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THE FRACTURE PATTERN OF NORTH-CENTRAL KANSAS AND ITS RELATION TO HYDROGEN SOIL GAS ANOMALIES OVER THE MIDCONTINENT RIFT SYSTEM

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B.S., University of Nebraska, 1983

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ABSTRACT

Lineament analysis of digitally filtered gravity and aeromagnetic data for that portion of north-central Kansas bounded by 38.5°N. and 40.0°N. latitude and 96.0°W. and 98.0°W. longitude suggests the basement is characterized by a bimodal set of linear compositional discontinuities. These discontinuities are interpreted to reflect an intrabasement fracture pattern with modal orientations of about N.40-50°W. and N.10-30°E. These prefered orientations are also expressed as linear elements in a revised contour map of the Precambrian surface configuration, indicating Phanerozoic movement has taken place along many of them. The northwest-oriented fracture set parallels regional basement fault zones associated with the Middle Proterozoic(?) Missouri gravity low and may have resulted from the tensional(?) stresses responsible for formation of that feature. The north-northeast-oriented set parallels the central axis of the Midcontinent rift system and probably reflects extensive tensional faulting inferred to have accompanied the Middle Proterozoic (Keweenawan) rifting. Alternatively, both sets could reflect even older upper-crustal anisotropy. Clustering of historic earthquake and recent microquake epicenters around several of these fracture zones demonstrates that some are still active. Such recurrent seismicity, perhaps in combination with differential isostatic rebound since Pleistocene glaciation, could provide a mechanism for upward propagation of these zones.

Although surface faults are virtually unknown from the study area, correlation between the locations and modal orientations of

the inferred basement fractures and both Landsat photolineaments, and linear drainage segments, is good to fair. This may imply that many of these fractures are expressed at the present land surface as zones of preferential weathering, perhaps in the form of linear zones of increased joint density.

Comparison between the magnitudes of nearly 600 hydrogen soil gas measurements and their relative proximity to these suspected fractures indicates that at least some of these zones may extend to the present land surface and act as preferential conduits for vertical migration of free hydrogen gas or gas-charged fluids. However, it is concluded that the present soil-gas sample spacing (0.5 to 1.0 mi.) is too coarse to accurately define the exact surface traces of these fractures. The viability of future exploitation of the hydrogen is still unknown, but will probably depend on more precise definition of these zones, the presence of a suitable trapping mechanism, and drilling and completion practices appropriate for the occurrence.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES
(In back pocket)

INTRODUCTION

Background Information

In 1982, unusually high concentrations of free hydrogen (30 to 40 mole %) and nitrogen (60 to 70 mole %) were detected in casing-head gases of the CFA Oil Co. #1 Scott well in northwest Morris County, Kansas (Goebel, et al., 1983a; 1983b) and the CFA Oil Co. #1 Heins well (Plate 1) in southern Geary County, Kansas (Goebel, et al., 1984). Hydrogen was subsequently detected during actual drilling of several other nearby wells (Goebel, et al., 1985) and numerous hydrogen anomalies were indicated along two soil-gas sample traverses (Plate 1) run by the Kansas and U.S. Geological Surveys in 1984 (McCarthy, et al., 1986; McCauley and Watney, 1984). Although the origin of the nitrogen has remained somewhat of an enigma, a search of the relevant literature revealed a minimum of eight possible mechanisms for generating such anomalously high concentrations of hydrogen in the subsurface (Angino, et al., 1984). The absence of appreciable CH_4 or CO_2 with the gases is indicative of an abiogenic source for the hydrogen. Isotopic ratios and thermodynamic calculations yield possible equilibration temperatures around 10 degrees C or lower (somewhat below ambient temperature), implying a deuturium-depleted gas source. The currently most plausible origins for the Kansas occurrences include ground-water mixing, mantle outgassing, and the the hydration of FeO-rich minerals (for example olivine) during serpentinization/deserpentinization of mafic or ultramafic rocks (Coveny, et al., 1987). Of these theories, the latter may be favored by the position of the occurrence above the southern end of the Keweenawan-age Midcontinent rift system (central North American rift system), known to contain partially serpentinized mafic rocks (Berendsen, et al., 1988), and close proximity to several known kimberlite plugs (Mansker, et al., 1987). Analyses of gases exsolved from drilling muds during drilling of the CFA Oil #1 Simpson well (Coveney, et al., 1987, fig. 3), CFA Oil #1 Amthauer well (Plate 1), and wireline well logs of other nearby wells (Goebel, 1985) have established a stratigraphic range for the hydrogen extending from soil level to the top of the Precambrian basement, further suggesting an intrabasement source.

Although the maximum areal extent of the occurrence is still rather poorly defined, soil-gas sampling along extensive traverses (Plate 1) indicates areas in at least 10 Kansas counties are involved. The highest levels of hydrogen detected along initial soil-gas traverses were from near the centers of "unusually straight" stream valleys and an area of Pleistocene(?) age sand dunes northwest of Abilene (Angino, 1985). Although Phanerozoic strata in the area of the gas occurrences are essentially flat lying, the locations and orientations of many streams and rivers in eastern Kansas are thought to have been influenced by regional joint trends (Baehr, 1954; McCauley, et al., 1975), near-surface faults (DuBois, 1978), and reactivated basement fracture zones (Kirk, 1968; Berendsen, et al., 1978). This suggests that both the near-surface concentrations and subsurface movements of the hydrogen may be strongly fracture controlled. If this is true, then knowledge of the fracture patterns may provide a fundamental key to understanding the origin, possible trapping, and potential development of this resource. Although down-hole gas pressures have so far been quite low (slightly above 1 atm., Coveney, et al., 1987, p. 42), it is conceivable that such widespread occurrences of anomalous soil-gas hydrogen could represent the surface expression of a very significant (if economically extractable) future source of energy and raw materials. Indeed, Shcherbakov and Kozlova (1986, p. 120) have predicted that "in the future the extraction and refining of gases containing hydrogen will become a separate branch of industry."

Study Objectives

In an attempt to clarify further any relationship between subsurface fractures and hydrogen gas distribution, an integrated analysis of geologic, geophysical, geochemical, and remotely sensed data was undertaken for a large area of north-central Kansas. The primary objectives of this study as originally stated were: 1) to determine the fracture pattern of the study area with an emphasis on remote techniques, 2) to relate fracture types and trends to possible tectonic origin(s) and modern crustal stress regime, 3) to compare hydrogen soil-gas anomalies with fracture locations, and 4) to develop a working model for subsurface movement of the hydrogen.

DESCRIPTION OF STUDY AREA

Location and Surficial Geology

The study area comprises that portion of north-central Kansas lying between 96 and 98 degrees west longitude and 38.5 and 40 degrees north latitude, corresponding to the entire Manhattan and northern one half of the Hutchinson 1:250,000-scale series U.S. Geological Survey topographic quadrangle sheets. It covers approximately 28,500 km^2 (11,000 $mi.^2$) of surface area and includes all or portions of 25 Kansas counties (Figure 1).

Strata cropping out in the study area range from Late Pennsylvanian through Recent in age (Kansas Geological Survey, 1964). Late Paleozoic and Cretaceous rocks include a sequence of interlayered marine carbonates and fine terrigenous clastics. The Middle Permian age Wellington Formation crops out in the central portion of the study area. It includes a thick salt sequence, the Hutchinson Salt Member, in much of the Kansas subsurface (Watney and Paul, 1980), but this salt has been removed from all except the southwesternmost part of the study area by surface erosion and subsurface solution (Plate 1). Deposits of Cenozoic age are of generally minor importance except for thick alluvial fills in larger stream valleys and a mantle of Pleistocene glaciofluvial sediments northeast of the Kansan age glacial terminus (Plate 1). Locally in northern Dickinson and portions of surrounding counties, sandy areas and small sand dunes of Quaternary age occur on the uplands (Dunlap, 1977; Jantz and Saffry, 1980; Sloanaker, 1950).

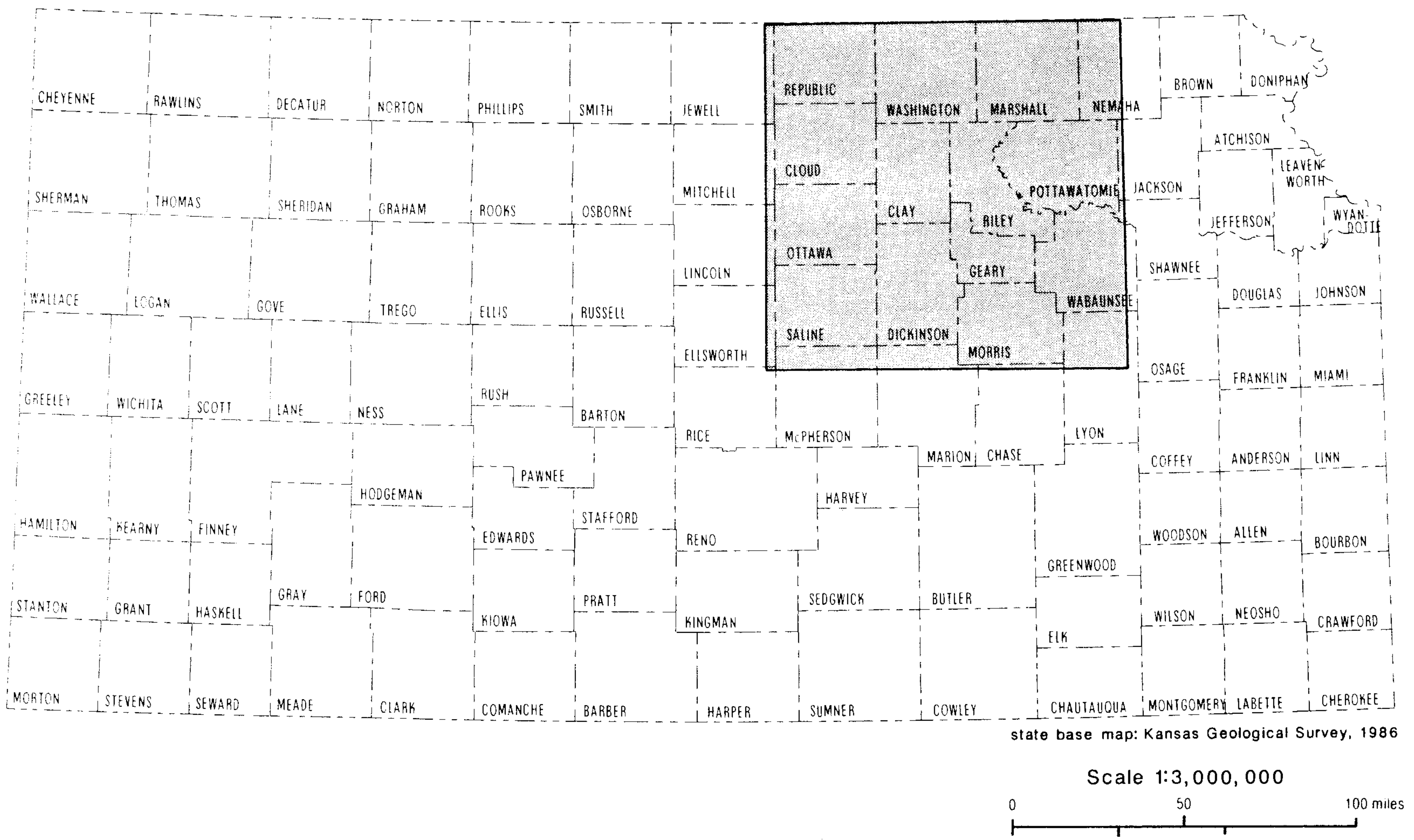


Figure 1. Kansas base map showing location of study area (shaded).

Basement Lithologies and Proterozoic Tectonics

The lithologic and structural characteristics of Precambrian rocks in north-central Kansas are known only from widely scattered drill hole samples and regional correlations. Holes penetrating basement rocks within the study area number only about 280, but most of these occur in a few areas of higher drilling density (Plate 4) and very few were drilled more than a few meters (10's of feet) into Precambrian rocks (Bickford, et al., 1979, 1981; Denison, et al., 1984). Among the notable exceptions to this general depth rule are the Hodgen Oil #1 and #1-4 Finn wells in Marshall County, and the Texaco USA #1-31 Poersch well in Washington County (Plate 1). The Finn wells both penetrated over 450 m. (1500 ft.) of Precambrian rocks, and Poersch well is reported to have penetrated approximately 2600 m. (8,450 ft.) of Precambrian gabbros, basalts, and arkosic clastics (Berendsen et al., 1988). An extensive discussion of the units encountered in the Poersch well and their possible interpretation is available from Berendsen and others (1988). Unfortunately, no additional data are currently available for the Finn wells.

The study area lies within the Central Plains tectonic province (Figure 2), an early Proterozoic accretionary terrane consisting predominantly of mesozonal granitoid rocks and gneissic metamorphic rocks of primarily amphibolite grade facies (Bickford, et al., 1986; Sims and Peterman, 1986). Because rocks of this province are exposed at the surface only in southeastern Wyoming, it has been defined primarily on the basis of gross geophysical expression, and the analysis of limited cuttings and core samples available from drill

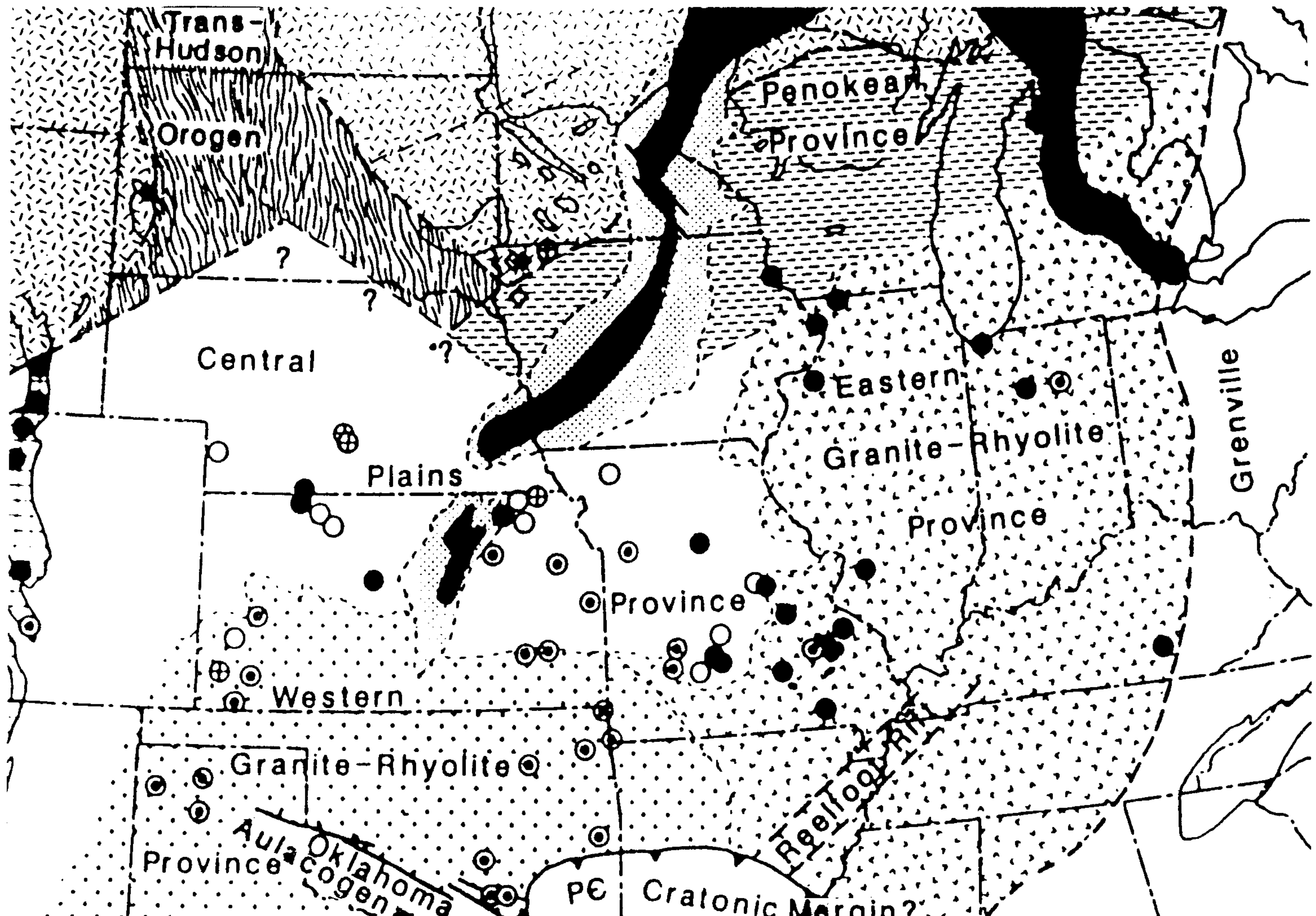


Figure 2. Map of regional Precambrian radiometric-age provinces (after Bickford, <u>et al</u>., 1986, Fig. 1).

holes. Most of these samples possess cataclastic textures, suggesting they underwent a period of extensive shearing and deformation after emplacement. Those samples that have been radiometrically dated yield early Proterozoic ages ranging from 1,800 to 1,600 million years ago (Ma). Locally within the province a set of anorogenic plutons dated between 1,480 and 1,450 Ma occurs. They yield nondeformed samples, and thus roughly bracket the timing of the shearing episode (Denison, et al., 1984, p. C7). A northwest-southeast-oriented tectonic grain (Figure 3) that may also reflect this deformation has been inferred for the terrane in eastern Kansas and western Missouri (Bickford, et al., 1986; Sims and Peterman, 1986) largely on the basis of geophysical and structural trends. Farther east in central Missouri, a northwest-southeast-trending gravity low (the Missouri gravity low) and corresponding set of structural features (Missouri tectonic zone) has been mapped within the province that has been variously interpreted as a rifted arm of a possible "rrr-type" type triple junction (Guinness, et al., 1982; Kisvarsanyi, 1984), major transcurrent fault (Arvidson, et al., 1982), or collisional suture (Bowring, et al., 1988) that apparently predated a middle Proterozoic (1,485 to 1,350 Ma) epizonal granite-rhyolite terrane underlying much of southern Missouri, southern Kansas, and Oklahoma. Detailed analysis of regional aeromagnetic data in south-central Kansas by Gay (1986, 1988) suggests that an more complex history of Proterozoic tectonism than previously supposed may be recorded in the basement there.

Perhaps the single most striking feature of regional Bouguer

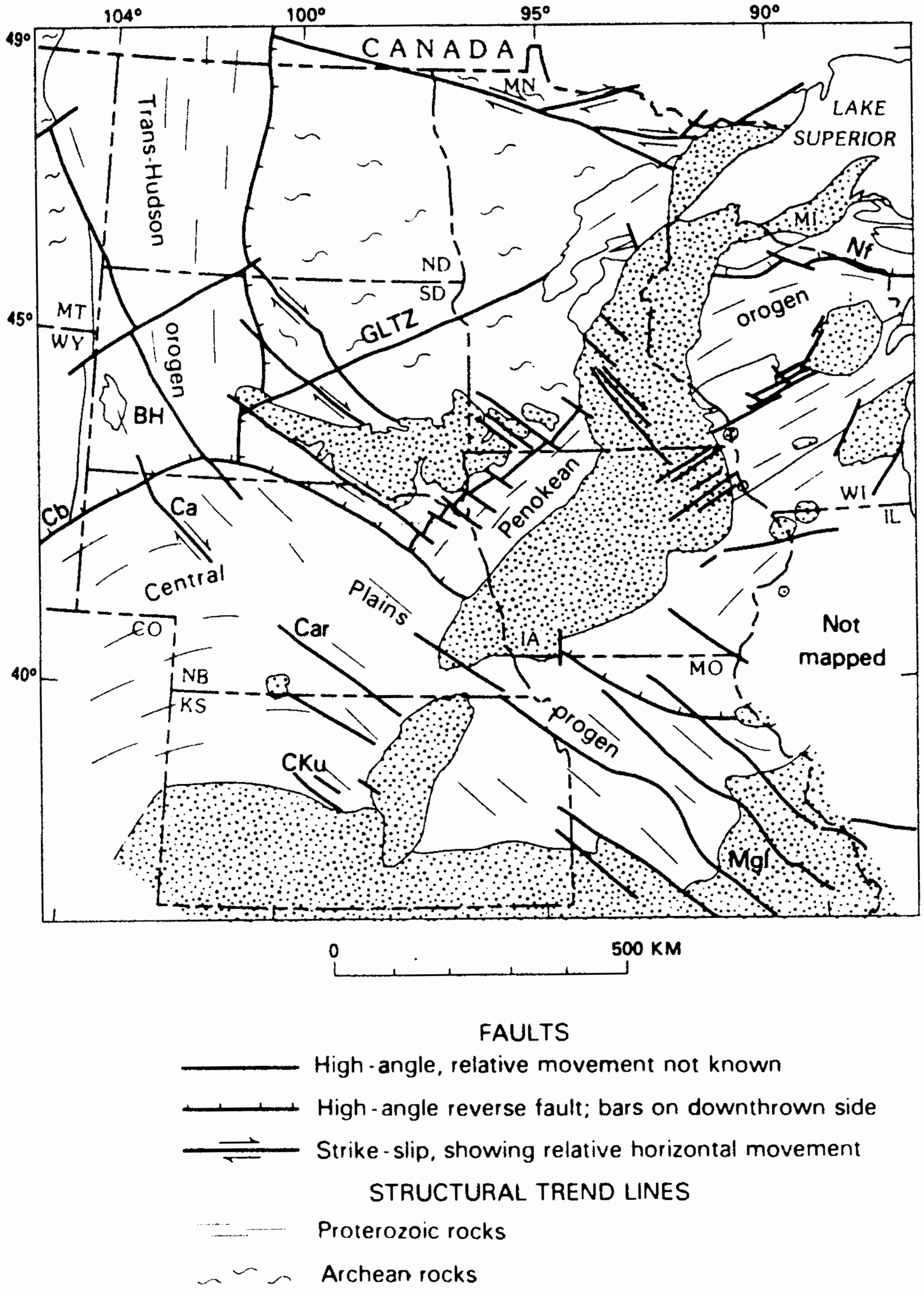


Figure 3. Map of regional basement structures (after Sims and Peterman, 1986, Fig. 2).

gravity maps (eg. Hildenbrand, et al., 1982) and magnetic maps (eg. Zietz, 1982) is the Midcontinent geophysical anomaly (MGA). The MGA corresponds to the middle Proterozoic (Keweenawan) age "central North America rift system" (CNARS) of Ocola and Meyer (1973), also known as the "Midcontinent rift system". The CNARS extends from Lake Superior southwest to at least the southern boarder of Kansas (Figure 2) and may continue into Oklahoma (Yarger, 1983). Basalts cropping out in the Lake Superior region and sampled in boreholes into the CNARS farther south yield middle Proterozoic radiometric ages ranging from 1,250 to 950 Ma (Berendsen, et al., 1988).

The CNARS has generally been interpreted as an "aborted rift," but debate continues about the precise plate-tectonic event that produced this apparent failure (Gordon and Hempton, 1983). The CNARS cuts obliquely across the previously established Archean and Proterozoic accretionary margins (Van Schmus and Hinze, 1985) and this may have been a factor in its "failure." Several apparent offsets occur along the trend of the CNARS and these have generally been interpreted as transform faults (Carlson and Treves, 1988; Chase and Gilmer, 1973), but Van Schmus and Hinze (1985, p. 373) suggested "the rift system was deflected along preexisting structures" at these locations. This latter interpretation agrees with Ramberg and Smithson's (1975) conclusion that rift-related faulting generally follows preexisting fractures locally and the major trends of rift zones reflect deep-seated crustal inhomogeneities. One such offset occurs just north of the study area in southeastern Nebraska and may correspond with the northwest extension of the older(?)

Missouri gravity low mentioned above (Arvidson, et al., 1982).

The study area lies astride the northern Kansas portion of the CNARS (Figure 2). Early interpretations of the CNARS structure in Kansas (Coons, 1966; Coons, et al., 1967; Scott, 1969) proposed a central basalt-cored horst block and two flanking clastic basins. Deep seismic reflection profiling over the CNARS in 1981 by the Consortium for Continental Reflection Profiling (COCORP) program in northeastern Kansas (Plate 1) has confirmed its rift nature (Brown, et al., 1983; Gries, 1984; Serpa, et al., 1984), but according to their interpretation, the CNARS is now thought to consist of an asymmetric fault-bounded basin roughly 80 km (50 mi.) wide and upto 8 km (5 mi.) deep. The basin is apparently segmented into several sub-basins by major east-dipping normal faults and these are now known to be filled with an interlayered sequence of coeval basalt (900 to 1100 Ma) and arkosic clastics deposited during the time of rifting (Berendsen, et al., 1988; Dickas and Mundrey, 1988). This sequence of clastics, loosely termed the Rice Formation by Scott (1966), had received considerable attention recently as a possible commercial hydrocarbon source (Dickas, 1984; Fritz, 1985; Gustavson, 1983; Herman, et al., 1985; Lee and Kerr, 1983, 1984; McCaslin, 1984; Newell, et al., 1988a, p. 3), although initial testing has been disappointing (Berendsen, et al., 1988). The presence of a large mafic intrusive body at mid-crustal levels underlying the central portion of the rift basin is indicated by gravity modelling (Somanas, 1984) and a low velocity body in the upper mantle is suggested by teleseismic residuals data (Hahn, 1980; Miller, 1983).

Near the Lake Superior area, the rift zone is characterized by two prominent sets of faults: a set of high-angle flanking faults striking parallel to the trend of the rift, and a second set of shorter but more numerous transverse faults striking generally perpendicular to the trend of the rift and cutting the older set (see Van Schmus and Hinze, 1985, Fig. 4, p. 370). Although they were probably originally high-angle normal faults generated during Keweenawan time by the tensional forces responsible for the rifting event, some of the flanking faults now possess considerable reverse stratigraphic throw and must therefore represent subsequent compression of the rift zone. For example, there is an indication on deep seismic reflection data in southwestern Iowa that substantial Precambrian reverse throw may be present along certain rift-related faults there (Herman, et al., 1985, p. 25). Reprocessing and interpretation of the Kansas COCORP data has also suggested possible thrust displacements (Berendsen, et al., 1988, p. 12) along features previously supposed to be listric normal faults (Serpa, et al., 1984). Few of the transverse faults in the outcrop area show this reverse sense of movement. Because similar sets of "gridded" (axis-perpendicular and axis-parallel) faults characterize many rifts worldwide (Ramberg and Smithson, 1975), it seems reasonable to assume such a set also typifies the CNARS in the subsurface to the south and west of the Lake Superior area. In fact, Berendsen and others (1988, Fig. 18) portray such a gridded fault pattern for a portion of the CNARS in northernmost Kansas, which includes roughly the northeastern third of the study area (Figure 4).

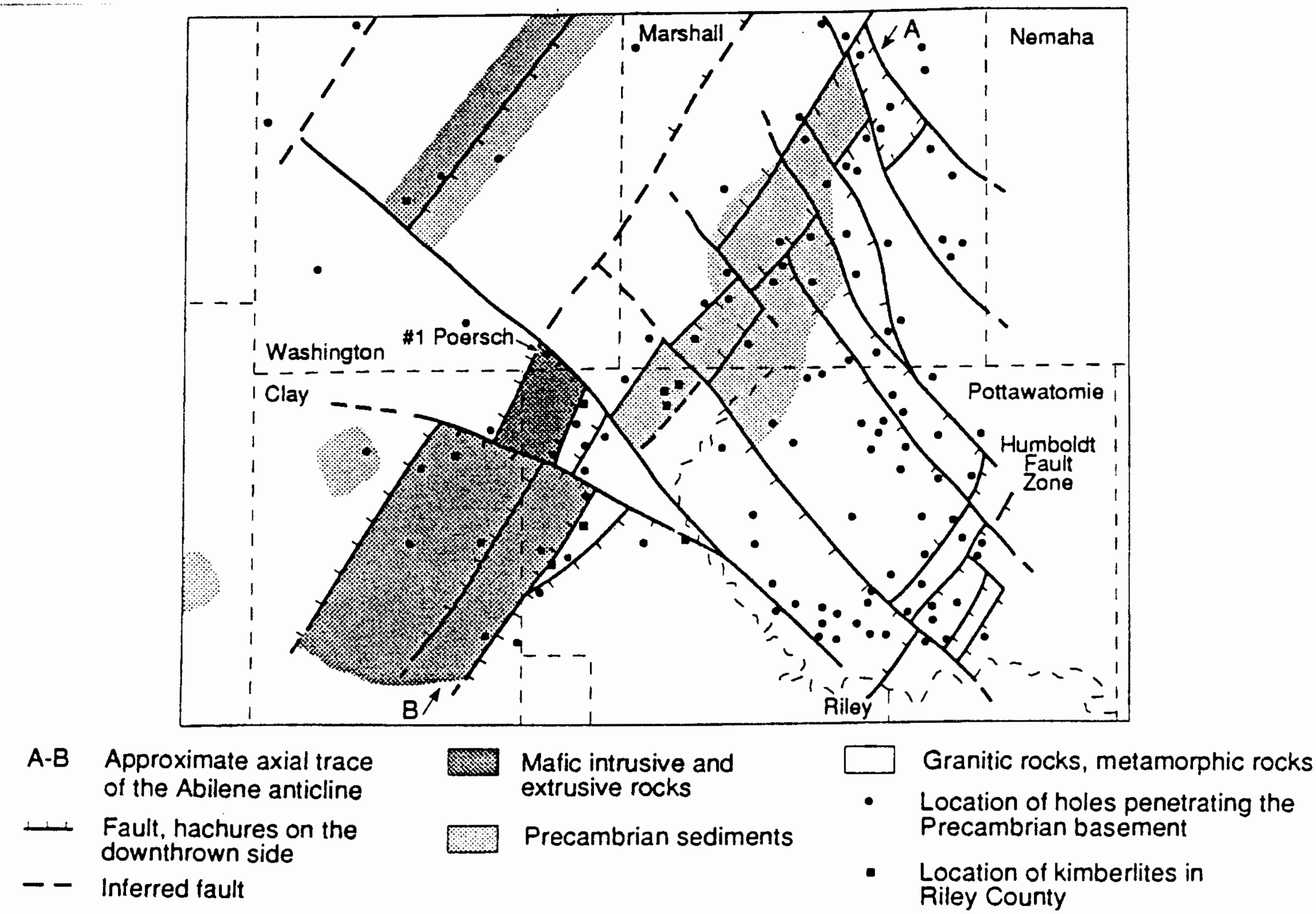


Figure 4. Tectonic map of the Midcontinent rift in Kansas (after Berendsen, et al., 1988, Fig. 18).

Contrary to the statement by Van Schmus and Hinze (1985, p. 376) that the CNARS shows little evidence of post-Keweenawan reactivation, the Midcontinent rift in Kansas appears to correspond to an area of periodic epierogenic deformation and Paleozoic faulting, relatively abundant modern seismicity and active basement faults, and numerous kimberlite intrusives (see below). These features, in addition to a Cambrian age (545 Ma) carbonatite intrusion just north of the study area in Nebraska (Brookins, et al., 1975a, 1975b; Carlson, 1988) attest to the deeply fractured and periodically reactivated nature of the Midcontinent crust along the CNARS (Nishimori and Powell, 1980, p. 30-39; Sykes, 1978).

Phanerozoic History

In comparison with the Proterozoic, the Phanerozoic depositional history and structure of the study area is relatively well known. Lower and middle Paleozoic strata preserved in the subsurface of the study area consist predominantly of marine carbonates and siliciclastics deposited near the margin of the relatively stable North Kansas basin (Figure 5). During this time period, plate tectonic interactions at the continental margins produced generally minor, epeirogenic deformation over portions of the CNARS in Kansas (Berendsen, et al., 1988, p. 4) and other basement-involved structures throughout much of the Midcontinent. At least three such orogenic episodes are recorded in the form of regional unconformities and thickness trends within the lower and middle Paleozoic strata of the study area (Willoughby and Berendsen, 1978a,

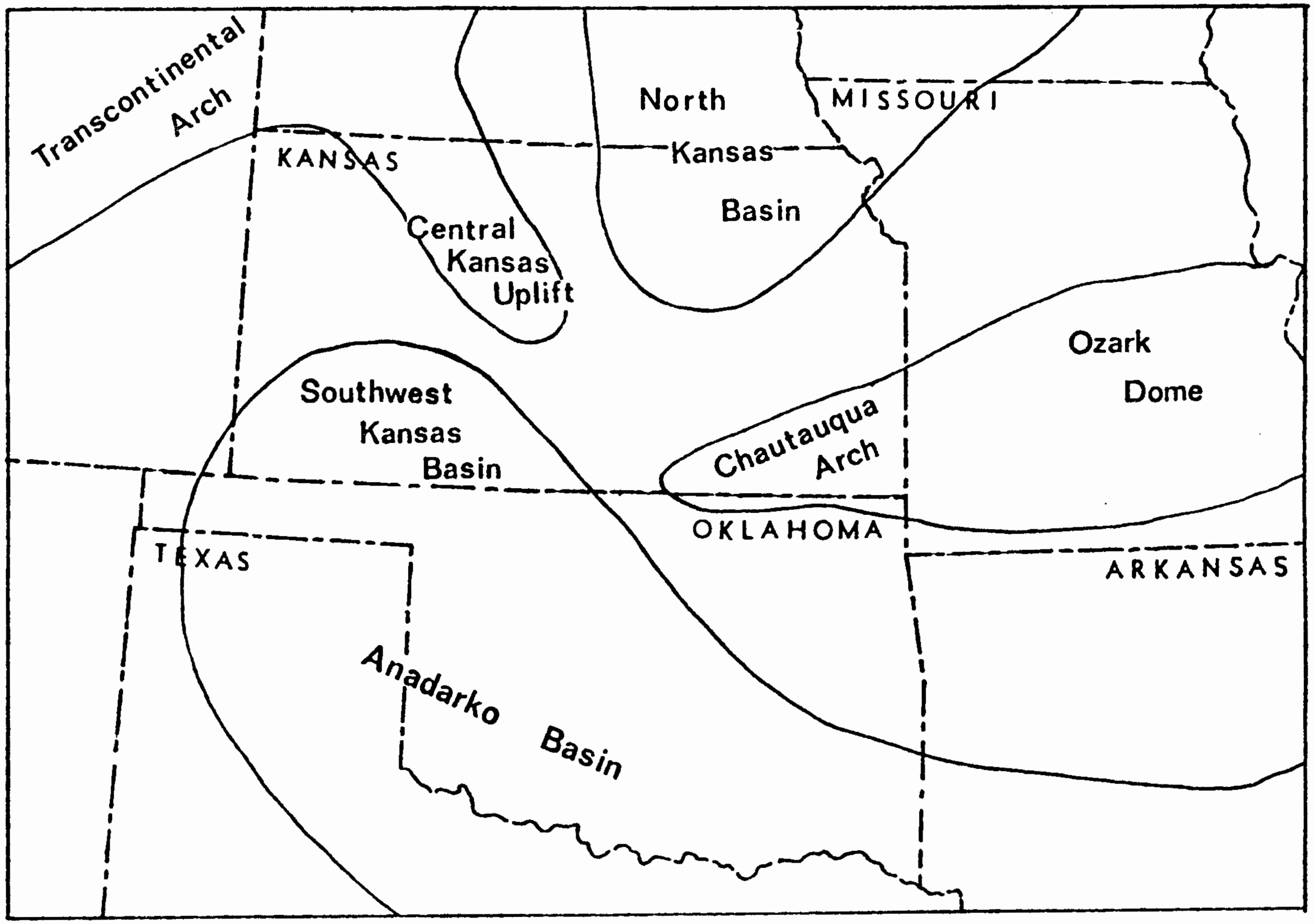


Figure 5. Map of pre-Late Mississippian regional structures (after Roehl, 1985, Fig. 19).

1978b), and locally as anomalous lithologies (Berendsen and Doveton, 1988). Detailed discussions of the gross regional Paleozoic stratigraphic and structural relations preserved in the study area are available elsewhere (Lee, 1943, 1956).

Near the close of Mississippian time the collision of the southern margin of the present North American plate with the South African plate produced north-northwest-directed principal horizontal stress, culminating in the Early Pennsylvanian Ouchita orogeny. Compressive stress was propagated cratonward from the Ouachita orogenic front of northern Arkansas and southern Oklahoma and produced major uplift along the Humboldt fault zone, Abilene anticline, and similar structures throughout much of the Midcontinent (Carlson, 1988; Howe, 1988). This Late Mississippian, Pennsylvanian, and (?) Early Permian tectonic episode resulted in the formation of the Nemaha anticline which subdivided the former North Kansas Basin into the present day Salina and Forest City basins (Figure 6). This uplift may have been a result of convergent left-lateral strike-slip (wrench) faulting along preexisting northeast-trending basement faults (Blair and Berendsen, 1985, 1988; Davis, 1984; Fenster and Trapp, 1982; Heyl, 1977; Phipps, 1983). Detailed subsurface studies indicate the Nemaha anticline/Humboldt fault zone consists of a complex series of scissor faults, sigmoid anticlines, horst and graben features, pull-apart basins (Berendsen and Blair, 1986a; Eccles, 1981; Newell, 1987; Steeples, 1982), en-echelon fault zones (Fath, 1920, 1921; Foley, 1926), reverse-slip faults (Smith and Anders, 1951; Steeples and Yarger, 1983), and anastomosing fault

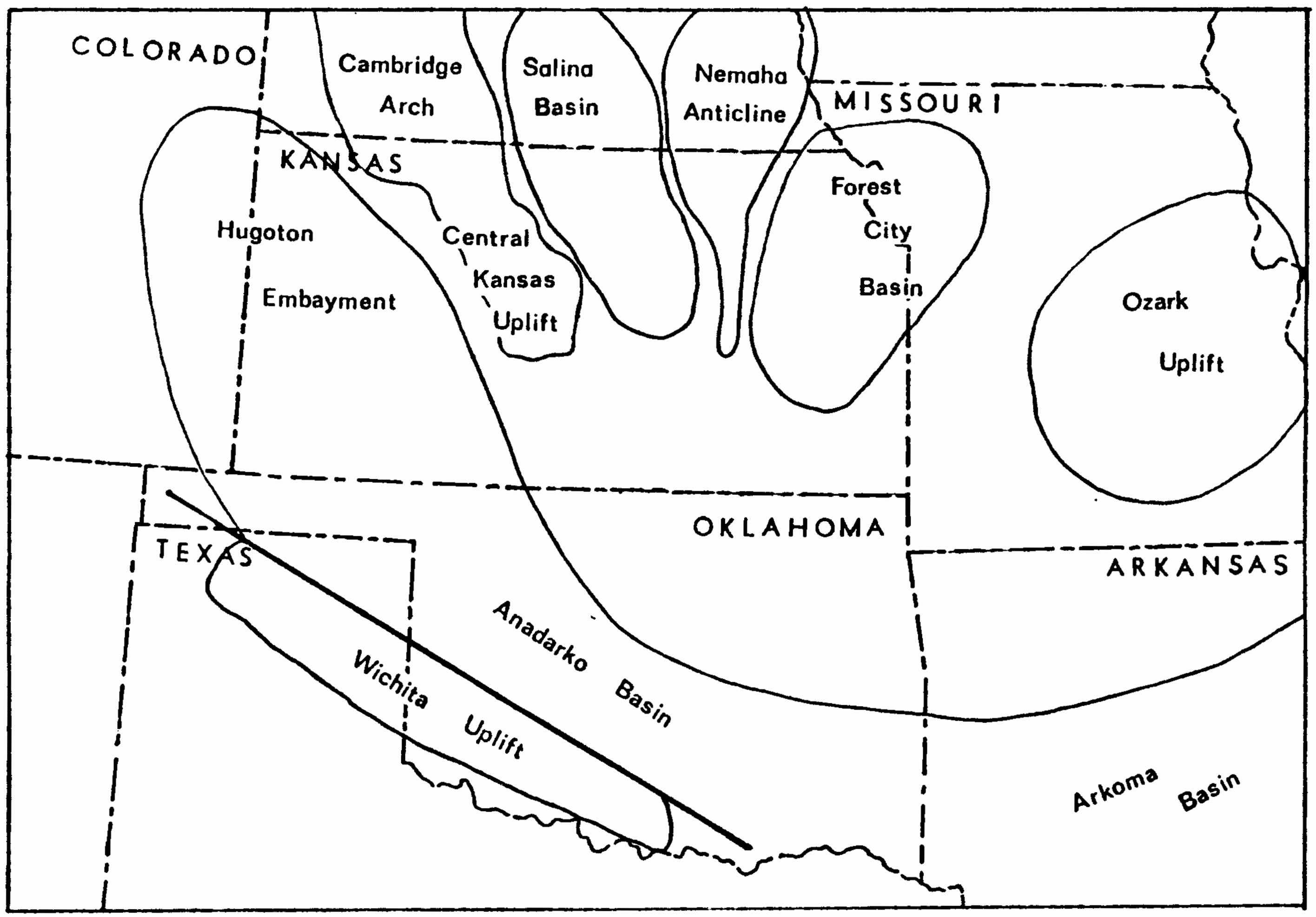


Figure 6. Map of post-Late Mississippian regional structures (after Roehl, 1985, Fig. 20).

zones (Burchett and Arrigo, 1978), all of which are features consistent with wrench fault deformation (eg. Harding, 1973; Maxwell and Wise, 1958; Moody, 1973; Moody and Hill, 1956, 1964; Prucha, 1964; Sylvester, 1982; Wilcox, et al., 1973). Thus, the Humboldt fault zone within the study area almost certainly represents a rift-marginal fault complex of the CNARS in Kansas that was reactivated periodically throughout the Paleozoic (Berendsen and Blair, 1986, p. 4; Serpa, et al., 1984; Somanas, 1984; Yarger, 1983, p. 29).

Minor continued uplift along the Nemaha structural trend, and to a lesser extent the associated Abilene anticline (Figure 7), through Late Pennsylvanian and Early Permian times produced significant bathymetric irregularities which had a pronounced local control on marginal marine depositional environments and biota (Fisher, 1980; Lorenzen, 1973; Sporleder, 1987; Stewart, 1963, p. 12) as well as important regional and local effects on overall sequence thicknesses and lithologies (Eccles, 1981; Merriam, 1963, p. 98-101, 107-112, 118-119). Similar apparent Pennsylvanian and Permian lithotectonic relationships have been suggested elsewhere in the Midcontinent (eg. Watney and Wilson, 1983), although they may have resulted in part from passive differential compaction over existing structures (Gentile, 1968, 1979, 1984, p. 36; Steeples and Yarger, 1983).

Mesozoic and Tertiary strata are not present over the uplift within the study area, having either never been deposited, or else, deposited and subsequently removed. However, studies of overlapping relations to the north in eastern Nebraska and western Iowa indicate the Nemaha anticline was again uplifted during the Cretaceous to

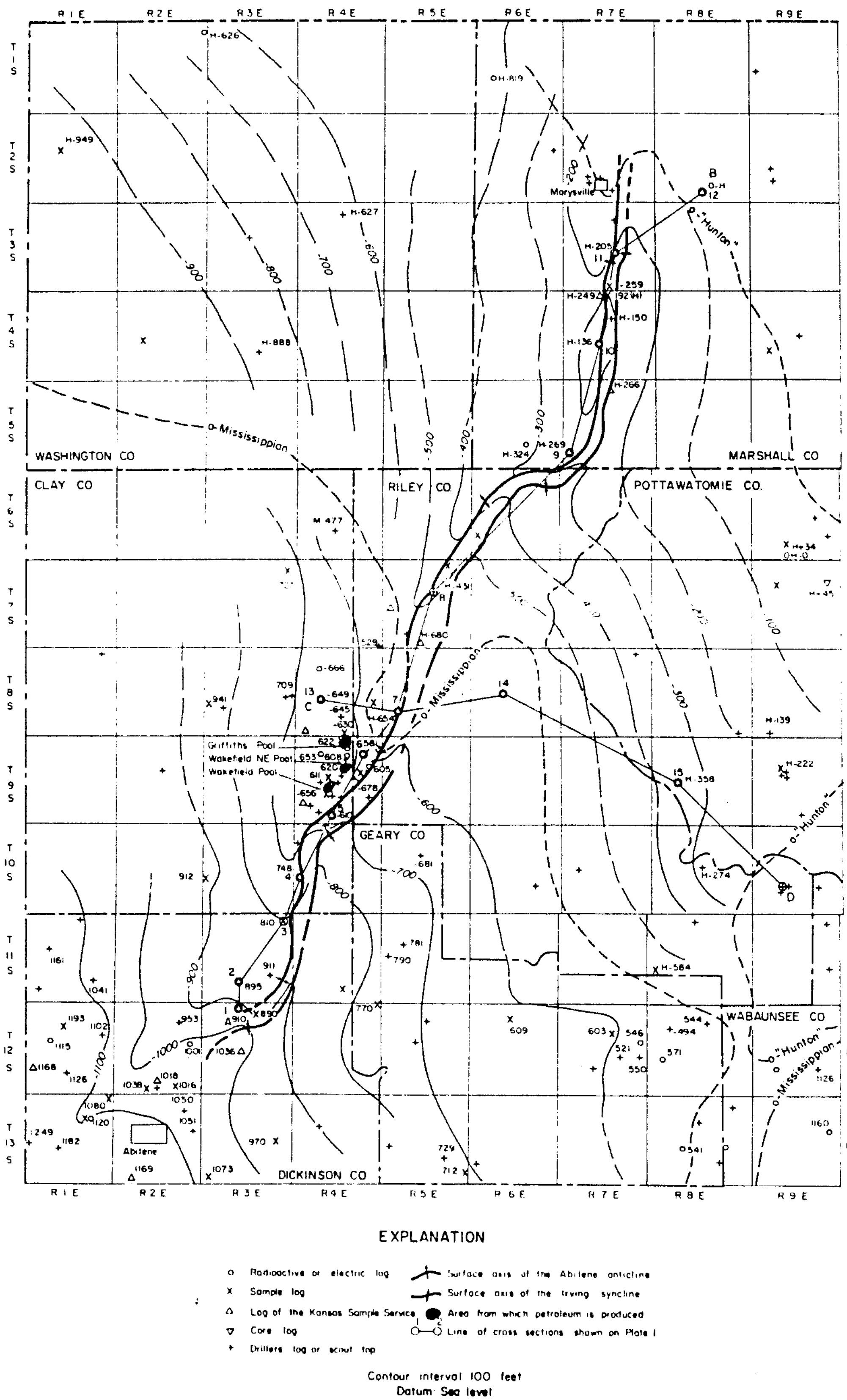


Figure 7. Map showing location of Abilene anticline (after Shenkel, 1959, Fig. 2).

early Tertiary Laramide orogeny (Bunker, 1981; Bunker, et al., 1981; Carlson, 1988). The presence of numerous Cretaceous-age kimberlite intrusives in close proximity to the uplift (Plate 1) has also been cited as evidence for renewed tectonic activity during Laramide time by Chelikowsky (1972), Fenster and Trapp (1982), and Taylor (1950). The northwest-southeast orientations of kimberlite outcrops and their associated magnetic anomalies have been cited as evidence for emplacement along similarly oriented fractures (Brookins, 1970a, 1970b; Mansker, et al., 1987). Chelikowsky argued on the basis of these orientations, regional joint trends, and major fault geometries for right-lateral reactivation of the Abilene anticline and Humboldt fault system in response to east-west directed Laramide principal horizontal stresses, although the evidence for such an interpretation is not clearcut (Steeples, 1982, p. 58-59). It does seem possible that considerable stress could have been transmitted as far cratonward as north-central Kansas on the basis of Bird's (1984, Fig. 10) model for Laramide foreland deformation and associated Great Plains crustal thickening. The Chadron-Cambridge arch, a structurally related uplift of western Nebraska and northern Kansas (Figure 6), was apparently rejuvenated as recently as the Pliocene and Pleistocene (Stanley and Wayne, 1972).

Seismic activity has persisted along the CNARS to the present time as evidenced by historic earthquake epicenter data (Burchett, et al., 1983; DuBois and Wilson, 1978; Eccles, 1981) and microquake records (Steeples, et al., 1987). The modern principal horizontal stress (PHS) is oriented approximately east-northeast/west-southwest throughout much of the Midcontinent according to regional well-bore breakout data, earthquake fault-plane solutions, and various measures of in-situ stress (Dart, 1987; Zoback and Zoback, 1980).

Faults and Joints

At present, northern Kansas lies within the Prairie Plains monocline structural province of the central stable region of the North American craton (Jewett, 1951). Regional dips of a few meters per kilometer (about 14 feet per mile) or less (<1 degree) to the west are common, although smaller structures can have important local effects. Only a few surface faults have been recognized within the Paleozoic rocks of the study area and all are relatively small in length and vertical displacement (Bruton, 1958; Eccles, 1981; Hooker, 1956; Underwood and Polson, 1987, 1988). Even fewer surface faults have been mapped previously within Cretaceous strata of the study area (Hoppie, 1980; Mack, 1962). The Humboldt fault zone may reach the surface in Nemaha and northeastern Pottawatomie counties (Du Bois, 1978; Ratcliff, 1957), but this has been disputed (Seyrafian, 1977). Published studies of subsurface structure in the vicinity of study area oil and gas fields suggest basement-involved faulting has played an important role in localizing many of these accumulations (Curtis, 1960; Smith and Anders, 1951). Berendsen and others (1988, p. 4) state that Paleozoic reactivation of study area basement faults resulted in the formation of many Kansas structures. This is in accordance with the findings of Merriam (1963, p. 227) that a close correlation exists between the orientations of 99 subsurface anticlines (Figure 8A) and 50 suspected subsurface faults (Figure 8B) in central and northwestern Kansas. Berendsen and Blair (1986a) utilized subsurface elevations from 3,794 wells to construct a series of contour maps for six important Paleozoic horizons in central Kansas, including approximately the southern fourth of the study area. They mapped a large number of previously named structural features, as well as many unrecognized structures, including numerous possible subsurface faults. Their maps also show a close correlation exists between the locations and orientations of faults and anticlines in central Kansas.

Although joints are the most common fractures observed in the outcrops of Kansas, they have received only limited study. Prominent regional joint sets striking N.2-4°E. and N.10-14°W. in the Upper Cretaceous Niobrara Formation of Hamilton County were remarked upon by Bass (1926, p. 80). Although not in Kansas, Melton's (1929) early work in Oklahoma deserves mention here. He measured approximately 4,000 joint trends in Pennsylvanian and Lower Permian rocks at 106 localities in central and southeastern Oklahoma. He determined a dominant set strikes N.37°W., correlating closely with the strike of faults in the eastern Oklahoma "en echelon" fault belt (Fath, 1920, 1921, p. 150-155), and a less prominent set strikes about N.65°E. Neff (1949) compiled a large number of joint orientations for Lower Permian limestones cropping out in each township of Riley County and determined the existence of a primary set oriented about N.72°E. and a subsidiary, somewhat variable, set striking about N.25°W. He postulated that the primary set developed in

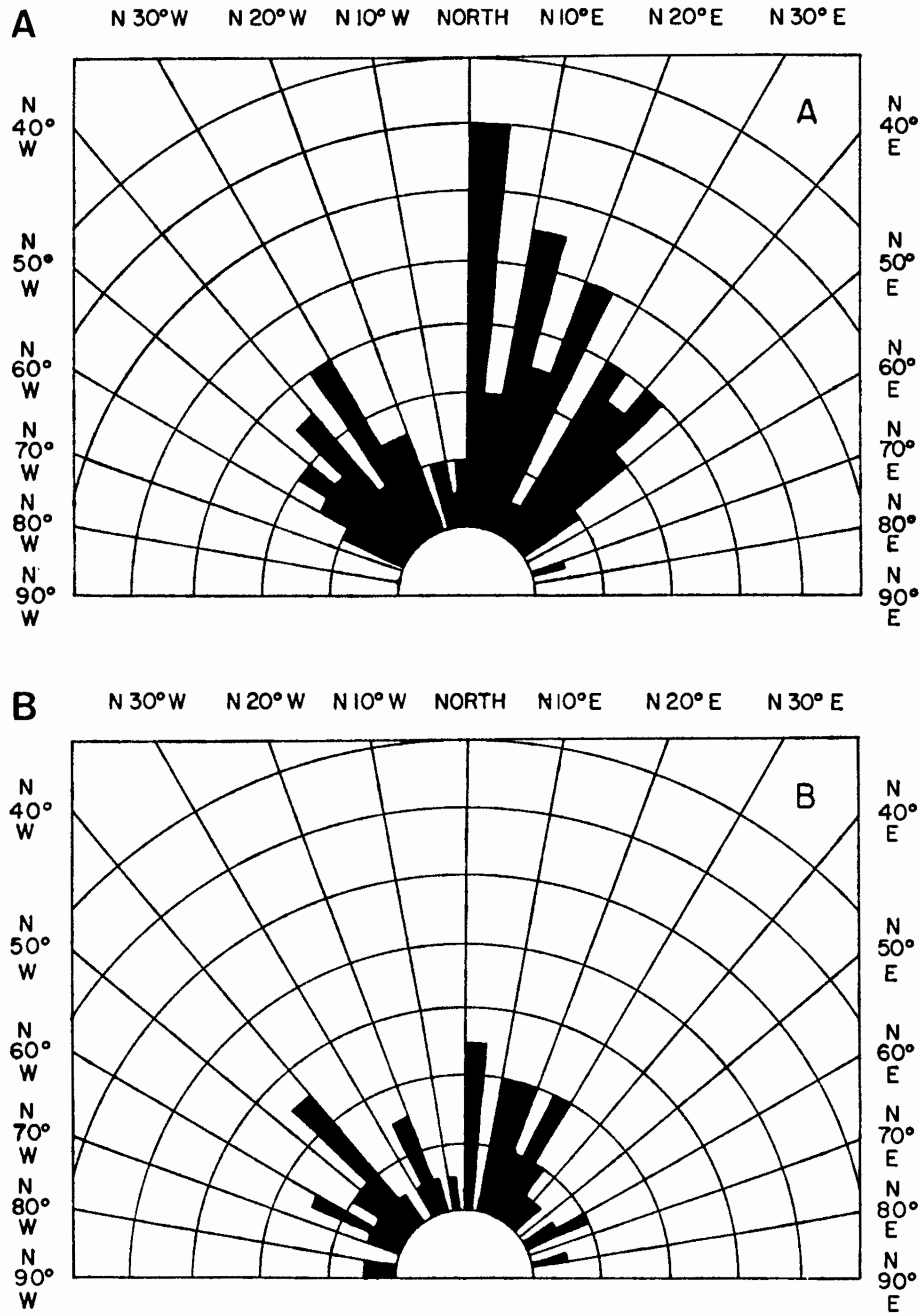


Figure 8. Rose diagrams of A) Kansas fold axis trends, and B) Kansas subsurface fault strikes (after Merriam, 1963, Fig. 137).

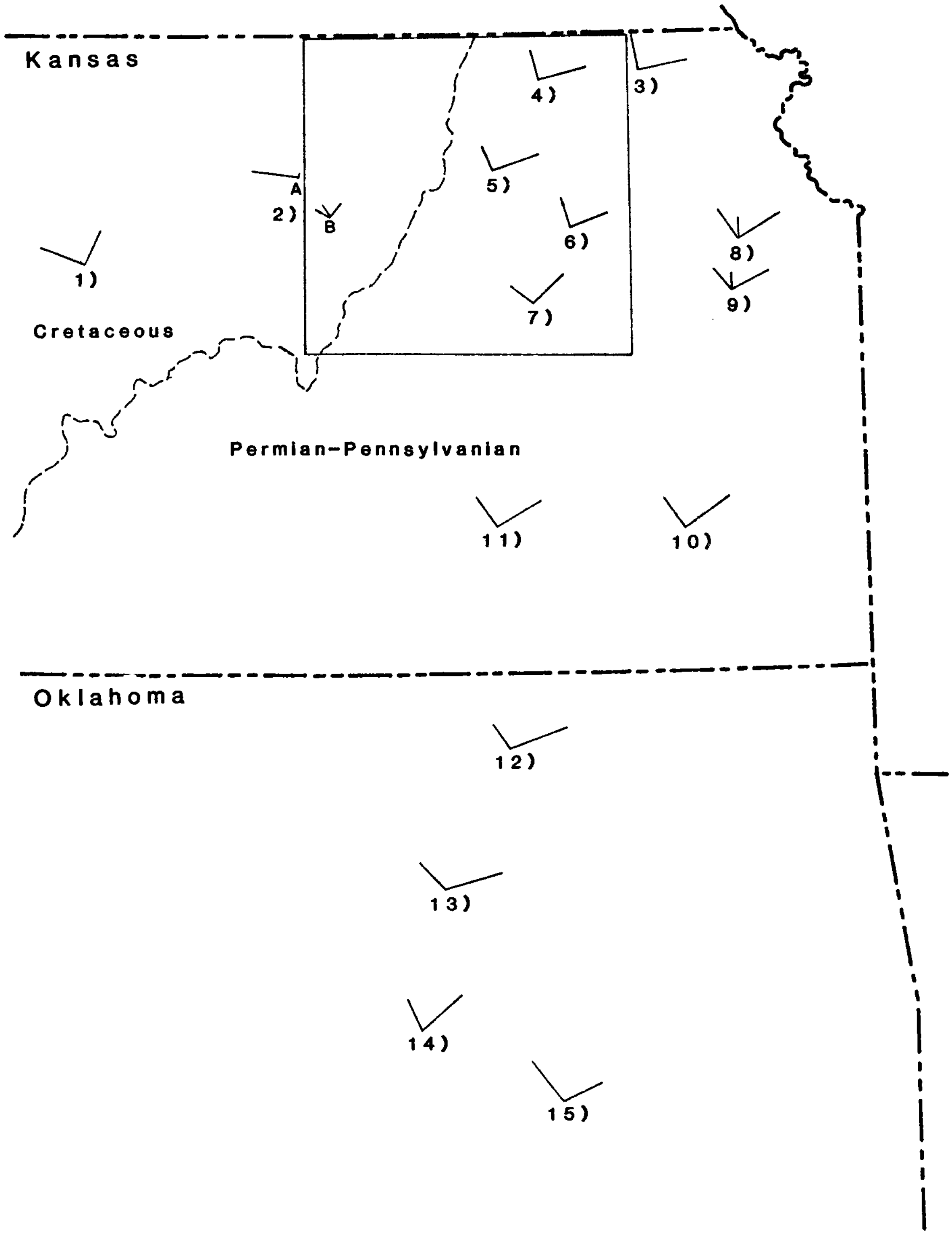
response to late Paleozoic northwest-southeast directed tensile stress, and the secondary set developed differentially in response to irregularities of local basement structure (i.e. Nemaha and Abilene anticlines). Nelson (1952) mapped an unstated number of joint trends in the Permian limestones of Marshall County and determined (p. 31) a major set strikes at N.76°E. and a minor set strikes at N.15°W. He combined these findings with Neff's (1949) data from adjacent Riley County in an attempt to determine any influences of Precambrian basement structures on the surface fracture pattern of the area. He concluded (p. 54-59) that the joint pattern expressed at the present land surface reflects an "upward transmission and progressive rotation" of a much older basement joint pattern.

Wagner (1961) used low-altitude aerial photos to map joint traces in Upper Pennsylvanian limestones and sandstones over much of Wilson County and recorded two general groups of N.55°E. and N.35°W. Stewart (1962) used a similar method to map 10,065 fracture (joint) traces in northern Cleveland County, central Oklahoma (due south of Sumner County, Kansas). He demonstrated a prominent set oriented at about N.49°E. and a secondary mode at about N.24°W. Later Stewart (1967) recorded 881 joint orientations on outcrops of four Upper Pennsylvanian limestones of Atchison, Jefferson, Douglas, and Osage counties. He documented a dominant set of "shear" joints trending N.60°E., a less common set of tension joints trending N.35°W., and a third set of short, tight joints trending about N.3°E. Ward (1968) measured the orientations of 5,777 joints in Upper Pennsylvanian and Lower Permian limestone outcrops of Butler, Cowley, Greenwood, Chase, and Marion counties. He found two prominent sets with orientations that also average N.60°E. and N.35°W. He stated (p. 21-22) that no correlation was apparent between the orientations of joints and underlying faults, the joints were post-Early Permian and pre-Early Cretaceous in age, and they may have formed as a result of northwest-southeast directed horizontal compressive stress generated during the uplift of the Ouchita Mountains. Jefferis (1969) measured approximately 320 joint orientations in two Upper Pennsylvanian limestones of southern Douglas County. He found (p. 20, Fig. 9) two sets of well developed joints trending about N.63°E. and N.41°W, and a third set of short and tight joints trending about N.2°W. Hagen (1972, 1985) mapped the surface traces of 2615 joints in Lower Permian limestones of Osage and Kay counties in north-central Oklahoma (just south of Cowley County, Kansas) as they might relate to waterflooding success. He found a "remarkably uniform" major set at N.70°E. and a much less common mean at N.35°W. DuBois (1978) measured the orientations of an unstated number of joints in Lower Permian limestones of northestern Nemaha County. She found two pronounced sets oriented at about N.85°E. and N.35W. Macfarlane (1979) measured about 180 joints in Lower Permian limestones of northeastern Morris County. He found (his Plate C) a prominent set at N.45°E. and a less common set at N.52°W. Hoppie (1980) measured 311 joints on 98 outcrops of the Lower Cretaceous Kiowa Shale and Lower(?) Cretaceous Dakota Sandstone, and 190 joints from 48 exposures of the Upper Cretaceous Greenhorn Limestone in Ottawa, Cloud, and Mitchell counties. He found (p. 52, Fig. 12) one well-developed set trending N.83°W. in the Greenhorn Limestone, but no distinct modes were apparent in data for the older clastic units. He concluded that the joints of the Cretaceous rocks of north-central Kansas were not formed in the same tectonic province as those in the upper Paleozoic strata of eastern Kansas. Eccles (1981) documented a few joint trends in Lower Permian Limestones of western Wabaunsee and eastern Riley counties. He determined (p. 40) means of N.76°E. and N.12°W. for joints in Wabaunsee County, and (p. 45) means of N.65°E. and N.21°W. for Riley County sets.

The most recent studies of Kansas joint orientations and their possible origins are those of Drees (1974) and Neuhauser (1983, 1986). They measured the orientations of 250 joints in the Upper Cretaceous Fort Hays Limestone Member of Ellis County and determined a dominant set strikes N.70°W. and a less prominant set strikes N.25°E. Neuhauser attributed the formation of these two sets to a conjugate shear couple developed in response to nearly east-west directed compressive stress of probable early Tertiary (late-Laramide orogeny) age.

A summary of relevant statistics for each of the foregoing studies is presented in map form on Figure 9. Each symbol represents a single study, and the orientation and length of each ray corresponds to the orientation and relative abundance of each joint set measured in a given study. Note the relative consistancy of the two sets expressed in Pennsylvanian and Permian rocks, and their distinct discordance with sets in the Cretaceous strata to the west. The implication of this finding with respect to the drainage pattern

Figure 9. Regional joint sets of eastern Kansas and eastern Oklahoma [Data sources for Cretaceous units: 1) Neuhauser (1986), 2A) Hoppie (1980, Greenhorn Limestone), and 2B) Hoppie (1980, Kiowa and Dakota formations). Data sources for Upper Pennsylvanian and Lower Permian units: 3) DuBois (1978), 4) Nelson (1952), 5) Neff (1949), 6) Eccles (1981), 7) Macfarlane (1979), 8) Stewart (1967), 9) Jefferis (1969), 10) Wagner (1961), 11) Ward (1968), 12) Hagen (1985), 13) Melton (1959), 14) Stewart (1962), and 15) Melton (1929)]. Note that the two regionally consistant joint sets in Pennsylvanian and Permian rocks differ significantly from the set(s) mapped in Cretaceous units.


Kansas
Cretaceous
Permian-Pennsylvanian
Oklahoma
A
B
1)
2)
3)
4)
5)
6)
7)
8)
9)
10)
11)
12)
13)
14)
15)

and the possible structural significance of Landsat photolineaments is discussed below.

Drainage Pattern

The drainage pattern of Kansas and its origin represents an interesting aspect of Kansas geology that has received rather sporadic attention over the years, but little detailed study. At first glance, the drainage network over much of Kansas appears to demonstrate a "textbook example" of the basic dendritic pattern expected for areas of flat-lying rocks of fairly uniform lithology (Howard, 1967). However, on closer inspection (Plate 2) it becomes apparent that certain orientations are more prevalent than others, producing a distinctly subdendritic to rectangular drainage pattern. This deviation from purely dentritic suggests some form of structural control influenced drainage development in Kansas (Morisawa, 1985, p. 145).

Early works on the relationships between drainage and structure in Kansas are qualitative to semiquantitative at best. Bass (1928, 1929, p. 17-23) remarked on the pronounced asymmetry of many Kansas drainage basins and suggested differential weathering effects due to topographic aspect, rather than structural or tectonic influences, were the cause. During his study of regional joint systems, Nelson (1952) noted the distinctly rectangular nature of the drainage pattern in Riley and Marshall counties. He stated (p. 47) "probably more than 75 percent of the streams in Riley County show some joint control." Melton (1959) determined the relative frequencies of drainage orientations in southern Kansas and northern Oklahoma and found that the most abundant stream trends were strongly correlated with the solar insolation angle (i.e. oriented preferentially north-south) and secondarily with regional joint patterns. This solar influence on drainage was most pronounced in lower order basins, whereas apparent joint effects were strongest on higher order streams. This conclusion differs somewhat from the findings of Baehr (1954) who studied drainage and rock structure in three small drainage basins in Geary and Riley counties, Kansas. Baehr stated (p. 57) that bedding and joints acted as the primary controls on headward migration of gullies and minor tributaries cutting the thick Permian limestones of his study area. He did not attribute any components to nongeologic (i.e. solar) effects.

Merriam (1955, p. 82) commented briefly on the obvious angularity of drainage patterns in western Kansas and later (Merriam, 1963, p. 254) suggested a bedrock fracture control. Kirk (1968) noted a rectilinear pattern existed for much of the drainage pattern of eastern Kansas. He correlated the prominent stream trends with surface fractures, basement faults, earthquake epicenter distribution, geophysical anomaly trends, and the location of surface igneous intrusions, but offered no quantitative data in support. Ward (1968) remarked (p. 15) on the apparent influence of regional joint sets on both the overall drainage pattern, and the specific locations of many smaller drainageways. Chelikowsky (1972, p. 7) also mentioned an "angular pattern" to the drainage network of Riley County which he attributed to the regional joint pattern, but did not offer any data to support this assertion. Hagen (1972, 1985), during his study of joints in north-central Oklahoma, noticed that they had apparently exercised a strong control on drainage orientations. He ascribed a less prominent north-south drainage maximum (Melton's "solar insolation effect"?) to bedding control and all minor orientations to "Precambrian shears." McNaughton (1974; McCauley, et al., 1975) utilized an optical Fourier transform of Landsat satellite imagery to define dominant stream trends for several portions of north-central Kansas. They argued that tectonic influences had produced zones of weakness in the surface strata along which streams tended to preferentially downcut. Seyrafian (1977, p. 35-42) examined some straight stream segments during his study of the Humboldt fault zone in northeastern Pottawatomie County, and concluded that strike-slip faulting might account for their locations and orientations, although obvious stratigraphic evidence for faulting was lacking. Berendsen and others (1978) utilized the linear trends of major eastern Kansas rivers to define structural lineaments in the Precambrian basement, although they did not state exactly why this relationship should be true.

More recently, Hoppie (1980) evaluated statistically the possible geologic influences on the morphology, including orientation, of the Solomon River in north-central Kansas. He concluded that the orientation of a portion of the river flowing over the Cretaceous Greenhorn Limestone may have been determined by a well-developed joint set in this unit, but elsewhere the evidence was inconclusive. Merriam and Sorensen (1982, Fig. 2) mapped a set of prominent topographic lineaments in Elk, Greenwood, and Chautauqua counties, Kansas, and suggested (p. 3) that they reflect regional basement fault-block structures.

Most recently, the author (Johnsgard, 1986, 1987) studied the orientations of 4426 straight drainage segments at three scales within a large portion of north-central Kansas (including the entire present study area) in an attempt to clarify this apparent relationship between structure and drainage. A distinct N.0-10°E. drainage orientation mode (Melton's (1959) "solar insolation angle" mode?) occurs in all areas and at all scales examined. However, a satisfactory mechanism (other than "solar insolation") for producing this trend is still lacking. Among geologic controls, regional joint trends were most strongly correlated with drainage in small order drainage basins and regional fold axes correlated best with river and major stream orientations. Because very few surface faults have been mapped in this area (see above), correlation between surface fault trends and drainage orientations was difficult to assess. However, the finding of Merriam (1963, p. 227) that the orientations of regional folds in Kansas are strongly correlated with (controlled by?) regional subsurface fault trends implies that the angular orientations of many study area rivers and streams were perhaps determined by subsurface faults, rather than regional joint sets as previously supposed. This also agrees with a statement of Berendsen and Blair (1984; 1986a, p. 11) that many suspected central Kansas subsurface faults have corresponding drainage and topographic features.

PREVIOUS INVESTIGATIONS

Fracture Detection

A large number of techniques for detecting the locations and orientations of subsurface fractures exist. These range from geologic methods, such as direct observation of joints and faults in the field, to a diverse number of geochemical, geophysical, and remote sensing methods. The suitability of a given technique to a particular application depends on factors such as geologic setting, allowable costs, time considerations, necessary precision in locating individual fractures, and availablity of supporting information (Goldstein, 1985).

Among geologic methods, surface studies of fault and joint orientations have received considerable attention in the past. Regional joint trends are easily determined from simple outcrop measurements. Unfortunately, surface joint trends may not reflect major fracture patterns at depth, (Ludvigson and McAdams, 1980, p. 13). In addition, such studies often contain severe investigator-induced biases due to improper selection and sampling of outcrops, and only rarely include important information such as joint spacing and character (La Pointe and Hudson, 1985). Field mapping may be useful in defining the locations of major faults, but minor faults or those with little stratigraphic displacement are easily missed, particularly in areas with thick vegetative cover or sparse bedrock exposures. Likewise, in areas where subsurface control is good, structure mapping can often accurately resolve many fault locations.

Unfortunately, in areas of widely spaced drill hole data, such as the Salina Basin area of northern Kansas, even major faults may be impossible to recognize.

Down-hole studies, such as borehole televiewing and "fracture-finder" type electric logging, can also provide absolute measurements on the locations and orientations of individual fractures, but must be performed on uncased holes soon after drilling. Similarly, thin-section studies require the acquisition of oriented cores during drilling. All down-hole methods suffer from very limited areal resolution.

Among surface geophysical approaches to fracture detection, potential-field methods such as gravity and magnetic mapping have received only limited use, primarily because they tend to reveal only intrabasement discontinuities and lack the ability to resolve precisely the locations of individual fractures (Lewis and Haeni, 1987). Electromagnetic methods such as earth resistivity and Very Low Frequency (VLF) radiowave surveys have been used to detect subsurface fractures with varying success (Anderson, 1981; Crumpton and Badgley, 1959; Steele, 1982), but are time-consuming and of limited applicablity. In regions with fairly high levels of seismicity, for example southern California and Missouri's New Madrid area, plotting accurately-located earthquake epicenters may produce alignments that can be related to fracture locations with some certainty. One of the more widely used methods for mapping natural fracture systems is high-resolution reflection seismic data (Tillman, 1983, p. 165). Unfortunately, seismic studies suffer from fairly high acquisition and processing costs and the inability to resolve fractures along which little or no vertical movement has occured (Aguilera, 1980).

Lineament Analysis

One of the most widely used and almost universally accepted approaches to mapping fracture locations and orientations is lineament analysis of topographic maps, potential-field geophysical data, and remotely sensed imagery. In spite of this widespread acceptance and use, the terminology of lineament analysis is little agreed upon and has undergone many changes since the time Hobbs (1904, 1911) first described linear topographic alignments in the landscape of the northeastern United States. In this paper I will follow the general definition of a lineament as set forth by Caran and others (1981) as "a figure that is perceived in an image or other factual representation of a solid planetary body that is linear and continuous, has definable end points and lateral boundaries, has a relatively high length to width ratio, a descernable azimuth, and is shown or presumed to correlate with planetary elements whose origin is geologically controlled." Under this definition, any linear features perceived on topographic maps, visible or infrared spectral data (eg. aerialphotos or Landsat satellite images) or any linear discontinuities on potential-field geophysical data can be termed lineaments. To reduce confusion somewhat, linear topographic features (including linear stream segments) could be termed "geomorphic lineaments", linear spectral features could be termed "photolineaments", and those apparent on geophysical data could be termed "geophysical lineaments", or more specifically, "gravity lineaments" and "magnetic lineaments". This is the specific usage followed herein.

Since the time of Hobbs (1904, 1911) early papers on the subject, geomorphic lineaments and various types of photolineaments have probably received the most attention as possible indicators of subsurface fractures (eg. Caran, et al., 1981; Gilluly, 1977; Haman, 1961, 1964). Readily apparent on virtually any topographic map, aerial photo, or space image of almost any earth terrain (Gay, 1973, appendix 2), both types lineaments have generally been considered the surface traces of subsurface fractures of various types. Unfortunately, in many early lineament studies the precise geologic origin of these lineaments was not addressed or was stated as "unclear". Lineaments were simply mapped and a structural connotation was assumed with little substantiating data (Anderson, 1981, p. 1). The apparently limited value of these early investigations (Gilluly, 1977) probably resulted from inadequate study documentation, inconsistent mapping methods, and indiscriminate use of terms such as "lineation," "lineament," "photolinear," "linear feature," "alignment," and "fracture trace," (Caran, et al., 1981; O'Leary and Friedman, 1978; O'Leary, et al., 1976a, 1976b). Some researchers could demonstrate good agreement between the trends of shorter lineaments and the orientations of major (regional) joint sets (eg. Boyer and McQueen, 1964; Brown, 1961; Dean, et al ., 1985; Loar, 1985), which strongly suggested a genetic relationship. In other studies a particular linear feature was shown to correspond to a zone of more intense jointing in the underlying strata (Lattman and Matzke, 1961) and less often to mappable surface faults (Brown, 1961; Elifrits, 1982; Jefferis, 1969). The largest of linear features were generally correlated with suspected basement faults (eg. Dean, et al., 1984; Hughes, 1983; Lattman, 1958; Maughan and Perry, 1983) and sub-continental sized fracture zones (Wise, 1969).

Salisbury and Merriam (1984) showed that the major Landsat photolineament orientations present in an area of southeastern Canada and New York with outcropping Precambrian crystalline basement rocks were also present in adjacent areas where the basement was overlain by thick lower Paleozoic strata. They suggested that the tectonic forces responsible for creating these lineaments in both areas either: 1) post-date the sediments altogether, or 2) that some other mechanism caused existing pre-Paleozoic lineaments to promulgate upward from the basement subsequent to deposition of the sediments. They favored the latter interpretation. Elsewhere, studies in terrains covered by Pleistocene glacial deposits and other unconsolidated sediments have indicated bedrock fractures are also represented by corresponding fractures in the overlying deposits and as photolineaments on images of these areas (DuBois, 1978; Mollard, 1958; Rumsey, 1971; Thumult, 1984). Among the mechanisms that have been suggested for producing such a upward propagation and surface expression of deeper fractures are earth tides, earthquakes and microquakes, plate tectonic compressional and tensional stresses, earth rotational stresses, and recurrent glacial loading and unloading (Rumsey, 1971, p. 30-32), and ground-water related processes (Berger and Aghassy, 1984). Inasmuch as the northeastern portion of the study area was glaciated during the Pleistocene (Plate 1) and locations of surface springs and seeps over much of the study area are probably controlled by near-surface bedrock joints (Donald Whittemore, verbal comm., June 1988), these latter two factors may be particularly relevant to the present investigation.

Regardless of their precise geologic origin, photolineaments are now routinely used by geologists for both reconnaissance-level and detailed structural analysis throughout the world. This is evidenced by both the abundant literature on geologic applications of remotely sensed data and an ongoing series of international conferences dedicated to the study of lineaments in general, of which seven have been held since 1974 (eg. Gabrielson, et al., 1983). Regional and local analyses of photolineaments are now frequently used as an aid in assessing the tectonic structure and petroleum potential of frontier basins (eg. Halbouty, 1976, 1980; Moore and Anderson, 1985), targetting areas for mineral exploration (eg. Halbouty, 1976), locating zones of enhanced ground water or natural gas yields (Cooley, 1984; Jammallo, 1983; Rauch, 1984; Rodgers and Anderson, 1984), defining fractured zones important to geothermal energy development (Goldstein, 1985), and predicting fracture trends that might affect induced fracturing of petroleum reservoirs and enhanced recovery operations (Alplay, 1969; Hagen, 1985; Shumaker, et al., 1976).

Within Kansas and nearby areas, photolineaments have been mapped on aerialphoto mosaics by Stelljes (1964), on radar imagery by Jefferis (1969), and on Landsat satellite imagery by Anderson (1981), Callen (1983, 1985), Cooley (1984, 1986), Dwivedi (1983), McCauley (1988), McCauley and others (1978), Patton and Manwaring (1984), Peterson (1979), Podwysocki (1974), Proctor and others (1979), and Toweh (1978), among others. The tectonic implications of some of these studies are discussed in the Results section below.

Gravity and magnetic lineaments have also generally been considered to reflect possible basement faults, although the literature on their analysis is not as numerous as for lineaments on topographic maps and remotely sensed images (Lewis and Haeni, 1987). Many of the basic principles of gravity and magnetic lineament interpretation are given by Dean and others (1984), Gay (1972), Jammallo (1983), Ossinger (1983), Peterson (1985a, 1985b), and Rasmussen (1983), to mention a few. Yarger (1983) mapped aeromagnetic lineaments in Kansas (Figure 10) and considered most of these features (p. 29) to correspond to unmapped intrabasement faults and other lithologic discontinuities. Lam (1987) mapped a large number of gravity lineaments in Kansas (Figure 11) and reached similar conclusions (p. 144) regarding their origin. Length-weighted azimuthal histograms ("rose diagrams") of Lam's eastern Kansas gravity lineaments and Yarger's eastern Kansas aeromagnetic lineaments are presented here (Figures 12A and 12B respectively). On figures 10 and 11 note a very prominant set of north-northeast-oriented lineaments in central Kansas (corresponding with the trace of the Midcontinent rift through Kansas) that produces a distinct mode centered on about

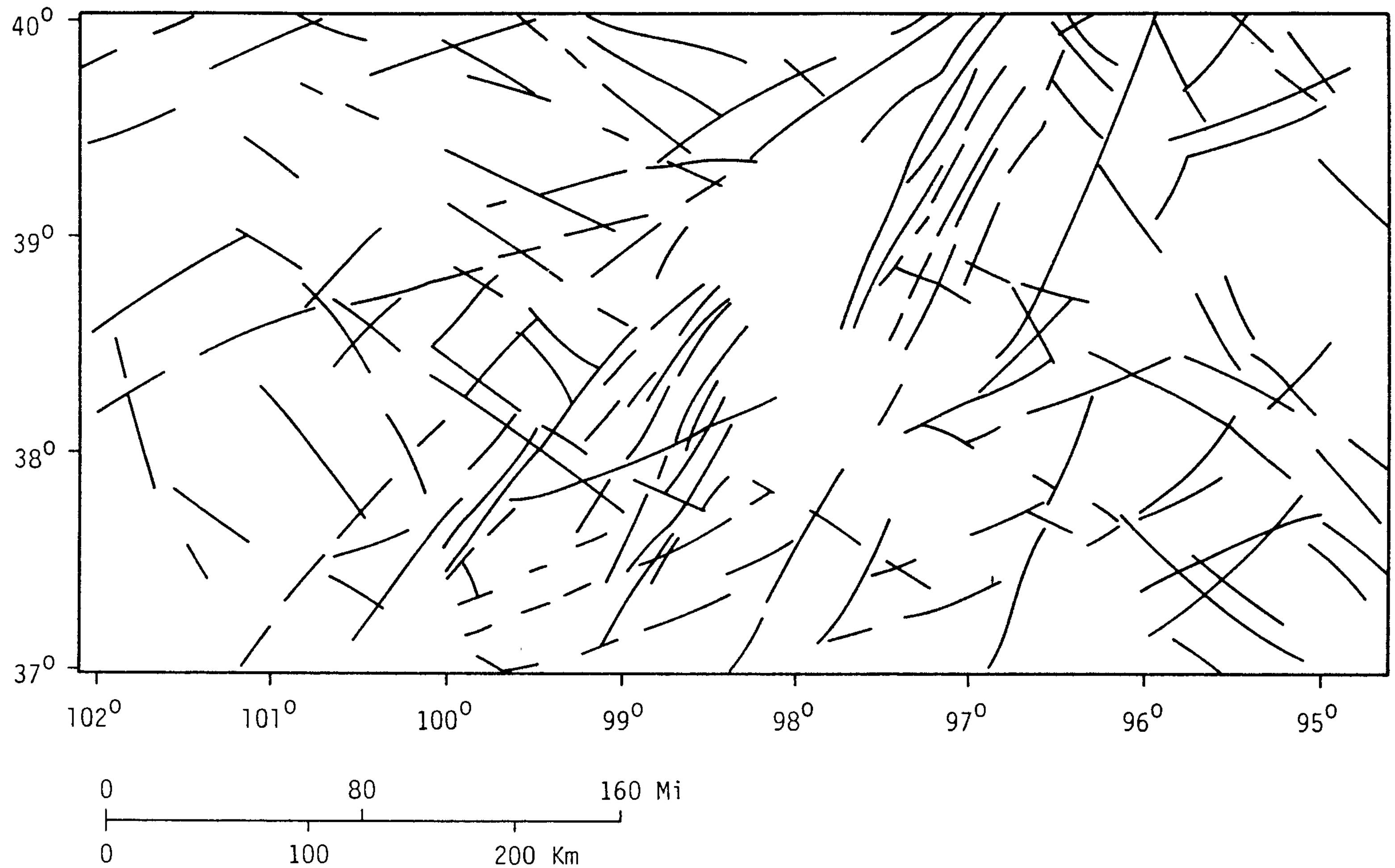


Figure 10. Map of aeromagnetic lineaments in Kansas (after Yarger, 1983, Fig. 13).

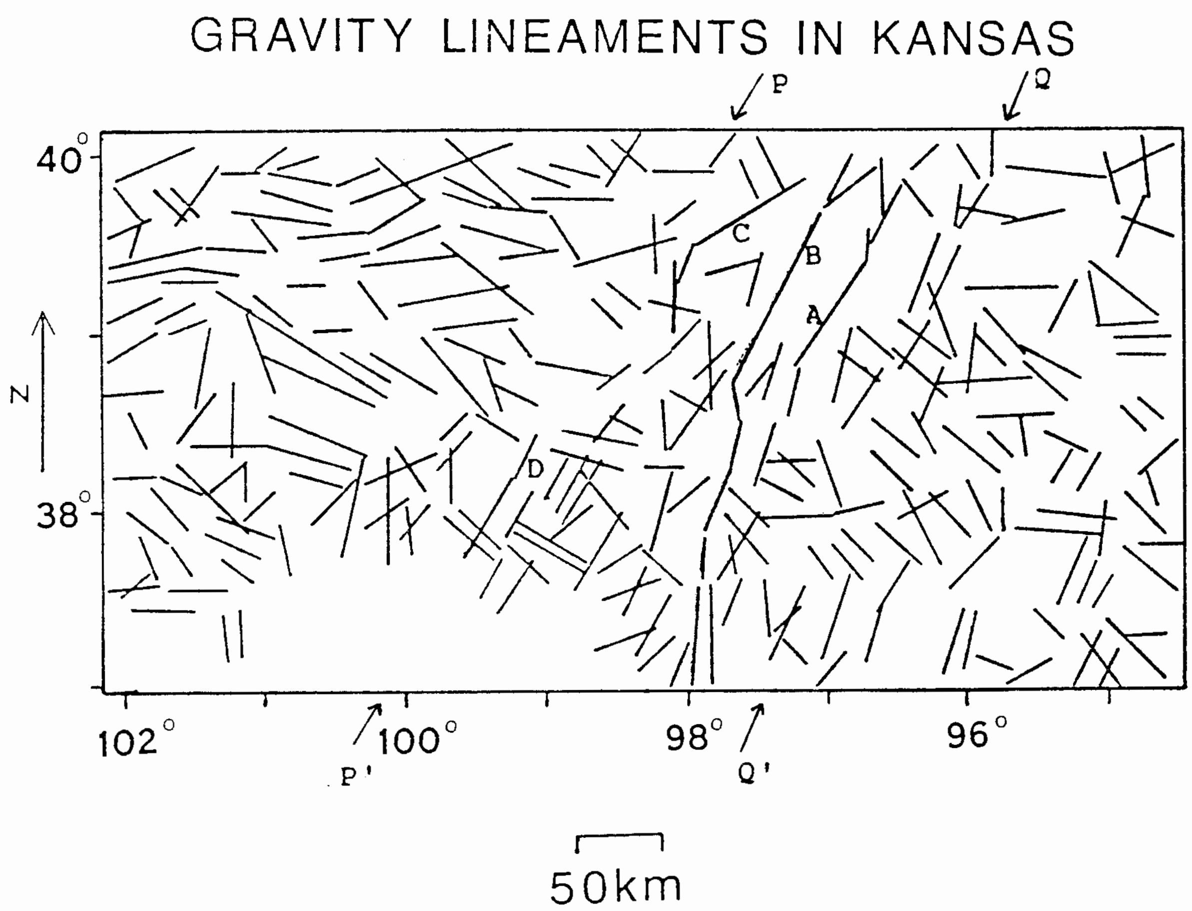


Figure 11. Map of gravity lineaments in Kansas (after Lam, 1987, Fig. 37).

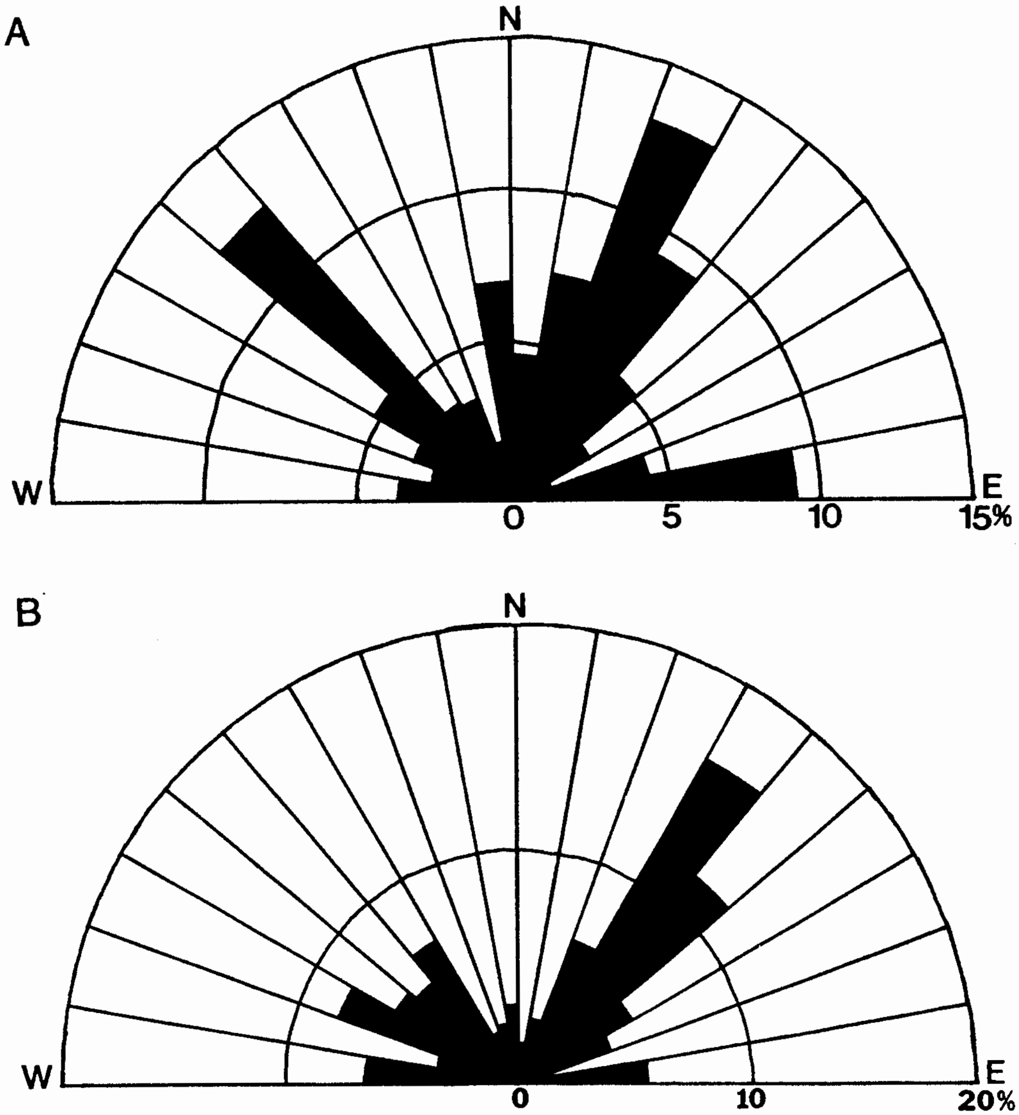


Figure 12. Rose diagrams of eastern Kansas A) gravity, and B) aeromagnetic lineaments (data from Lam, 1987; Yarger, 1983).

N.30°E. on each respective rose diagram (Figure 12). Note also a secondary mode centered on about N.50°W. on each rose diagram that results from a distinct set of northwest-oriented geophysical lineaments in eastern Kansas. Finally, note a third, much less distinct, east-west mode occurs in the gravity data and possibly in the aeromagnetic data. In a study of detailed gravity and aeromagnetic data in southeastern Kansas and adjacent Missouri, Adkins-Heljeson and others (1988) mapped prominent sets of NW-SE and NE-SW-oriented lineaments and likewise interpreted them to reflect the structural grain of the basement there.

Increasingly, multi-source integrated studies have been used to detect and map natural fracture systems. Such studies often rely on information sources as diverse as lineament analyses of gravity, magnetic and remotely sensed data; seismic reflection profiles; drainage-pattern analysis; oil-field distribution, engineering, and recovery parameters; geochemical anomalies; earthquake epicenter and focal plane data; surface and subsurface geologic mapping; and various borehole studies, such as in-situ stress measurements (see for example Thumult, 1984; Vixo and Bryan, 1984). Berendsen and others (1978) conducted such an integrated study for eastern Kansas, including the present study area, but portrayed their results on small scale maps, severely limiting their utility for subsequent detailed analysis at a local level. The present investigation is an attempt at a similar integrated study using much of the same data, but with the resultant maps presented at a possibly more useful final scale.

Drainage Pattern Analysis

Much of the literature on drainage analysis concerns determination of the nature of structural controls on general drainage development, rather than precise locations or orientations of individual structures that may have influenced particular stream locations or trends. Most quantitative drainage pattern studies involve measurement of drainage segment orientation frequencies to determine the degree of uniformity. In areas of flat-lying homogenous strata, drainage networks tend to display a nearly uniform distribution of drainage-segment orientations (Morisawa, 1963). Strong deviations from such uniformity can be interpreted to reflect the influences of lithology and structural fabric on drainage development (Flarity, 1978; Morisawa, 1985, p. 164; Schick, 1965). In areas of nonuniform stream orientations where close agreement exists between drainage orientation modes and dominant structural trends, such as joint, fault and fold orientations, it is probable that a high degree of structural control is reflected by the drainage pattern (Cox and Harrison, 1979; Judson and Andrews, 1955). This relationship is usually strongest with higher order drainage segments (Delano, 1977; Flarity, 1978; Jarvis, 1977). It follows then, that in such areas, there is a good likelihood that a given straight segment of a particular river or stream oriented close to a structural orientation mode may indicate the actual surface location of such a feature. Stated another way, an analysis of straight drainage segments (geomorphic lineaments) in an area of nonuniform drainage orientations could help reveal the surface traces of individual structural features, such as faults, joints and possibly folds, particularly where they correspond closely to any independent measures of potential fracture locations.

Soil Gases and Gas Migration

Surprisingly little has been written regarding the occurrence and interpretation of nonhydrocarbon gases in soils and the subsurface. Helium is perhaps the most commonly reported nonhydrocarbon gas targetted by soil geochemical surveys. Regional helium soil gas surveys are generally conducted in an effort to locate oil and gas fields, uranium and thorium deposits, or geothermal energy fields (eg. Cunningham, 1987; Cunningham, *et al*., 1987; Gole and Butt, 1985; Jones and Drozd, 1983; Pogorski and Quirt, 1980). Hydrogen determinations are occasionally incorporated in soil gas surveys related to petroleum exploration (eg. Nechayeva, 1968; Rodgers and Anderson, 1984), but opinions differ on anomaly interpretation. Sato and others (1984, p. 377) state that site characteristics, such as local geomorphology and geology, that must be considered in interpreting anomaly magnitudes. The potential for contamination from near-surface biogenic sources of hydrogen has also been suggested as a limitation on its utility as an exploration technique (Gole and Butt, 1985), but the soil-gas work and global hydrogen-budget models of Conrad and Seiler (1985) indicate that most soils, in fact, form a sink (not source) for hydrogen, and account for the annual destruction of up to 95% of the tropospheric hydrogen. Some hydrogen soil gas anomalies have been shown to correspond with the surface traces of active faults (Jones and Drozd, 1983, p. 942; Wakita, et al., 1980; Ware, et al., 1984) and nondiurnal temporal fluctuations in soil gas hydrogen concentrations in proximity to such features have received considerable attention recently as possible earthquake event predictors (see for example MgGee, et al., 1983; Satake, et al., 1984; Sato, et al., 1984, 1986; Sugisaki, 1984; Sugisaki, et al., 1983). The precise origin of this "active fault" hydrogen continues to be debated, but most investigators have attributed it to either the active shearing of water-rich minerals, or the release of "pent-up" hydrogen generated by the FeO/hydration (serpentinization) reaction mentioned above.

Helium and hydrogen, because of their small molecular sizes, low solubilities in ground water, and low chemical reactivities, are very mobile gases once generated (Hunt, 1979; McGee, et al., 1983). They are, therefore, capable of diffusing through all geologic materials over time, although these diffusion rates are generally low. Because of this high mobility, they cannot be retained in traditional geologic traps for long times geologically, and their presense in deeper subsurface gases (the Heins and Scott wells for example) implies continuous abiogentic generation at shallow crustal or deeper levels is taking place (Hunt, 1979; Rodgers and Anderson, 1984, p. 96). Although diffusion rates are generally low, higher gas-flux rates of several orders of magnitude are predicted for gases moving upward at depth along faults and fracture zones due to their fracture-enhanced permeability (Cunningham, et al., 1987, p. 213; Gold and Held, 1987, p. 419; Ware, et al., 1984). High amplitude, very localized (often single point) helium and hydrogen anomalies detected in soil gas surveys are thus interpreted to reflect such higher flux rates along near-surface fault zones (Cunningham, et al., 1987, p. 213; Driver and Brodine, 1985; Eremeev, et al., 1973; Jones and Drozd 1983; Ovchinnikov, et al., 1972). In addition, Shcherbakov and Kozlova (1986) reviewed a large number of subsurface Russian hydrogen occurrences and concluded (p. 126) that most anomalies occur in association with "zones of deep regional faults". Angino (1985) pointed out that many of the Kansas soil gas hydrogen anomalies acquired up until that time (now considered fairly small) occurred near the centers of river and stream valleys. McCarthy and others (1986, p. 17) speculated that this association indicated fault control on the near-surface migration of the Kansas hydrogen gas. In regional soil gas surveys with sample spacings of 1 to 2 miles (spacings for this study average 0.5 to 1.0 mi.) highly anomalous values are generally seperated from the statistically less anomalous background values prior to mapping in order to emphasize the larger regional trends that may relate to actual petroleum or other commodity deposit signatures (see for example Cunningham, et al., 1987). Alternatively, with close enough sample spacing (10-200 feet), the locations of these highly anomalous points can generally be used to actually map indirectly individual fracture and fault zones (Roberts and Roen, 1985).

METHODOLOGY

Imagery Analysis

Two general types of remotely sensed imagery were utilized in this study. These consisted of various Landsat products and low-altitude airphoto mosaics.

Landsat imagery in three formats was utilized in this study (Table 1). All images were selected on the basis of minimal cloud cover conditions, good to excellent image quality, and appropriate geographic coverage. The band 5 (near infrared) Thematic Mapper (TM) image dated Jan. 13, 1985 was also selected on the basis of the superior spatial resolution provided by this sensor and reported snow-on-ground measurements over the study area. According to the U.S. Weather Service (verbal comm., 1985) Jan. 10, 1985 snow cover ranged in thickness from about 44 cm (17 in.) at Concordia in Cloud County through 30 cm (12 in.) at Milford Lake in Geary County to 20 cm (8 in.) at Cottonwood Falls in Chase County. It was felt that such extensive snow cover and the low sun angle (23 degrees) would help obscure cultural features and reveal certain, otherwise subtle, topographic elements (Halbouty, 1976, p. 764; Morrison, 1976). The band 6 (thermal infrared) TM image dated Aug. 12, 1983 was obtained because it was felt that the minor drought conditions prevailing over the study area during the acquisition period would enhance those areas of anomalous vegetational stress (expressed as leaf surface temperature) resulting from the increased soil-moisture conditions expected near lineaments (Berger and Aghassy, 1984; Rum-

Table 1. List of Landsat imagery products used in study.

Image Number	Date	Sensor and Image Format	Scale
E-40392-16355-6	08/12/83	TM B&W film positive	1:1,000,000
E-50318-16370-5	01/13/85	TM B&W film positive	1:1,000,000
E-2 468-16225	05/04/76	MSS false-color print	1:500,000
E-30023-16272-B	03/28/78	RBV B&W positive print	1:250,000
E-30239-16292-B	10/30/78	RBV B&W positive print	1:250,000

sey, 1971, p. 31-32). The two Return Beam Vidicon (RBV) images were selected for the high spatial resolution provided by the sensor and the low sun angle conditions (32 and 44 degrees) during their acquisition dates.

The interpretation procedure for all Landsat image products was similar to that employed by Anderson (1981, p. 14-19) and Roark (1985, p. 22-23). A single transparent mylar overlay was attached to each image and several prominant river junctions or other distinctive landmarks were marked to aid in later registration of all overlays. Interpreted photolineaments were traced onto these overlays with a "00" Rapidograph ink pen and the aid of a straightedge. Positive prints were viewed under reflected fluorescent light conditions and transparencies were viewed using the transmitted light of a commercial fluorescent light table. Viewing was done at both low and high observation angles in an otherwise darkened room and all extraneous sources of light were eliminated to reduce eye fatigue. Various combinations of transparent colored acetate sheets (red, yellow, green, blue) were utilized to filter both sources of light (Peterson, 1979, p. 1000). In addition a 79 lines/cm (200 lines/inch) Ronchi ruling was used to aid in the locating of subtle alignments (Pohn, 1978). Each image was viewed for a period of 10 to 15 minutes (Caran _et_ _al_., 1981) and reexamined two additional times on later dates. All linear features were evaluated on air-photo mosaics (see below) to eliminate cultural features. Finally, all photolineaments observed on two different images, or at least twice on the same image, were transfered to a final overlay (Plate

2) with the aid of an optical enlarging/reducing table.

In addition to photolineaments determined by the above procedure, all linear features mapped in previous Landsat studies overlapping the study area (Callen, 1983; Cooley, 1984; McCauley, et al., 1978) were reevaluated on the higher resolution imagery available to this study and many of these features also appear on Plate 2. This was done in an attempt to reduce "single-operator bias" (Podwysocki, et al., 1975; Siegel, 1977).

Black-and-white panchromatic aerial photomosaics of the type prepared by the U.S. Agricultural Stabilization and Conservation Service (ASCS) and its predecessors, the U.S. Commodity Stabilization Service (CSS), the U.S. Production and Marketing Administration (PMA) and the U.S. Agricultural Adjustment Administration (AAA), acquired between 1938 and 1973, were made available to the author by the Kansas Applied Remote Sensing Center (KARS), the Remote Sensing Laboratory (RSL) of the University of Kansas, and the Kansas Geological Survey (KGS) for each county of the entire study area. In spite of some slight inherent geometric distortions, the airphoto mosaics proved invaluable for evaluating the geomorphic validity (ie. not cultural effects) and possible geologic causes of Landsat-derived features, because these large-scale images were readily available, and provided both good spectral definition and excellent spatial resolution (Peterson, 1979, p. 998).

Drainage Analysis

Linear elements of the study area drainage network represent a subset of data derived from an earlier study. Details of the mapping methodology, compilation, and possible interpretations of these data are available elsewhere (Johnsgard, 1986, 1987). In general, these data represent a combination of the linear drainage segments of the study area drainage network as portrayed on the 1,000,000-scale U.S. Geological Survey base map of Kansas and the 1:250,000-scale U.S. Geological Survey Manhattan and Hutchinson topographic map sheets. The drainage lines on these maps were originally traced from aerial photos and are thus portrayed in considerable detail. A map of these linear segments is not included herein. However, the drainage network as portrayed on the 1:2500,000-scale maps is available (Plate 2) for comparison with the linear features obtained from the other data sources.

Gravity Data

Gravity data used in the present study comprise a subset of an ongoing state-wide gravity survey being conducted by the Kansas Geological Survey. Within the study area data were acquired by the Survey over a period of several years using a Worden gravimeter a stations located every 1.6 km (1.0 mi.) or 3.2 km (2.0 mi.) along east-west transects spaced either 9.6 km (6 mi.) or 6.4 km (4 mi.) apart respectively (see Lam, 1987, Fig. 6 for actual station locations). These relative gravity measurements were tied into the International Gravity Standardization Net to establish absolute gravity values. Earth tide, meter drift, free-air, and Bouguer corrections were applied using a Bouguer density value of 2.67

gm/cm^3. Terrain corrections were not performed due to the low topographic relief of Kansas. Gridding of the data at 1.6 km by 1.6 km (1.0 mi. by 1.0 mi.) allowed for spectral domain filtering (see below) to produce various map products. Estimated overall accuracy of the final gridded data is thought to be better than 0.5 mgal (Lam, 1987).

Gravity map products used in this study were produced by digital filtering of an appropriate subset of the Kansas gravity dataset. Filtering operations applied included calculation and removal of a tenth-order trend surface, as used by Lam (1987, p. 133) to enhance the contributions of shallow basement sources, and production of two low-angle synthetic illumination images (Yarger, et al., 1984) at "sun" azimuths of 120 degrees (ESE) and 235 degrees (SW) of north to enhance NNE-trending and NW-trending features respectively (for state-wide examples of these products see Lam, 1987). The orientations for these latter two filters were selected on the basis of two distinct maxima in the orientation plot of Lam's (1987, Fig. 38) gravity lineaments of eastern Kansas (recompiled here as Figure 12A). Paper copies and color plots of the resultant images were plotted at a scale of 1:250,000 using the Kansas Geological Survey's Versatek plotter and at a scale of 1:1,000,000 with the Survey's Tektronics color plotter, respectively.

Mylar overlays were then placed over each map and the trends and lengths of all apparent linear gravity features were traced onto them. The final map (Plate 3) represents a composite of all linear features appearing at least twice on these overlays. In addition, the linear features of Lam (1987, p. 143, Figure 11 here) were reevaluated on the study area plots and retraced at the new scale when considered appropriate.

Aeromagnetic Data

Aeromagnetic data used in this study are part of a high-quality aeromagnetic survey of the entire state of Kansas completed by the Kansas Geological Survey between 1975 and 1979. Data were acquired with an airborne proton-precession magnetometer at a nominal elevation of 762 m (2500 ft.) above sea level along east-west flight lines with a 3.2 km (2 mi.) spacing and a 2.0 second sample rate. Resultant measurements were thus spaced about every 0.16 km (0.1 mi.) along track. Data were subsequently regridded to 1.6 km by 1.6 km (1.0 mi. by 1.0 mi.) using a nearest neighbor approach and are believed to be accurate to about 5 nanoteslas (5 gammas). Yarger (1981, 1983) gives additional details on acquisition and reduction of the basic dataset.

The aeromagnetic map products used in the present study were produced from a subset of the state-wide dataset using existing Fast Fourier Transform computer routines on the Kansas Geological Survey's Data General computer. Yarger (1981, 1983) utilized the same algorithms to produce a set of digital images for interpreting the gross features of the state's magnetic field. Processing procedures applied in this study included "reduction to the pole", "downward continuation", "second vertical derivative", and "synthetic illumination" (for state-wide examples of these products see Yarger, 1983). Reduction to the pole is used to remove the effect of the earth's inclined magnetic pole and thereby improves the resolution of anomaly locations. Downward continuation is a mathematical procedure to calculate the magnetic field at a specified elevation below the original measurement plane and has the effect of enhancing shallow basement anomalies. Since the rock bodies responsible for these near-surface anomalies are the ones most likely to have produced structural deformation in the overlying strata, this operation was applied to the data. Magnetic data were "downward continued" to 2,000 feet below sea level, the approximate average top of the Precambrian surface in the study area. The second vertical derivative of the magnetic field is often useful for enhancing near-vertical contacts between materials of differing magnetic properties (Vacquier, et al., 1951) and was therefore thought to be particularly useful for defining possible intra-basement faults in the study area. The prominent orientations of eastern Kansas linear magnetic features mapped by Yarger (1983, p. 28) for eastern Kansas (Figure 12B) are strikingly similar to the trends of eastern Kansas gravity lineaments (Figure 12A) as mapped by Lam (1987, p. 147). Therefore, synthetic illumination using the same "sun angles" as in the gravity processing (see above), was used to enhance study area magnetic features.

A similar set of contour and color plots was again obtained and a series of mylar overlays were prepared by tracing all lines representing linear magnetic features onto them. The final map of magnetic lineaments (Plate 3) also represents a composite of linements observed on two or more images. Here again, those linear magnetic features mapped by Yarger (1983, p. 28, Figure 10 here) in the study area were also reevaluated and many were retraced onto the final overlay at the new scale.

Earthquake Foci Data

Data on earthquake and microquake epicenter locations used in this study (Tables 2 and 3 respectively) were taken from published sources (DuBois and Wilson, 1978; Steeples, et al., 1987) and recent unpublished data on file at the Kansas Geological Survey (Greg Hildebrand, written comm., May 6, 1988). Historic earthquake epicenter data of DuBois and Wilson was originally compiled from written descriptions by earthquake witnesses and damage accounts, and are presented in Modified Mercalli magnitudes. Because of the somewhat subjective and imprecise nature of these records, epicenter locations as plotted (Plate 1) may be subject to considerable locational error. Microquake data has been acquired by a local seismograph network only since 1977 and event magnitudes are recorded in Richter scale units. Epicenters of these events are located with greater precision. A discussion of root-mean-squared locational errors and estimated focal depths is available elsewhere (Steeples, et al., 1987). Relative to the interpretation of distinct clusters of epicentral locations (Plate 1), Steeples (1982) has stated (p. 73) that "the trends of microquake activity [in Kansas] define zones in the basement, where sufficient fault-related permeability might exist to allow the circulation of fluids from the deep crust."

Table 2. List of historic study area earthquakes (Data from DuBois and Wilson, 1978).

Date	Longitude	Latitude	Magnitude (M. M. units)
04/24/67	96.30	39.17	VII-VIII
01/07/06	96.5	39.2	VII
09/23/29	96.6	39.0	V
10/21/29	96.5	39.2	V
10/23/29	96.8	39.0	II-III
12/07/29	96.57	39.18	V

Table 3. List of recent study area microquake events (Data from Steeples, et al., 1987; Greg Hildebrand, written comm., 1988).

Date	Longitude	Latitude	Magnitude (Richter)
01/11/78	96.2013	38.8673	1.6
04/14/78	96.3475	39.8143	1.9
05/22/78	96.2963	39.1410	2.3
11/01/78	97.3435	39.8378	1.7
01/24/79	96.0823	39.6188	1.5
06/03/79	97.7887	39.4442	2.2
06/15/79	97.2203	39.8402	1.9
06/26/79	96.0165	39.2963	2.0
06/30/79	97.2798	39.9383	3.1
06/30/79	97.2923	39.9085	1.4
07/01/79	97.2787	39.8973	2.0
08/02/79	96.5627	38.9297	2.2
12/07/79	97.6192	39.6943	2.0
02/11/80	97.3080	39.9343	2.1
04/16/80	97.2712	39.9060	1.6
06/30/80	96.8753	38.8673	2.5
09/07/80	97.7147	39.5892	1.5
07/08/81	96.0787	39.0673	1.5
04/24/82	96.1838	39.2937	1.0
09/06/82	96.3001	39.3462	1.6
10/26/82	96.5253	39.5045	1.8
02/09/83	97.7247	38.6057	1.7
07/12/83	96.3088	39.2470	0.8
08/24/83	96.3105	39.1443	1.5
01/13/84	96.2367	39.3740	1.7
02/03/84	96.3093	39.5322	1.4
08/12/84	96.7575	38.7117	1.9
03/02/85	96.9305	39.5815	1.8
04/05/85	97.6218	39.5770	1.7
04/25/85	96.3607	39.3342	1.0
04/26/85	96.9400	39.5815	1.2
06/20/85	96.7575	39.1652	0.8
11/01/85	96.2013	39.3375	1.5
09/01/86	96.1815	39.2973	1.6
11/05/86	96.5498	38.6627	1.4
11/09/86	96.0922	39.4407	1.0
01/09/87	97.5723	39.7803	2.0
02/19/87	96.3923	39.5365	1.4
06/10/87	97.9243	39.7058	1.6
08/16/87	96.4253	39.1492	2.2
10/30/87	96.3590	39.1977	1.5
12/26/87	96.2450	39.1705	1.7
03/17/88	97.1403	38.8888	1.3

Structural Information

Prior to drafting Plate 4, the author prepared a revised version (not shown) of Cole's (1976) and Sims' (1985) maps of the Precambrain surface. Well control for this map consisted of about 280 oil and gas tests that penetrated the Precambrian and was taken primarily from Cole and Watney (1985), with post-1983 data provided by the University of Kansas, Project Upper Crust (Lanny Latham, written comm., May 11, 1988), and the Kansas Geological Survey (Lynn Watney, written comm., May 13, 1988). In addition to basement faults mapped by Cole and Sims, the locations of known or suspected faults mapped in overlying strata (Berendsen and Blair, 1986, Map 6; Curtis, 1960; Newell, 1987) were extended down to the Precambrain surface following the assumption of Berendsen and Blair (1986, p. 3) that "a fault present in a mapped unit must cut the underlying older rocks as well." On Plate 4 these "probable faults" appear to be concentrated along the Nemaha uplift because of the fairly high drilling density there and very limited well control over the remainder of the area. Additionally, linear structural trends on the revised basement map that could conceivably represent faults were annotated on this map in much the same fashion as Berendsen and others (1978, Fig. 3) treated Cole's (1976) map. Features portrayed as "possible faults or fractures" on Plate 4 are thus a composite of those mapped by Berendsen and others (1988, Fig. 18, reproduced as Figure 4 here) and additional basement fractures interpreted in this study from the above-mentioned basement structure trends, and lineaments interpreted from geophysical, remotely sensed, drainage, and earthquake foci data (see Discussion section below).

Soil Gas Data

Soil gas measurements used in the present investigation (Plate 1) represent a composite of 190 soil gas hydrogen values obtained by the U.S. Geological Survey in July, 1984 (McCarthy, et al., 1986; McCauley and Watney, 1984) and an as yet unpublished dataset of just over 400 measurements acquired since that time by Ernest E. Angino and coworkers as part of an ongoing study of the Kansas hydrogen occurrence. Soil gas samples and hydrogen determinations for these two studies were obtained by different techniques.

The procedure used by the U.S. Geological Survey has been described in considerable detail by McCarthy and others (1986, p. 9). In general, it consisted of driving a 0.75 m (2.5 ft.) long hollow steel probe in the soil, withdrawing a 5 cm^3 (0.3 in^3) gas sample with a syringe, and analyzing it immediately in a truck-mounted mass spectrometer. This uncalibrated procedure produced measurements of relative hydrogen concentration only. Values reported here as "small anomalies" and "medium anomalies" on Plate 4 from this dataset are those considered "possible anomalies" and "anomalies" by McCauley and Watney (1984, Fig. 5B, 10) on the basis of degree of positive deviation from their daily (downward) trends. The very shallow nature of their sampling depth probably produced considerable diurnal variations in hydrogen concentrations (Gole and Butt, 1985, p. 2112; Sato, et al., 1986, p. 12,321) which they apparently did not attempt to account for. The deeper sampling of the Angino group was an attempt to overcome this problem.

The methodology of Angino and coworkers has not been previously described and is outlined here (Ernest E. Angino, verbal comm., May 27, 1988). Trailer or truck-mounted power soil augers were used to drill 5 cm (2 in.) diameter holes to average depths of about 3 m (10 ft.) [actual range = 2-4.5 m (6-14 ft.)] at locations on private lands spaced about every 1.6 km (1.0 mi.) [locally 0.8 km (0.5 mi.)] along sample traverse roads (Plate 1). Holes were cased with commercially available 5 cm (2 in.) diameter polyvinyl chloride (PVC) pipes of an appropriate length. PVC pipes had been slotted on the lower 60 cm (2 ft.) and were fitted on the top with a septum-equipted PVC end cap. Pipes were pumped to partial vacuum and left undisturbed for a period of about 15 minutes, allowing soil gasses to collect within the pipes. Gas samples were then withdrawn through the septa with a 100 cm^3 (6.0 $in.^3$) syringe and analyzed immediately in portable gas chromatographs. 269 analyses were performed prior to the 1987 field year and utilized a Hewlett Packard 5890A model gas chromatograph having a thermal conductivity detector and a 1 meter capillary column. This technique produced only relative measurements of soil gas hydrogen concentrations (sample locations indicated as "Relative Values" on Plate 1). Gas analyses performed since that time utilized a field-ruggedized, HNU Series 301 model portable gas chromatograph with a thermal conductivity detector and a 4 meter capillary column. Alternate analyses of 100 cm^3 (6.0 $in.^3$) samples of a calibrated gas standard (stated concentrations of 1000 ppm $\pm$ 1% H_2, 500 ppm $\pm$1% He) during this latter period allowed absolute determinations of 135 hydrogen concentrations to be made (sample locations marked "Absolute Values" on Plate 1). Subsequent resampling of some of the older, "relative" stations empirically demonstrated a nearly linear relationship existed between the two types of measurements.

To facilitate comparison of hydrogen anomaly magnitudes from these two sources, highly anomalous measurements were grouped into 4 relative classes in an approach that differs slightly from that of Cunningham and others (1987, p. 218). The population means and standard deviations of each group ("Relative Values", and "Absolute Values") were determined seperately (Figure 13), and all values exceeding the mean for the data type were considered anomalous for mapping purposes. All measurements below the mean for each data type were considered to represent a regional "background" population (although quite high by global standards, see for example Ware, _et al._, 1984), and are portrayed on Plate 4 accordingly. Measurements between 0 and 1, 1 and 2, 2 and 3, and those greater than 3 standard deviations above the population mean for each respective group are portrayed on Plate 4 as "small", "medium", and "large" anomalies respectively. Interestingly, 32% of the values of each group exceed the corresponding means and are thus considered anomalous. This may be an indication that both populations represent statistically valid samples of a single population in spite of slightly different gas sampling procedures and analytical techniques.

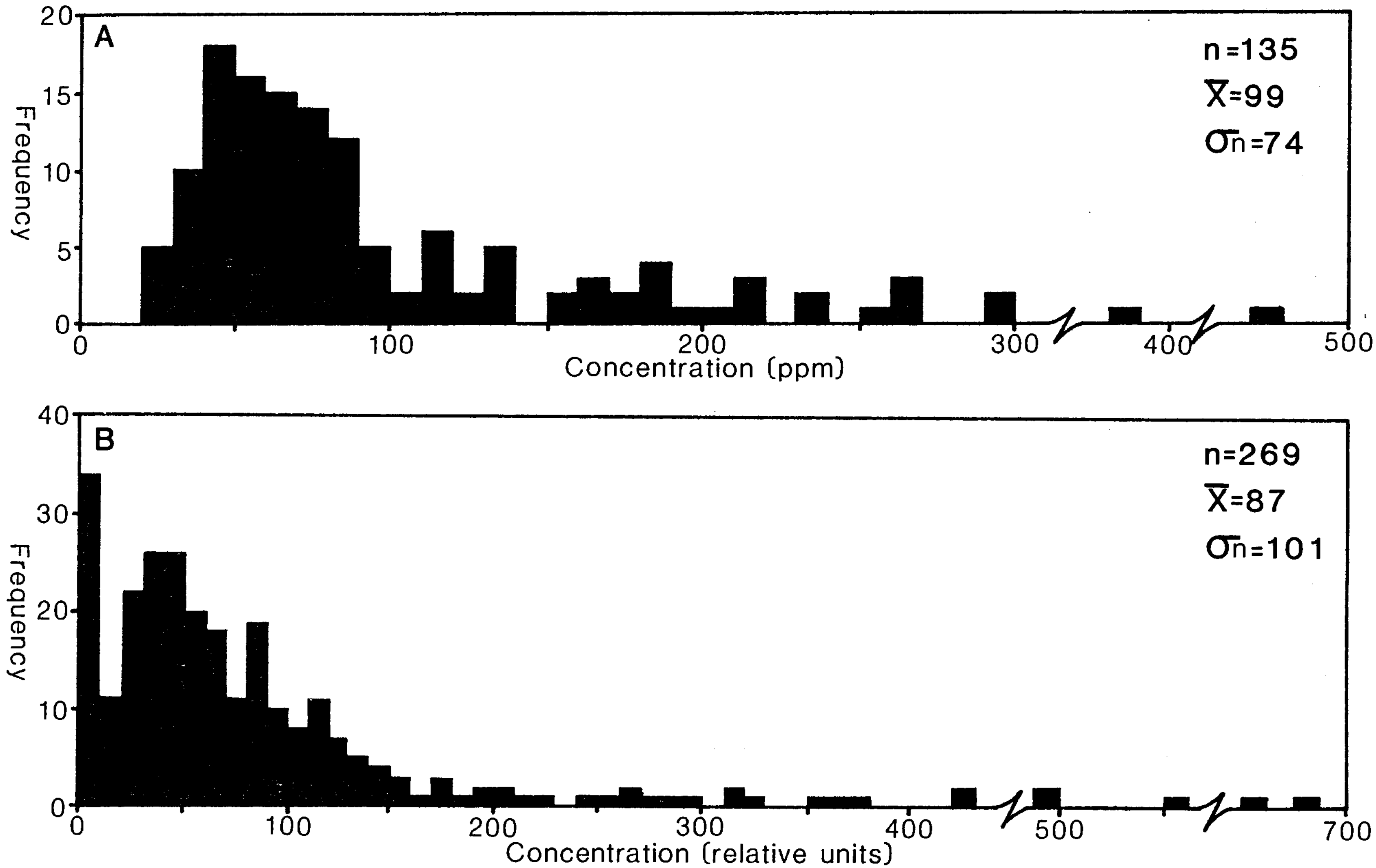


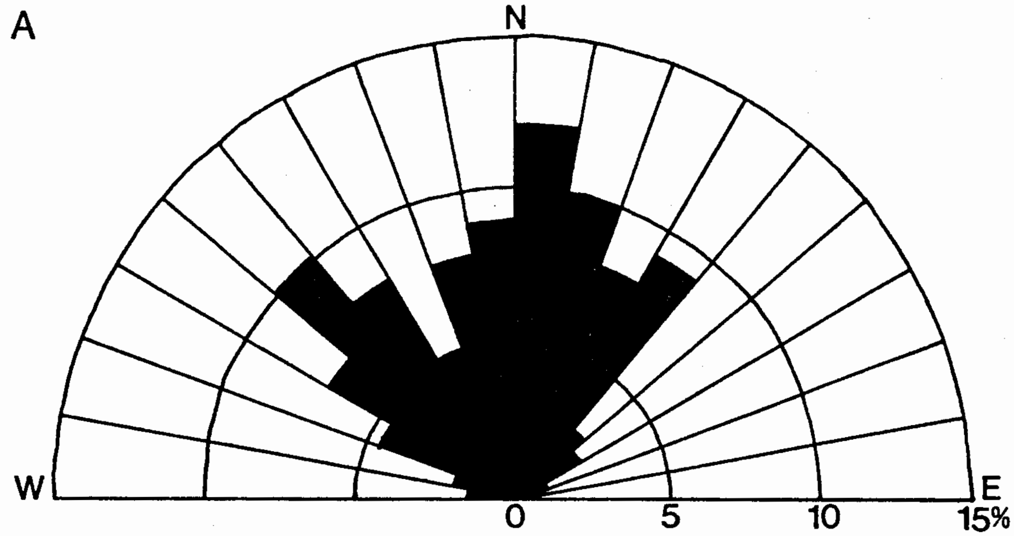
Figure 13. Histograms of A) "absolute", and B) "relative" hydrogen soil gas measurements.

RESULTS

Drainage Analysis

Analysis of drainage network maps for that portion of Kansas lying between 38 an 40 degrees north latitude and 96 and 98 degrees west longitude (including all of the present study area) was completed at an early stage in this investigation and resulted in the delineation of 644 linear stream segments totaling 6023 km (3743 mi.) in length from all drainage basins exceeding 10 km^2 (3.9 $mi.^2$) in area. A more detailed discussion of the results from this analysis is available elsewhere (Johnsgard, 1986, 1987), but, in general, the correlation of the single broad north-south mode in this data with known geologic controls was found to be poor. Nonetheless, a length-weighted azimuthal histogram ("rose diagram") has been compiled in 10 degree increments from the linear drainage segments mapped during that investigation and is included here (Figure 14B) for comparison with other linear feature data.

Length-weighted values, as opposed to simple orientation frequencies, were utilized in compiling the drainage rose diagram, and all subsequent diagrams, because this approach permits direct quantitative comparisons of orientation tendencies for many data types to be made, regardless of sample size. In addition, correlation coefficients between linear-feature orientation frequency and cummulative length for each data type are all slightly positive (eg. for drainage alignments, r = +0.11), indicating that those linear features possessing the more abundant orientations also tend to be



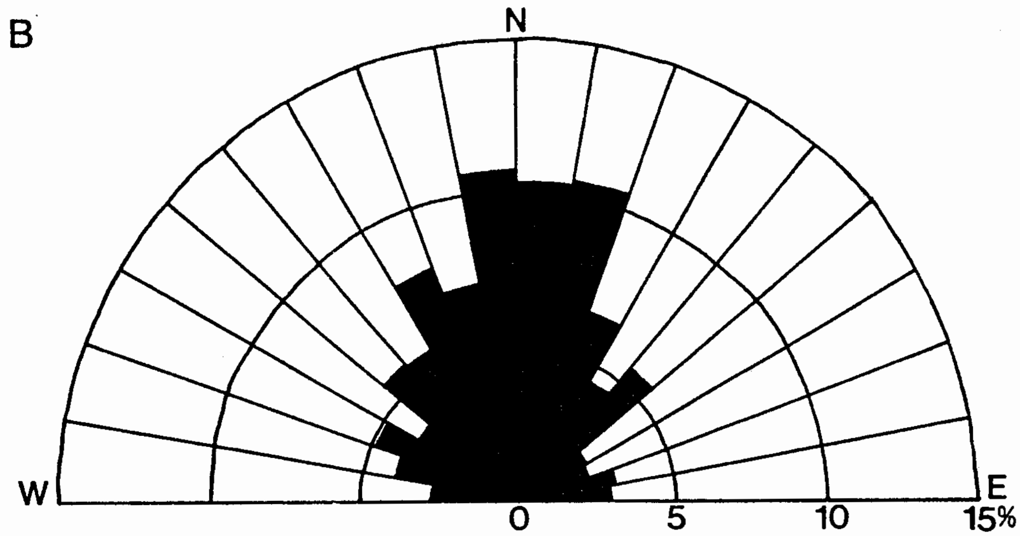


Figure 14. Rose diagrams of A) study area Landsat photolineaments, and B) study area drainage trends.

slightly longer. These two factors (length-weighting, and positive length/frequency correlations) are additive and thus tend to produce fairly "spikey" rose diagrams. Note also that the radial scales (in percentage by length) of these diagrams vary from figure to figure in order to portray the maximum rays of each diagram at approximately similar physical lengths, further facilitating comparison of the different types of data. During examination of these rose diagrams, the reader should bear in mind that a truly random distribution of linear element orientations would statistically tend to produce a rose diagram with all 18 rays of approximately 5.6% in length (100% / 18 rays = 5.6% / ray).

Imagery Analysis

Analysis of study area Landsat imagery produced a composite of 242 straight or nearly straight photolineaments totaling 2132 km (1325 mi.) in length and 50 distinctly curved photolineaments. Comparison of these photolineaments with the drainage network (Plate 2) shows that almost all photolineaments of both types correspond to linear or semicircular drainage features respectively. This finding concurs with most previous studies reported in the literature. Given that most of these features correspond with surface drainage elements, the locations of which are precisely defined, both the locational accuracy and orientational precision of these features are considered very good. Some of the strongly curved photolineaments ("curvilineaments" of some other authors) also appear to correlate with structural domes, horsts, or grabens as mapped by Berendsen and Blair (1986), and Cole (1976) along the Nemaha anticline, and, to a lesser degree, with circular aeromagnetic (Yarger, et al., 1981) or gravity (Yarger, et al., 1985) anomalies. Other than these general observations, further analysis of the possible tectonic significance of curved photolineaments was not attempted.

Cursory examination of Plate 2 reveals that two fairly distinct azimuthal modes are present in the straight photolineament data. These trends have been quantified with a length-weighted rose diagram (Figure 14A) of their orientations. Because of the obvious difficulties and dubious value in determining average azimuthal values for the strongly curved photolineaments, these features have been excluded from this compilation. One wide, but fairly distinct, mode occurs at about N.10°E. A less prominant and narrower mode occurs at about N.40°W. Note that neither of these modal orientations agrees well with any of the well-documented regional joint trends (N.60-75°E., N.10-35°W., and N.70-83°W.) of the eastern Kansas-Oklahoma area as discussed above.

This bimodal distribution of study area photolineaments resembles fairly closely the results of Anderson's (1981, Fig. 7b) study of Landsat photolineaments in an adjoining area of southeastern Nebraska, although his modes appear to be offset clockwise by about 20 and 10 degrees respectively. In addition, he interpreted (p. 19) a broad northeastern maximum to represent a composite of two narrower modes. From extensive comparisons with many possible geologic causes, he concluded that many of the photolineaments could mark the surface traces of a periodically rejuvenated regional basement fracture system.

These two prominant modes at N.40°W. and N.30°E., as well as two less frequent modal orientations of N.15°W. and N.65-70°E., were also present in the Landsat photolineaments mapped by Dwivedi (1983). He attributed both sets of photolineaments to a conjugate fracture system produced by wrench faulting of the Nemaha anticline and related structures near his study area in south-central Kansas. Jefferis (1969, Fig. 10A) also documented a nearly identical N.40°W. mode and a N.50°E. mode in radar photolineaments from southern Douglas County which he ascribed (p. 31) to "major faults and zones of fracture concentrations." Callen (1983) mapped a large number of Landsat photolineaments in the Forest City basin and concluded that at least two individual features in Atchison, Jefferson, and Leavenworth counties, Kansas, reflected two previously unrecognized northeast and northwest-oriented basement faults. He later (1985) used several basinwide trend surface maps of mean photolineament azimuths to infer a distinct influence of the Missouri gravity low on the structural development of the basin.

Orientation statistics have apparently never been compiled for the remainder of the major photolineament studies in Kansas (Cooley, 1984, 1986; McCauley, 1988; McCauley, et al., 1978; Podwysocki, 1974), but visual examination of each these maps demonstrates that both the northeast and northwest modes are regionally pervasive. For example, Cooley (1984) mapped a large number of Landsat photolineaments in western Kansas, and that portion of his map which overlaps the southwestern corner of the study area is presented here (Figure 15). Note that, although photolineaments with virtually

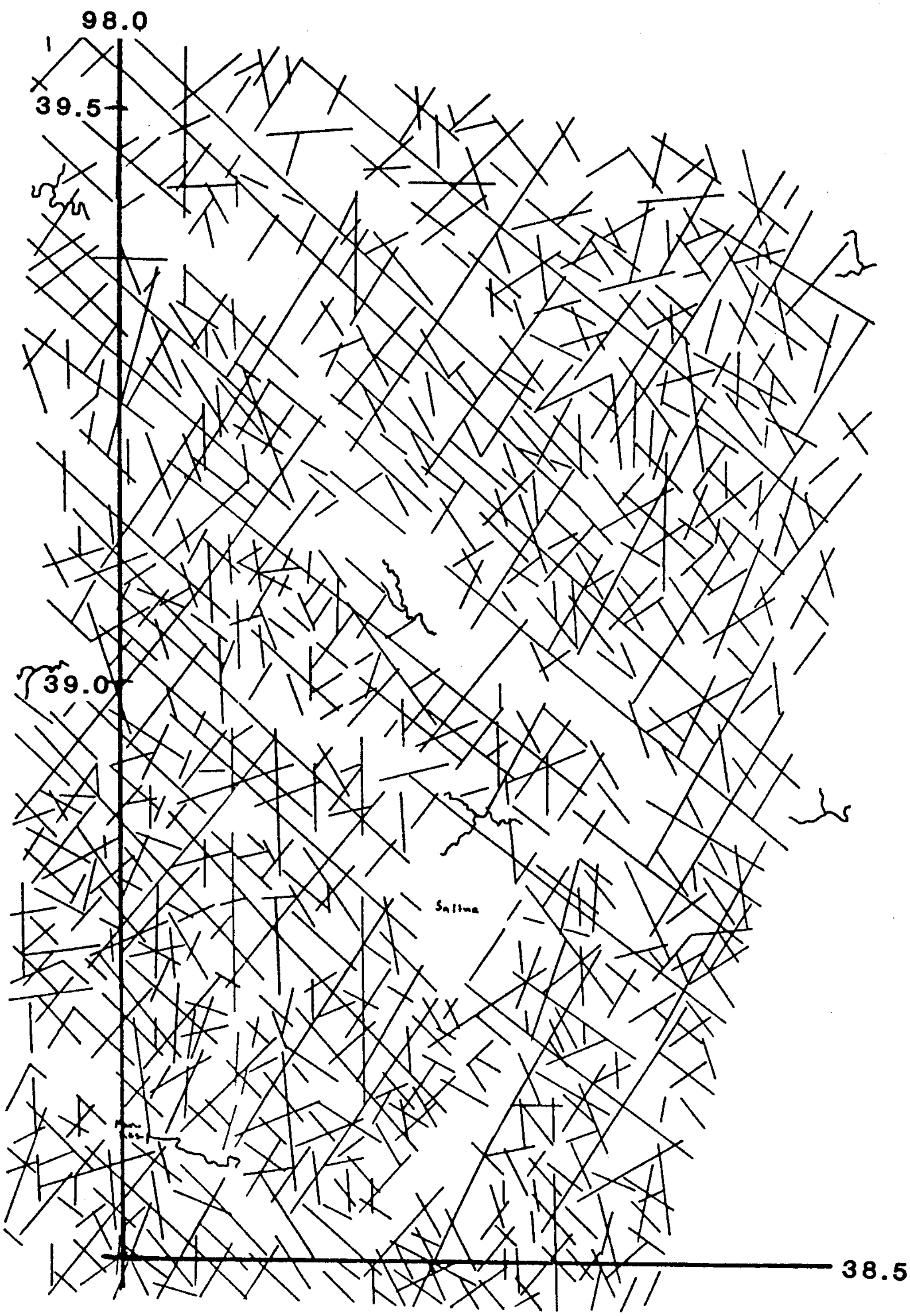


Figure 15. Map of Landsat photolineaments in the southwestern corner of the study area (after Cooley, 1984).

every orientation are present, north-northeast and northwest-oriented features are much more abundant and tend to be considerably longer than the others. Although it is fairly obvious that not every single one of the photolineaments he mapped corresponds to an actual geologic or structural feature, it is apparent that a nonrandom componant is certainly present and it does at least seem likely that it could reflect such a genetic origin.

Gravity and Magnetic Features

Upon initial examination of Plate 3 it is readily apparent that two prominant orientations also exist for both types of linear geophysical elements mapped. Compilations of the 71 gravity lineaments totaling 1687 km (1048 mi.) in length , and 94 magnetic lineaments 2560 km (1591 mi.) in cumulative length (Figure 16) appearing on this map serve to clarify these two prominant modes. These modes are nearly identical in both orientation and magnitude on both rose diagrams, and correlate well with the modes determined by Lam (1987) for gravity and Yarger (1983) for aeromagnetic lineaments in eastern Kansas (Figure 12). They are also remarkably similar to the modes determined for photolineaments above. Given the reasonable spatial resolution of the original aeromagnetic data (see Methodology section), the locational and orientational precisions of the magnetic features are considered fairly good, although not as good as photolineament data. However, the wide spacing of gravity stations over most of the study area (see Methodology section) probably degraded gravity feature locational and, to a lesser extent, orientational

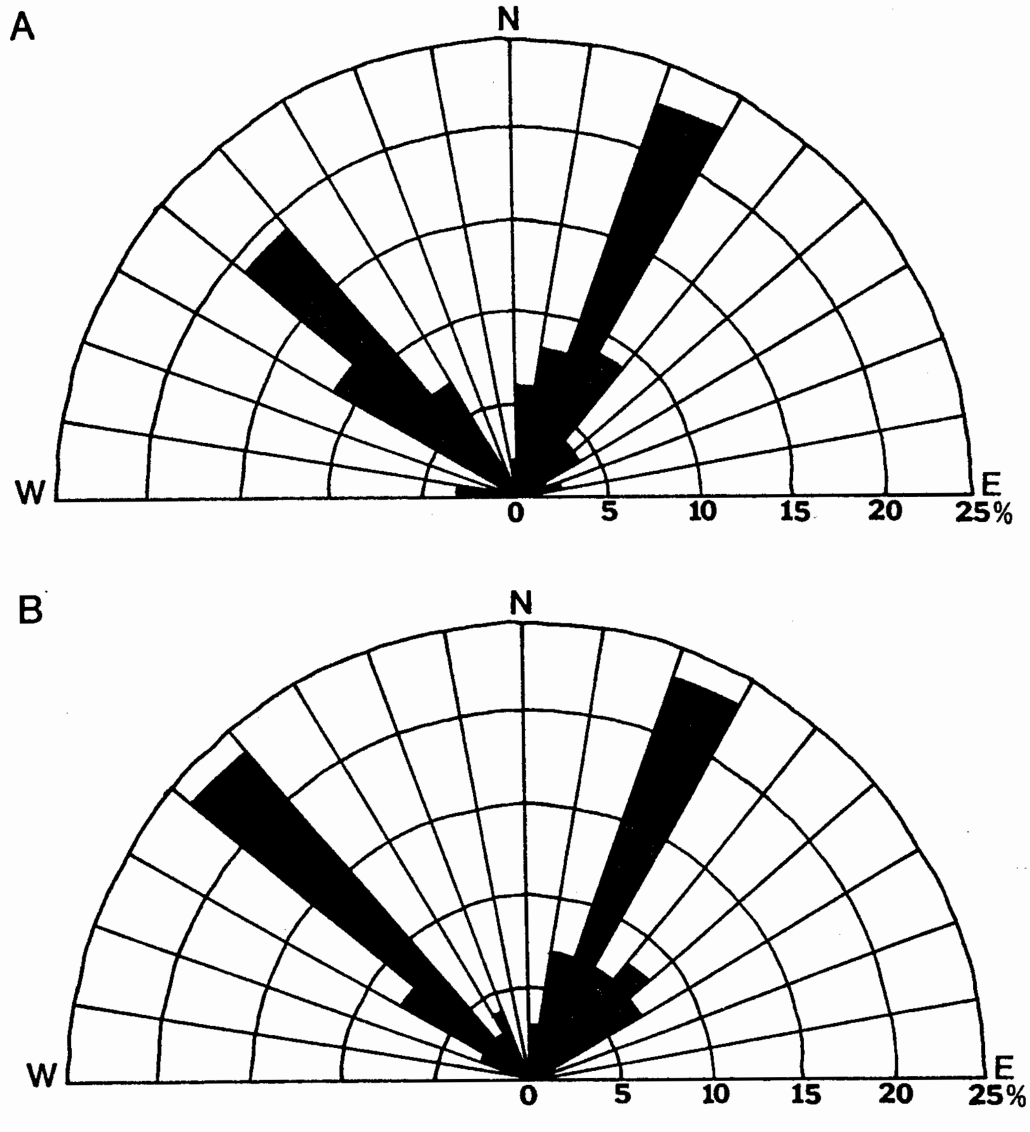


Figure 16. Rose diagrams of A) study area aeromagnetic lineaments, and B) study area gravity lineaments.

accuracies considerably.

With closer examination of Plates 2 and 3, it becomes apparent that the patterns of linear features in the northwestern half of each map differ somewhat from those present in the southeastern halves. A more-or-less distinct discontinuity between these patterns appears to correspond with the location of the eastern flank of the Abilene anticline. Additional rose diagrams have thus been compiled for Landsat (Figure 17), gravity (Figure 18), and magnetic (Figure 19) features with respect to whether they have been mapped northwest of, or southeast of, the Abilene anticline. Although both of the prominant modes mentioned above are still apparent in both gravity and magnetic trends, their relative importance is reversed across the Abilene structure. Northwest-oriented geophysical features predominate in the eastern portion of the maps, whereas north-northeast trending features are considerably more abundant to the west. This is also true for Landsat photolineaments, but the north-northeast mode has shifted to nearly due north for photolineaments in the western half of Plate 2. The possible significance of this shift is not understood.

Basement Structure

The 49 linear features, totaling 1505 km (935 mi.) in length, mapped on the revised contour map of basement configuration (see Methodology section) are shown on Plate 3 and their orientations are compiled on Figure 20A. Again note a prominant mode centered on N.30-40°E. and a very small secondary mode at about N.50°W.

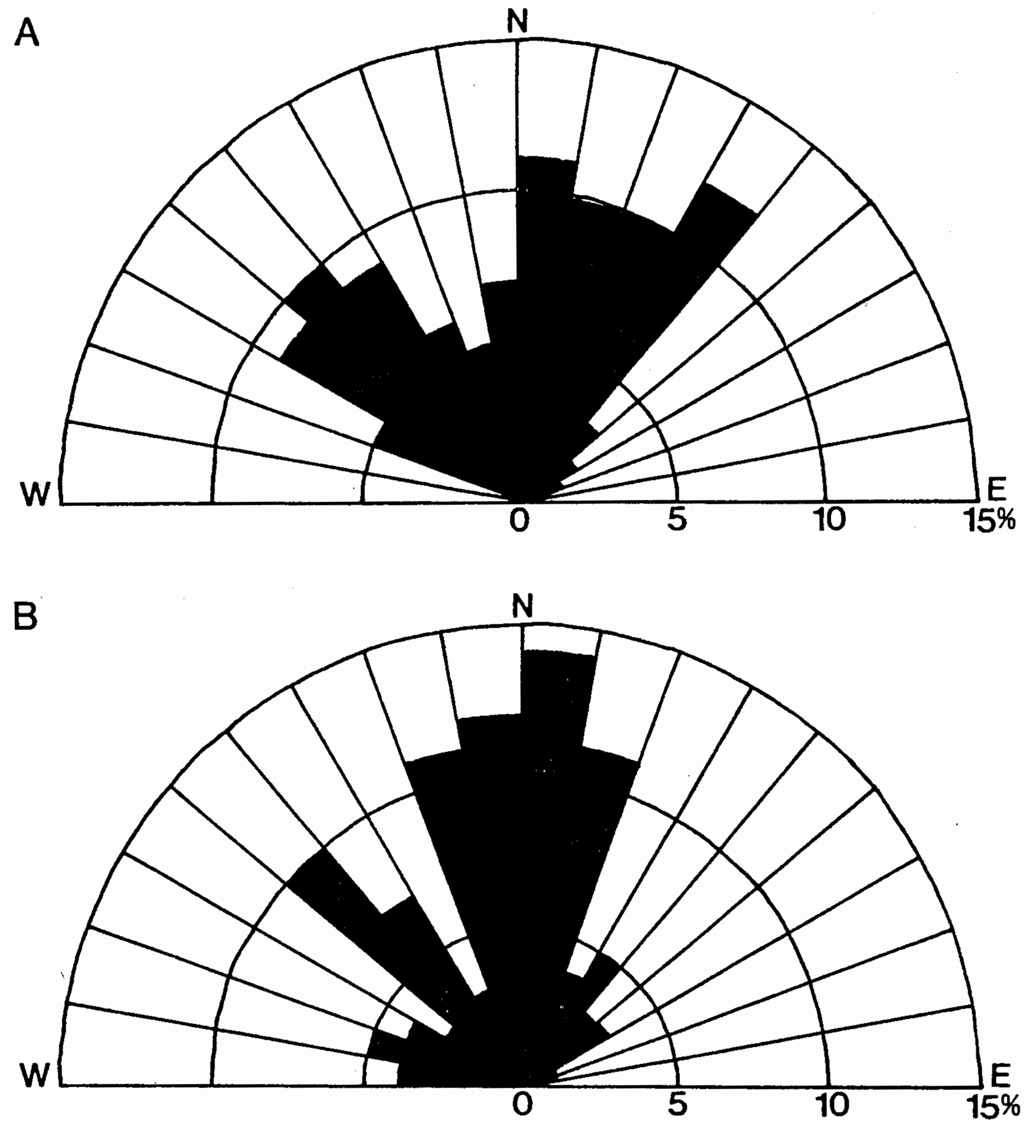


Figure 17. Rose diagrams of study area Landsat photolineaments A) east of, and B) west of Abilene anticline.

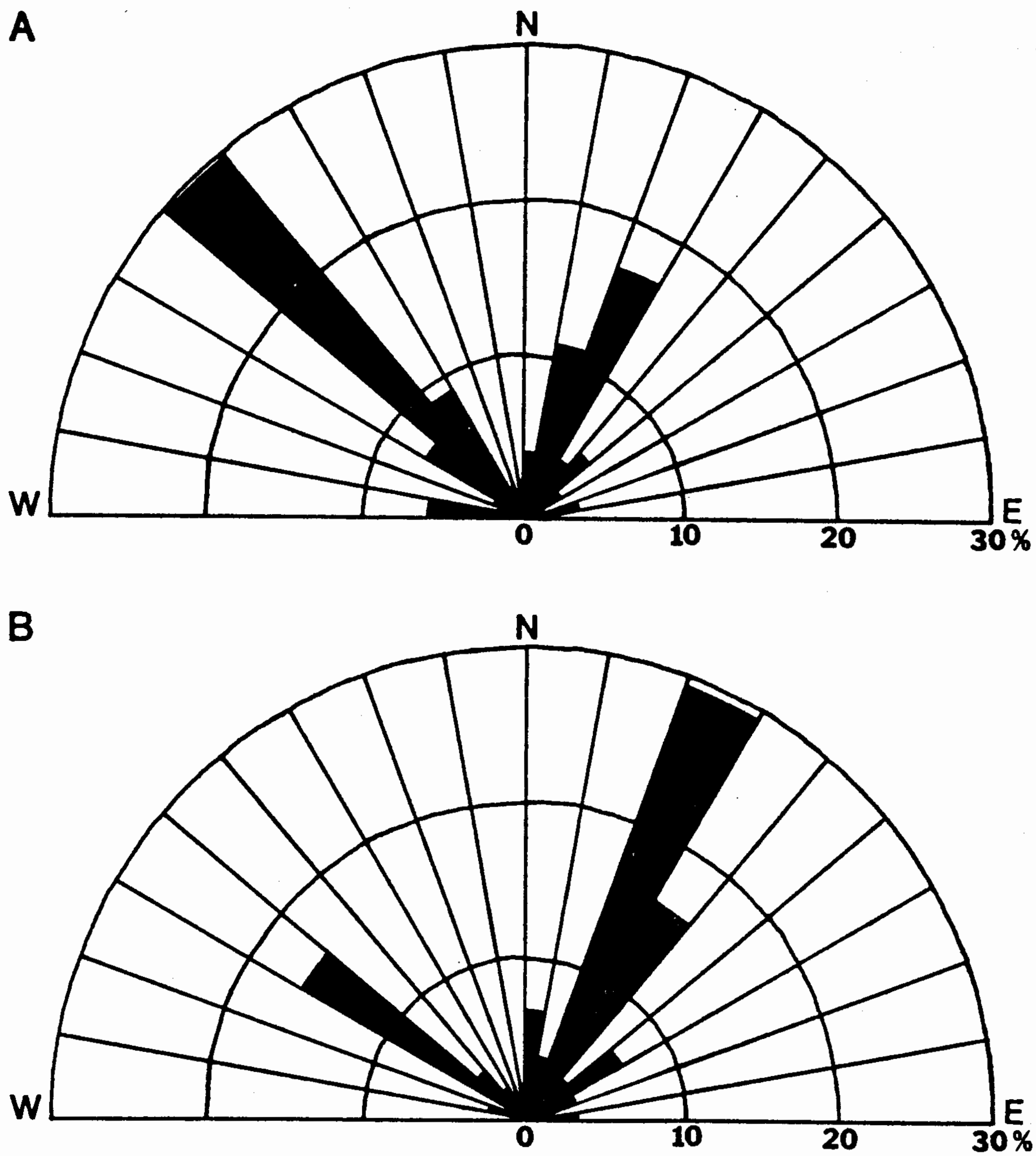
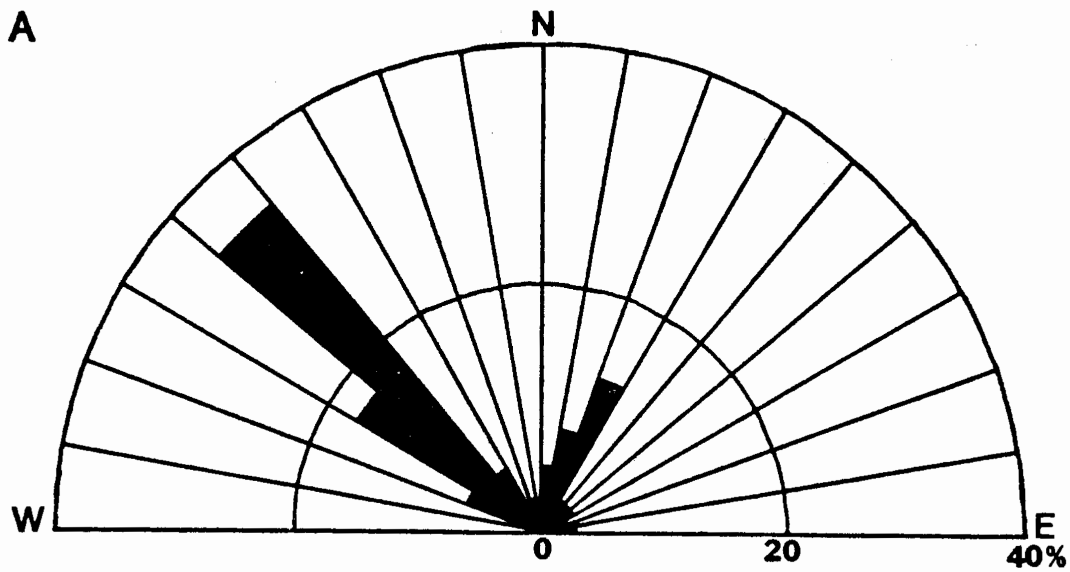


Figure 18. Rose diagrams of study area aeromagnetic lineaments A) east of, and B) west of Abilene anticline.



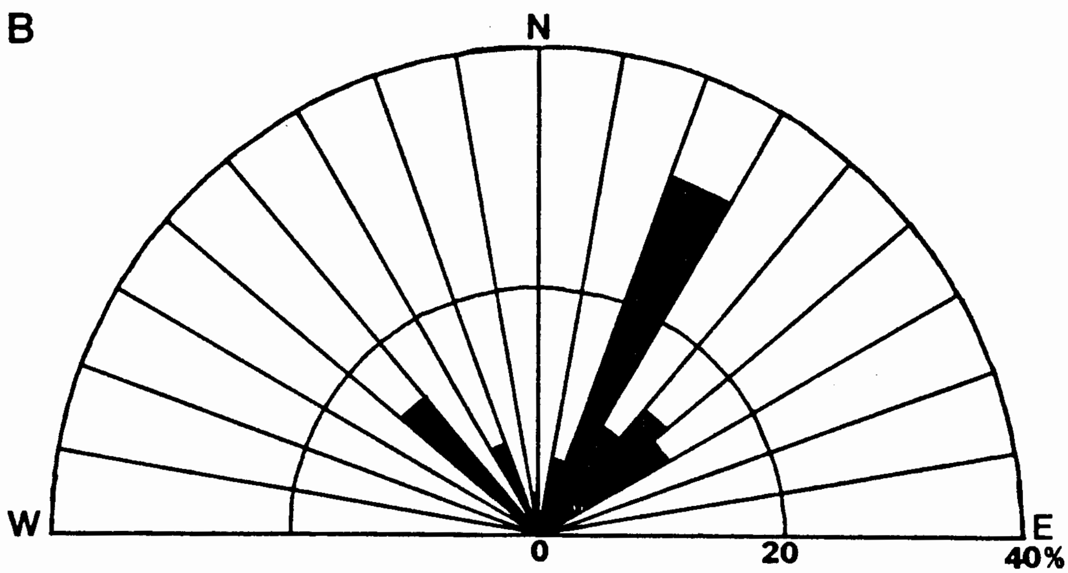


Figure 19. Rose diagrams of study area gravity lineaments A) east of, and B) west of Abilene anticline.

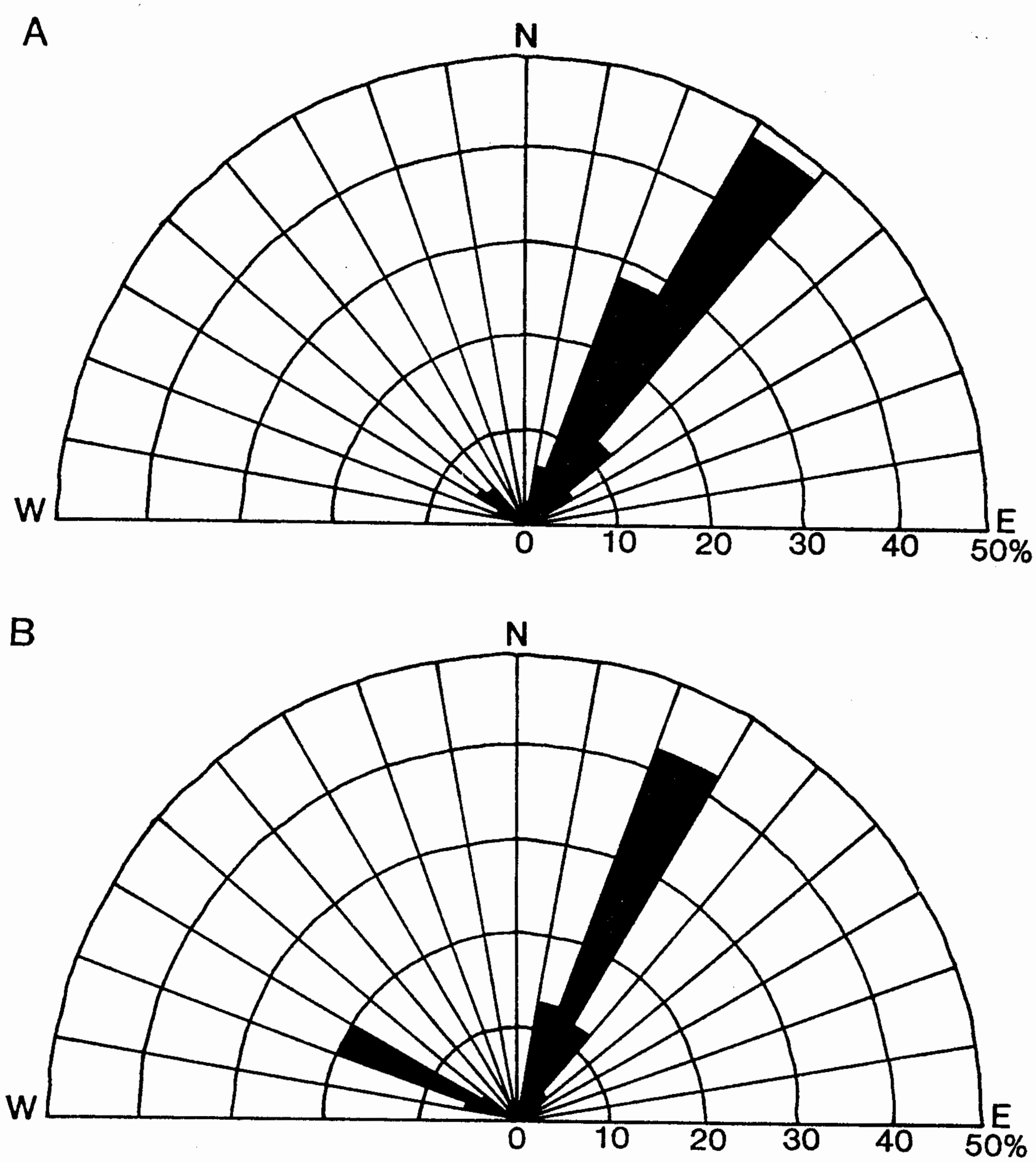


Figure 20. Rose diagrams of study area A) structural lineaments, and B) faults (data from Berendsen and Blair, 1986; Newell, 1987).

DISCUSSION

Structural Interpretations

In general, with the possible exception of drainage trends, each of the foregoing compilations of data appears distinctly bimodal, with prominant modes at about N.40-50°W. and N.10-30°E. This close correlation of orientation statistics for linear features extracted from such widely differing basic data sources [ie. certain river and stream orientations (linear drainage segments) and areal spectral reflectance characteristics (Landsat photolineaments), areal variations in rock magnetic properties (magnetic lineaments) and rock density (gravity lineaments), and basement surface configuration (linear structural trends)] implies a similar genetic cause. Comparison of these features with the locations (Plate 4) and orientations (Figure 20B) of the 73 probable study area faults as previously mapped using subsurface data by Berendsen and Blair (1986) and Newell (1987) indicates a close correlation exists here also, again implying a causal relationship. Many of the gravity and magnetic linear features mapped elsewhere in Kansas are thought to correspond in both orientation and location with basement discontinuities controlled by faults and anticlines (see Introduction and Methodology sections above). Therefore, I suggest that the two prominant modes for linear features in the structural, geophysical, and remotely sensed data sets of the study area also reflect a bimodal basement fracture and fault system. Thus, all features portrayed as "possible faults or fractures" on Plate 4, with the exception those modified after Berendsen and others (1988, Fig. 18, presented here as Figure 4 in Introduction section), have been inferred on the basis of linear features on recorded on Plates 2 and 3. In general, the locations of most of these "possible faults or fractures" were interpreted from any combination of spatially coincident gravity lineaments, aeromagnetic lineaments, structural lineaments, linear drainage segments, or Landsat photolineaments. Some were inferred on the basis of aeromagnetic lineaments alone, particularly those oriented either NW or NNE, and a few represent linear features that correlated well with the extensions of previously mapped subsurface faults. A discussion of each feature and contributing data sources would be too lengthy to include here, so the reader is urged to consult the source maps (Plates 2, and 3) for the following discussion and during evaluation of the interpretative map (Plate 4).

Many, perhaps most, of the northwest-oriented fractures in the eastern portion of Plate 4 are probably genetically related to a set of similarly oriented basement fault zones previously infered to exist in the granitic basement over much of eastern Kansas and western Missouri (Berendsen and Blair, 1984; Berendsen, et al., 1978; Kisvarsanyi, 1974; McCracken, 1971). One of these, the Bolivar-Mansfield fault zone (Plate 4), appears to intersect the Nemaha anticline in a structurally complex portion near southeast Riley County and continues westward through the Abilene anticline very close to several of the Riley County kimberlites (Berendsen, et al., 1988, p. 16). These northwest-oriented fractures parallel the bounding faults of the Missouri gravity low and it seems possible that this fault set could represent a Phanerozoic structural event imposed on the basement rocks of the region, or could have originated from tensional fracturing of the upper crust during the middle? Proterozoic (>1,350 to 1,485 Ma) tectonic event thought to be responsible for producing the Missouri gravity low. It also seems possible that the locations and orientations of these faults, as well as the overall trend of the Missouri gravity low, may reflect regionally pervasive set of even older crustal weaknesses. These weaknesses could also have resulted from the roughly dated (1,800 to 1,400 Ma ?) middle Proterozoic shearing episode discussed above (see Introduction section), or could conceivably have been incurred even earlier during early Proterozoic accretion of the Central Plains province itself (Bickford, et al., 1986, p. 494). Yarger (1983, p. 27) has stated that most of the northwest-oriented aeromagnetic features of eastern are interupted at the rift by the north-northeast features which characterize this zone, implying that "the northwest grain is older than the rift." Alternatively, the mechanism which produced the northwest set could postdate formation of the rift and have simply failed to produce many of these features within the preexisting rift zone.

Likewise, many of the inferred north-northeast oriented fractures, so pervasive along the Nemaha anticline and west of the Abilene anticline, probably correspond with basement fault zones trending parallel to the Midcontinent rift system axial zone and may have resulted from tensional stresses associated with middle Proterozoic (about 1,100 to 950 Ma) formation of this rift, although they too may reflect earlier crustal anisotropy.

The north-northeast-oriented fractures show an apparent tendency (Plate 4) to be expressed as zones of fairly closely spaced fractures (notably the Nemaha and Abilene anticlines, Washington structure, and possibly the Belleville fault) sep~~e~~arated by wide areas of relatively unfractured basement. Of these four zones, two (Nemaha and Belleville) are spatially coincident with abundant historic seismic activity (Plate 1). The former is expressed by over 1,000 m (3,000 ft.) of vertical Phanerozoic fault displacement and the latter corresponds with the traditionally mapped western limit of the Rice Formation (Bickford, et al., 1979). The other two features (Abilene and Washington) have been interpreted as the eastern and western boundaries of rift-related mafic basement rocks respectively (eg. see Bickford, et al., 1979), and correspond with both the steepest gradients on the central gravity high of Bouguer gravity maps (eg. Yarger, et al., 1985) and distinct discontinuities on aeromagnetic images of the study area (eg. Yarger, et al., 1981). In addition, the Abilene anticline was observed (see Results section) to mark the boundary between two distinct areas of linear-feature characteristics, but shows only about 100 m (300 ft.) of Phanerozoic vertical displacement.

I believe these latter two features (Abilene and Washington) reflect deep crustal zones that acted as fundamental controls on the location and structure of the rift zone during extension, including magma intrusion and extrusion, but are no longer very active tectonically (as shown structurally and seismically), perhaps because of "healing" by the extensive rift-related magmatism. The proximity of the Riley County (Cretaceous age) kimberlites to the Abilene anticline could reflect this deep crustal fracturing. The other two features (Nemaha and Belleville) could have acted as important controls on rift-basin and post-rift basement geometry, affecting the locations of the "east Rice basin" and "west Rice basin", but were sufficiently distal from active rift magmatism that they have remained zones of deep crustal weakness through the present.

Taken together these two infered fault sets comprise a well defined "gridded fault pattern" similar to that proposed for the northern portion of the Midcontinent rift in Michigan, Minnesota, and Wisconsin (McSwiggen, et al., 1987; Van Schmus and Hinze, 1985) and typical of continental rifts in general (Ramberg and Smithson, 1975). This bimodal fracture system could segment the upper crust of northern Kansas into large orthogonal blocks, as has been suggested for elsewhere in the Midcontinent (eg. Zabawa, 1978). It is probable, given the relatively thin cover of Phanerozoic sediments relative to the thick Precambrian crust, that such a pervasive system of deep fractures (particularly the unhealed rift marginal sets) could have been periodically reactivated by external tectonic stresses through time (Ford, 1983). Theoretically at least, the orientation of any individual fracture plane relative to these stresses would determine the style of deformation (normal, reverse, strike-slip, or a combination thereof) associated with any rejuvenation event (Peterson, 1985a, 1985b). The complex fault geometries and horst/graben structures presently associated with some of these fault zones (eg. Humboldt fault zone) may represent near-surface fault splays resulting from several episodes of convergent wrench movement along the deeply seated (possibly listric) rift-marginal master faults (see Wilcox, et al ., 1973, Fig. 15; Zabawa, 1978, Fig. 27). Episodic reactivation of such zones could also have produced differential uplift or downdropping of larger crustal blocks, causing local paleobathymetric and paleotopographic relief (Gustavson, 1983). Such irregularities might have resulted in important lithologic and structural trends in the overlying Phanerozoic sedimentary package, particularly in water-depth sensitive near-shore settings (see Introduction section). With adequate constraints on paleostress fields and fracture orientations it might be possible to predict deformational styles and related lithostratigraphic influences (including petroleum trapping potential) in the Phanerozoic rocks of the poorly explored, deeper portions of the Salina basin (Berendsen, et al., 1988, p. 4; Newell, et al., 1988b). Conversely, in areas of sufficient control, such as along certain portions of the Nemaha structure, consideration of fault plane geometries and associated lithotectonic expressions of deformational styles could perhaps serve to confirm or refute reconstructions of regional paleostress fields.

The spatial proximity of modern seismicity (Plate 1) to many of these supposed faults (Humboldt fault zone, Belleville fault, and, of particular note, the Poersch fault) strongly suggests that movement continues along at least some of them at present. Such activity could be responsible for propagating these fracture zones upward to the present land surface, perhaps in the form of zones of more intense jointing or more rarely as actual faults with stratigraphic offsets, where they are now expressed as modern drainage alignments and photolineaments. The overall lack of resistant beds in the Wellington Formation and the resultant paucity of outcrops over much of the central portion of the study area (where the largest hydrogen anomalies occur) precluded evaluation of this hypothesis in the field using a suitable approach for detecting such zones (for example see Wheeler and Dixon, 1980).

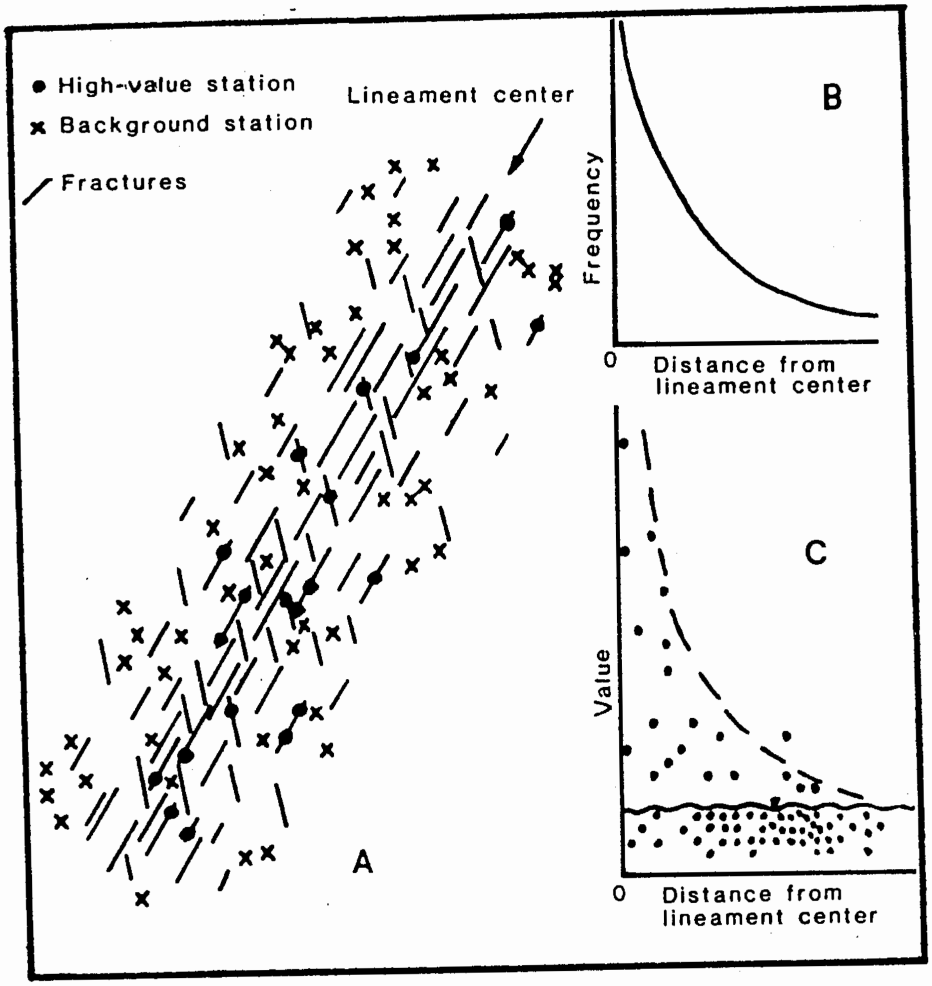
If such intensely jointed zones do exist, however, they could theoretically provide enhanced permeability pathways for vertically moving free hydrogen gas or gas-charged fluids. It is also likely that their ages and tectonic history could have produced different internal geometries, thereby affecting relative permeabilities (Schrauf and Evans, 1984). Furthermore, their three dimensional orientations relative to the modern horizontal stress field should profoundly influence their fluid conductivity characteristics (Merin and Moore, 1986). Internal geometry factors (age, genetic origin, etc.) being equal, those fracture zones oriented subparallel with the modern principal horizontal stress (ie. approximately east-northeast) would be expected to be the most "open" to vertically migrating fluids.

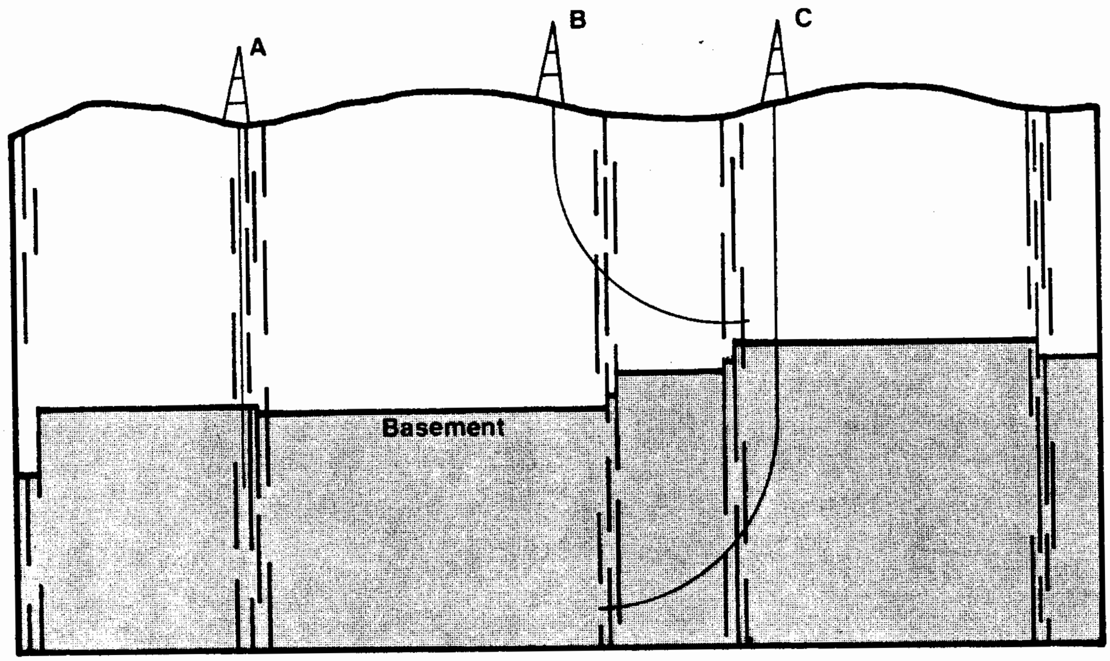
Correlation of Fractures and Soil Gas Anomalies

Visual inspection of the locations of linear features (Plates 2 and 3), infered fractures (Plate 4), and anomolous soil gas samples (Plate 4) reveals that many of the "medium," "large," and "very large" hydrogen anomalies occur on, very near, or along the extensions of linear features and suspected fractures. Of particular note are several anomalies located along the two infered faults bounding the northern extension of the Lindsborg anticline, numerous anomalies along the Chapman Creek fracture, and several anomalies (including the largest "relative" sample of all) located near the Poersch fault mentioned above. Additional examples could be cited. Some "small" anomalies also appear to be spatially correlated with such features. Given the large sample spacing (0.5 to 1.0 mi.), these findings are somewhat surprising, and suggest a slightly positive correlation may exist between anomaly magnitudes and their relative proximities to linear features in spite of the coarse sample spacing. However, note that a large number of nonanomalous values also occur close to linear features. This relationship has been noted in other studies. Richers and others (1986, Fig. 13) provided a hypothetical fracture model that can account for these observations (Figure 21 here). Additional soil-gas sampling at close intervals (50 to 200 ft.) across one or more of the above mentioned specific features might serve as a test of the model in Kansas. Sampling across the trace of a surface fault documented in Ottawa County (Hoppie, 1980; Mack, 1962) that parallels the inferred northwest-oriented fracture set, and might help establish the relative importance of actual fault zones as hydrogen conduits (Ware, et al., 1984) for the Kansas occurrence. Smoothed regional trends of

Figure 21. Hypothetical model of near-surface fracture zone (after Richers, et al., 1986, Fig. 13). A) Plan view showing increased joint intensity and anomalous sample frequency near lineament (fracture zone). Note that the overall trend of the lineament may or may not correspond with the strikes of individual joint sets. B) Joint frequency relative to distance from lineament center. C) Hydrogen anomaly magnitude relative to distance from lineament center. Note that both background and high-value samples exist within lineament.

Figure 22. Schematic diagram of recommended drilling technique (after Roark, 1985, Fig. 29). Vertical lines represent fracture zones which may be expressed at the surface as stream valleys. Note relative difficulty of intersecting these narrow fracture zones with a conventionally drilled well (A) and increased likelyhood using deviated drilling (B and C). Not to scale.


High-value station
Background station
Fractures
Lineament center
A
B
Frequency
0
Distance from lineament center
C
Value
0
Distance from lineament center


A
B
C
Basement

soil gas hydrogen values (Angino, et al., 1988) are probably more likely to reflect the gross geometry of deep source areas or zones, than localized near-surface transportation routes.

I believe that the apparent correlation between fracture locations and hydrogen soil-gas anomaly magnitudes, however slight, does reflect vertical movement of the gas through basement fault and fracture zones into corresponding (implied, but as yet undocumented) near-surface fracture zones. Probably the most accurate, and perhaps only, way to verify the existance and nature of these infered fracture zones, to quantify their various permeability factors, and determine their relative importance as hydrogen conduits would be to actually penetrate several of these zones with appropriately located boreholes utilizing deviated drilling techniques (Figure 22), and perform relevant core analyses and drillstem tests. Among the particular features to be recomended for such testing at this point are the inferred Chapman Creek fracture zone, faults flanking the Lindsborg anticline (eg. Salina fault), the Poersch fault, and any other pronounced anomaly/linear feature combinations detected by additional soil-gas sampling. Assuming such zones were penetrated and showed evidence of substantially enhanced hydrogen movement, determination of the presence or absence of a reasonably hydrogen-impermeable sealing horizon (salt?, bentonitic shale?) could affect the potential exploitability of the occurrence. And finally, if the viability of a hydrogen resource could be demonstrated, additional reconnaissance-level soil-gas sampling and down-hole testing along much of the Midcontinent rift system might be warranted.

CONCLUSIONS

Fracture Pattern

The Precambrian basement rocks of the study area are typified by a bimodally distributed fracture pattern with modal orientations close to N.40-50°W. and N.10-30°E. This bimodal fracture pattern is expressed as linear trends in gravity and aeromagnetic data, earthquake foci locations, structural surfaces, kimberlite axes, and as stratigraphic offsets in seismic data. Surficial indications of it, such as drainage alignments and spatial variations in spectral response as detected by Landsat (ie. photolineaments), may reflect zones of increased near-surface joint intensity over deeper fault zones.

The northwest-oriented fracture set is apparently the older set and may date from tensional forces associated with middle(?) Proterozoic formation of the Missouri gravity low or perhaps earlier accretion of the Central Plains orogen. The north-northeast fracture set probably resulted from axial-parallel normal faulting in response to tensional stresses during Keewenawan age rifting of the Midcontinent rift system, but it is also possible that both the gross rift trend and subsidiary fault locations may also have been largely controlled by older crustal weaknesses.

This bimodal fracture pattern has been periodically reactivated differentially throughout Phanerozoic time in response to changes in crustal stress regimes, due primarily to plate tectonic interactions at the North American continental margins. This periodic reactivation is expressed as progressive-displacement-through-time (growth) faults, fault-proximal Paleozoic lithology and thickness changes, localized Cretaceous intrusive activity, and modern seismicity. The styles of movement along particular fractures have changed variously with geologic time and this is probably a function of fracture plane orientation and principal stress direction. Nearby tectonic events (eg. Ouchita orogeny, Laramide orogeny) have produced major local effects and well-constrained paleostress directions for these events may permit predictive modeling of resultant deformation styles on the basis of fracture orientations in areas of poor subsurface control (Salina basin for example). Parallel sets of through-going fractures (Belleville and Nemaha fault zones) could also have acted as conjugate shear couples, resulting in local reorientation of the principal horizontal stress, complicating this interpretation procedure considerably. The origin and tectonic history of a given fracture has probably influenced its internal geometry and intrinsic permeability characteristics. The modern principal horizontal stress in the Midcontinent is oriented approximately east-northeast-west-southwest. Fracture-geometry considerations aside, knowledge of subsurface stress orientations might permit predictions of the relative "openness" (net permeability) of individual fractures or fracture sets, such as might affect intrafracture fluid movement.

<u>Soil Gas Relations</u>

Hydrogen detected in soil gases undoubtly originates below the Phanerozoic-Precambrian interface, perhaps from the active serpentinization of rift-related mafic rocks, perhaps from deep circulation and mixing of different formation waters, perhaps from deep-crustal or mantle outgassing. It almost certainly moves vertically primarily through fractures, either dissolved in formation fluids or as free gas. The present soil-gas sample density is probably insufficient to delineate, with any degree of certainty, the individual near-surface fracture zones acting as these possible conduits.

Evaluation of the viability of potential future exploitation of the hydrogen probably hinges on very accurate delineation of the major fracture zones through which hydrogen could be moving (not possible in this study due to inadequate data source resolutions), the presence of suitable sealing horizons (salt?, bentonitic shales?), and the use of appropriate well drilling and completion practices.

Future Research

Suggestions for further research related to the fracture pattern of north-central Kansas, the Midcontinent rift system, and the Kansas hydrogen occurrences include:

1) Digital processing and reinterpretation of the higher resolution (1 mile by 1 mile nominal station spacing) gravity data presently being acquired over the study area by the Kansas Geological Survey.

2) Acquisition, enhancement, and interpretation of high resolution, low altitude aeromagnetic data.

3) Installation of additional seismic stations to improve loca-

tional accuracy and provide a lower event-magnitude detection limit.

4) Acquisition of short, high resolution seismic lines across the Abilene anticline, Washington structure, or Belleville fault to determine if Phanerozoic deformation is fault-controlled and the importance of these structural zones at sub-Phanerozoic levels.

5) Acquisition of closely spaced (50 to 200 feet) soil-gas hydrogen determinations across those linear features spatially correlated with substantial hydrogen anomalies in the present data set (eg. Chapman Creek) or known surface faults (eg. Ottawa County) to test for the presence of near-surface enhanced gas-flux effects.

6) Evaluation the possible influence of geomorphic and soil factors (texture, clay mineralogy, moisture content, etc.) on hydrogen anomaly magnitudes.

7) Determination of hydrogen gas contents of any presently cased petroleum wells and selected ground water wells in the Clay County, northern Dickinson County, eastern Ottawa County, and northern Saline County area.

8) Rig-side determination of hydrogen content of gases exsolved from drilling muds during the drilling of all future petroleum tests in the vicinity of the Midcontinent rift, both in Kansas and elsewhere along its extent.

9) Targetting of a specific fracture zone for testing, use of directional drilling to increase probability of fracture intersection, and appropriate core analysis and drill-stem testing.

10) Extension of reconnaissance-level sampling to the north and west to further define the areal extent of the gas occurrences.

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