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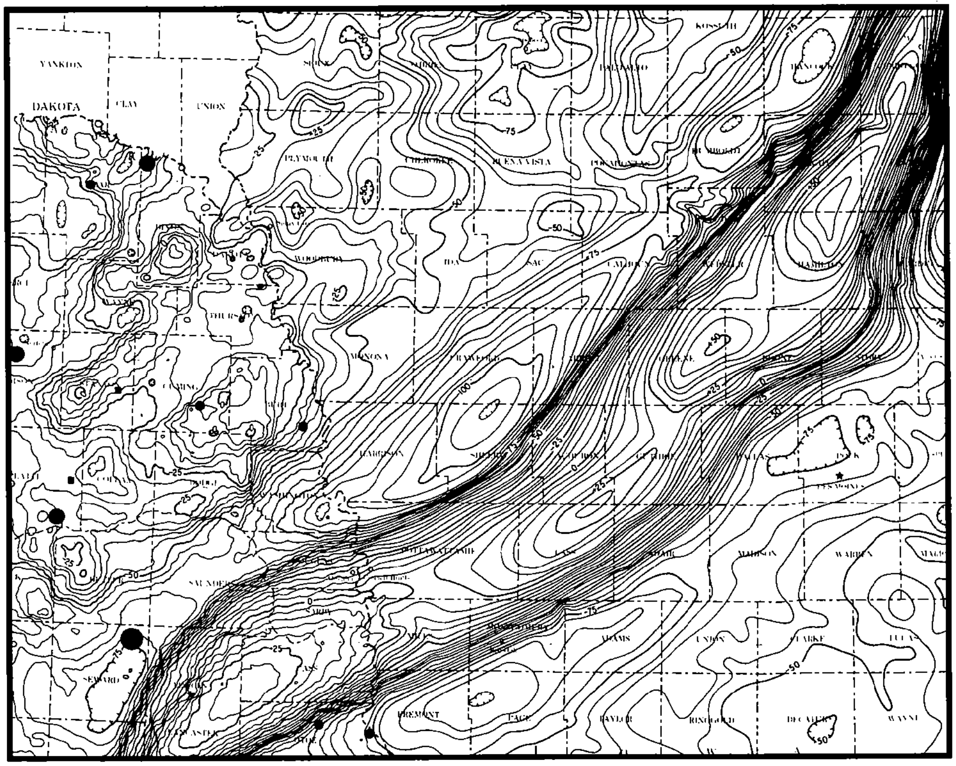

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SEISMICITY AND TECTONIC RELATIONSHIPS OF THE NEMAHA UPLIFT AND MIDCONTINENT GEOPHYSICAL ANOMALY

(Final Project Summary)

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ABSTRACT

The geological surveys of Iowa, Nebraska, Kansas, and Oklahoma conducted a 4- to 6-year investigation of the seismicity and tectonic relationships of the Nemaha Uplift and associated geologic features in the Midcontinent. Regional geological, gravity, aeromagnetic, seismological, and topographic information were compiled on 1:1,000,000-scale base maps. The following maps were prepared: (1) earthquake epicenter and station location, (2) lineament, (3) geologic bedrock, (4) structure contour (base of Kansas City Group or older Pennsylvanian rock units), (5) Precambrian configuration, (6) Bouguer gravity anomaly, (7) aeromagnetic, and (8) Precambrian rock type.

One correlation between earthquakes and tectonic structures was made. There appears to be recent as well as historical earthquake activity associated with the Humbolt Fault zone, southeastern Nebraska and northeastern Kansas.

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INTRODUCTION

Six years ago the U.S. Nuclear Regulatory Commission (NRC) initiated a number of cooperative programs with state geological surveys and (or) universities to study areas of anomalously high seismicity east of the Rocky Mountains. The program objectives were as follows:

1) Synthesize and analyze all available seismic, geologic, and geophysical data in the study regions.
2) Conduct seismic studies and install seismic networks.
3) Conduct geologic structural studies with emphasis on characteristics of faulting.
4) Produce regional geologic, seismicity, seismotectonic, tectonic-province, and geophysical maps, at a uniform scale, for nuclear-facility siting.
5) Attempt to identify earthquake mechanisms and relate them to tectonic structures.

The Nemaha Ridge/Midcontinent Geophysical Anomaly is one of five principal areas east of the Rocky Mountain front that has a moderately high seismic-risk classification. The Nemaha Uplift, which is common to the states of Oklahoma, Kansas, and Nebraska, is approximately 415 miles (670 km) long and 12-14 miles (20-40 km) wide (fig. 1). The Midcontinent Geophysical Anomaly (MGA) extends southward from Minnesota across Iowa and the southeastern corner of Nebraska and probably terminates in central Kansas. A number of moderate-sized earthquakes—magnitude 5 or greater—have occurred along or west of the Nemaha Ridge.

The state geological surveys of Oklahoma, Kansas, Nebraska, and Iowa conducted a 4- to 6-year investigation of the seismicity and tectonic relationships of the Nemaha Uplift and associated geologic features in the Midcontinent (fig. 1). This investigation, which began in October of 1976, was intended to provide data to be used to design

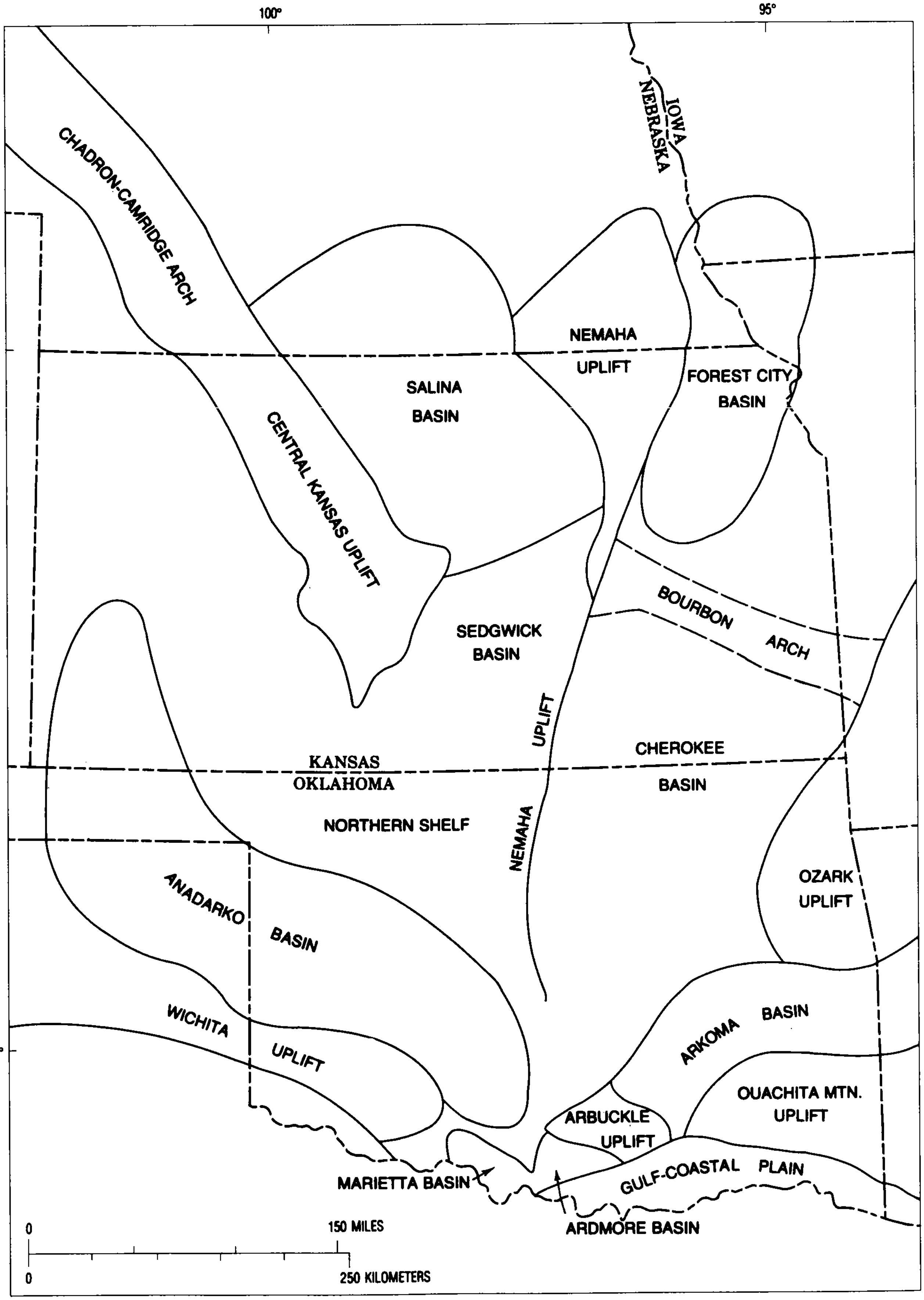

Fig. 1. Major geologic and tectonic provinces of the Midcontinent.

nuclear-power plants. However, the information is also being used to design better large-scale structures, such as dams and high-use buildings, and to provide the necessary data to evaluate earthquake-insurance rates in the Midcontinent.

Except for the preparation of a seismotectonic map, objectives 1 through 4 were achieved. To accomplish these objectives, an interdisciplinary approach, which utilized the fields of geology and geophysics, was used. Regional geological, gravity, aeromagnetic, seismological, and topographic information was compiled at a scale of 1:1,000,000 and displayed on plates 1 and 2 (pocket). The following maps were prepared: earthquake epicenter and station location, lineament, geologic bedrock, structure contour (base of Kansas City Group or older Pennsylvanian rock units), Precambrian configuration, Bouguer gravity anomaly, aeromagnetic, and Precambrian rock type.

After considerable thought and numerous discussions, it was decided not to prepare a seismotectonic map. We felt that the concept for such a map must be better defined and the practical value of such a map be more evident.

Objective 5, identification of earthquake-source mechanisms, was partially accomplished. No definite correlations could be made between earthquakes and tectonic structures except for the Humboldt Fault zone in southeastern Nebraska and northeastern Kansas.

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IOWA

(O. J. Van Eck)

The southwestern Iowa area (fig. 2) was chosen for seismicity and tectonic study because of the close proximity of the juncture of two major tectonic features, the Nemaha Ridge and Midcontinent Geophysical Anomaly (MGA). Earlier workers had recognized a structural zone that extended in an arcuate pattern from at least the vicinity of Thurman, Fremont County, to Redfield, Dallas County, Iowa (Thurman-Redfield structural zone). That structural zone was seen to coincide very closely with the MGA as then defined by available gravity data. Later acquisition of aeromagnetic data more clearly defined the MGA in Iowa, but the aeromagnetic data were of small value in helping to refine the understanding of the Thurman-Redfield structural zone.

Because of the paucity of surface exposure and subsurface data for southwestern Iowa, it was necessary to rely heavily upon geophysical methods to obtain the data required to refine our understanding of the tectonics of the area. Aeromagnetic coverage of the area was complete, and some widely spaced gravity data were available. Over 1,500 gravity stations were added and 18 miles of seismic profiling were completed during the study period.

With the additional gravity data a new Bouguer anomaly gravity map was prepared. Modeling of the gravity and aeromagnetic data led to interpretations of the lithology and configuration of the Precambrian basement. Models based on detailed gravity gradients indicate that vertical post-Precambrian movement on individual faults may range up to 300 meters or more. By combining the information obtained by modeling geophysical profiles and limited deep well data, a map of the geology of the Precambrian basement of southwest Iowa was generated. The interpretation of the MGA that emerges

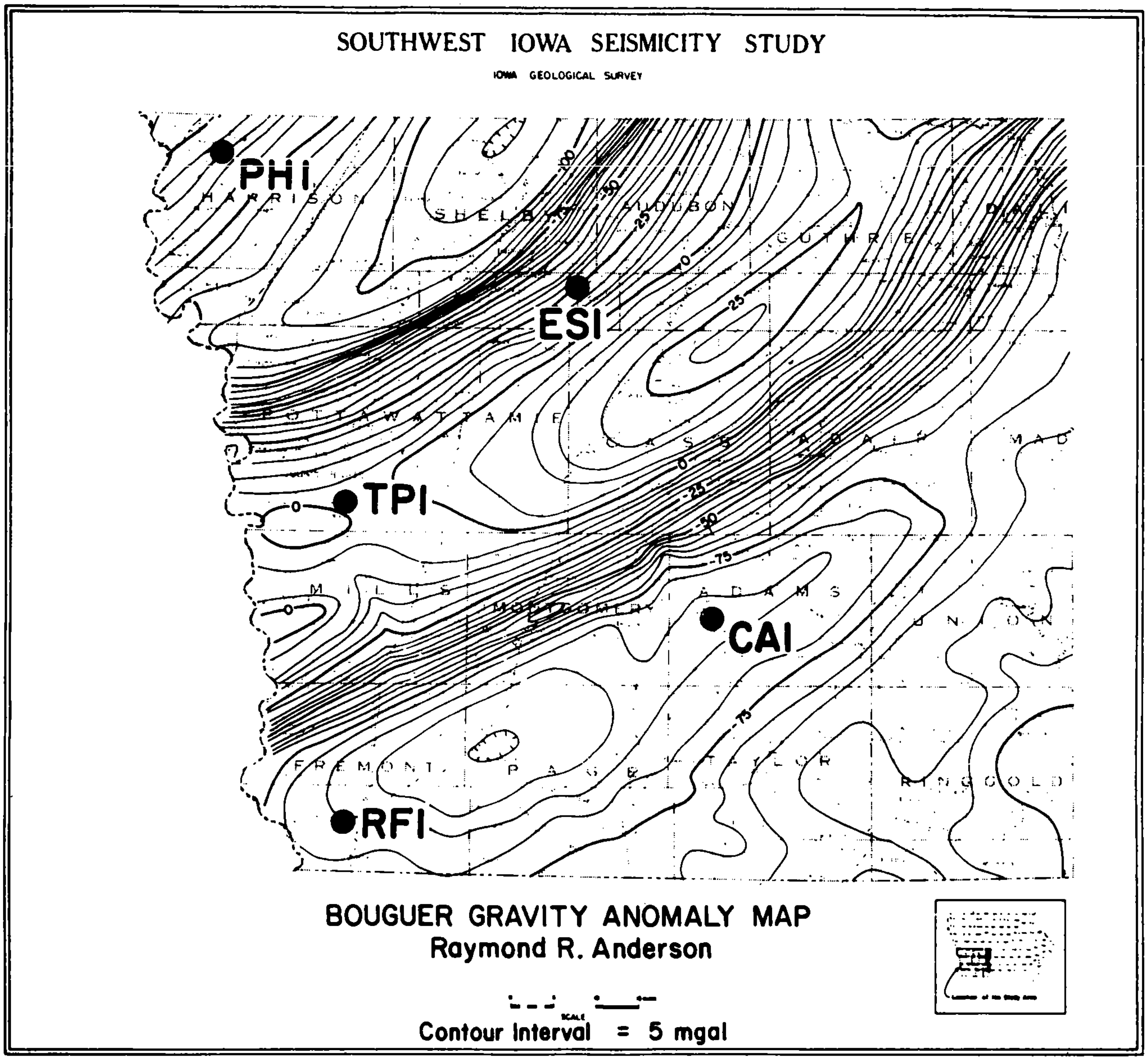

Fig. 2. Map of study area showing location of microearthquake-monitoring stations.

includes a central horst of igneous intrusives and extrusives, extensively faulted, and overlain in some areas by Keweenawan clastics. The horst is flanked by a series of high-angle faults, with most of the observed vertical displacement along two structural zones, one along the northwestern margin, the other along the southeastern margin. The horst is flanked by clastic-filled basins that reach a maximum interpreted depth of 10 km. The structural zones are referred to as the Northern Boundary Fault zone and the Thurman-Redfield structural zone, respectively.

The interpretations of the seismic profiles provide a much better understanding of Paleozoic structures of the region. These interpretations show Paleozoic structural features to have minor displacements when compared to nearby interpreted basement features. Late Paleozoic folding at Grant (Montgomery County) and Middle River (Adair County), minor post-Silurian faulting at Stennet (Montgomery County) and Harlan (Shelby County), and several possible periods of faulting and folding at Malvern (Mills County) are examples of these Paleozoic structures.

These interpretations suggest that most of the deformation on the Thurman-Redfield structural zone and Northern Boundary Fault zone occurred prior to the deposition of the Late Mississippian and Pennsylvanian strata. They also suggest that the forces that later deformed these sediments were more localized. The superposition of some of these Paleozoic structures over larger basement structures suggests reactivation of the older features.

A major part of the study was the monitoring of seismic activity in and around the southwestern Iowa study area. Five seismic stations straddling the MGA were operated, with the first station starting in December 1979 and the full system operating by October 1980. Despite various operational problems, the seismic network was successful in recording numerous very low-magnitude events. These events were recorded at only one station, and thus epicenters could not be determined. This indicates that low-level seismic activity persists in southwestern Iowa. The network was also very successful in the recording of regional microseism (Richter magnitudes 3-2) and provided useful data to other network operators in the Nemaha Ridge-MGA study.

When data on the frequency and intensity of recent local microearthquakes and isopach mapping of southwestern Iowa are incorporated with gravity and seismic data, the conclusion is that the Thurman-Redfield structural zone and Northern Boundary Fault zone have been periodically active through most of Paleozoic time and are still active today.

NEBRASKA

(R. R. Burchett)

Nebraska can be subdivided into several major geologic and tectonic provinces (fig. 3). There are two major structural features in eastern Nebraska: the Nemaha Uplift, a north-south feature bounded on the east by the Humboldt Fault zone, and a northeast-southwest feature, the Midcontinent Geophysical Anomaly (MGA), bounded on the south by the Union Fault zone. For the NRC study, 1976-1982, we (1) compiled and obtained seismotectonic data, (2) obtained and interpreted geologic and geophysical data for regional and local areas, and (3) participated in an areawide microearthquake-recording network.

Results presented primarily in map form in this report summarize most of the data collected during the 6-year study (pls. 1 and 2). These data show that (1) the Humboldt and Union Faults are not single structures but include a series of complex faults and (or) steep dips offsetting rocks at least as young as Permian in age, (2) surface and near surface faults and folds probably reflect reactivation of older structures, (3) gravity and magnetics are useful tools for determining structure and the nature of the basement, (4) geologic and geophysical evidence indicates zones of crustal weakness in eastern Nebraska, (5) glacial rebound does not appear to be the cause of earthquakes in eastern Nebraska, and (6) microearthquakes recently recorded in Kansas and Nebraska indicate that the Humboldt Fault zone is still active.

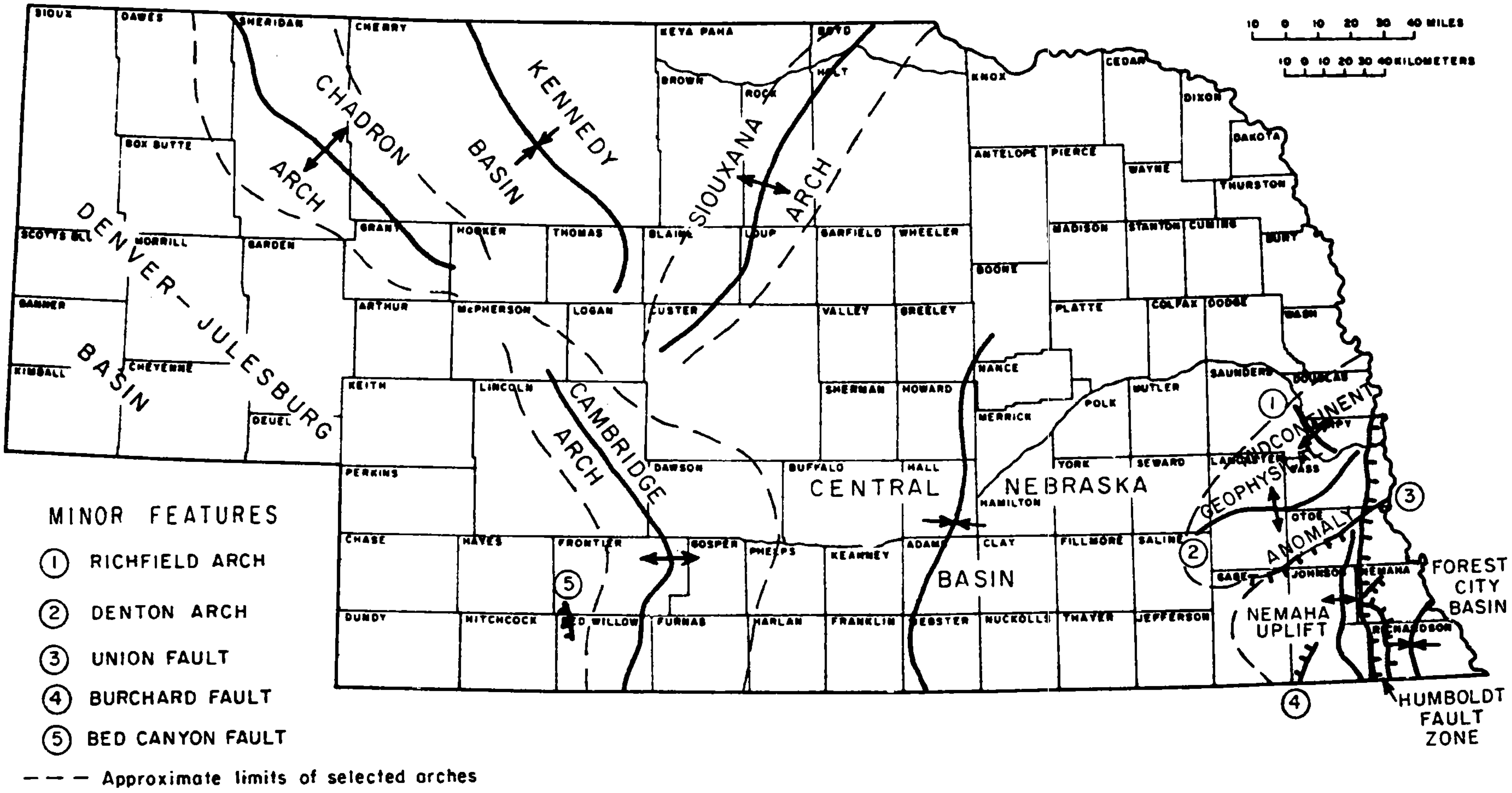

Fig. 3. Principal structural features of Nebraska.

KANSAS

(F. W. Wilson)

Since beginning operation in November 1977, the Kansas seismograph network has recorded approximately 40 microearthquakes and small felt earthquakes within the NRC study area of eastern Kansas (fig. 4). The pattern of seismic activity has, for the most part, duplicated the locations of earthquake epicenters reported during the period of record beginning in 1867 (DuBois and Wilson, 1978).

The most active area is along and parallel to the Humboldt Fault zone, which is the eastern boundary of the buried Nemaha Uplift. In the northern part of this zone, microearthquakes and felt earthquakes in the vicinity of Manhattan, Kansas, are associated with the Humboldt zone itself and known or inferred northwest-southeast cross-cutting faults and structural features.

In the same area, a linear zone of microearthquake activity parallels the Humboldt Fault zone to the east along the deepest part of the Forest City Basin. This activity may be associated with the axis of the syncline or the inferred buried trace of the northwest-southeast cross-cutting trend of the Bolivar-Mansfield structural zone of Missouri (McCracken, 1971).

Southward along the Humboldt zone, pods of activity are similarly associated with cross-cutting structural features.

The second most active area is a northeast-southwest-trending zone near the Nebraska border in Washington, Republic, and Cloud Counties. A felt earthquake, reported from Mitchell County in 1928, may also be associated with that zone.

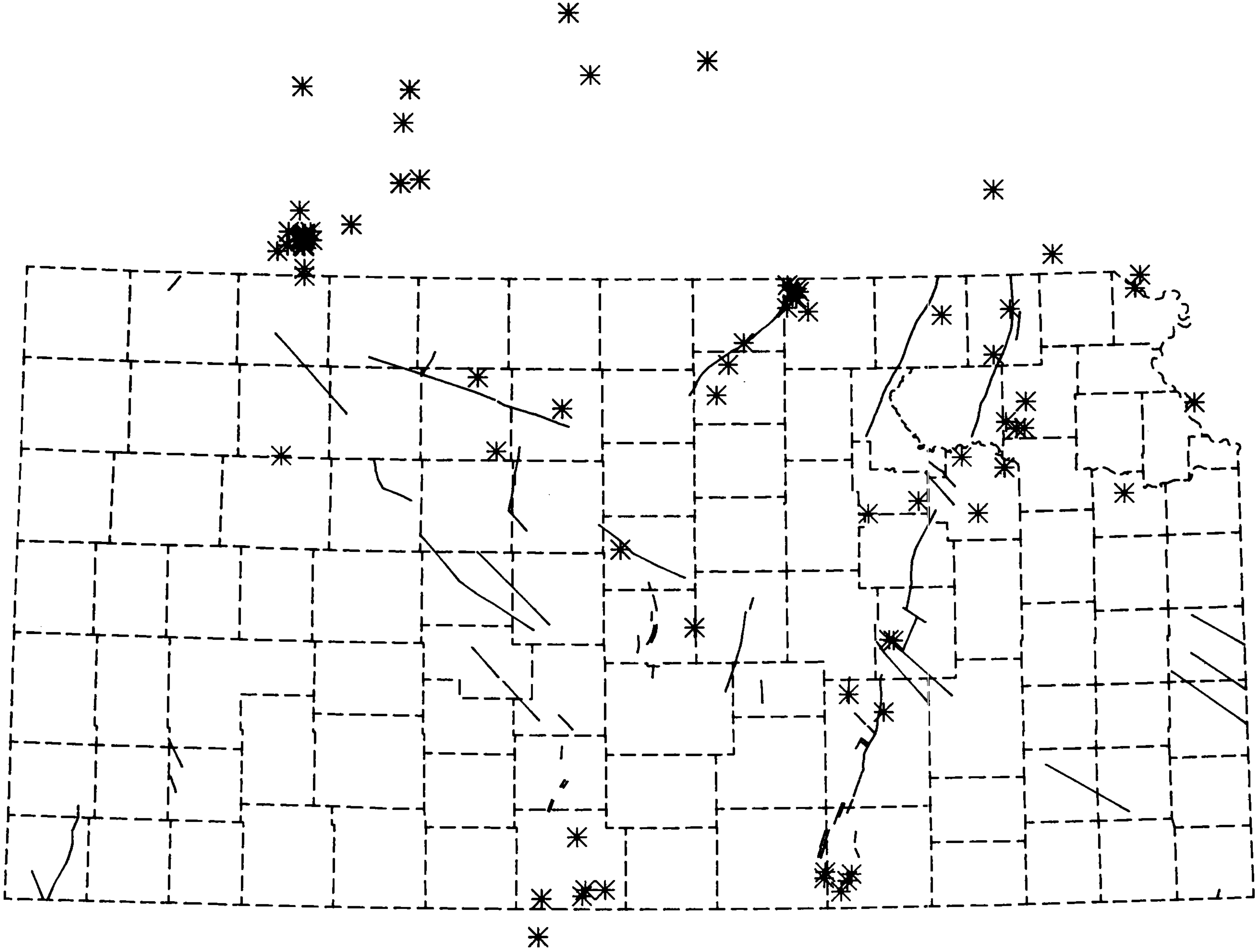

Fig. 4. Microearthquakes(*) and faults (/) in Kansas. (GIMMAP/KGS February 1982 Lambert Conformal 1:3,000,000)

These earthquakes occur along an inferred fault zone at the western side of Cambrian-Precambrian clastic-filled basins that parallel the late Proterozoic Central North American Rift System (see gravity and aeromagnetic maps, pl. 2, map B, map C).

The third most active area is in extreme northeastern Kansas in Doniphan County and adjacent counties in Missouri and Nebraska.

This northwest-southeast-trending zone is now believed to be associated with a newly reported gravity feature called the Missouri Gravity Low (Arvidson and others, 1982). The Missouri Gravity Low lies on a series of northwest-southeast-trending structural zones across Missouri (McCracken, 1971).

The gravity low coincides with a magnetic lineament which Zietz (1981) traces from central Montana to eastern Kentucky.

Because the feature seems to offset the Central North American Rift System in a left-lateral sense, Arvidson and others (1982) suggest that it may be a major transcurrent- or wrench-fault system which has been reactivated at various periods of geologic time.

Other small earthquakes and microearthquakes in northeastern Kansas occur along or adjacent to the southern limits of Kansas glaciation and may be the result of continued glacial isostatic adjustment or rebound.

This study has shown that earthquakes in eastern Kansas are related to major structural features known or interpreted from geological, structural, and geophysical studies. From this I conclude that the most likely areas of future earthquake activity in Kansas are in the vicinity of the east flank of the Nemaha Uplift and along the Central North American Rift System and the flanks of its bounding basins, particularly where these are intersected by cross-cutting structural features.

Because the Central North American Rift System (CNARS), the Nemaha Ridge, and the Forest City Basin are cut by a probable deep crustal fracture zone in southeastern

Nebraska, future stronger seismic activity is likely in that area and along paralleling zones such as the Manhattan trend.

Secondary zones southward along the trend of the Nemaha Uplift and the CNARS may be the loci of additional seismic activity, particularly where these zones are intersected by cross-cutting structural features.

OKLAHOMA

(K. V. Luza)

The Nemaha Ridge consists of a number of uplifted crustal blocks typically 3 to 5 miles (5 to 8 km) wide and 5 to 20 miles (8 to 32 km) long that occupy a northeast-southwest zone. This zone, approximately 30 miles (48 km) wide in northern Kay County, narrows southwestward until it is less than 6 miles (10 km) wide in northern Kingfisher County. In northern Kingfisher County, the Nemaha Fault zone abruptly changes direction, with the principal trend being northwest-southeast.

Fine- to medium-grained clastic rocks of Permian age overlie the Nemaha Uplift structures in central Oklahoma (pl. 1, map C). Except for a few localities, surface geologic relationships offer little insight into understanding the structural relationships associated with the Nemaha Uplift. Therefore, to gain a better understanding of the geologic and tectonic history of the Nemaha Ridge, we constructed three structure-contour maps of key stratigraphic horizons: the top of the Viola Formation (Ordovician), the base of the Pennsylvanian, and the top of the Oswego Formation (Middle Pennsylvanian) (pl. 1, map D). These units were selected because they have been penetrated by a large number of boreholes and because they are easily recognizable on electric logs. Data from more than 20,000 wells were used to construct these structure-contour maps.

The structure-contour maps reveal a complex fault pattern associated with the Nemaha Uplift. This fault pattern is dominated by several discontinuous uplifts such as the Oklahoma City, Lovell, Garber, and Crescent Uplifts. These features form a fault zone that extends from Oklahoma City in a northwesterly direction. Near the Kingfisher-Garfield County line, the orientation of the fault zone becomes north-northeast and extends northward through Kansas and terminates in southeastern Nebraska. The southern end of the Nemaha Ridge is believed to be the Oklahoma City Uplift and its associated faults. Another fault zone, the McClain County Fault zone, intersects the Oklahoma City Uplift in southern Oklahoma County. This fault zone, which is composed of a number of subparallel faults and is thought to be temporally related to the Nemaha faults, trends south-southwest and terminates against the Pauls Valley Uplift in Garvin and southern McClain Counties.

In central Oklahoma, particularly near the axis of the Nemaha Ridge, the basement-rock surface slopes gently southward. It is approximately 4,000 feet (1,220 m) below the surface near the Kansas border and is 8,000 feet (2,440 m) deep near Oklahoma City (pl. 2, map A). Denison (1966, 1981) classified the central Oklahoma basement rocks into the following four units: (1) Washington Volcanic Group, (2) Spavinaw Granite Group, (3) Osage Microgranite, and (4) Central Oklahoma Granite Group (pl. 2, map D). The isotopic ages range from 1,150 to 1,270 million years, and these ages, when considered with analytical variations, indicate a main period of thermal activity about 1,200 million years ago.

In 1978, a program was initiated to collect detailed gravity and magnetic information in the Nemaha Uplift project area. Barrett (1980) and Santiago (1979) established 400 gravity and magnetic stations in parts of Kingfisher, Blaine, Major, Kay, Garfield, Grant, and Canadian Counties. The magnetic data were used to check the validity of an earth model constructed from the gravity data.

The gravity and magnetic anomalies calculated from the Barrett (1980) and Santiago (1979) geologic models correlate well with the observed anomalies. Their models show the causative bodies to be several vertical prisms, such as dikes, with a positive density contrast of 0.26 gm/cm^3 with respect to the surrounding basement rocks. Most of these dikes have apparent susceptibility contrasts in the range of 2.6×10^{-3} e.m.u. It was assumed that the basement rocks in this region have a granitic composition (Denison, 1966). The positive density contrast and high magnetic susceptibility of the dikes are of the magnitude that would be expected for mafic igneous intrusive rocks, such as diabase. It seems probable that the mafic igneous dikes modeled in the Kingfisher and Medford areas represent diabase dike swarms that failed to penetrate through the granitic basement. Perhaps this region represents the southern terminus of a Keweenawan mafic-belt complex that failed to develop into a rift.

Hayden (1982) established 301 gravity and magnetic stations in Canadian County and parts of Caddo, Oklahoma, Cleveland, Lincoln, Payne, and Logan Counties. Preliminary examination of the gravity and magnetic data indicates that the study area can be divided into two regions or quadrants. The free-air anomalies in the northeastern quadrant, which contains the Edmond maximum and the Nemaha Uplift, follow surface-elevation contours. This relationship suggests that this area is in isostatic equilibrium. The crust underlying the southwestern quadrant, the site of numerous earthquakes, does not conform to any simple model of isostasy. The free-air anomalies express an inverse and nonlinear correlation with rising topography. The crustal blocks in this region may be as much as 35 percent out of equilibrium.

Significant gradient changes in the magnetic data along a northwest-southeast trend suggest faulting within the basement in southwestern Canadian County. This feature occurs in close proximity to the observed earthquake activity. The basement discontinuity closely parallels the northern shelf-Anadarko Basin interface. Since this region does not appear to be in isostatic equilibrium, perhaps the crust is adjusting to attain equilibrium. As a possible consequence of this process, earthquakes occur along this discontinuity.

A total intensity aeromagnetic map for the Enid and Oklahoma City 1° x 2° Quadrangles was prepared from the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) data by Noel F. Rasmussen (pl. 2, map C). The magnetic data were used to prepare an interpretive map that shows high and low magnetic anomalies, fault patterns, and basement-rock lithologies. Three lithologic units are clearly defined by the change in the magnetic intensity on the aeromagnetic map. They include the Washington Volcanic Group, the Central Oklahoma Granite, and the Spavinaw Granite Group. Five dominant high and low anomalies feature the Lamont Ring Complex (high), the Central Oklahoma metamorphics (low), the Tulsa Mountains (high), and the Greenleaf and Osage Island maxima (highs). Six major fault zones were identified: (1) north-south Nemaha, (2) east-west Garfield-Noble, (3) southwest-northeast Osage, (4) southwest-northeast Cushing, (5) Hughes County, and (6) Creek County fault complexes.

The principal goal of the seismological program was to establish a regional seismograph network to supplement the existing seismological capability at the Oklahoma Geophysical Observatory. The Oklahoma network of seismograph stations consisted of three distinct parts, one part of which is the Oklahoma Geophysical Observatory (TUL). The seismic responses at TUL are recorded on 14 paper-drum recorders; 16 seismograms are recorded on 16-mm film. Seven semipermanent, volunteer-operated seismograph stations and three radiolink stations, whose signals are recorded on five drum recorders at the observatory, constitute the second and third parts of Oklahoma's regional network (pl. 1, map A).

From 1897 through 1976, Oklahoma had approximately 128 known earthquakes. From January 1, 1977, to December 31, 1981, 255 additional earthquakes were located in Oklahoma. Plate 1, map A shows the distribution of all known Oklahoma earthquakes.

The pre-1977 earthquake data, when combined with the 1977-81 earthquake data produce at least one seismic trend in north-central Oklahoma (fig. 5). There appears to be a 25-mile-wide (40-km) and 90-mile-long (145-km) zone that extends northeastward from near El Reno toward Perry. The El Reno-Perry trend appears to cut diagonally across the Nemaha Uplift structures at about a 30° angle. The southern end of this trend, the El Reno-Mustang area, appears to be more active than the middle and northern parts. The recent as well as the historic earthquake data seem to support this

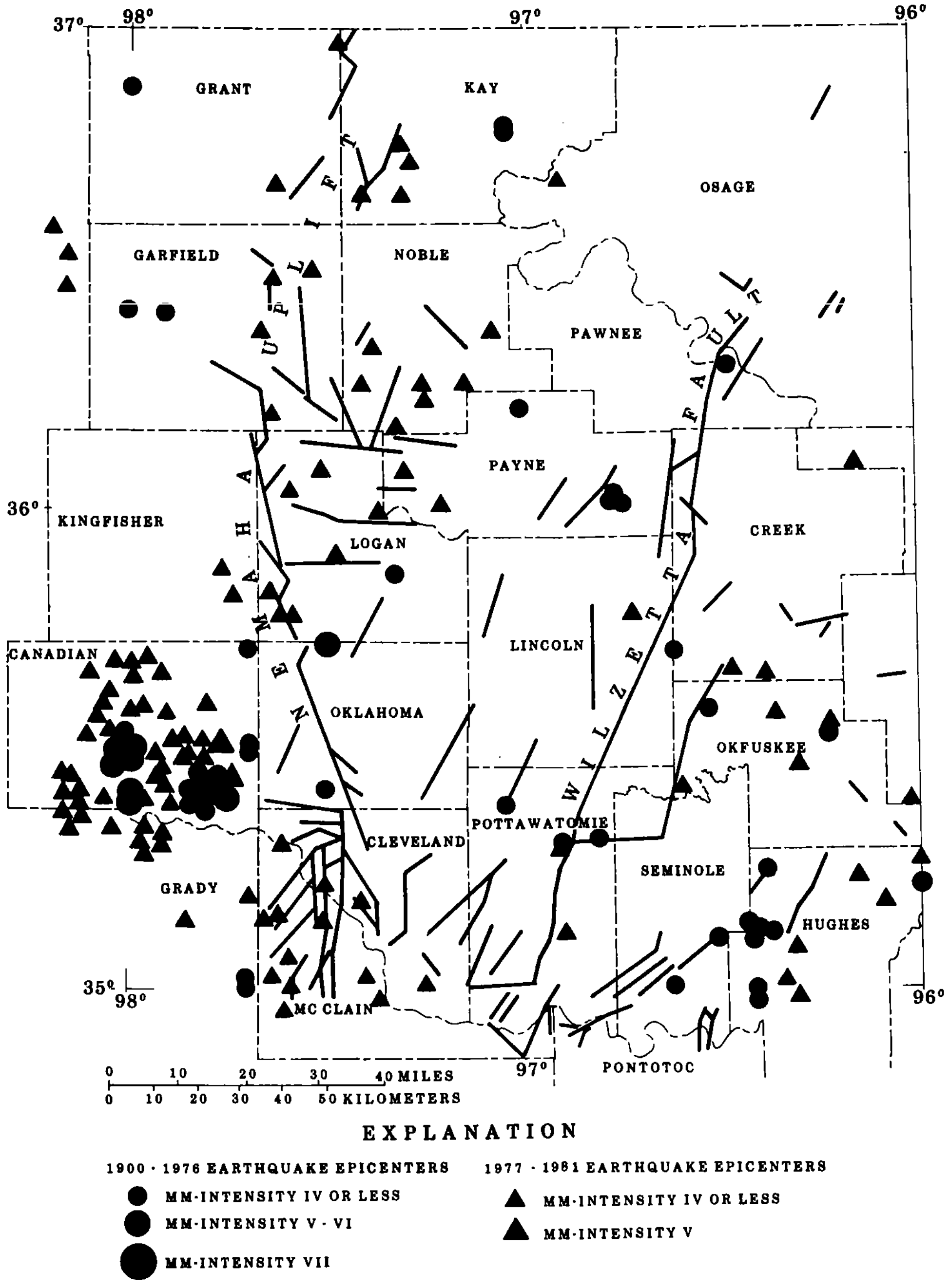

Fig. 5. Distribution of faults that cut pre-Pennsylvanian strata, and earthquake epicenters for north-central Oklahoma (Wheeler, 1960; Jordan, 1962; unpublished reports).

observation. The Canadian County earthquakes appear to coincide with the northern shelf-Anadarko Basin interface. The breakover from shelf to basin appears to coincide with lower Paleozoic faults that probably were initiated when the Anadarko Basin began to develop in Middle Cambrian time. It should be noted that most of these structures are not manifested in upper Paleozoic rocks.

It is not clear what the earthquake activity between El Reno and Perry represents. We are not sure whether the zone is the result of a coincidental plot of earthquake epicenters and (or) whether it is related to some unknown northeast-trending structure(s). There do not appear to be any major Paleozoic structures in the vicinity of the zone. However, an interpretation of the aeromagnetic data suggests northeast-southwest-trending Precambrian features in the vicinity of the earthquake zone.

The earthquake epicentral data show three other seismic trends worthy of discussion. One trend is situated between Norman and Pauls Valley. This trend closely parallels the McClain County Fault zone, which is about 25 miles (40 km) wide and 37 miles (60 km) long. This fault zone consists of a number of subparallel faults and consequently, a number of fault blocks within the zone. Small adjustments between fault blocks may be producing some of the earthquakes in this region. Furthermore, this area is the site of recent oil and gas activity. Perhaps some of the earthquakes are related to reservoir-stimulation techniques utilized by the petroleum industry.

Another trend occurs in south-central Oklahoma. There, earthquake activity is concentrated in the Wilson area, Carter and Love Counties. This area is situated within a complex structural zone that is part of the southern extension of the Wichita Mountain frontal-fault zone. The earthquake activity probably is related to fault-block adjustments as well as to oilfield activity. We have one documented case where massive hydraulic fracturing in an oil well produced earthquakes in the Wilson area. We suspect that some of the other earthquake activity in this region is man related.

The last general area of earthquake activity lies along and north of the Ouachita front (Arkoma Basin) in southeastern Oklahoma. The earthquake activity forms a diffuse, broad pattern and appears to be unrelated to known Paleozoic faults.

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APPENDIX: Publications (reports, papers, and abstracts) related to the Nemaha Uplift study

I: Iowa Geological Survey

II: Nebraska Geological Survey

III: Kansas Geological Survey

IV: Oklahoma Geological Survey

I. IOWA GEOLOGICAL SURVEY

(O. J. Van Eck, principal investigator)

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(K. V. Luza, principal investigator)

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