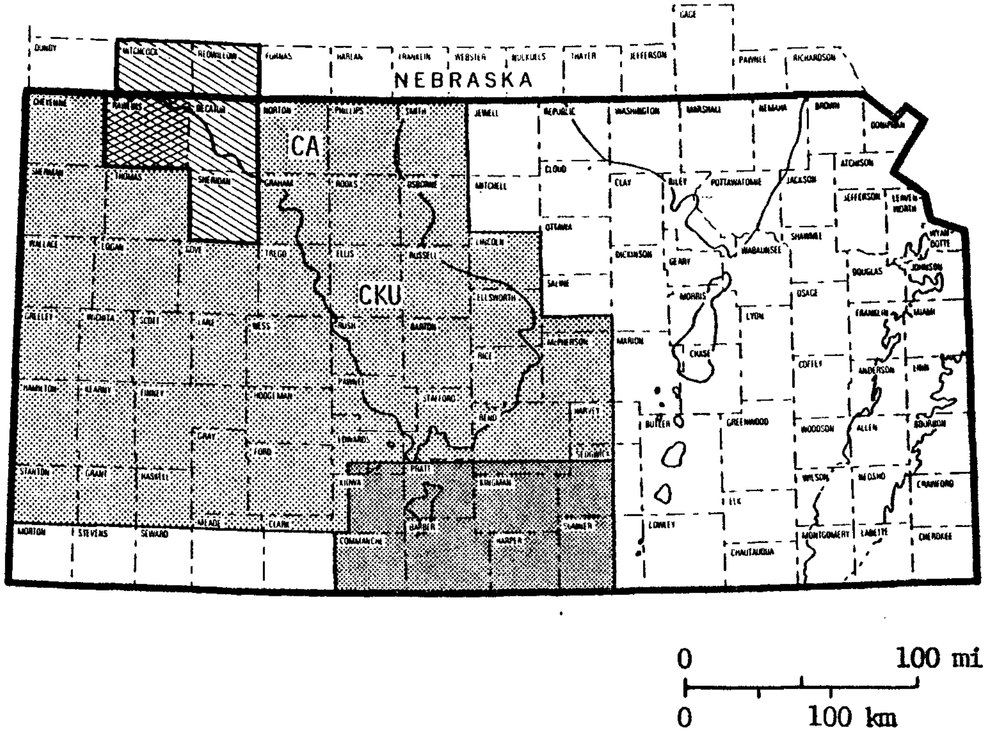
Figure 22. Shaded isopach map of the residuals of the trend surface of the marine interval of the H zone.

Zero, +4, and -4 contour marked and labeled. Darker shading represents greater positive residual. A broad carbonate buildup is identified (CB). Rawlins (RA) and Thomas (TH) counties are locations of micritic carbonate buildups in the zone which have been identified from cuttings to contain phylloid algae.

Figure 23. K zone and J zone: (1) strike of shelf becomes increasingly more east-west in contrast to pattern established in Middle Carboniferous; (2) extensive black shales and thick sequences of regressive carbonate reflecting major inundation of shelf; (3) pronounced change in regional thickness in central and southern shelf interpreted as a response to greater subsidence near the Anadarko basin (active epeirogenic movement); (4) extensive tracts of oolite on southern shelf and grainstone on northern shelf in response to sloping, energetic shelf (ramp); (5) good petroleum reservoir potential over much of western Kansas in both K and J zones.

Figure 24. I and H zones: (1) broadening of positive area on northern shelf and along CKU; (2) regional thickening to south restricted to extreme southwestern edge of map in I and not present in the H zone interpreted as a general quiescence of epeirogenic movement, i.e., reduced subsidence into Anadarko basin; (3) I zone experience loss of marine deposits across northwest shelf, no recognized deposits of marine shale, and predominately shallow-water regressive carbonates, together suggesting a lesser inundation of the shelf during the I zone; (4) patchy black shale development and thinner regressive shale in the H zone suggest intermediate inundation of the shelf during the H zone; (5) H zone with isolated thickening of micrite-supported carbonate some identified as phylloid algal mounds; (6) predominance of micrite-rich carbonate rock in H zone reflects a relatively flat shelf (platform) upon which waves and currents dissipated to produce a dominant, low-energy setting.

1

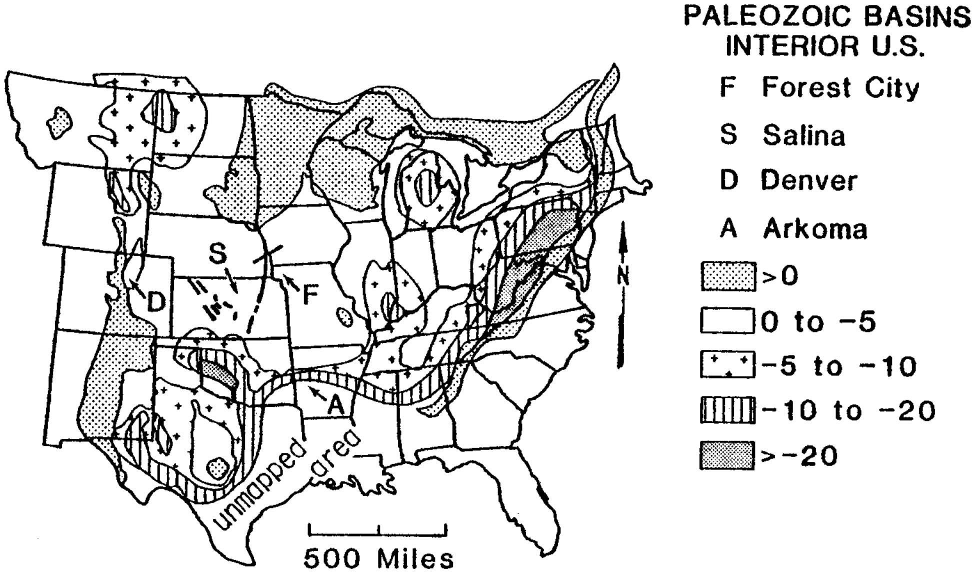


2

| LITHOFACIES | GENERAL INTERPRETATION | THICKNESS |
|---|---|---|
| UPPER SHALE | NONMARINE, PALEOSOLS | 0-20 FT.<br>(0-6 m) |
| | | SHARP |
| UPPER CARBONATE | SHALLOWING UPWARD MARINE | 10-60 FT.<br>(3-18 m) |
| | | ABRUPTLY GRAD. |
| LOWER SHALE | MARINE, COMMONLY ORGANIC-RICH | 2-6 FT.<br>(.5-2 m) |
| | | ABRUPTLY GRAD. |
| LOWER CARBONATE | UPWARD DEEPENING MARINE | 0-10 FT.<br>(0-3 m) |
| | | SHARP |

↑
BOUNDARY

3



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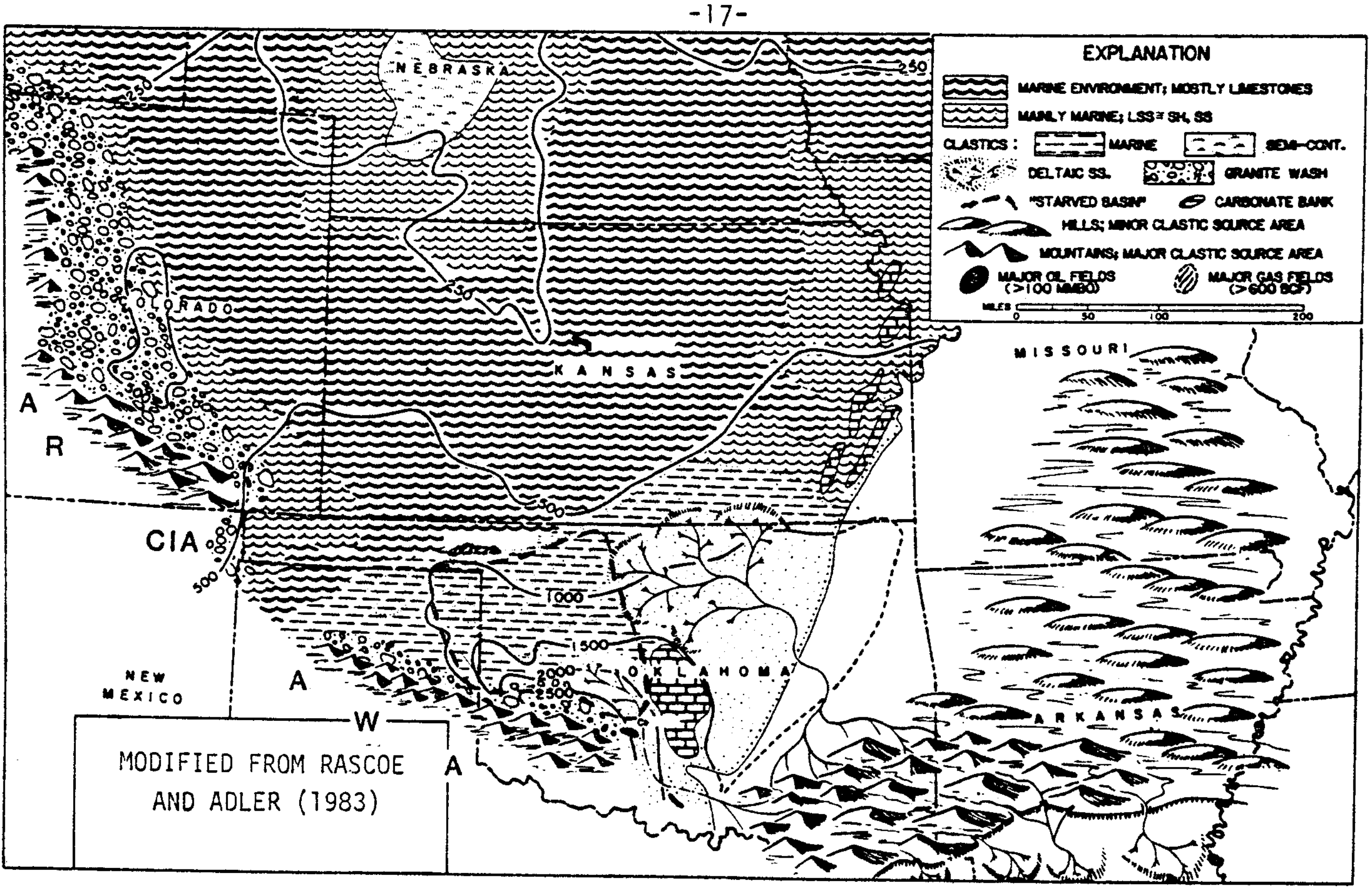

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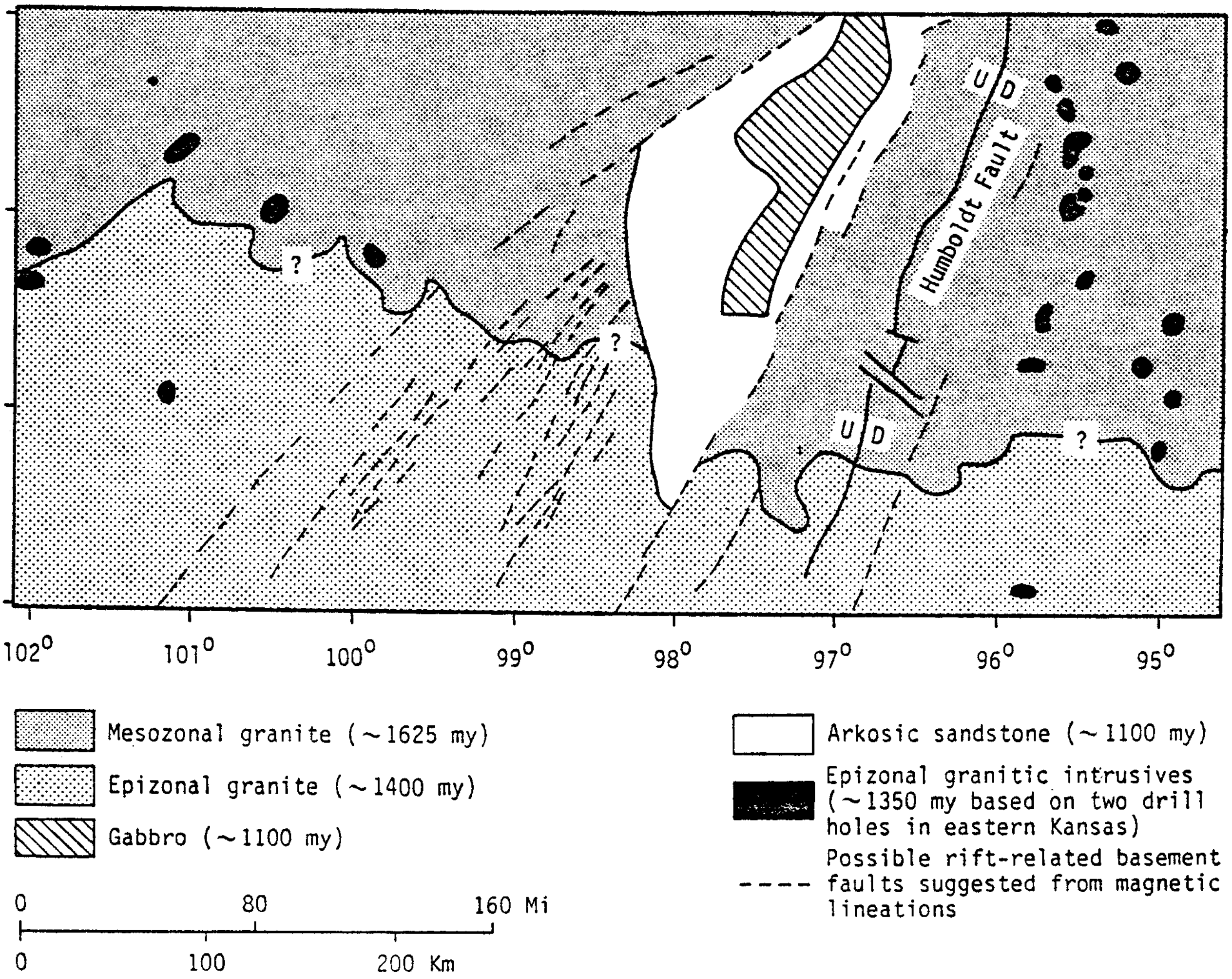
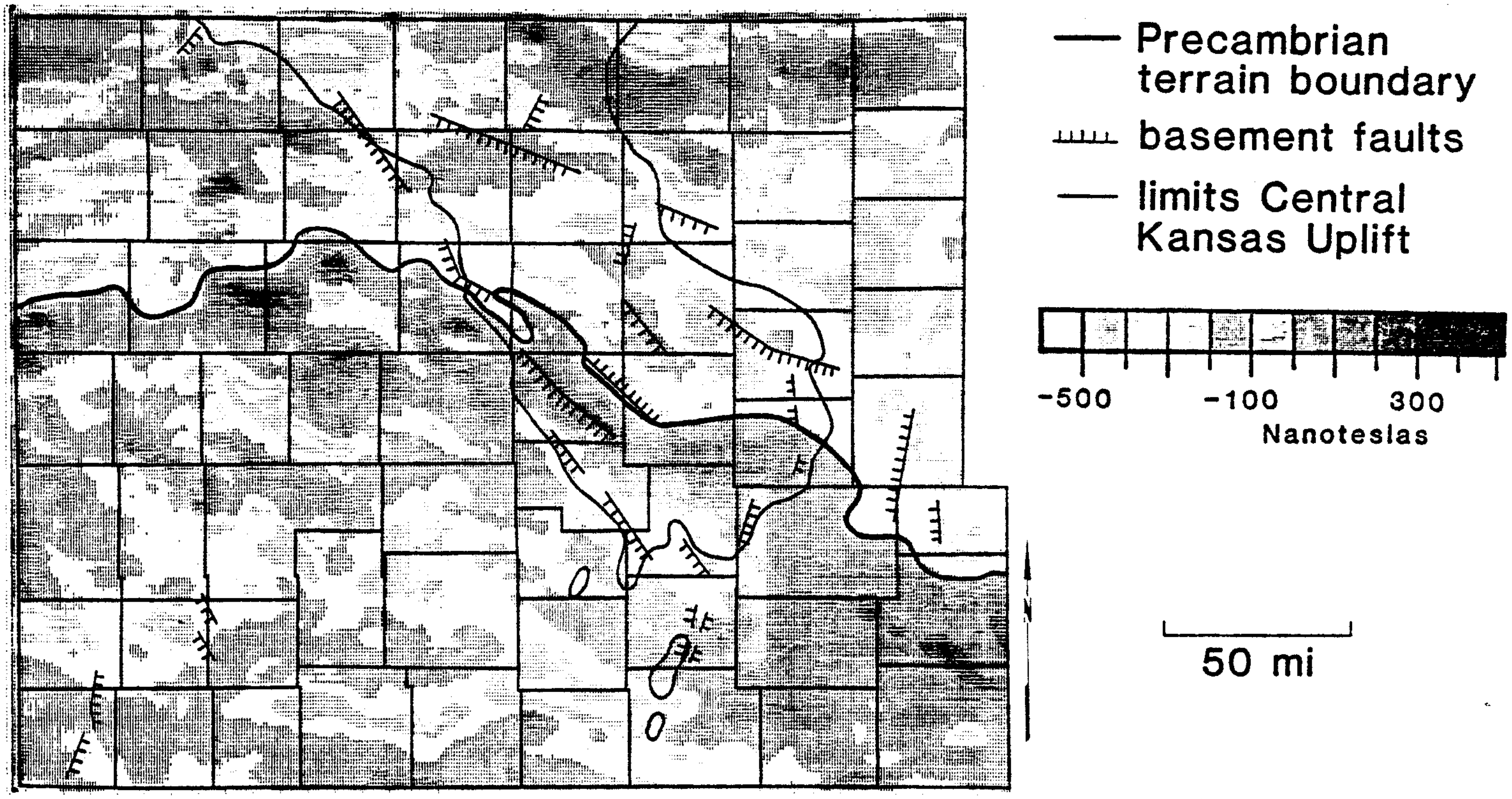


6

Pole Correction Map of Magnetic Field (Yarger, 1983)



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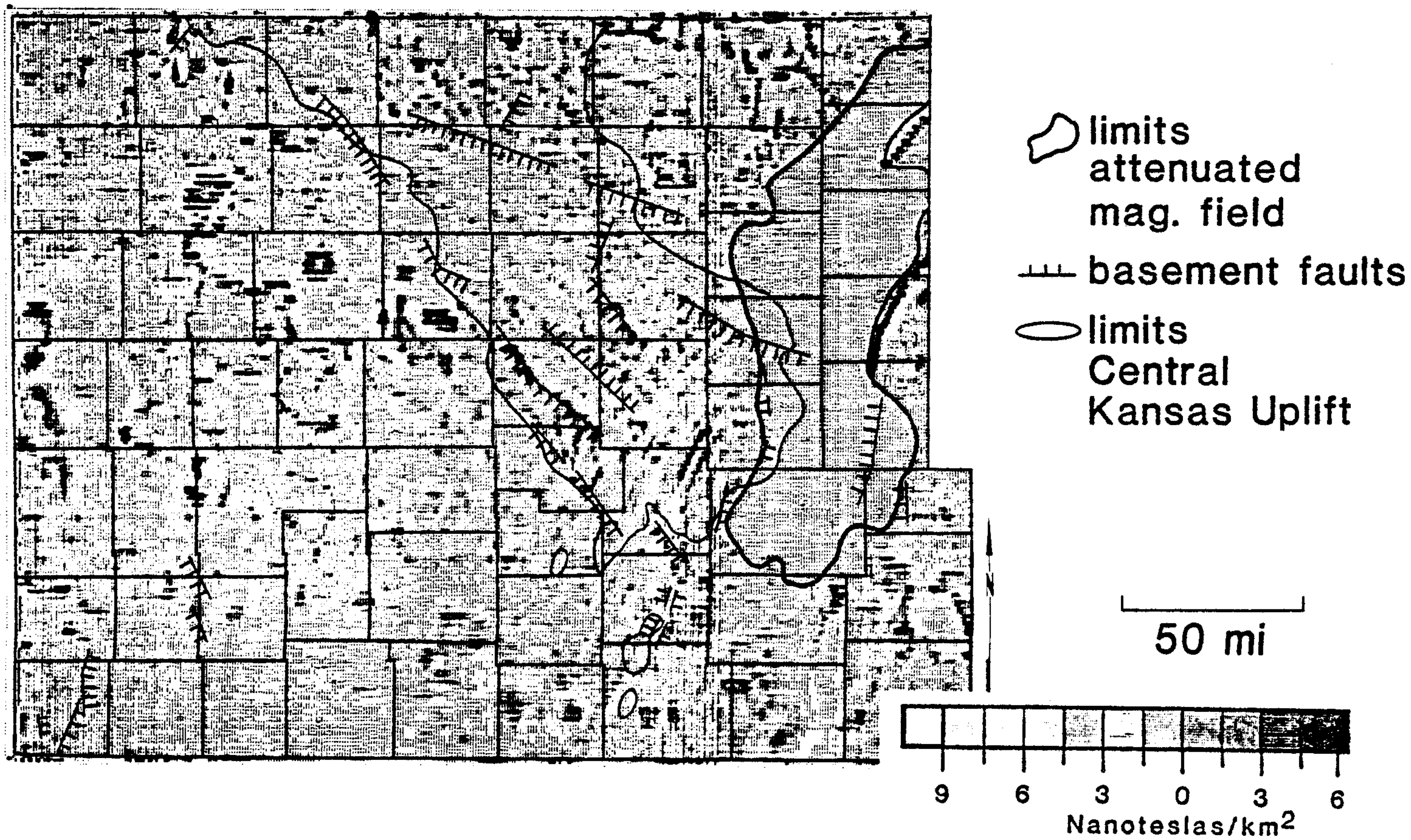
2nd Vertical Derivative of Mag. Field (Yarger, 1983)



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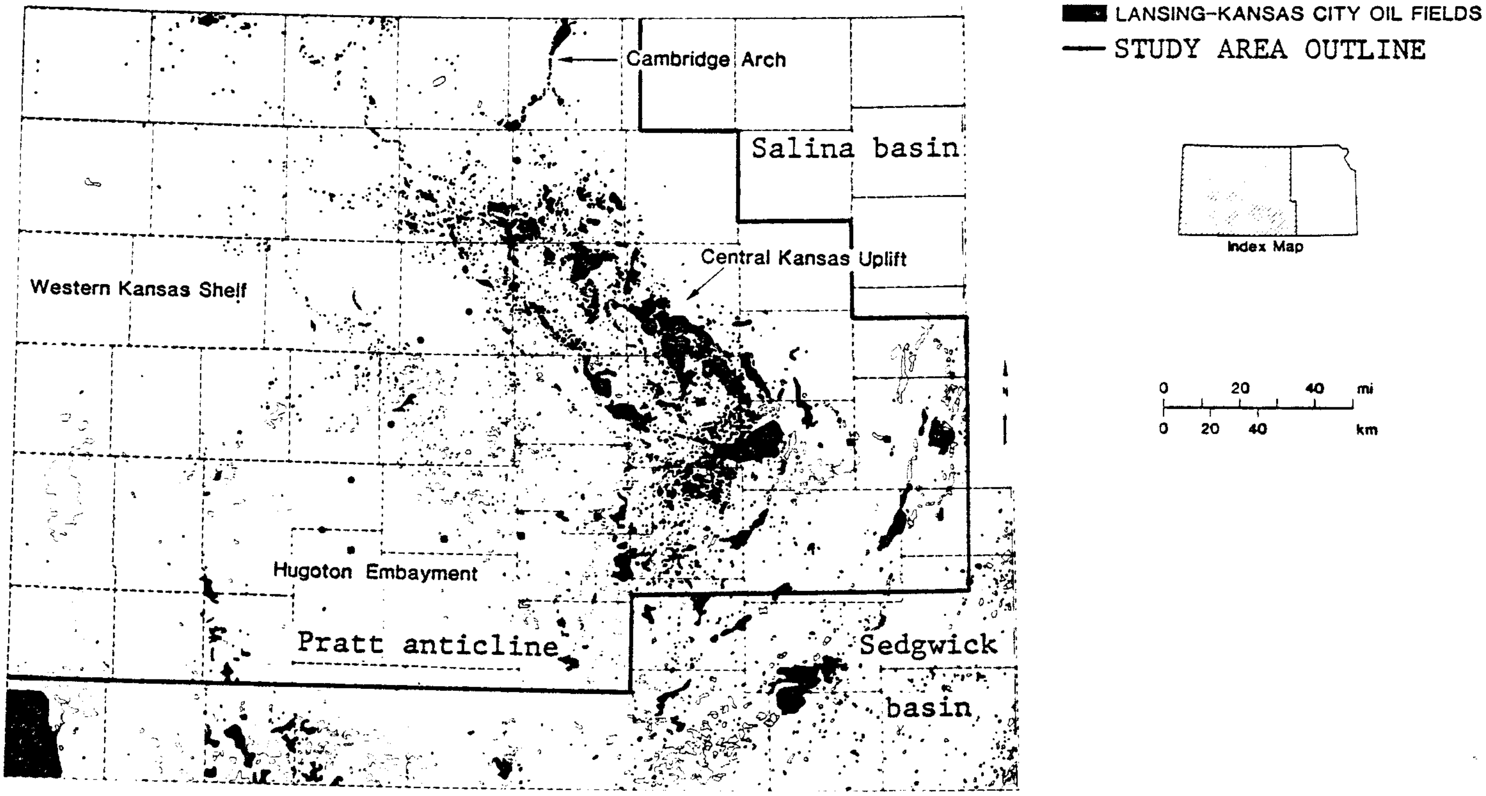
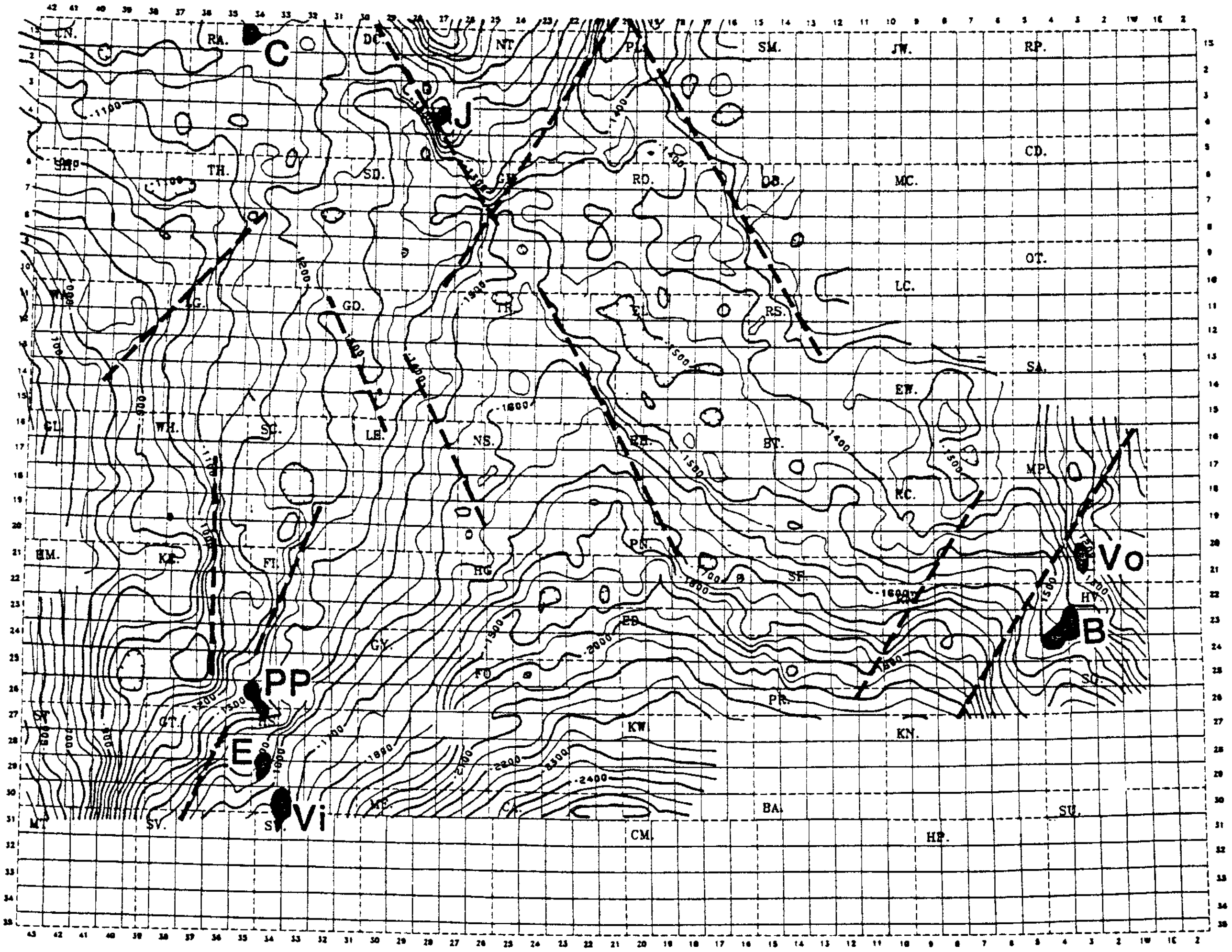

LANSING-KANSAS CITY OIL FIELDS
STUDY AREA OUTLINE
Cambridge Arch
Salina basin
Central Kansas Uplift
Western Kansas Shelf
Hugoton Embayment
Pratt anticline
Sedgwick
basin
Index Map
0 20 40 mi
0 20 40 km

9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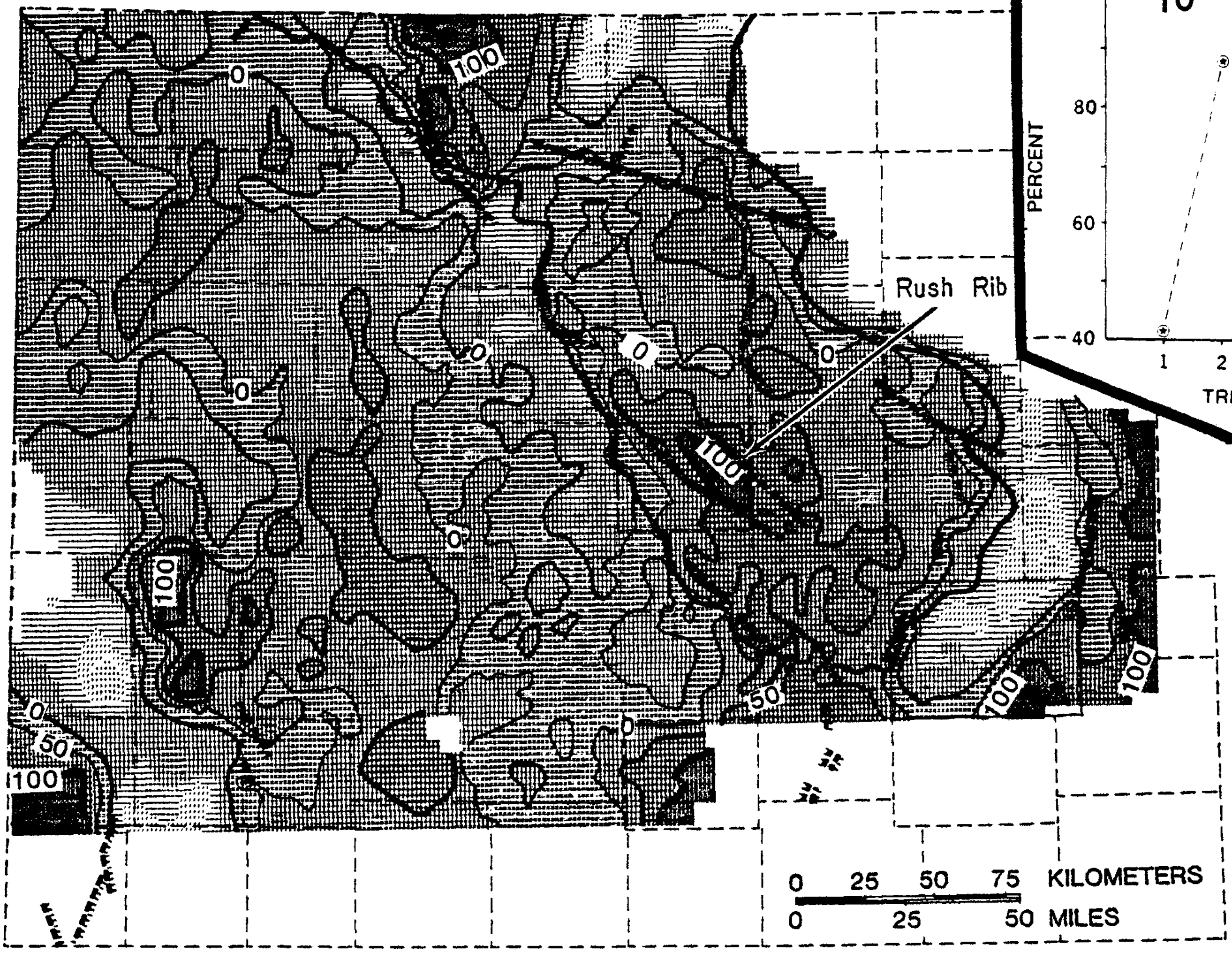
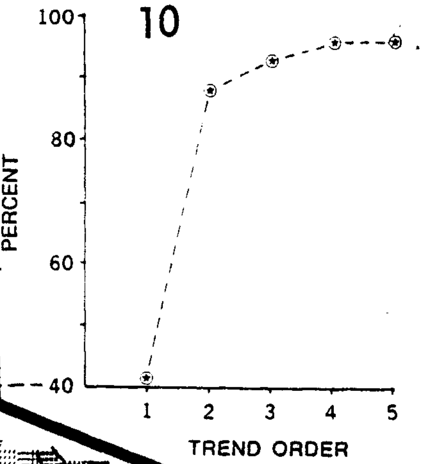
E
Vi
Vo
B
CN.
RA.
DC.
NT.
PL.
SM.
JW.
RP.
SH.
TH.
SD.
GH.
RO.
OB.
MC.
CD.
CL.
GO.
TR.
EL.
RS.
LC.
OT.
WA.
SA.
EW.
GL.
WH.
SC.
LE.
NS.
RH.
BT.
RC.
MP.
HM.
KE.
FI.
HG.
PN.
SF.
HV.
GY.
ED.
PR.
SG.
ST.
GT.
HS.
FO.
KW.
KN.
MT.
SV.
SW.
ME.
CA.
BA.
CM.
HP.
SU.
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2200
2300
2400

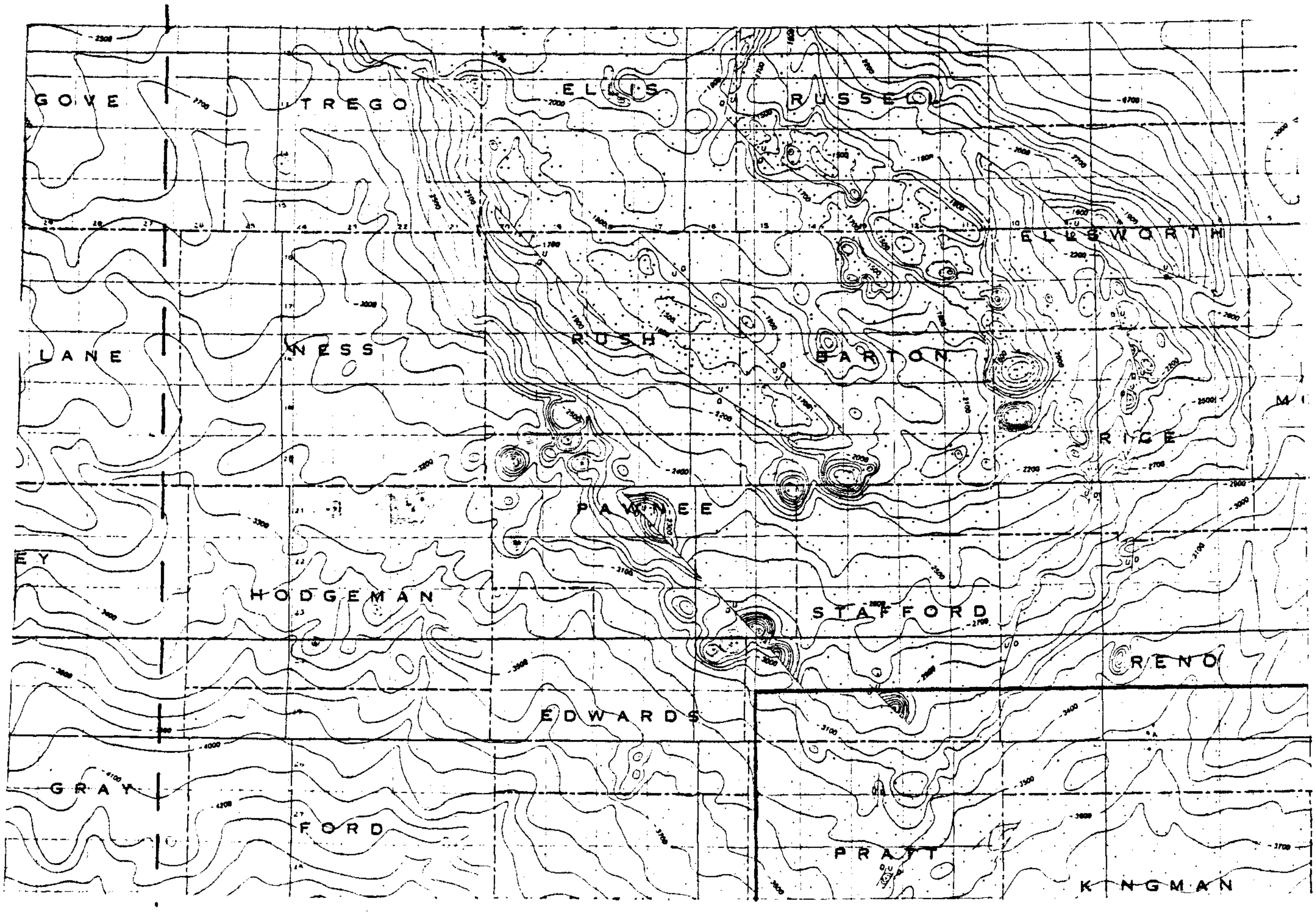
11


0
0
0
0
0
0
0
0
0
0
100
100
100
100
100
100
50
50
Rush Rib
0 25 50 75 KILOMETERS
0 25 50 MILES

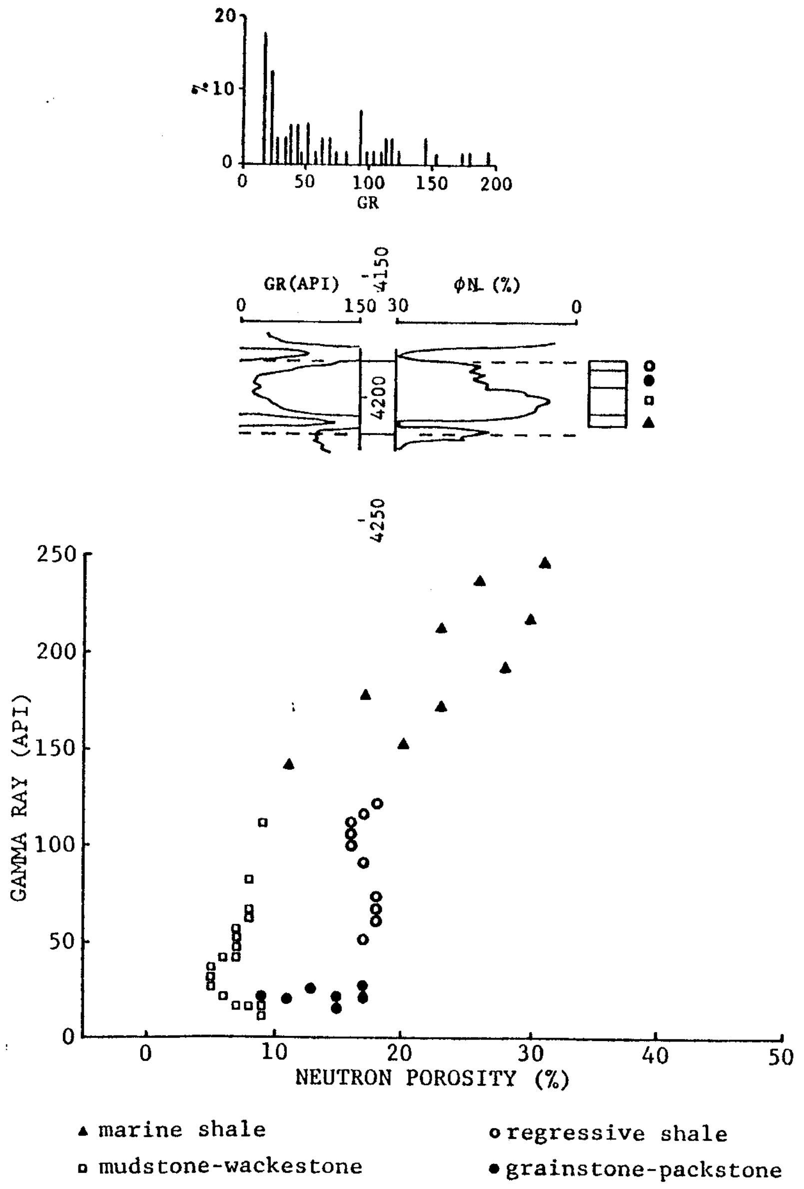
10


100
80
60
40
PERCENT
1
2
3
4
5
TREND ORDER

12

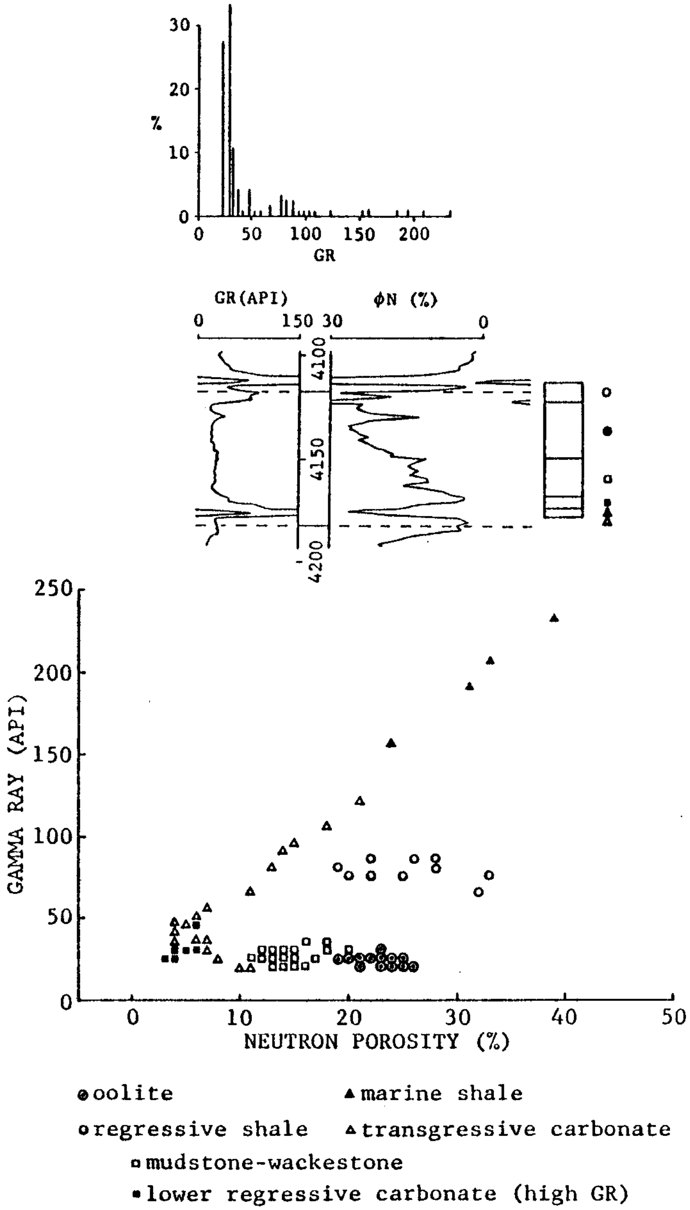

GOVE
TREGO
ELLIS
RUSSELL
ELLSWORTH
LANE
NESS
RUSH
BARTON
RICE
PAWNEE
HODGEMAN
STAFFORD
RENO
EDWARDS
GRAY
FORD
PRATT
KINGMAN

**13**



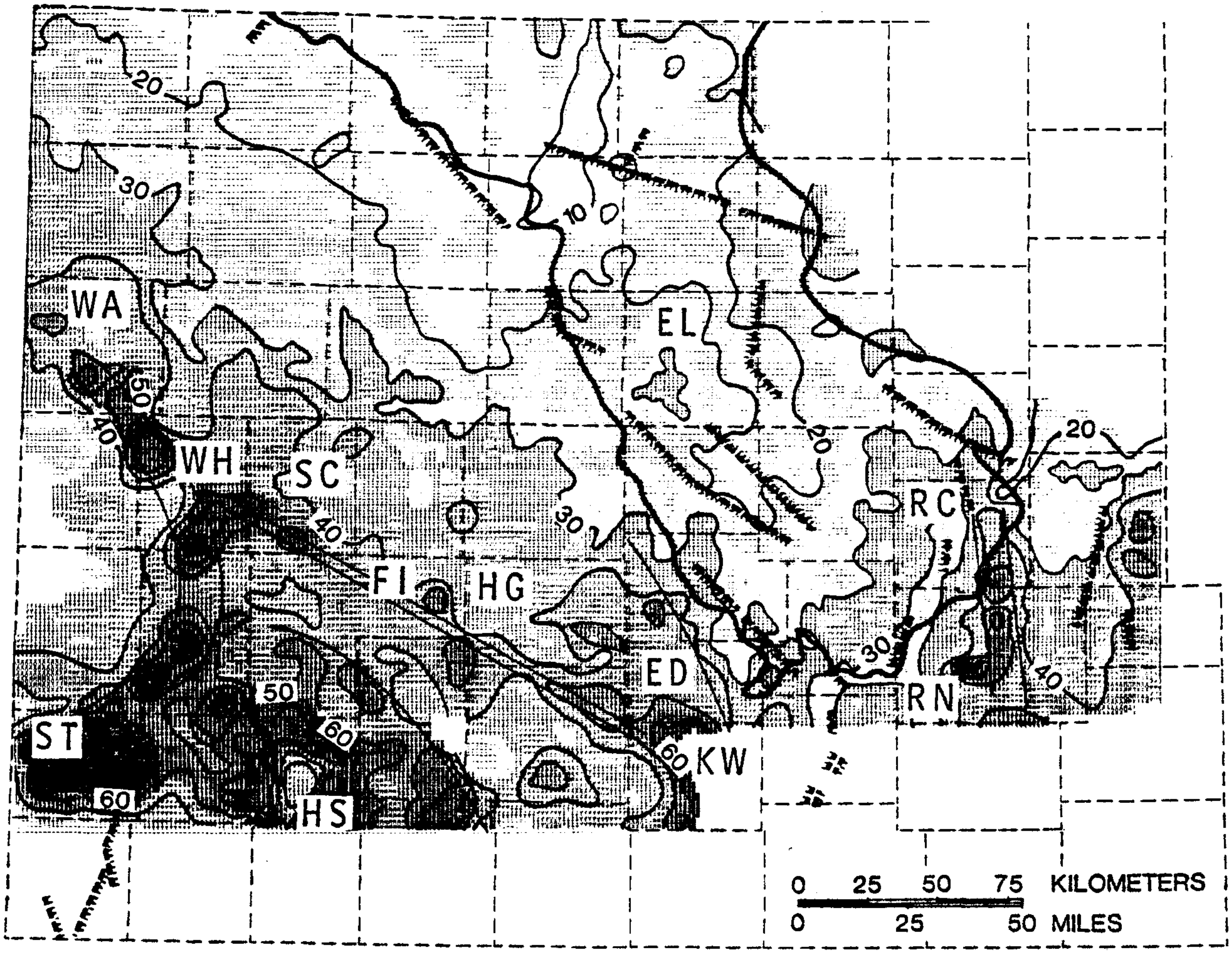
%
20
10
0
0
50
100
150
200
GR
GR(API)
0
150
30
φN (%)
0
4150
4200
4250
GAMMA RAY (API)
250
200
150
100
50
0
0
10
20
30
40
50
NEUTRON POROSITY (%)
▲ marine shale
○ regressive shale
□ mudstone-wackestone
● grainstone-packstone

**14**

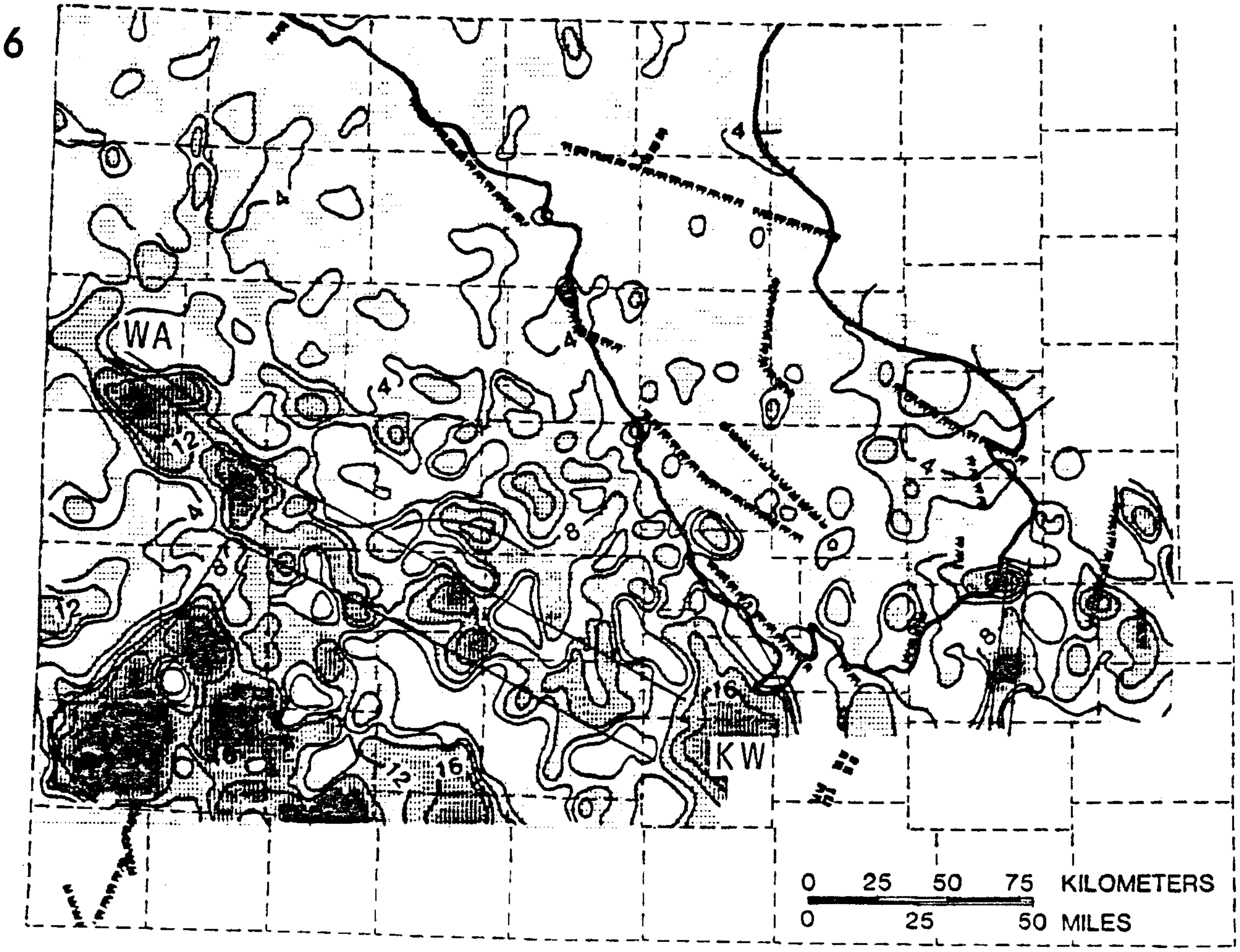


%
30
20
10
0
0
50
100
150
200
GR
GR(API)
0
150
30
φN (%)
0
4100
4150
4200
GAMMA RAY (API)
250
200
150
100
50
0
0
10
20
30
40
50
NEUTRON POROSITY (%)
⊙ oolite
▲ marine shale
○ regressive shale
△ transgressive carbonate
□ mudstone-wackestone
■ lower regressive carbonate (high GR)

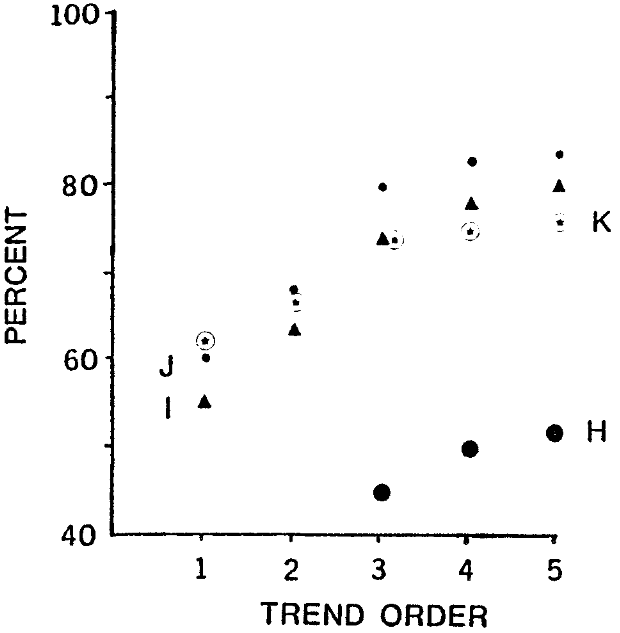
15


20
30
10
WA
50
40
WH
SC
40
30
EL
20
20
RC
FI
HG
ED
30
RN
40
50
60
ST
60
60
KW
HS
0 25 50 75 KILOMETERS
0 25 50 MILES

16

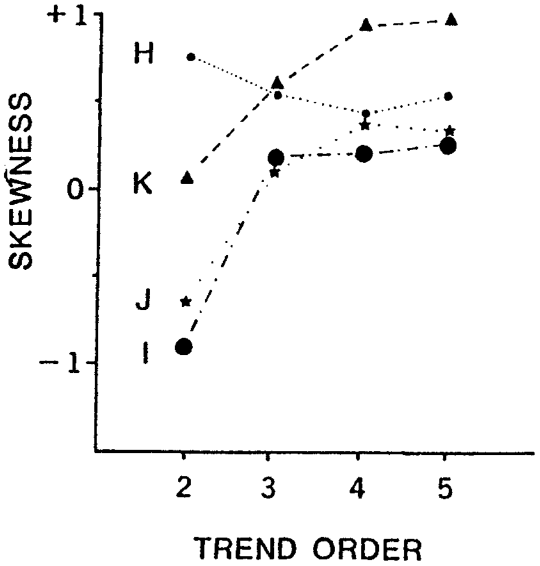

4
4
WA
4
4
12
4
8
8
4
12
8
16
16
KW
12
16
0 25 50 75 KILOMETERS
0 25 50 MILES

17



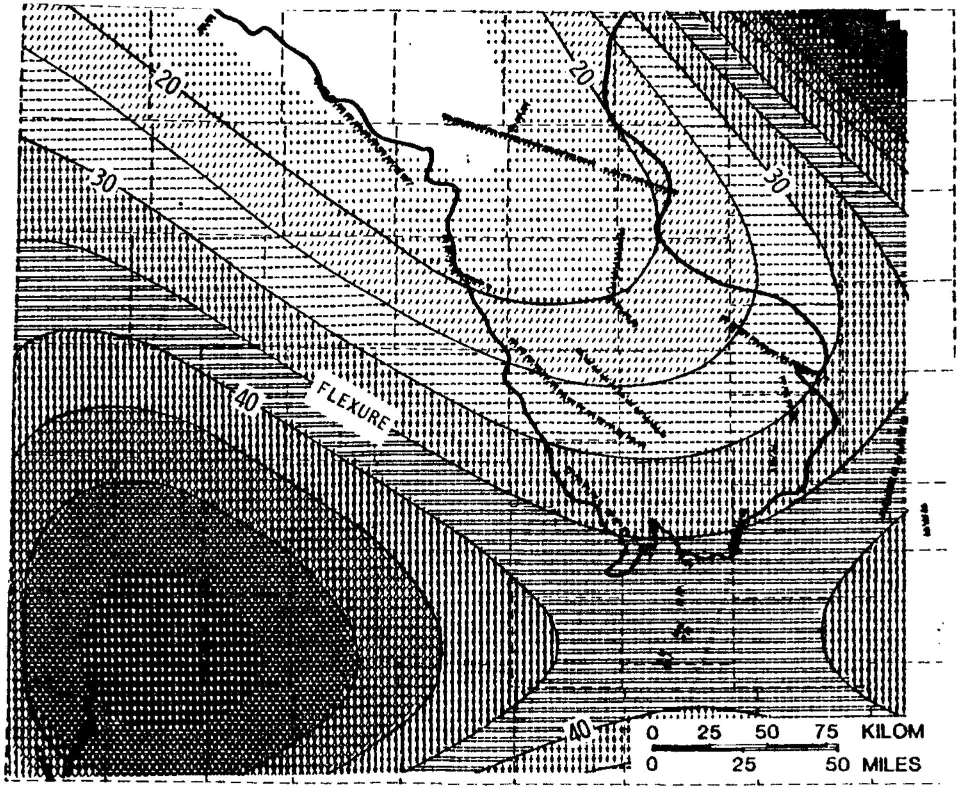
100
80
60
40
PERCENT
J
I
K
H
1
2
3
4
5
TREND ORDER

18



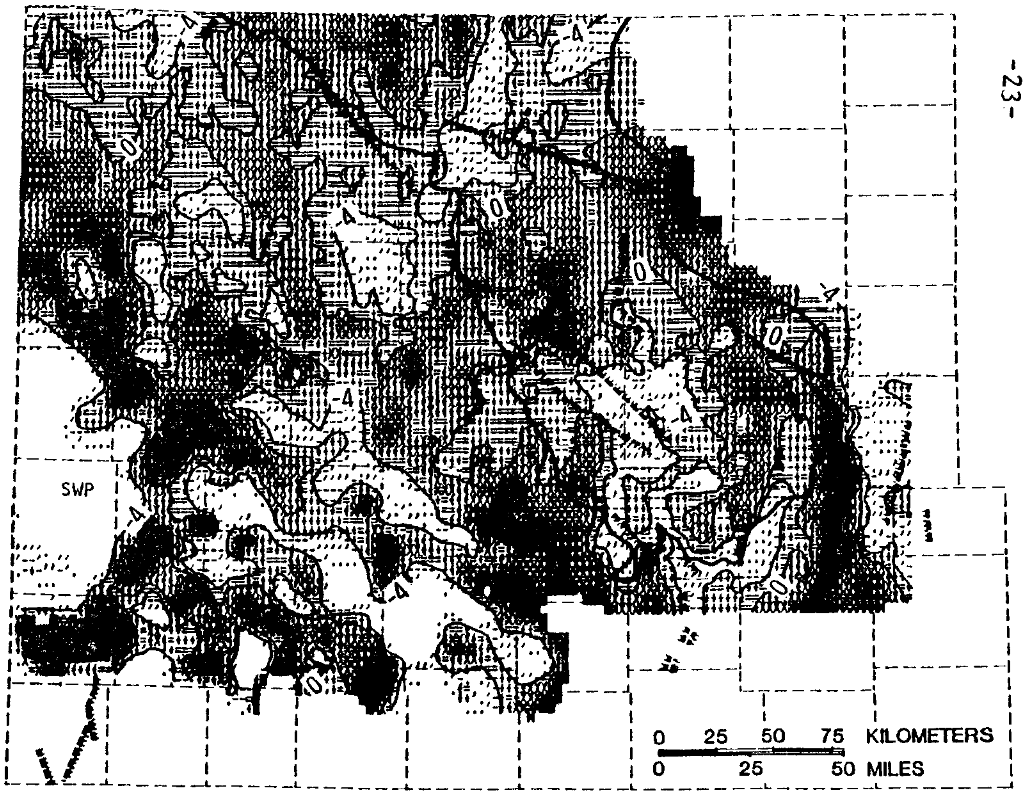
+1
0
−1
SKEWNESS
H
K
J
I
2
3
4
5
TREND ORDER

19



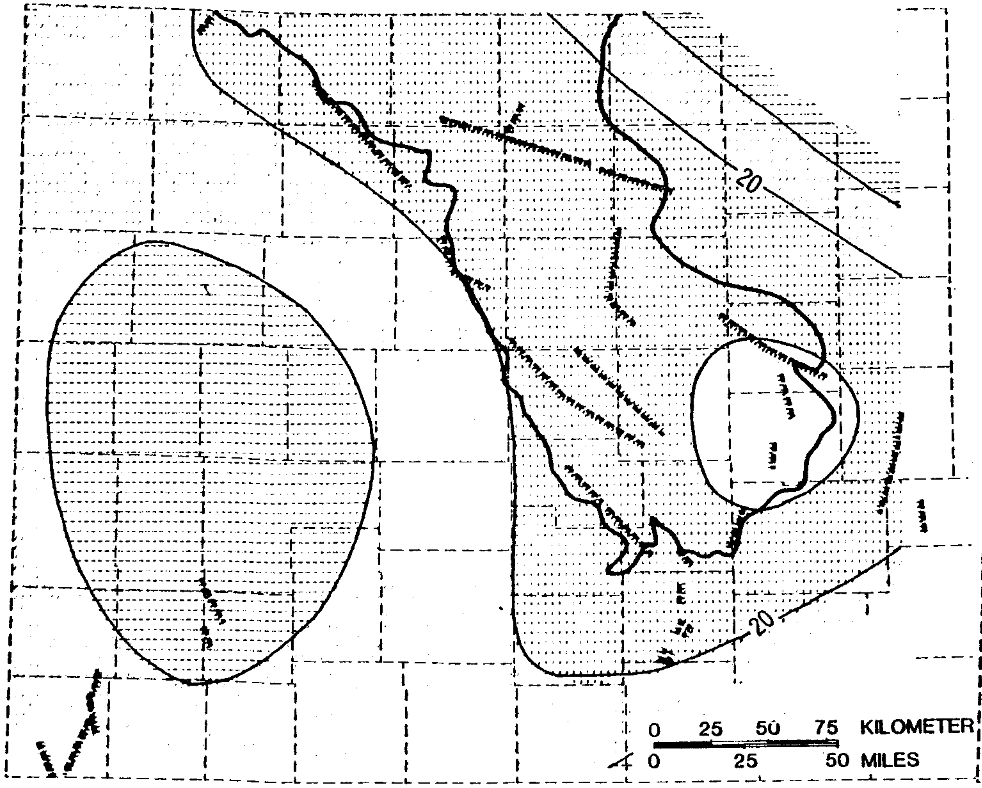
20
30
20
30
40
FLEXURE
40
0 25 50 75 KILOM
0 25 50 MILES

20

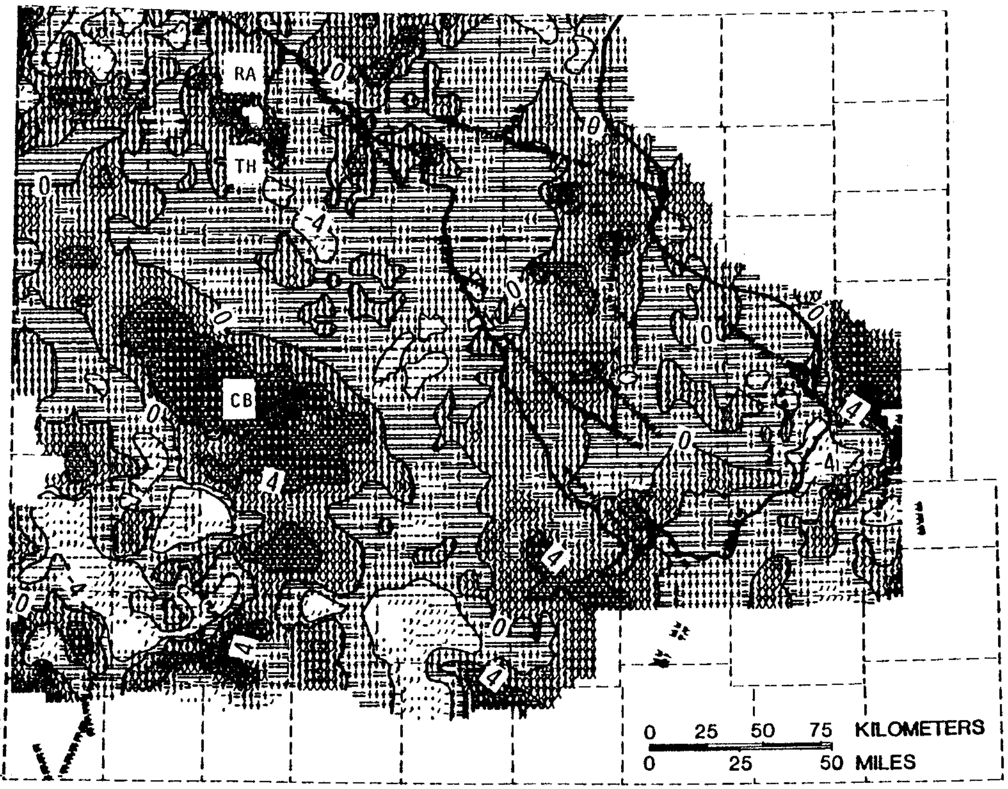


-4
0
-4
0
-4
0
-4
-4
0
SWP
-4
-4
0
0
0 25 50 75 KILOMETERS
0 25 50 MILES

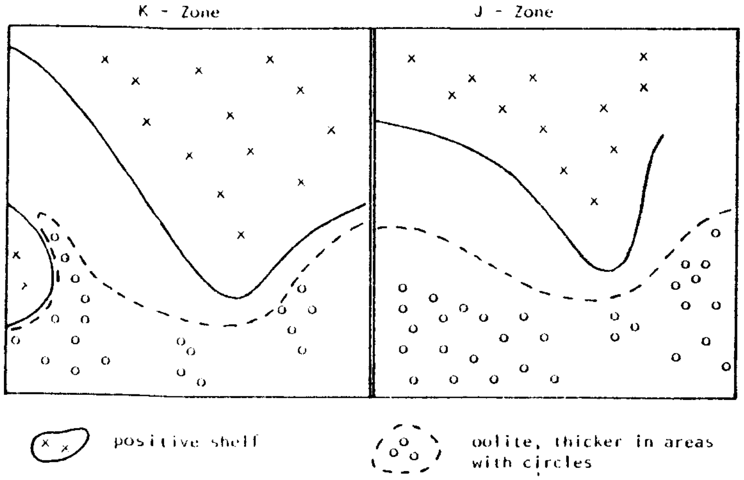
21


20
20
0 25 50 75 KILOMETER
0 25 50 MILES

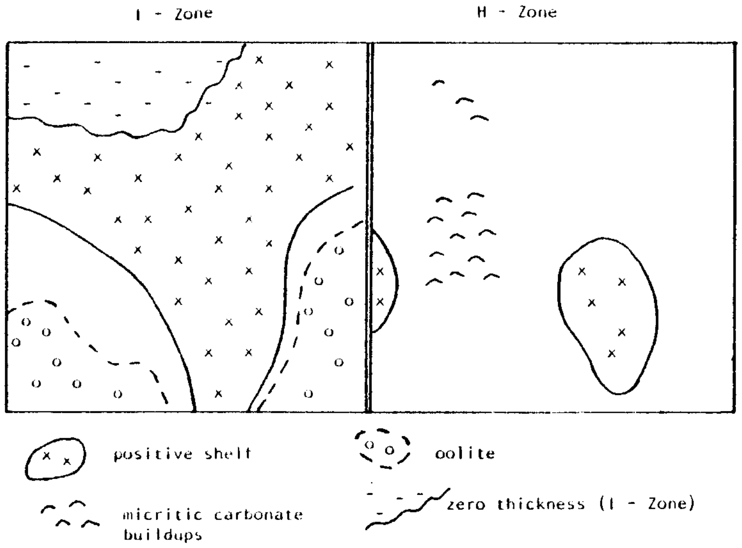
22


RA
TH
CB
0
-4
4
0 25 50 75 KILOMETERS
0 25 50 MILES

23


K - Zone
J - Zone
positive shelf
oolite, thicker in areas with circles

24


I - Zone
H - Zone
positive shelf
oolite
micritic carbonate buildups
zero thickness (I - Zone)