Special Publication 82-1
ISSN 9275-0929

SEISMICITY AND TECTONIC RELATIONSHIPS OF THE NEMAHA UPLIFT IN OKLAHOMA PART IV

Prepared by
Kenneth V. Luza
James E. Lawson, Jr.

with

Contributions by
Christopher Barrett
Noel F. Rasmussen
Donald J. Santiago
Robert C. Shoup

September 1981

Oklahoma Geological Survey
The University of Oklahoma
Norman, OK 73019

Prepared for
Division of Reactor Safety Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Under Contract No. NRC 04-76-0314

Published in 1982 by
Oklahoma Geological Survey

Special Publication Series

The Oklahoma Geological Survey's Special Publication series is designed to bring new geologic information to the public in a manner efficient in both time and cost. The material undergoes a minimum of editing and is published for the most part as a final, author-prepared report.

Each publication is numbered according to the year in which it was published and the order of its publication within that year. Gaps in the series occur when a publication has gone out of print or when no applicable publications were issued in that year.

This publication is issued and printed by the Oklahoma Geological Survey as authorized by Title 70, Oklahoma Statutes, 1971, Section 3310, and Title 74, Oklahoma Statutes, 1971, Sections 231-238. 500 copies have been prepared for distribution at a cost to the taxpayers of the State of Oklahoma of $980.

NOTE: Parts I and II of this study on Seismicity and Tectonic Relationships of the Nemaha Uplift in Oklahoma are available separately from National Technical Information Service, Springfield, Virginia 22161, as follows:

Part I (NUREG/CR-0050) costs $6.00 for a paper copy, and $3.00 for a microfiche copy. Part II (NUREG/CR-0875) costs $9.50 for a paper copy, and $3.50 for a microfiche copy.

Part III (NUREG/CR-1500) is available from the Oklahoma Geological Survey as Special Publication 81-3. The cost is $4.00 and the publication may be ordered from The Oklahoma Geological Survey, 830 Van Vleet Oval, Room 163, Norman, Oklahoma 73019.

Parts I, II, and III were prepared for the U.S. Nuclear Regulatory Commission. Although information is presented in addition to that given in Part III and Part IV, Parts I and II are essentially progress reports. A final report that will give the results of the entire study in some detail is expected to be published sometime in 1983 as an OGS Circular.

ABSTRACT

A lineament map was prepared for north-central Oklahoma. Three categories of lineaments--high, confident, and low--are portrayed on the map. The Nemaha Uplift project area contains 90 linear features derived from Landsat imagery. Of these, eight are high confident, 16 are confident and 66 are low confident. One high confident lineament trend correlates with some of the earthquake-epicenter data in Canadian County.

A detailed gravity map was prepared for the Kingfisher and Medford maxima. It is probable that these anomalies are the result of the intrusion of mafic igneous rocks, such as diabase, into a granitic mass. Perhaps this region represents the southern terminus of a Keweenawan mafic-belt complex that failed to develop into a rift.

A total-intensity aeromagnetic map for the Enid and Oklahoma City 1° x 2° Quadrangles was prepared. Five dominant high and low anomalies, six major fault zones, and three lithologic units were defined by the change in the magnetic intensity on the aeromagnetic map.

During 1980, 64 earthquakes were located by the Oklahoma Geophysical Observatory and the Kansas Geological Survey. By state, they are distributed as follows: 49 in Oklahoma, 8 in Kansas, 2 in Nebraska, 2 in Missouri, 2 in Texas, and 1 in Arkansas.

A study of earthquake distribution and intensity values in Oklahoma led to the development of a seismic-source zone map for Oklahoma and parts of the adjacent states. Six seismic-source zones were identified. For each zone, except one, a magnitude-frequency relationship was determined.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Most of the earthquake epicenters in north-central Oklahoma do not appear to correspond with major geologic structures. An attempt was made to relate linear and (or) curvilinear features, identified on Landsat imagery, to geologic structure. The lineament analysis was conducted by Shoup (1980) for bands 5 and 7 of two Landsat scenes, March 1976 and July 1977, covering north-central Oklahoma.

Three categories of lineaments--high, confident, and low--are portrayed on a lineament map for north-central Oklahoma (fig. 2). High-confidence lineaments are those observed on three or four images. Confident lineaments are those observed on two images, whereas low-confidence lineaments are those observed on only one image.

The area that embraces the Nemaha Uplift project contains approximately 90 linear features derived from Landsat imagery. Of these, eight are high confidence, 16 are confident, and 66 are low confidence. One of the high-confidence lineaments, the El Reno lineament, was selected for detailed study.

There was some correlation of Shoup's El Reno lineament with the earthquake-epicenter data in Canadian County. The trend of the El Reno-Perry earthquake zone is N. 40° E., whereas the trend of the El Reno lineament is N. 65° E. Several of Shoup's confident and low-confidence lineaments have northeast-southwest orientations that plot near or within the El Reno-Perry zone. Perhaps this association is coincidental, or maybe these linear features reflect structural features yet undefined.

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 a 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.

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. 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 County 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.

Two of the regional, analog recording stations, Carnasaw Mountain Lookout Tower (CRO) and Ponca City (PCO), were relocated to new sites. Three triggered-digital seismographs were installed near El Reno.

During 1980, 64 earthquakes were located by the Oklahoma Geophysical Observatory and the Kansas Geological Survey. By state, they are distributed as follows: 49 in Oklahoma, 8 in Kansas, 2 in Nebraska, 2 in Missouri, 2 in Texas, and 1 in Arkansas.

The major Oklahoma earthquake trends evident in earlier data appear in the 1980 earthquake data set. Generally, the earthquakes in Canadian County do not appear spatially related to the Nemaha Uplift. However, four earthquakes in north-central Oklahoma apparently occurred directly on the Nemaha axis and its associated faults.

Five earthquakes in McClain County appear to define a new seismic trend. When these are considered together with two earthquakes in Cleveland County, and with three Garvin County earthquakes, there is a hint of a trend along the McClain County fault zone, a series of en-echelon faults extending southward from Norman toward Pauls Valley in Garvin County.

A study of earthquake distribution and intensity values in Oklahoma was used to divide Oklahoma and parts of the adjacent states into six seismic-source zones. For each zone except one, a magnitude-frequency relationship was developed. It is hoped that this study will lead to the development of a better understanding of seismo-tectonic relationships.

GEOLOGICAL INVESTIGATIONS

Introduction

The Oklahoma Geological Survey, in cooperation with the Kansas, Nebraska, and Iowa Geological Surveys, is conducting a 5-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, is principally intended to provide data that can be used to better design nuclear power plants. However, the results of these studies may also be used to better design large-scale structures, such as dams and high-rise buildings, as well as to provide the necessary information to evaluate insurance rates in the Midcontinent.

The report summarizes project progress and project results for the fourth year (January 1, 1980, to December 31, 1980) conducted in Oklahoma. Progress summaries for FY 1977, FY 1978, and FY 1979 were published as NUREG/CR-0050 (Luza and others, 1978), NUREG/CR-0875 (Luza and Lawson, 1979), and NUREG/CR-1500 (Luza and Lawson, 1980) respectively.

Landsat Imagery Study

Most of the earthquake epicenters do not appear to correspond with major geologic structures in north-central Oklahoma. An attempt was made to relate linear and (or) curvilinear features, identified on Landsat imagery, to geologic structure. Perhaps a better understanding of earthquake-structure relationships will evolve from this study.

The study area, which encompasses approximately 13,000 square miles (33,672 km^2), includes Oklahoma City near the southeast corner and Great Salt Plains near the northwest corner (see fig. 2 for approximate location). The

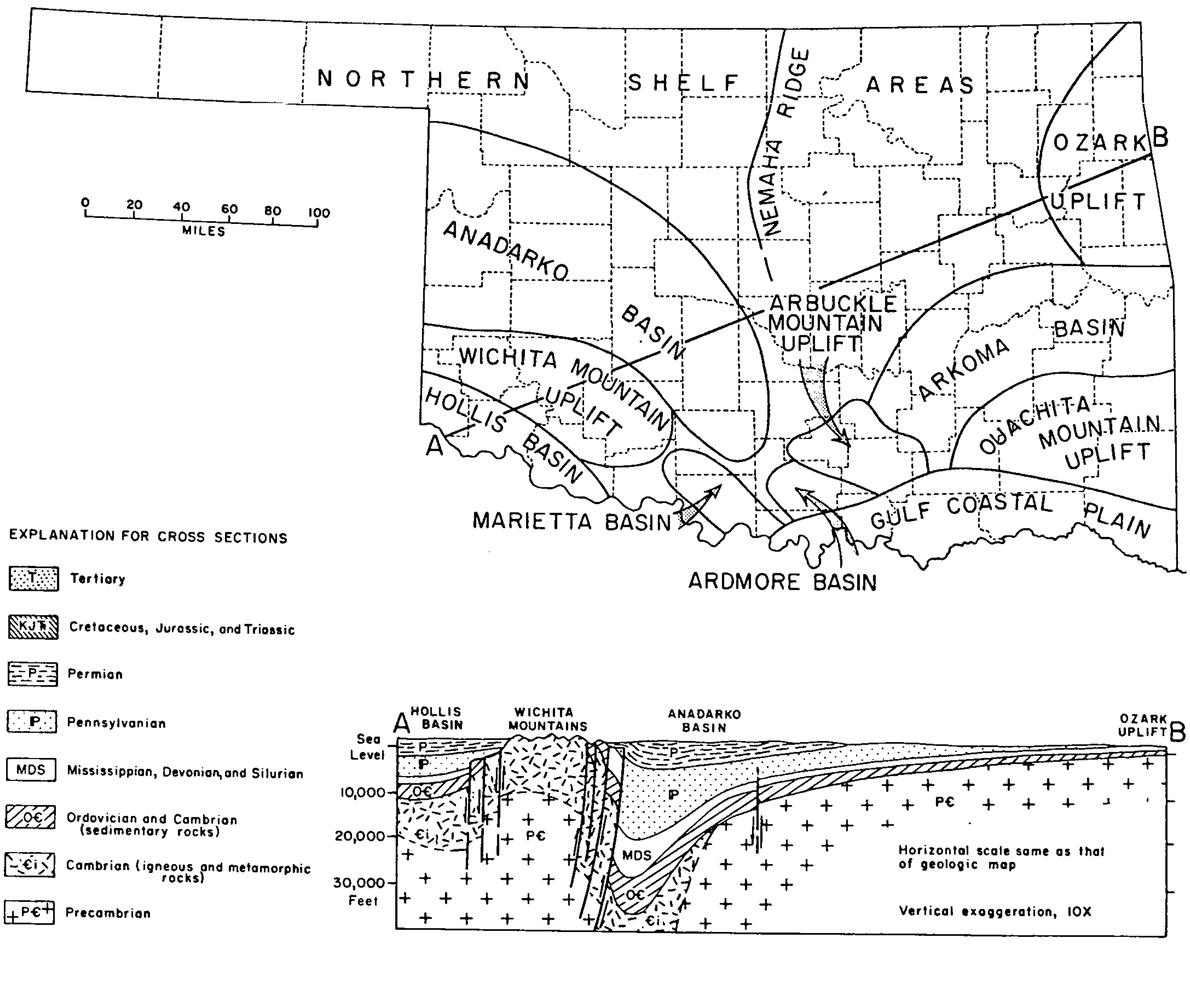

Fig. 1. Major geologic and tectonic provinces of Oklahoma.

lineament analysis was conducted by Robert C. Shoup (1980) for bands 5 and 7 of two Landsat scenes, March 1976 and July 1977 covering north-central Oklahoma (Path 30, row 35, World Wide Landsat Reference System).

Shoup (1980) applied a rotational linear-enhancement process, described by Lawton and Palmer (1978), to each of the four images. The process resulted in significant improvement in the number of lineaments interpreted for all but the July band-7 image. Shoup attributed the poor results for this image to insufficient contrast within the continuous-tone image.

Excluding the July band-7 image, an average of 67-percent improvement in recognizable lineaments was achieved through the tone-line process. An average of 107 lineaments were mapped from band 5 of the two scenes. Tonal lineaments, and a composite of tonal and aligned stream-segment lineaments, make up most of the lineaments recognized from the band-5 images. An average of 94 lineaments were mapped from band-7 of the two scenes. Tonal lineaments, a composite of tonal and aligned stream segments, and stream-segment lineaments make up most of the lineaments recognized from the band-7 images.

Three categories of lineaments--high, confident, and low--are portrayed on Shoup's (1980) lineament map for north-central Oklahoma (fig. 2). High-confidence lineaments are those observed on three or four images. Confident lineaments are those observed on two images, whereas low-confidence lineaments are those observed on only one image.

The lineament lengths for each band and scene were summed for every 5 degrees and plotted on rose diagrams. The lineaments for all bands and scenes demonstrate the following orientations: N. 40°W. to N. 60°W., N. 20°W. to N. 35°W., N. 35°E. to N. 50°E., and N. 60°E. to N. 80°E. Of the lineaments mapped from the band-5 scenes, an average of 57 percent are oriented in these

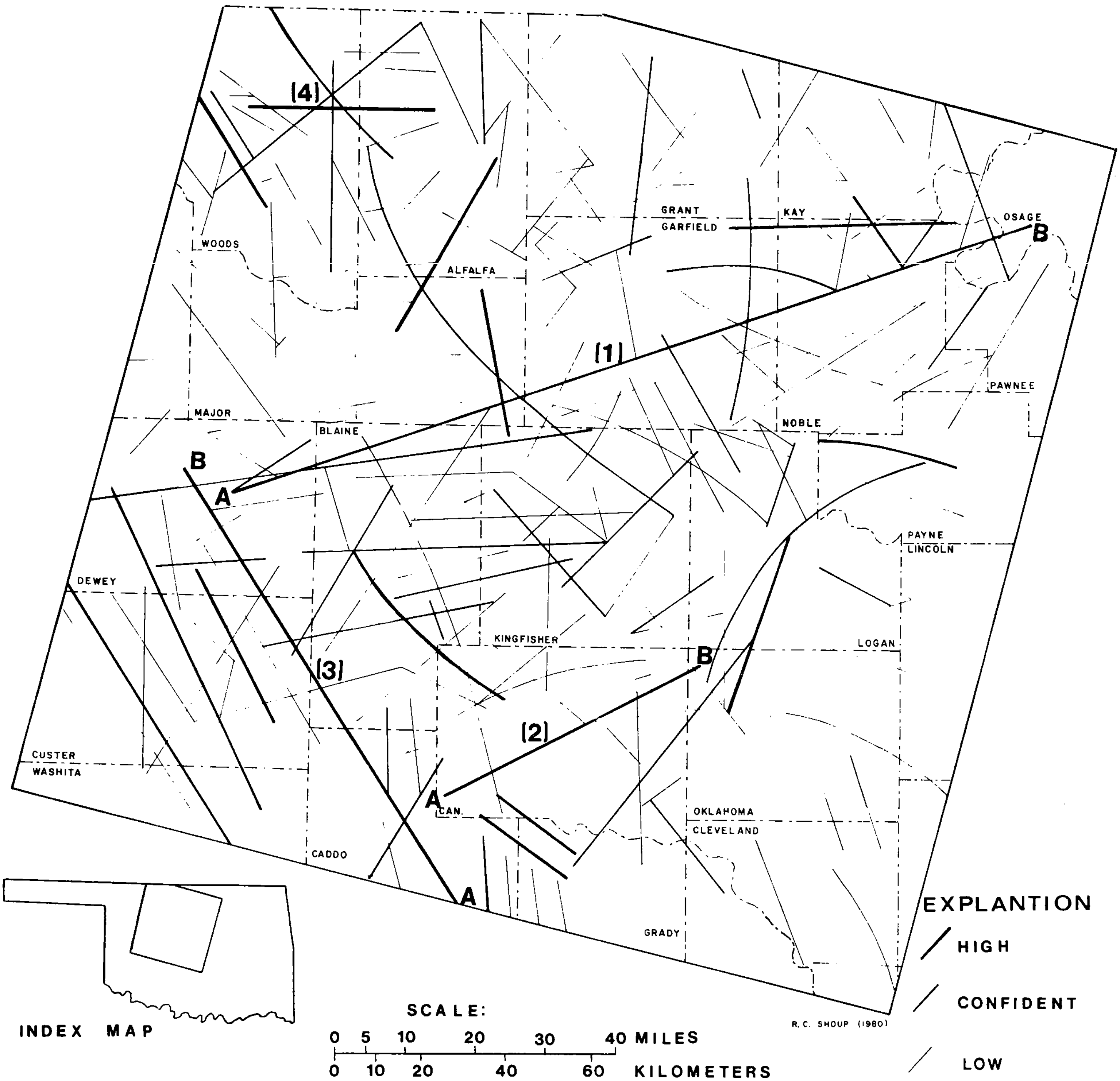

Fig. 2. Lineament map for north-central Oklahoma. Three categories of lineaments (high, confident, and low) are portrayed on the map (Shoup, 1980). Detailed studies include (1) trans-Oklahoma lineament, (2) El Reno lineament, (3) Oklahoma-Louisiana lineament, and (4) Woods County lineaments.

arcs. An additional 19 percent are oriented within 5° of those arcs. An average of 49 percent of the total lineaments observed on the band-7 scenes are oriented within these preferred arcs. An additional 25.5 percent are oriented within 5° of those arcs.

Shoup selected four high-confidence lineaments or lineament systems for detailed investigation. He named these the (1) Trans-Oklahoma lineament, (2) El Reno lineament, (3) Oklahoma-Louisiana lineament, and (4) Woods County lineament swarm (fig. 2). Of these four, two--the Trans-Oklahoma lineament and the El Reno lineament--occur within the Nemaha Uplift study area. These two lineaments are discussed in some detail.

Trans-Oklahoma Lineament.--The Trans-Oklahoma lineament is 120 miles (193 km) long and extends from the Canadian River, T. 18 N., R. 16 W., in Dewey County, through Blaine, Major, Garfield, and Noble Counties, terminating along the Arkansas River, T. 24 N., R. 4 E., in Osage County. The expression of this lineament varies from image to image and is most readily identified on the March band-5 image, on which it is a composite lineament. On this image it consists of a total boundary except in Noble County, where it is composed of straight segments of Red Rock Creek and the Arkansas River.

On the March band-7 image, its expression is more subtle. It is recognizable as a tonal boundary west of the Cimarron River and as straight stream segments in Noble County. Its expression is difficult to distinguish between.

On the July band-5 image the lineament consists of a tonal boundary from the Canadian River to Enid. While subtle, its expression is tonal from Enid to the Arkansas River, where it is coincident with a straight segment of that river. On this image, Red Rock Creek is not recognizable as a stream segment.

The lineament on the July band-7 image is expressed as a tonal boundary from Canton Reservoir to the Cimarron River. While subtle, the lineament's expression varies from tonal to a tonal boundary between the Cimarron River and the Arkansas River.

Field reconnaissance in Dewey County indicates that the expression of the lineament is due to a shallow, linear depression 9 to 45 m wide. This depression is marked by increased vegetation growth and tree cover; at several localities it is associated with natural ponds and marsh areas. The cause of this depression is unresolved, but it may be related to the collapse of solution cavities within the Permian evaporite sequence in the subsurface. It is doubtful that this depression represents a fault zone, as the rocks are similar on either side.

At several places in Dewey County, fracture orientations were measured at N. 40-50° W., N. 40° E., N. 80° W., and N. 70° E. In Garfield County, however, most fractures were oriented north-south, east-west, N. 20° E., N. 50° W., and N. 60-70° E. While well developed at most locations, the N. 70° E. fracture set appears to be superimposed on a regional systematic fracture system.

Structure-contour maps were prepared of the top of the Viola Formation (Ordovician) and the top of the Brownville Limestone (Upper Pennsylvanian) in the vicinity of Enid, Oklahoma to determine if there is a relationship between the surface expression of the lineament and subsurface structure. A gentle west-southwestard-plunging anticinal feature appears to coincide approximately with the Landsat lineament. This feature is discernible on both the Viola and Brownville structure-contour maps; however, on the Brownville map it is more subtle.

Six cross sections were constructed across the lineament to determine what relationship, if any, exists between the lineament and folding. The cross sections were keyed to the tops of the following units, ranging from Pennsylvanian to Ordovician: Checkerboard Limestone, Big Lime, Verdigris Limestone, Pink Lime, Inola Limestone, Woodford Shale, and Sylvan Shale. These units were selected because they commonly are reported on scout tickets. Four of the cross sections are in Garfield County, and the remaining two are in Major and Noble Counties.

The cross-section data suggest that the Trans-Oklahoma lineament is closely associated with a gentle fold that varies along its length from a gentle anticline to a slight flexure and is present in the interval from the Viola Limestone to the Brownville Limestone, although it may continue to the surface. Although the lineament is in the vicinity of this fold, its trace rarely coincides with the fold axis. It appears that vertical joints striking N. 70° E. are associated with this fold. In Garfield County, these joints are superimposed on the regional systematic fracture system. The orientations of this fold and its associated joints, and the involvement of the Brownville Limestone, suggest a mild post-Gearyan compression from the south-southeast. Because the lineament trace does not coincide with the fold axis, because the predominant expression of the lineament is a tonal boundary, and because the depression observed in Dewey County is associated with natural ponds and marshes, Shoup (1980) concluded that the Trans-Oklahoma lineament was not caused directly by the fold itself but by slight changes in soil moisture and ground water along joint surfaces.

<u>El Reno Lineament</u>.--The El Reno lineament trends N. 60° E. and is approximately 40 miles (63 km) long. The lineament extends from the Canadian River, sec. 4,

T. 11 N., R. 9 W., in Canadian County, through El Reno and Piedmont, into Oklahoma County, where it terminates near the West Edmond Oil Field at the Nemaha Ridge, sec. 12, T. 15 N., R. 4 W.

The lineament is most readily identified on the March band-5 image, where it is a composite lineament consisting of a tonal boundary from the Canadian River to El Reno and a tonal stripe from El Reno to the Nemaha Ridge. The lineament's expression is similar on the March band-7 image, although it is more subtle from the Canadian River to El Reno. Consisting primarily of a tonal stripe, the lineament is subtle and difficult to identify on both the July band-5 and band-7 images. Its expression was best observed on the line enhancements for both of these images.

Aerial-photo analysis of this region indicated, at several places, that stream and stream tributaries correspond to the trace of the lineament. Most notable of these streams is a part of Deer Creek, which flows along the lineament trace for approximately 3 miles (5 km) slightly south and west of Piedmont. Although the lineament's correspondence to stream segments does not offer an explanation as to the cause of the lineament, it does explain why the lineament is expressed on Landsat scenes.

The geologic map for eastern Canadian County (Bingham and Moore, 1975, sheet 1) shows that along the trace of the lineament the formation contacts demonstrate abrupt bends. These bends, while controlled in part by topography and drainage, may indicate some offset along a previously undefined fault. Therefore, it was decided to study the subsurface structure in this area.

Viola Formation and Big Lime (Oswego) structure-contour maps were prepared for parts of Canadian, Oklahoma, and Logan Counties. The top of the Viola ranges in elevation from -5,300 feet (-1617 m) in T. 15 N., R. 4 W., to -11,300 feet (-3447 m) in T. 12 N., R. 8 W. The dip is fairly consistent at 250 feet per mile (47 m/km), and the strike throught the area is N. 30° W. The structure map for the Viola reveals several fault trends. Two of the four faults coincide closely with the trace of the lineament. One fault is 14 miles (23 km) long and extends from sec. 36, T. 14 N., R. 6 W., to sec. 1, T. 14 N., R. 4 W. The orientation changes from N. 70° E. to N. 62° E. in sec. 26, T. 14 N., R. 5 W. The offset ranges from 50 feet (15 m) to 300 feet (92 m) and is down to the northwest. A second fault, approximately 12 miles (19 km) long, extends from sec. 12, T. 12 N., R. 8 W., to sec. 14, T. 13 N., R. 6 W.

The Big Lime (Oswego) ranges in elevation from -4,500 feet (-1373 m) in T. 15 N., R. 4 W., to -8,000 feet (-2440 m) below sea level in T. 12 N., R. 8 W. The dip, which ranges from 100 to 150 feet/mile (19 to 28 m/km), is toward the southwest, and the strike throughout the area is generally N. 30° W.

The Big Lime is not as complexly faulted as the Viola Formation. Two fault zones in the Big Lime coincide closely with the lineament trace. One fault has a N. 62° E. orientation and extends from sec. 9, T. 14 N., R. 4 W., to sec. 36, T. 15 N., R. 4 W. This fault, which corresponds to a fault in the Viola, is down to the northwest and has an offset of approximately 150 feet (46 km). A second fault, 15 miles (24 km) long, has a N. 45° E. orientation and extends from sec. 33, T. 12 N., R. 8 W., to sec. 4, T. 13 N., R. 6 W. The offset varies from 50 to 150 feet (15 to 46 m) and is down to the southwest.

Segments of the El Reno lineament apparently coincide with subsurface fault zones. Fault complexity increases with depth and more than likely involves basement rocks. The offset along individual faults that make up this zone varies from 50 to 600 feet (15 to 183 m), with the amount of offset generally increasing with depth.

Some evidence suggests that strike-slip displacement has occurred along the fault zone. The Nemaha-Uplift structure is offset approximately 1 1/2 miles (2.4 km) in a right-lateral sense along the trace of the lineament. While dip-slip movement can account for the apparent right-lateral displacement, the change in the downthrown nature of one of the faults suggests that some strike-slip displacement has occurred. Regardless of the nature of this fault zone, there appears to be a strong relationship of faulting in the subsurface to the El Reno lineament.

Discussion.--The area that embraces the Nemaha Uplift project, essentially east of 98° longitude (see figure 1), contains approximately 90 linear features derived from Landsat imagery. Of these, eight are high confident, 16 are confident, and 66 are low confident. One of the goals of the lineament-analysis project was to determine what, if any, relationship exists between known structural features, such as those identified by subsurface analysis (Luza and Lawson, 1980), and the linear features. Many lineaments recognizable on Landsat images cannot be recognized on aerial photographs or by ground-truth surveys. While the expression of lineaments is often assumed to be fault related, lineaments can be caused by other natural features both geologic and nongeologic.

Shoup (1980) reasoned that lineaments caused by geologic features can be expected to remain consistent through some reasonable time interval. Therefore, lineaments recognizable on several images acquired from various seasons have a high probability of being geologically related. Shoup concentrated his detailed studies on four high-confident lineaments and found that these features could be related indeed to faults, folds, and (or) joint patterns. Unfortunately, most of the remaining linear features do not correspond to known major structural patterns in this region. Perhaps detailed investigations can resolve the causes for the remaining lineaments.

Another aspect of this investigation was to ascertain whether or not there is a correlation between mapped linear features and earthquake epicenters in the Nemaha Uplift region. Most earthquakes in this region occur in a zone 40 km wide and 145 km long that extends northeastward from El Reno, Canadian County, toward Perry, Noble County. Most of the earthquakes that define this zone have occurred in Canadian County, so that the southern end of this trend appears to be more active than the middle and northern parts. Thus some correlation of Shoup's El Reno lineament with the earthquake-epicenter data in Canadian County is apparent. The trend of the El Reno-Perry earthquake zone is N. 40° E., whereas the trend of the El Reno lineament is N. 65° E. Several of Shoup's confident and low-confident lineaments have northeast-southwest orientations that plot near or within the El Reno-Perry zone. Perhaps this association is coincidental, or maybe these linear features reflect structural features yet undefined.

GRAVITY AND MAGNETIC STUDIES

In 1978, a program was initiated to collect detailed gravity and magnetic information in the Nemaha Uplift project area. This study was intended to augment previously published small-scale maps compiled by Jones and Lyons (1964) and Lyons (1964) (see fig. 3 for regional gravity map). It was hoped that more detailed information would give better insight about basement lithologic contrasts as well as deep-seated structures.

The first two investigations were conducted in the vicinity of the Medford and Kingfisher maxima in north-central Oklahoma. Lyons and Jones speculated that these anomalies in Oklahoma are associated with the Midcontinent gravity high and may be indicative of an extension of the Keweenawan rift system into Oklahoma.

Barrett (1980) and Santiago (1979) established 400 gravity and magnetic stations in parts of Kingfisher, Blaine, Major, Kay, Garfield, Grant, and Canadian Counties. Measurements were taken at 3-mile (4.8 km) intervals along north-south lines; and east-west lines were spaced 6 miles (9.6 km) apart. A Worldwide gravimeter and a Geometrics proton precession magnetometer were used to collect the data. Data were corrected for instrumental and diurnal variations and elevation, and a Bouguer gravity-anomaly map (fig. 4) and a total-intensity magnetic-anomaly map were constructed. Two modeling techniques, a Talwani-Ewing type of magnetic-modeling program (Talwani, 1965) and a vertical-prism-styled modeling algorithm for gravity data (Cordell and Henderson, 1968), were used for data interpretation.

The magnetic data were used to check the validity of an earth model constructed from the gravity data. The induced magnetic anomalies attributed

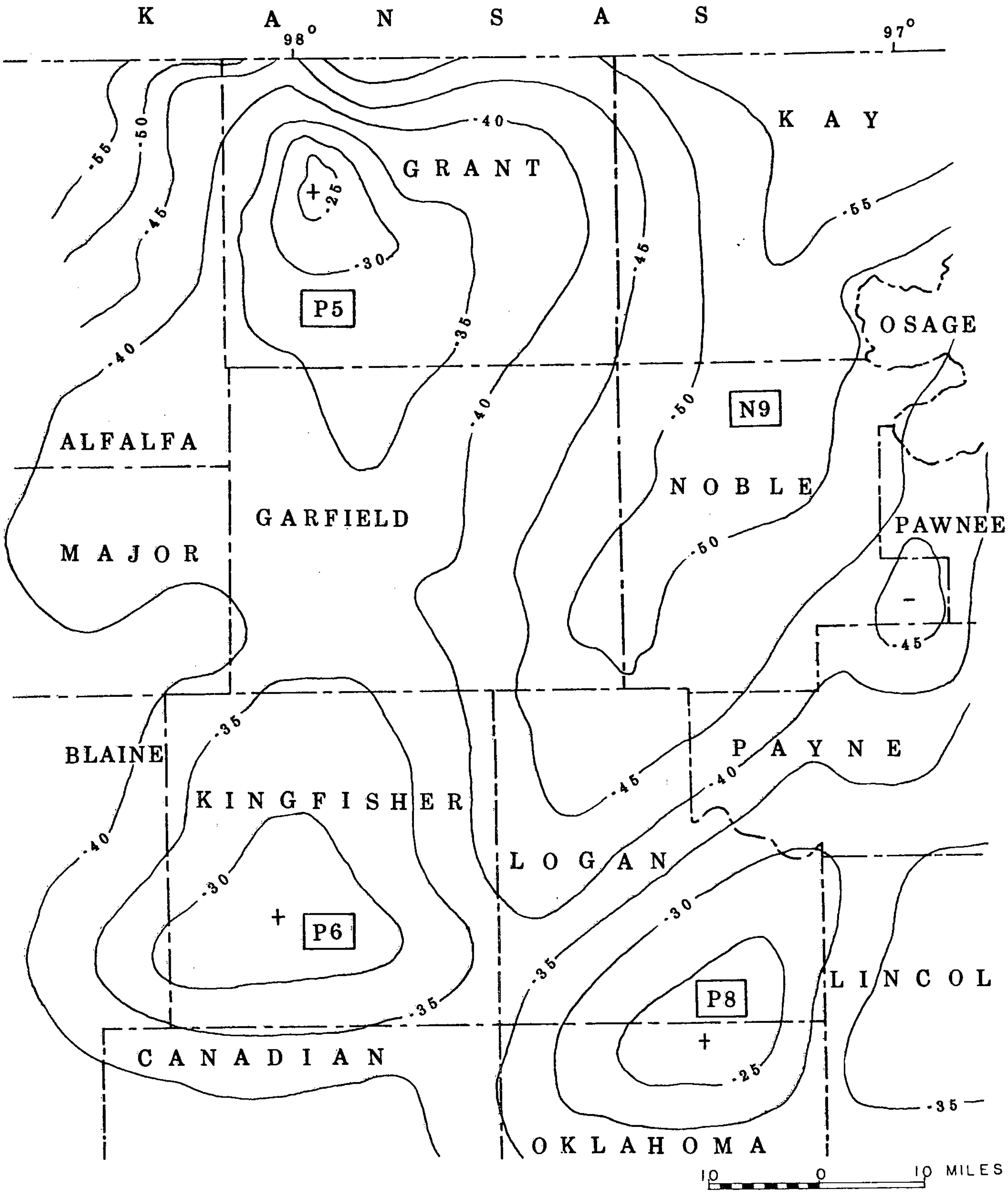

Fig. 3. Gravity anomalies: Medford maximum (P5), Kingfisher maximum (P6), Edmond maximum (P8), and granite ridge mimimum (N9), identified by Lyons (1964). Contour interval, 5 milligals.

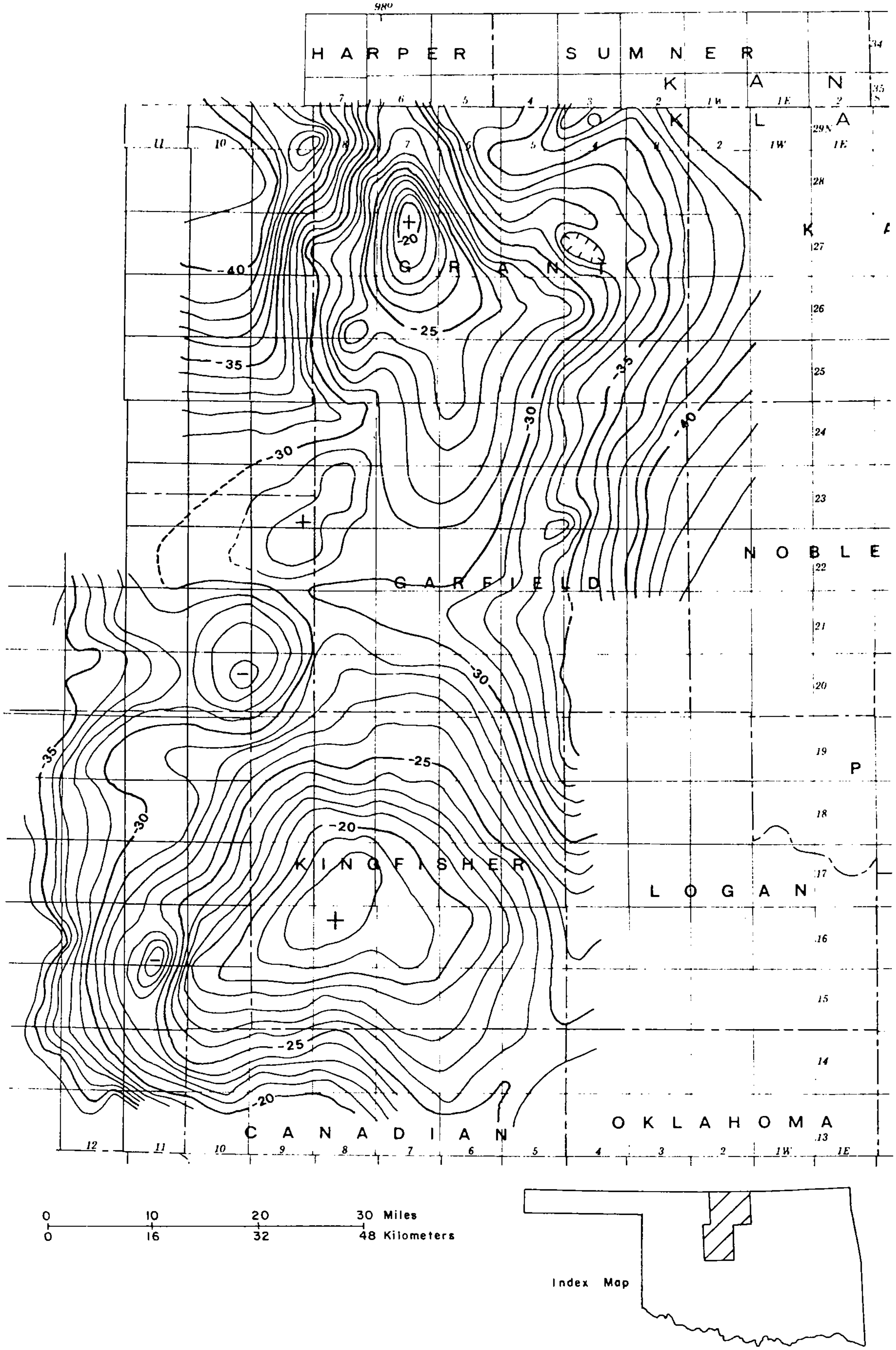

Fig. 4. Bouguer gravity map of north-central Oklahoma. Modified from Barrett (1980) and Santiago (1979). Contour interval 1 milligal.

to the inferred presence of the set of geologic bodies deduced from the gravity data were calculated for the following cases:

1. Induction with a constant magnetic-susceptibility contrast (.0035 e.m.u.) between the inferred geologic bodies and the surrounding "host" rock.

2. Induction with variable magnetic-susceptibility contrasts between the inferred geologic bodies and the surrounding "host" rock.

3. Induction with a variable magnetic-field vector (derived from the vector addition of a variable-magnitude, residual, thermo-remanent magnetic vector, and the Earth's present magnetic vector) and a constant magnetic-susceptibility contrast (.0035 e.m.u.) between the inferred geologic bodies and the surrounding "host" rock.

The calculated magnetic data were compared to the observed magnetic data. Adjustments were made in the magnetic-modeling parameters (applied to the inferred geologic bodies deduced from the gravity data) to bring the observed/calculated magnetic data into closer agreement. Once the desired tolerance was achieved, the magnetic-modeling parameters were reviewed. The amount of departure in the value of the magnetic-modeling parameters needed to make the calculated magnetic data match the observed magnetic data was taken to be a measure of the validity or accuracy of the Earth model constructed from gravity data.

The causative bodies of the Kingfisher and Medford maxima were modeled with apparent success as a collection of dense dikes with high magnetic susceptibility that intruded into a less dense basement rock of much lower magnetic susceptibility. These dikes seem to be related to the late Precambrian (Keweenawan) rift that is presumed to be the causative feature of the Midcontinent geophysical anomaly.

The gravity and magnetic anomalies calculated from the Barrett (1980) and Santiago (1979) geologic models correlate very 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 a 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.

AEROMAGNETIC STUDY

Introduction

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, Borehole Exploration, in Tulsa. These data were part of the aerial radiometric survey conducted for the Enid Quadrangle by Texas Instruments, Inc. (Open-File Report GJBX-100 [78]), and for the Oklahoma City Quadrangle by Geodata International, Inc. (Open-File Report GJBX-34 [76]). The map was constructed in order to assist in the interpretation of basement-rock lithologies and structure. These data supplement earlier work by Jones and Lyons (1964).

In the past, some older techniques relied on fewer control points for magnetic-data acquisition. The NURE magnetic information substantially increases the magnetic-data base for north-central Oklahoma. After processing the magnetic data, editing the displayed profiles, removing bad data, and smoothing and generating map grids, a contour-mapping package called SACM was used to make an accurate and detailed map of the area. This type of three-dimensional mapping of magnetic data has significantly improved the interpretation of magnetic data.

Field Magnetic Data Processing

The field data were recorded on a nine-track 800 BPI EBCDIC, fully IBM-compatible tape. All data have fixed-length records of 120 bytes and a block length of 1920 characters amounting to 16 records/block.

The area of study is situated between longitudes 96° to 98° and latitudes 35° to 37°, which is roughly about 112 miles by 137 miles (180 by 220 km).

First, the longitude and latitude coordinates were converted to orthogonal X-Y coordinates with an assumed fixed origin. Second, a grid spacing of 0.5 mile (800 m) along each axis (map scale, 1:250,000) was used to generate a gridded area of 274 rows and 224 columns. Then, using the numerical-approximation program of the SACM, the interpolated values were found at the grid points, which, in turn, were contoured by utilizing the plotter-contouring program in the package. The initial contour interval was 10 gammas, which is too fine for some uses but is better for accurate interpretation. A generalized version of the magnetic map, with a 50-gamma contour interval, is shown in figure 5.

In the course of this processing, an 11-point weighting function was applied to smooth out the unusually noisy data. The sampling rate was also reduced by a factor of 10, and bad data were hand-picked from the displayed profile without damaging the real signals.

Finally, the Enid and Oklahoma City Quadrangles were tied together in the following manner:

1. A constant value was added to all grid points to increase the datum so that the magnetic values more nearly matched.
2. A plot of the grid values for both quadrangles was made.
3. The values were hand contoured.
4. The magnetic values were adjusted to match at the quadrangle boundaries; the new values along with the original-data values for both quadrangles were then machine contoured.

Interpretation

The magnetic data were used to prepare an interpretive map that shows high and low magnetic anomalies, fault patterns, and basement-rock lithologies (fig. 6). Many of the features displayed on the map correspond with the previous known basement structures and lithologies. The following is a more

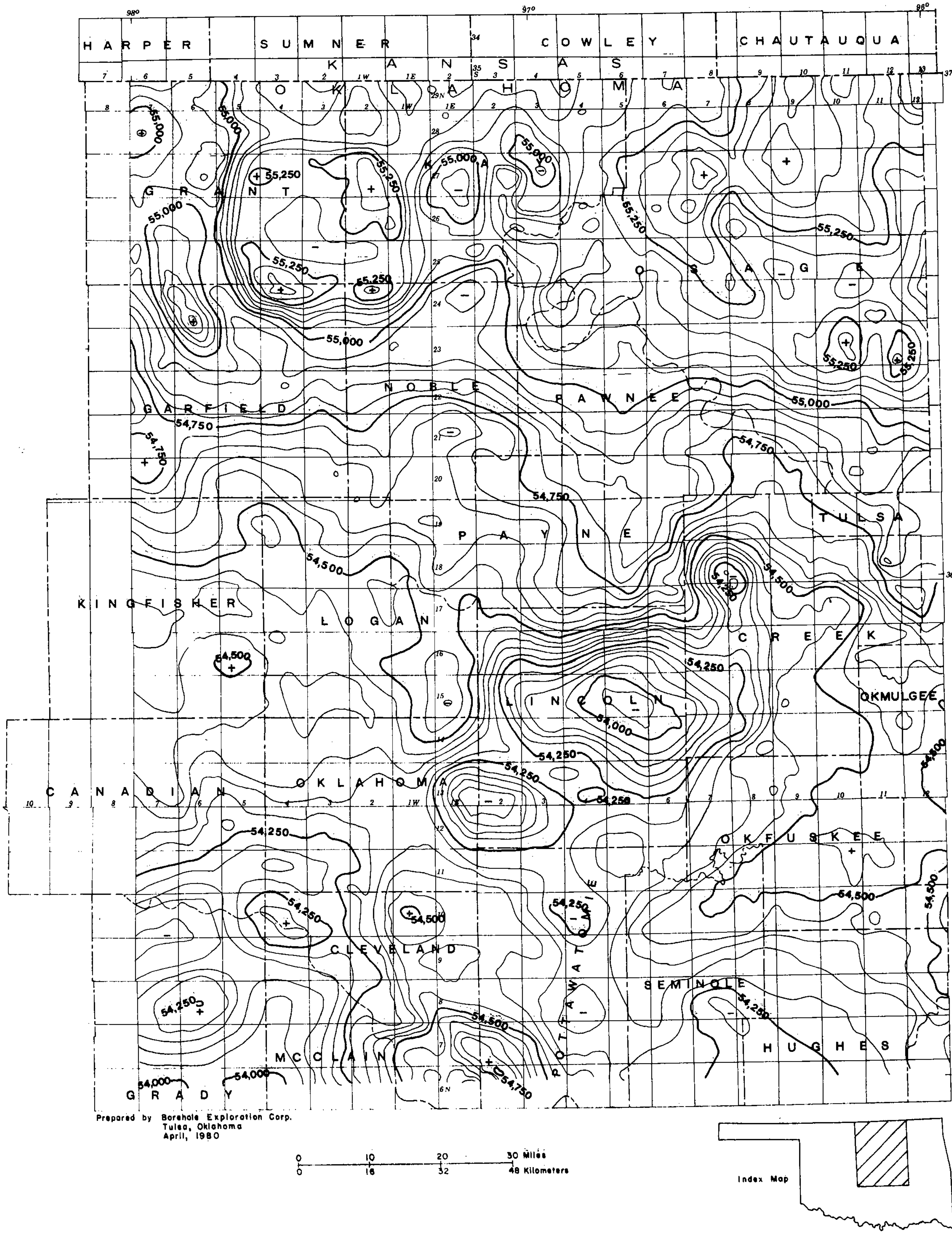

Fig. 5. Generalized total-intensity aeromagnetic map for Enid and Oklahoma City 1° x 2° quadrangles. Contour interval, 50 gammas.

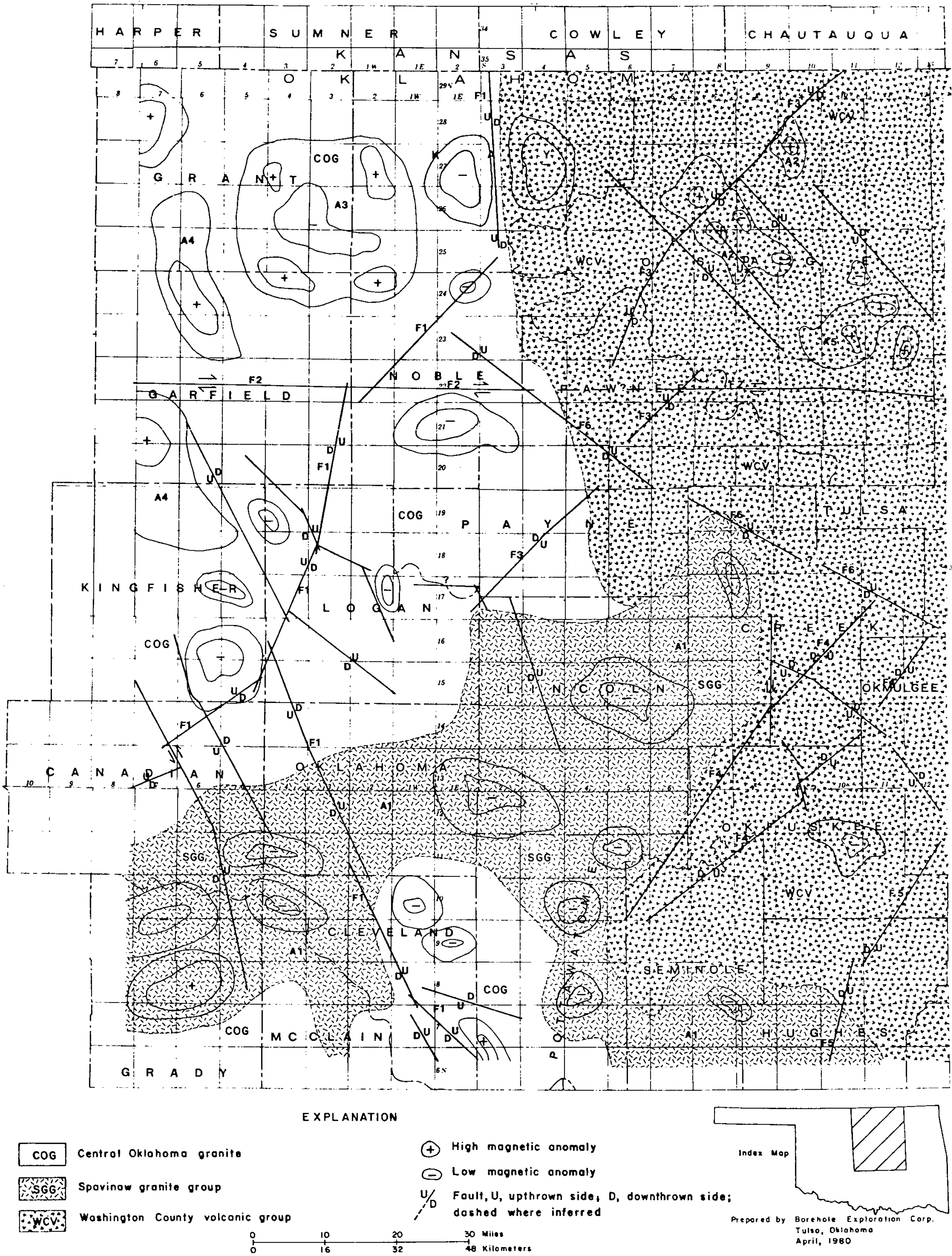

Fig. 6. Interpretive map showing high and low magnetic anomalies, fault patterns, and basement-rock lithologies.

specific discussion of the individual magnetic anomalies and faults displayed on the map and identified by symbols.

A1. Basement lithologic boundaries are revealed as regional magnetic gradients. Three major lithologic boundaries--the central Oklahoma Granite, the Spavinaw Granite Group, and the Washington County Volcanic Group--are present within the mapped area. The most noticeable magnetic gradient reflects the low-magnetic Spavinaw Granite Group. This minimum feature is dominated by low- to non-magnetic rocks trending in a northeast-southwest direction. The anomaly is due mainly to a definite lithological change from the Central Oklahoma Granite to the Spavinaw Granite Group, with some metamorphics probably present. The presence of metamorphic rocks may explain the low magnetic values of the area, which range from 53,900 to 54,300 gammas.

A2. This is a region of numerous high magnetic anomalies (55,200 to 55,400 gammas), trending northwest-southeast. These features, called the Tulsa Mountains, form structural highs on the Precambrian basement surface. The sharp, local topographic highs on the basement surface in this are possibly responsible for the hundreds of overlying drape structures in which some oil accumulations in Osage and Tulsa Counties are found.

A3. The Lamont Ring Complex is a circular magnetic anomaly, 25-30 miles (40-48 km) in diameter. It has a regional magnetic intensity of about 250 gammas and a total magnetic value of

55,200-55,300 gammas. Previous explanations of this well-known anomaly include Precambrian meteorite impact and (or) shield volcano. After detailed study, neither explanation seems acceptable. Another possible explanation for this feature, based on aeromagnetic interpretation and basement geology, is that it may be a ring complex. Silicate rocks, trachytes, and amphibole-granites are typical of granite ring complexes that occur in the St. Francois Mountains of Missouri (Kisvarsanyi, 1980).

A4. This magnetic high is the southward extension of the Greenleaf anomaly of Kansas, which is part of the Midcontinent gravity and magnetic anomaly of the Lake Superior Graben. This continental feature has been interpreted to be a rift filled with igneous rocks high in magnetic susceptibility. The adjacent Lamont Ring Complex is probably tectonically related to the Greenleaf anomaly as both the cause of the rifting and as the source of the igneous rocks filling this rift. This anomaly has been separated by a right-lateral fault with approximately 12 miles (19 km) of displacement. This particular fault is discussed later in item F2.

A5. This is the Osage Island maximum, which is due to a structural and lithologic change. Structurally, this area forms part of the Tulsa Mountain group as described in item A2. The associated change in lithology is from a rhyolitic flow to a microgranite emplacement. The approximate shape of this intrusion, as defined by well data, closely approximates the magnetic anomaly. The area is known to have stood as an island during Early Mississippian time, because the microgranite emplacement is more resistive to erosion.

F1. A major structural feature in the area is the Nemaha Fault (Ridge), a series of northeast- to north-south-trending faults extending northward from central Oklahoma through Kansas into southeastern Nebraska. The Nemaha Ridge consists of a number of small crustal blocks that were uplifted and eroded in Late Mississippian and Early Pennsylvanian time. Associated with the uplift are fault blocks that were rotated and moved laterally as in wrench-fault tectonics. As defined by magnetics, the Nemaha Fault complex is predominantly north-south; however, the fault-throw direction reverses throughout its extent, which is typical of the Nemaha Uplift. Several major faults intersect the Nemaha Fault between El Reno and Oklahoma City, and one fault offsets the Nemaha Fault in a left-lateral sense east of El Reno.

F2. A major right-lateral fault, extending through Garfield, Noble, and Pawnee Counties, is inferred. Strike-slip movement of about 10-12 miles (16-19 km) in an east-west direction is possible. The fault appears to be Late Pennsylvanian in age, since it displaces the Early Pennsylvanian Nemaha Fault. Additional evidence for this previously unknown fault is the offset of the Greenleaf anomaly (A4) and the offset of a series of minima in Noble County. Specific evidence for this fault is lacking in Pawnee County.

F3. The Osage Fault strikes in a northeasterly direction from Payne County through Pawnee and Osage Counties into southern Kansas. The major downthrow of the fault is to the southeast, except in Payne County, where it is to the northwest. The fault appears to define a lithologic contact between metarhyolite to the north and porphyritic rhyolite to the south, with the latter being the downthrown side. This fault is readily observed on the total-field magnetic map.

F4. This is a series of northeast-trending normal faults that include the well-known Cushing Fault. Most of these faults are Precambrian in age, as evidenced by the absence of faulting in the younger sedimentary rocks. The throw directions for these faults are indicated on the anomaly map. Two major faults, a strike-slip and a normal fault, intersect the fault series in a northwesterly direction. Separation along the fault is approximately 5 miles (8 km).

F5. Parallel to and southeast of the F4 fault series lies the Hughes County Fault zone. The northward extension of this fault is clearly defined by well-log data.

F6. This is the northwest-striking Creek County Fault, which appears to define a partial lithologic contact in a discontinuous manner. In northwestern Creek County it separates the downthrown Spavinaw Granite Group from the Washington County Volcanic Group (rhyolite flows).

Concluding Remarks

Interpretation of the Oklahoma City and Enid magnetic data has yielded results consisting of lithologic contacts, magnetic highs and lows, and fault patterns shown by map symbols in figure 6. A summary of the major conclusions that resulted from this study are listed below.

1. Three lithologic units are clearly defined by the change in the magnetic intensity on the aeromagnetic map (fig. 5). They include the Washington County Volcanic Group, the Central Oklahoma Granite, and the Spavinaw Granite Group.

2. The 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).

3. Six major fault zones were identified: the north-south Nemaha, the east-west Garfield-Noble, the southwest-northeast Osage, the southwest-northeast Cushing, and the Hughes County and Creek County fault complexes. These faults are not clearly defined in some areas, however. In these localities their trends and throws have been approximated.

SEISMOLOGICAL STUDIES

Regional Net

Introduction.--The goals and instrumentation of the seismological stations were discussed in the 1977 interim report (Luza and others, 1978). That report indicated that the Oklahoma network of seismograph stations consisted of three distinct parts. One part is the Oklahoma Geophysical Observatory (TUL), which includes seismographs to record both vertical and horizontal ground motion in several frequency passbands. The second consists of three radio-telemetry stations. Each station has a high-frequency vertical seismometer whose signals are telemetered to the Oklahoma Geophysical Observatory in the 216- to 220-MHz radio-frequency band. The third part consists of seven volunteer-operated seismograph stations. Each volunteer station comprises an ink-recording, high-frequency vertical seismograph operated by a volunteer who furnishes his or her own daily services to change records and set the timing system with WWV Bureau of Standards transmissions. The volunteers also furnish a location for the seismometer tank vault and an indoor location for the drum recorder and timing system (in four cases, the volunteers live on State Forestry or State Park property, and the stations were established by permission of the appropriate directors). We will discuss any new station(s) added to the regional seismograph network as well as the present station configuration.

Relocation of Two Volunteer Analog Recording Stations.--On July 23, 1980, Carnasaw Mountain Lookout Tower (CRO) was closed, owing to poor health and waning interest of the volunteer who had operated it for 3 years. Because a southeastern Oklahoma station is critical to locating earthquakes along the northern front of the Ouachita Mountains in Oklahoma, and occasional earthquakes in western Arkansas, another volunteer was sought in the same area.

The new station is located at Cedar Creek (CDO), about 20 km from CRO. Although the site at CDO is slightly noisier than CRO, CDO can be operated at the same magnification as CRO.

On October 31, 1980, Ponca City (PCO) was moved to a new volunteer site 0.5 km from the original site. The volunteer had helped to recruit the new volunteer and had operated the station up to the minute it was moved. The National Earthquake Information Service (NEIS) of the U.S. Geological Survey and the International Seismological Centre (ISC) in Newbury, England do not require a new international abbreviation for station moves where the seismometer is moved less than 1 km. The abbreviation PCO was retained, but the latitude, longitude, and elevation of the new site were placed in our computer file as well as in NEIS and ISC files.

The new site is closer to cultural-noise sources such as a paved road and the city of Ponca City. Therefore, we expected that the new site would be as noisy as the old site, or slightly noisier. However, we were able to double the magnification at the new site. This may indicate that there was an unrecognized electrical-noise problem at the original site.

Table 1 gives locations of all stations except the triggered digital stations. All stations, including those in Kansas, Nebraska, and Iowa, are shown in Figure 7. There are few changes in the qualitative ratings, except that quality and continuity of operation at QMO had dropped to D, a clear indication that the station should be moved soon.

Microearthquake Studies

Equipment Modifications.--In Part III (Luza and Lawson, 1980), substantial modifications to Sprengnether DR-100 were discussed. The modifications were so extensive that the unit has been renamed, by us, DR-100-OK. We note that

Table 1. Oklahoma station locations, operators, and ratings.

Abb	Geographic Name and County	Latitude (Deg. N.)	Longitude (Deg. W)	Elev. (meters)	Volunteer operator or Telemetry RF and AF operating date(s)	Geographic importance to network: At time of installation	Geographic importance to network: In final network configuration	Quality and continuity operation	Ground noise
TUL	Okla. Geophys. Obs. Tulsa County	35.900000	95.792500	256	OGO staff P/J/K/S 611208				
MZO	Mazie Landing (CLOSED) Mayes County	36.131639	95.300139	182	Randy Blackwell 760916-780616	(A)	(D)	(A)	(B)
OLO	Oologah (CLOSED) Rogers County	36.457250	95.710778	196	T/T/C Estes 761128-770807	(A)	(C)	(B)	(D)
GBO	Fort Gibson Cherokee County	35.852583	95.184306	302	217.00 MHz 1020 Hz 790719	B	B	A	A
WLO	SE of Wilson Love County	34.064778	97.369722	284	James L. Steel 770425	A	A	B	C
CRO	Carnasaw Mtn (CLOSED)	34.149917	94.555611	302	Wanda Webb 770517-800723	(A)	(A)	(D)	(A)
ACO	Alabaster Cavern State Park Woodward Co.	36.698556	99.146083	521	L. H. Shepherd 770622	A	A	A	B
PCO	Ponca City Kay County	36.691222	96.978222	325	Sam Sheehan 770705	A	A	A	B
RLO	Rose Lookout Twr. Mayes County	36.167000	95.025194	363	218.0 MHz 1360 Hz 770722	A	A	A	A
QMO	Quartz Mtn. St. Park Greer County	34.892917	99.307056	479	J. Briley 770729	A	A	D	B
MRO	Meridian Logan County	35.835556	97.226528	294	Roy F. Starks 780316	A	A	B	B
SIO	Slick Creek County	35.746333	96.307056	323	219.00 MHz 680 Hz 780712	A	A	A	B
RRO	Red Rock Canyon State Park Caddo County	35.456917	98.358444	482	Bud Turner 780809	A	A	A	C
CDO	Cedar Creek McCurtain Co.	34.190378	94.77254	230	Jim Martin 800801	A	A	B	B

* A. Excellent; very strong reason for every necessary effort to continue operation of station.

B. Good; no reason to move station.

C. Less satisfactory than desired; may consider moving station, though the move will have low priority if only one "C" is noted.

D. Although station is producing useful data, it should be moved or should be temporarily closed whenever part of the equipment is required by a higher rated station.

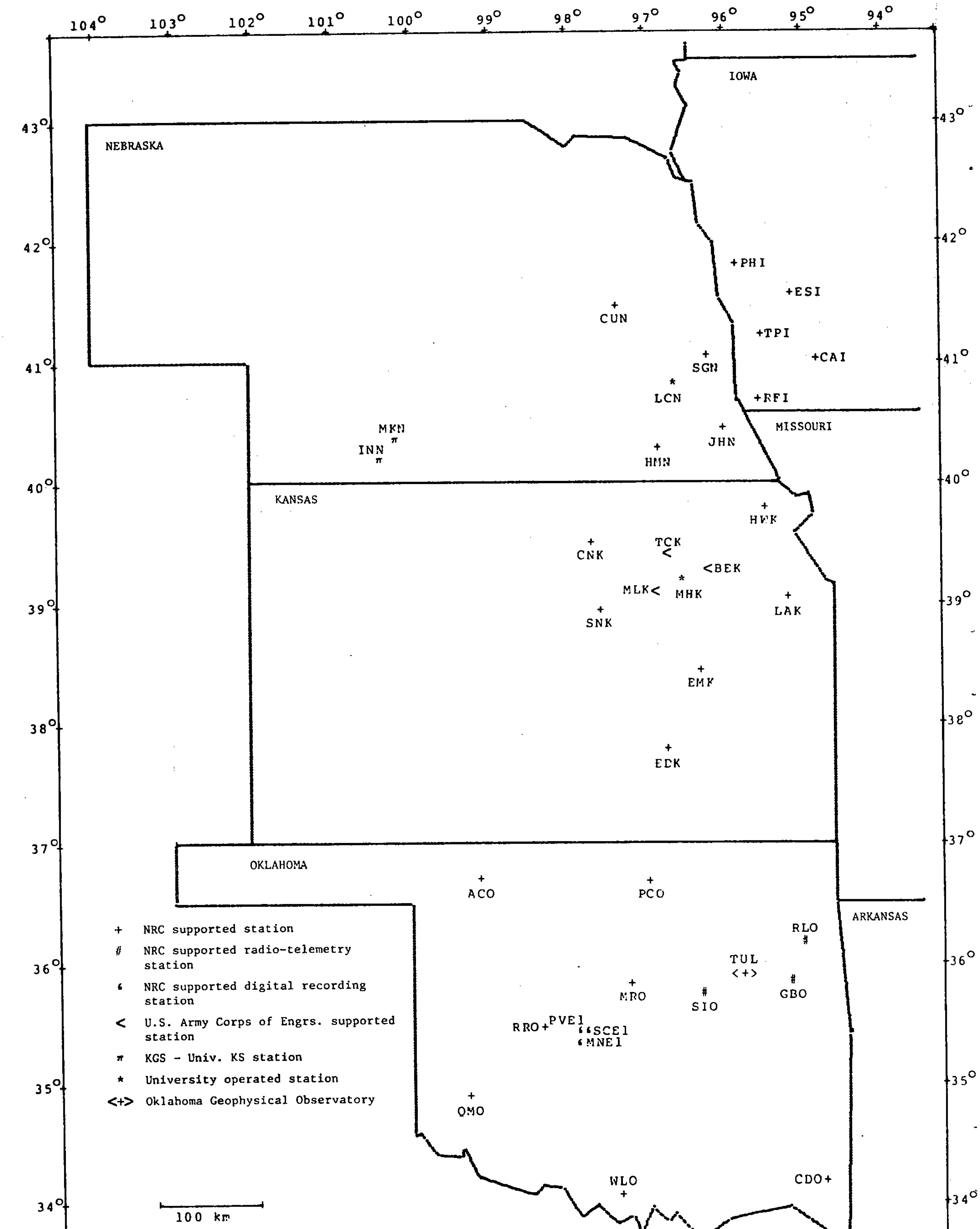

Fig. 7. Seismograph stations operating in Oklahoma, Kansas, Nebraska, and western Iowa, January 1, 1981.

Sprengnether Instrument Co. has now made one of our modifications standard on all units they make (see modification 2, page 47, Luza and Lawson, 1980).

In studying the false-alarm patterns in both noisy and quiet environments, we found that false triggers occurred in clusters of 10 or 20 rather than in an expected Poisson distribution. We assumed this to be caused by "toggling" of the Long Term Average, which is quantized in 20 mV quanta by an Analog-Digital-Analog (A-D-A) device. The A-D-A quantizer was not needed because of modification 2 referred to above. Therefore, we simply disabled the A-D-A converter. Clustered false alarms ceased, and false alarms tended to occur singly in Poisson distribution.

Station Installation.--On December 17, 1980, a triggered digital seismograph was installed at Shell Creek, Canadian County. On December 18, 1980, another triggered digital unit was installed east of Minco, Grady County. A third was installed on December 31 east of Union City, about 1 mile north of Pleasant View Cemetery. These were given four character abbreviations, which have not been entered in the international station lists. The first two letters are a geographic identifier, the third letter an array designation, and the last character number signifying the number of that station in the immediate locale. For example, MNE1 is near Minco (MN), is part of the El Reno array (E), and is the first station installed near Minco (1).

In a typical installation, the DR-100-OK unit is placed in a pump house, where it is well grounded and connected to AC power. An active WWVB antenna is placed on a 2-m galvanized pipe driven into the ground near the pump house. A two-wire shielded cable 60 to 300 m or more in length is run along a fence line, lying on top of the ground (with some short segments buried across gates where farm machinery may pass), to a 4.5-Hz vertical geophone that is buried from 0.1 to 0.3 m deep in alluvium. (There are practically no rock outcrops in the El Reno study area.)

The volunteers are asked to do little more than change tapes weekly and mail the tapes to us. Because each event has a tape header (and trailer) giving the unit serial number and date, we do not even ask the volunteers to label the tapes. However, to identify the origin of the occasional tape with no events, we label the plastic tape box with the station abbreviation when we send supplies of tapes.

The volunteer analog stations have drum recorders in a house where they can be serviced easily on a daily basis. Because the volunteers only have to service the digital units weekly, these units were placed in a well house or any remote building with commercial power, making it easier to get the geophone on one of the most remote spots on the farm. In the El Reno area, even this remoteness does not limit the noise greatly because of the following reasons:

1. Nearly 100% of the rural land is under cultivation.
2. There is a regional "boom" in oil drilling, and there are many producing facilities.
3. No rock occurs near the surface.
4. Nearly 100% of all section lines are roads, with moderate to heavy traffic including large oil tankers and other trucks.

The only excellent (by comparison) site we found was east of Minco, where conditions 2 and 4 listed above did not apply.

The station locations are given in Table 2 and shown in Figure 8.

Table 2. Stations in the El Reno array on December 31, 1980.

Name	Abbreviation	Symbol	Lat °N	Lon °W	Elev.(m)
Shell Creek	SCE1	S	35.438507	97.813971	408
Minco	MNE1	M	35.330972	97.891114	380
Pleasant View	PVE1	P	35.440365	97.896780	417

Figure 8 also shows the distribution of earthquakes located by the Oklahoma network since 1976. The large group in the southwest quadrant appears to be an isolated swarm, and it was not considered in station placement. Two stations are planned north and west of PVE1. It is hoped that the five-station array will define trends well enough to lead to relocation of some of the stations and (or) additional station locations, although with equipment presently available, it will be difficult to support more than five stations in the El Reno array. Two analog stations, RRO and MRO, are near enough to help locate earthquakes as small as mbLg 1.2, while earthquakes of mbLg 1.5 or above are recorded on several other network stations.

Station Operation.--The DR-100-OK recorders digitize the seismic channel and the WWVB time code 100 times per second each. The Short Term Average (one second) and Long Term Average (5 seconds) were set close together to minimize triggers from emergent automobile traffic. The trigger ratio was set at 6dB, but large numbers of false triggers required increasing it to 9dB. This corresponds to a sensitivity of -5dB below a step as defined on page 52 of Luza and Lawson (1980).

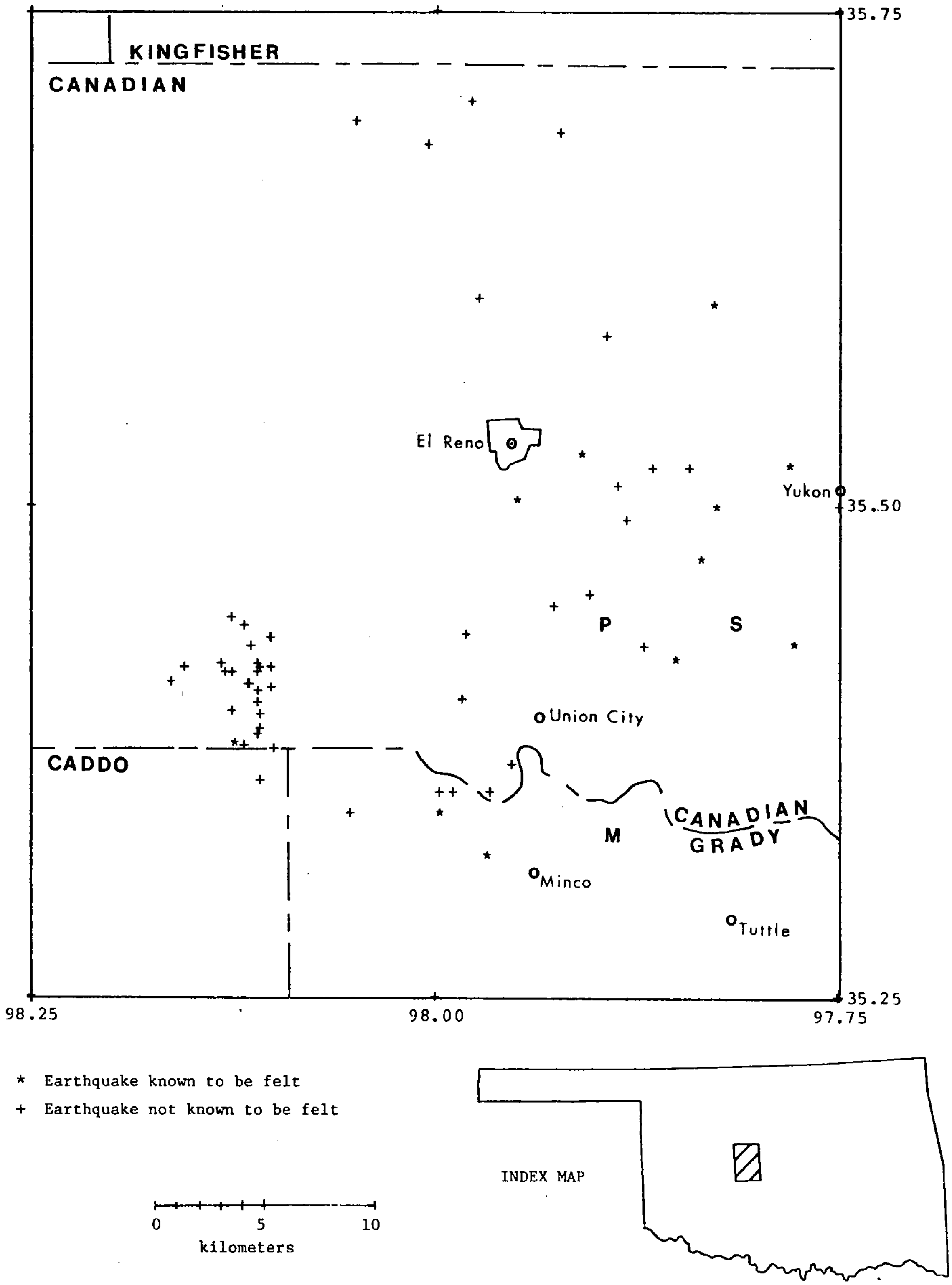

Fig. 8. Stations in the El Reno digital array (P, S, M) on December 31, 1980, with earthquake data for 1977, 1978, 1979, and 1980.

When tapes are received, the data are played back on a two-channel Hewlett-Packard 7402A pressurized ink recorder at 4 mm per second. Events that appear to be earthquakes are played back at 50-mm paper per second. All earthquake times and stations are put in a computer file that searches for coincidences each time the file is updated, using a broad 60-second coincidence window. Until December 31, only two stations were in operation for only 2 weeks, during which no coincidences were found.

Earthquake Distribution.--During 1980, 64 earthquakes were located by the Oklahoma Geophysical Observatory and the Kansas Geological Survey. By state, they were distributed as shown in Table 3. The complete catalog listing of all locations is given in Table 4 and shown in Figure 9. For comparison, Figure 10 shows all earthquakes located from January 1, 1977, through December 31, 1980, a 4-year period.

In 1980, 49 Oklahoma earthquakes were located by the Oklahoma Geophysical Observatory staff. Magnitude values range from a low of 0.9 (mbLg) in Kay County to a high of 3.0 (mgLg) in Canadian County. The listing represents only those earthquakes that could be located by using three or more seismograph records. Six earthquakes were reported felt by people living in the vicinity of an earthquake epicenter. Four felt earthquakes occurred in Love County, and two occurred in Canadian County. The larger of the Canadian County earthquakes (on November 2) was felt MM III-IV in Yukon, II-III in parts of Oklahoma City, IV in Mustang, and III in Bethany and Midwest City.

Table 3. Earthquake distribution by state.

State	Number located by Oklahoma Geophysical Observatory	Number located by Kansas Geological Survey
Oklahoma	49	1
Kansas	-	8
Nebraska	-	2
Missouri	-	2
Texas	2	-
Arkansas	1	-

The position relative to known surface structures for each hypocenter located in Oklahoma is checked against the Tectonic Map of Oklahoma (Arbenz, 1956). If the position is not within 3 km of a surface fault, the hypocenter is then plotted on the Pennsylvanian Map of Oklahoma (Jordan, 1962). If the hypocenter is within 3 km of a fault, as shown on either of these two published maps, the earthquake is presumed to be associated with the fault. The combined inaccuracy of the epicenter and the possible dip of the fault surface could easily allow a 3- or even a 5-km difference. Three earthquakes (March 9, June 15, November 13) were presumed to be associated with known surface faults along the northern front of the Ouachita Mountains. A November 13 earthquake was presumed to be associated with a fault exposed at the surface in Carter County. Thirteen earthquakes in Pontotoc, Garvin, Kay, Jefferson, and Love Counties were assumed to be associated with known pre-Pennsylvanian subsurface faults.

Table 4. Oklahoma Geophysical Observatory regional earthquake catalog, January 1, 1980–December 31, 1980.

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1980 JAN 5	071131.21	OK CANADIAN		1.9	1.7	1.7	35.586	97.894	5.0R	O
1980 JAN12	071256.45	OK GARFIELD		1.7		1.4	36.453	97.642	5.0R	O
1980 FEB 3	004630.05	OK LOVE		2.2	1.9	2.0	33.994	97.463	5.0R	O
1980 FEB 5	043235.45	OK LOVE	3	2.1	2.3	1.9	34.046	97.451	5.0R	O
1980 FEB11	054544.15	KS WASHINGTON				2.1	39.969	97.344	5.0R	K
1980 FEB21	204203.49	TX CARSON	F		2.9		35.292	101.084	5.0R	O
1980 MAR 9	035710.56	OK HASKELL		1.2	1.4	1.4	35.100	95.100	5.0R	O
1980 MAR 9	054549.97	KS CHASE				1.7	38.275	96.757	11.9	K
1980 MAR 9	092243.97	KS CHASE				1.6	38.271	96.730	5.0R	K
1980 MAR17	140231.21	OK MC CLAIN		2.3	2.2	1.9	35.047	97.566	5.0R	O
1980 MAR19	225057.93	OK MC CLAIN		2.4	2.4	2.0	34.980	97.644	5.0R	O
1980 MAR21	090956.41	KS DONAPHIN				1.6	39.918	95.199	5.0R	K
1980 MAR23	074901.56	OK KAY			1.4	1.4	36.655	97.391	5.0R	O
1980 MAR26	101157.32	MO HOLT				1.7	39.175	99.139	17.8	K
1980 MAR26	225658.31	MO HOLT				1.9	39.981	95.165	7.1	K
1980 APR 1	211632.26	OK PONTOTOC		1.9	1.8	1.8	34.726	96.762	5.0R	O
1980 APR 8	191806.93	OK HASKELL		2.1		2.1	35.165	95.301	5.0R	O
1980 APR16	071321.47	KS WASHINGTON				1.6	39.914	97.315	5.0R	K
1980 APR26	142148.50	NE DAWSON				2.3	40.733	99.732	5.0R	K
1980 APR29	195951.18	OK GARVIN		2.0	2.4	1.8	34.578	97.285	5.0R	O
1980 MAY28	040545.65	OK GARFIELD		1.8			36.168	97.602	5.0R	O
1980 MAY30	074402.72	OK ROGER MILLS		3.0	2.6	2.5	35.512	99.390	5.0R	O
1980 JUN 3	214150.31	OK LATIMER		2.3	2.1	1.7	35.000	94.932	5.0R	O
1980 JUN 6	013127.86	OK CANADIAN		2.6	2.3	2.2	35.402	97.983	5.0R	O
1980 JUN 6	031812.45	OK LOGAN		1.5			36.039	97.570	5.0R	O
1980 JUN 8	233334.30	OK LOVE		2.1	1.9	1.7	33.940	97.323	5.0R	O
1980 JUN 9	055042.20	OK LOVE			1.8	1.4	33.940	97.417	5.0R	O
1980 JUN 9	223712.29	TX GRAY	F		3.3	3.1	35.476	100.998	5.0R	O
1980 JUN15	125051.95	OK PITTSBURG				1.2	34.728	95.778	5.0R	O
1980 JUN29	161431.32	KS DOUGLAS				1.8	38.943	95.308	5.0R	K
1980 JUN30	010022.83	KS GEARY				2.5	38.874	96.871	15.4	K
1980 JUL 8	013444.01	OK LOVE		2.3	2.5	2.4	34.002	97.354	5.0R	O
1980 JUL18	142946.88	OK BECKHAM			3.2	2.8	35.180	99.698	5.0R	O
1980 AUG 5	171332.96	OK JEFFERSON				2.2	34.096	97.588	5.0R	O
1980 AUG10	101001.37	OK WOODS				2.1	36.867	98.867	5.0R	K
1980 AUG10	101002.58	OK WOODS		2.3	2.2		36.843	98.871	5.0R	O
1980 AUG13	055011.83	NE STANTON				2.1	41.893	97.100	10.0	K
1980 SEP 7	002233.40	KS CLOUD				1.5	39.589	97.715	8.3	K
1980 SEP 7	015014.23	OK CLEVELAND		1.9		2.2	34.953	97.258	5.0R	O
1980 SEP 7	080620.87	OK PITTSBURG		1.6	1.4	1.8	34.680	95.840	5.0R	O
1980 OCT 4	090220.56	OK PONTOTOC		2.2	1.8	2.1	34.694	96.612	5.0R	O
1980 OCT 8	083305.97	OK MC CLAIN		1.9	1.9	2.1	35.084	97.405	5.0R	O
1980 OCT21	090255.01	OK KAY		1.7	0.9		36.707	97.318	5.0R	O
1980 OCT28	050304.99	OK CLEVELAND		1.7	1.8	1.8	35.225	97.495	5.0R	O
1980 NOV 1	052613.85	OK CANADIAN	3	1.9	2.0	2.0	35.472	97.836	7.5R	O
1980 NOV 2	100049.03	OK CANADIAN	5	3.0	3.0	2.8	35.429	97.777	7.5R	O
1980 NOV 7	004633.07	OK KAY		2.1	1.7	2.0	36.638	97.326	5.0R	O
1980 NOV 7	005011.34	OK KAY		1.7	1.6	1.7	36.716	97.326	5.0R	O
1980 NOV13	002339.10	OK HASKELL		1.5		1.7	35.196	95.235	5.0R	O
1980 NOV13	235548.18	OK CARTER		1.8	1.8	1.8	34.367	97.077	5.0R	O

Table 4. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1980 NOV15	120659.08	OK GARVIN		1.7	1.8	1.7	34.820	97.187	5.0R	O
1980 NOV20	095039.73	OK KINGFISHER		1.5		1.6	35.871	97.733	5.0R	O
1980 NOV21	102553.61	OK GARVIN		1.9	1.9	1.9	34.857	97.359	5.0R	O
1980 NOV22	033410.24	OK ALFALFA		2.3	1.8	2.1	36.527	98.146	10.1	O
1980 NOV22	193502.77	OK OKMULGEE		2.7	2.5	2.7	35.379	95.995	5.0R	O
1980 NOV22	200430.13	OK OKMULGEE		1.8	1.4	1.7	35.356	95.987	5.0R	O
1980 NOV30	234401.99	OK GARVIN		2.3	1.8	2.2	34.795	97.360	5.0R	O
1980 DEC 4	012316.96	OK CARTER	F	1.9	1.8	1.7	34.096	97.401	5.0R	O
1980 DEC 4	234843.22	OK LOVE	F	2.1		2.1	33.942	97.352	5.0R	O
1980 DEC 5	000726.29	OK LOVE	F	2.6	2.4	2.4	33.909	97.284	5.0R	O
1980 DEC 5	095323.98	OK LOVE		2.2	2.0	2.0	34.002	97.323	5.0R	O
1980 DEC17	124945.46	OK GARVIN		2.8	2.9	2.8	34.855	97.464	5.0R	O
1980 DEC21	140555.45	OK MC CLAIN		2.2	2.1	2.2	35.017	97.592	5.0R	O
1980 DEC24	084827.53	AR MONTGOMERY				1.9	34.456	93.889	5.0R	O
1980 DEC30	151752.59	OK MC CLAIN		1.8		1.7	34.953	97.362	5.0R	O

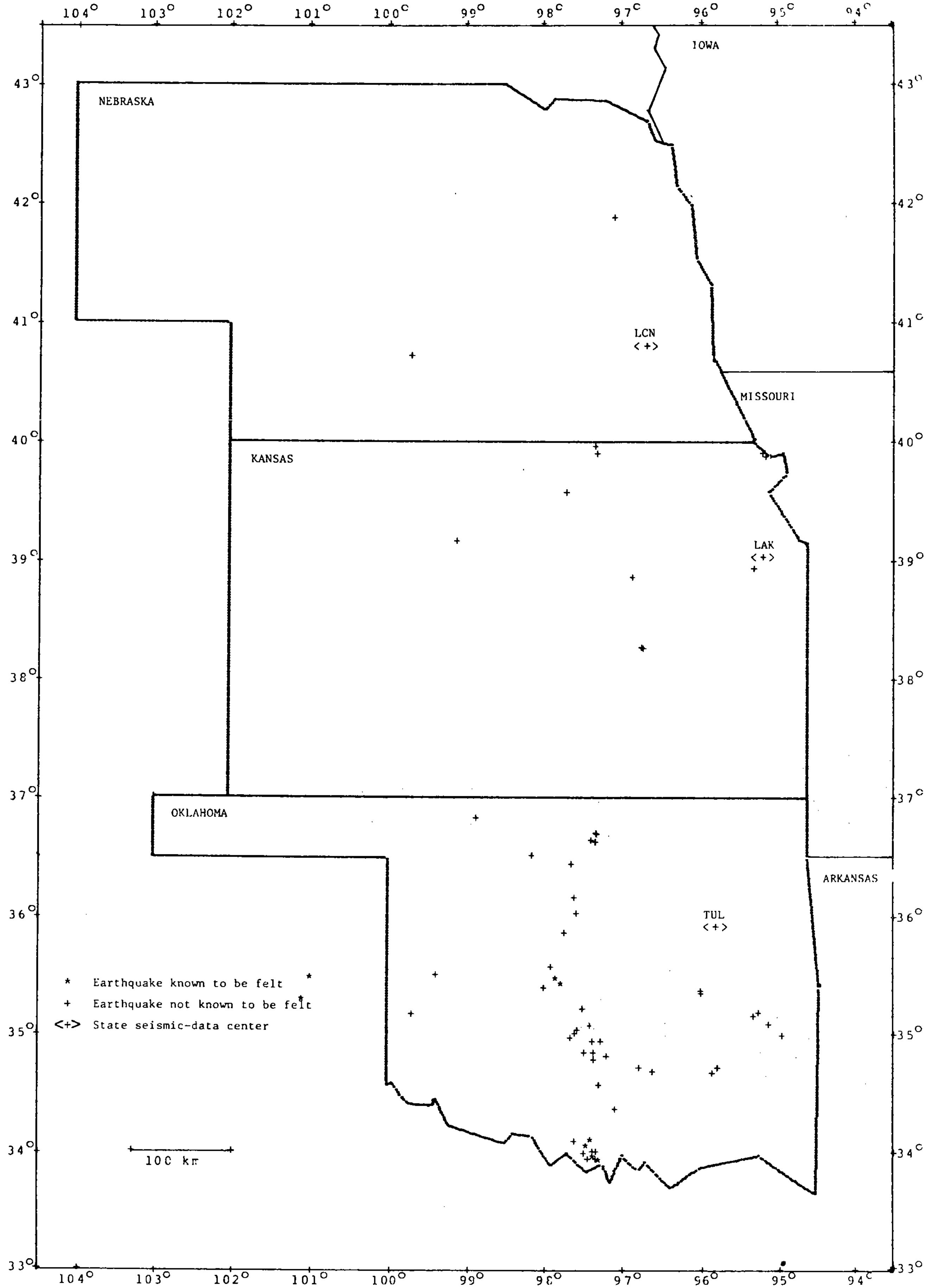

Fig. 9. Earthquake distribution for western Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, January 1 - December 31, 1980.

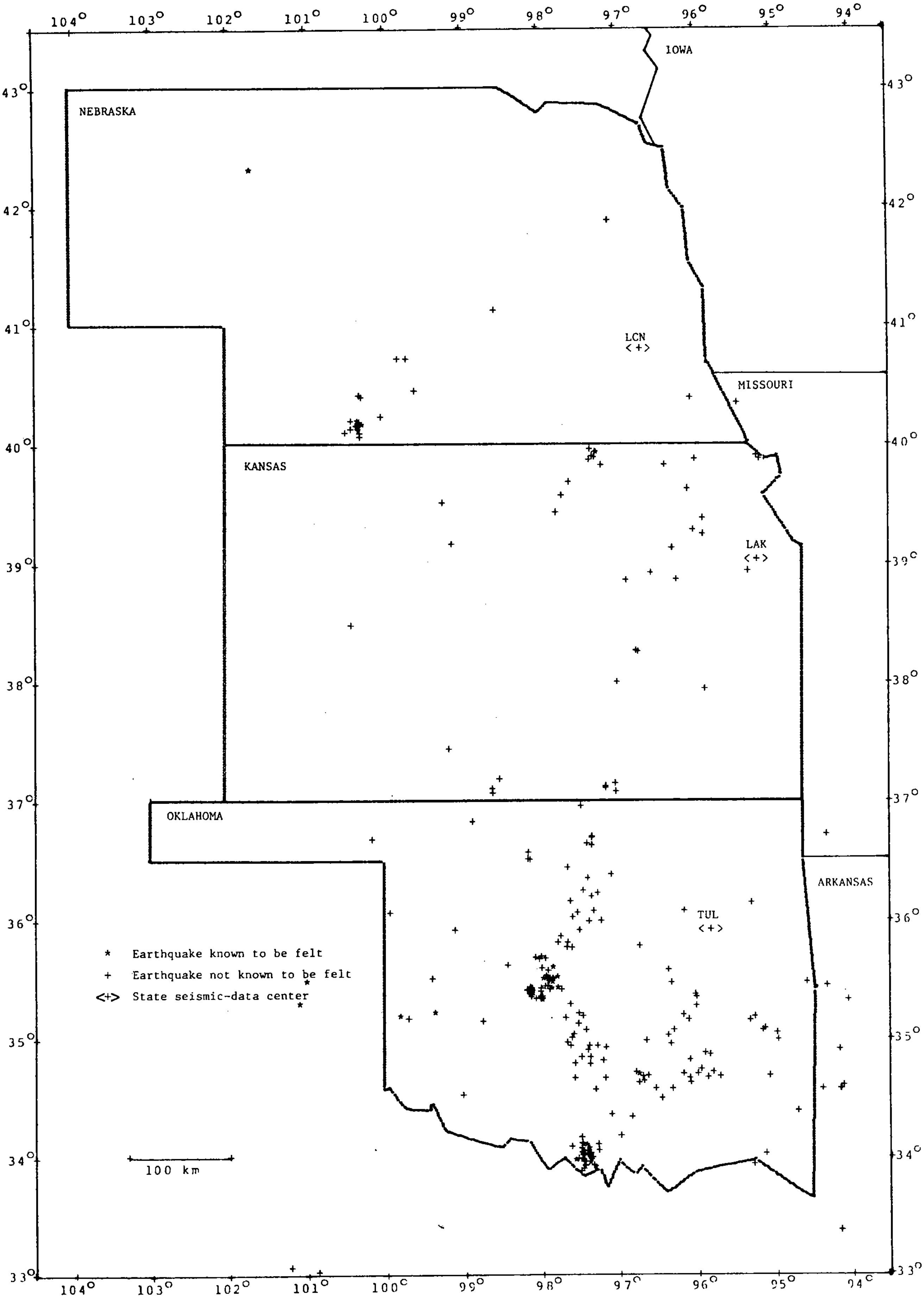

Fig. 10. Earthquake distribution for western Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, January 1, 1977, through December 31, 1980.

The major earthquake trends evident in earlier data appear in the 1980 earthquake data set. Generally, the earthquakes in Canadian County do not appear spatially related to the Nemaha Uplift (fig. 11). However, on March 23, May 28, June 6, and November 7, earthquakes in north-central Oklahoma apparently occurred directly on the Nemaha axis and its associated faults.

McClain County earthquakes on March 17, March 19, October 8, December 21, and December 30 appear to be defining a new seismic trend. When these are considered together with the September 7 and October 28 Cleveland County earthquakes, and with the April 29, November 15, and December 17 Garvin County earthquakes, there is hint of a trend along the McClain County fault zone, a series of en-echelon faults extending southward from Norman toward Pauls Valley in Garvin County.

During 1979 and 1980, the first three earthquakes known in Alfalfa County occurred, defining a minor center surrounded by a seismic territory.

Two counties experienced their first known earthquakes in 1980, Woods County (August 10) and Okmulgee County (mbLg-2.5 earthquake and mbLg-1.4 aftershock on November 22).

Oklahoma Seismic Source Zones

A study of earthquake distribution and intensity values in Oklahoma was used to divide Oklahoma and parts of the adjacent states into six seismic-source zones (Lawson, 1980). These zones, in order of decreasing seismic activity, embrace certain areas herein referred to as central Oklahoma (also referred to as zone 1.1), south-central Oklahoma (zone 1.2), north-central Oklahoma (zone 2.1), southeast Oklahoma (zone 2.2), west-central Oklahoma (zone 2.3), and residual (an area that encompasses all remaining parts

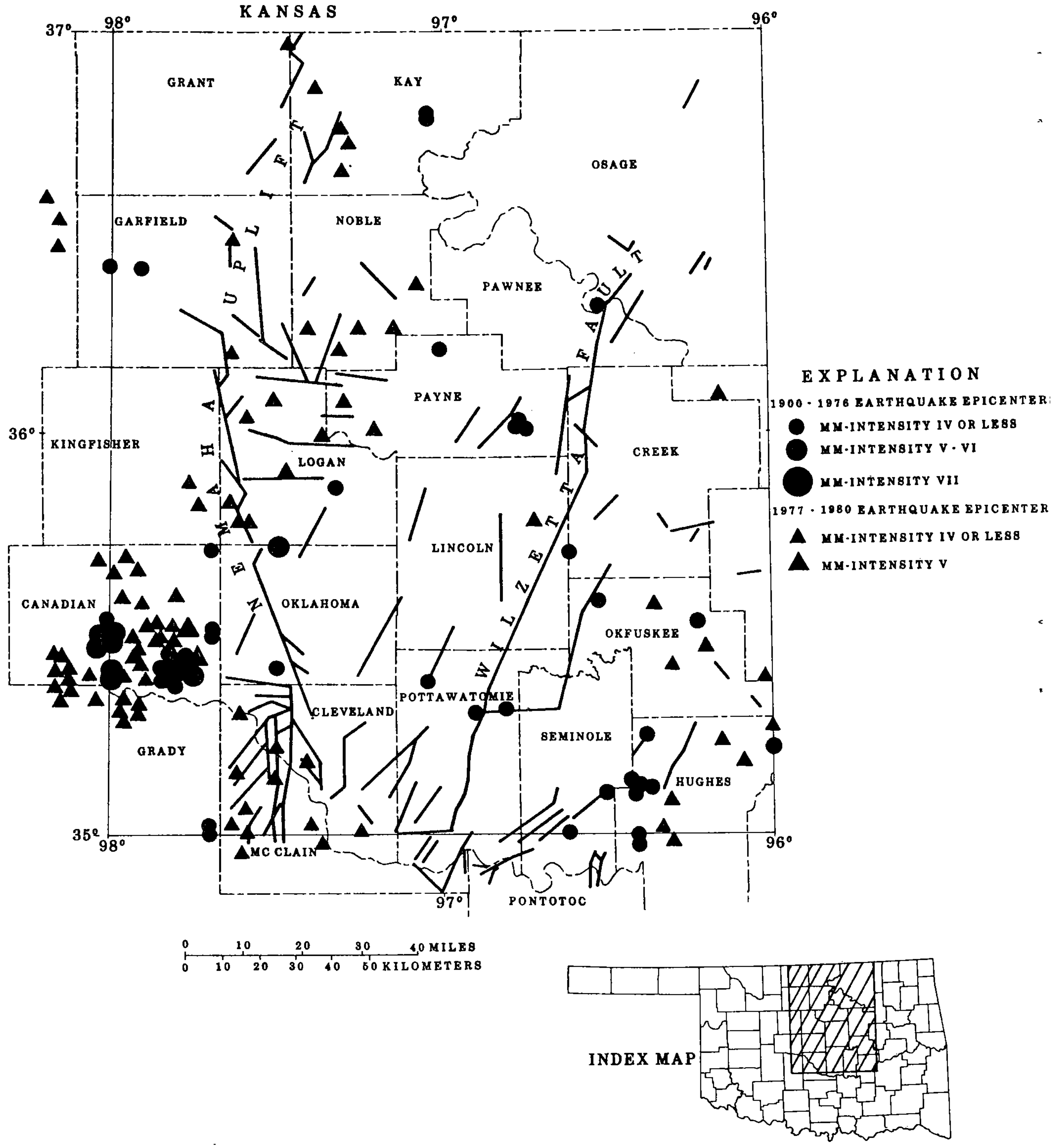

Fig. 11. Distribution of faults that cut pre-Pennsylvanian strata and earthquake epicenters for north-central Oklahoma (Wheeler, 1960; Jordan, 1962; Luza and Lawson, 1980).

of the state, zone 3.1). The first part of the number--1, 2, 3--is a semi-quantitative measure of the seismicity. The second part of the number--to the right of the decimal point--is an identifier.

The six zones, which are shown in Figures 12a and 12b, include some parts of surrounding states. All earthquakes known to have occurred to the end of 1979 are also included. Table 5 gives the descriptive names, zone numbers, areas, and precise boundaries of the zones.

For each zone except 1.2, a magnitude-frequency relationship was developed. These relations are given in Table 6. A discrepancy between historical and recent earthquakes in seismic-source zone 1.2 (south-central Oklahoma) has postponed the development of a magnitude-frequency relationship for that area.

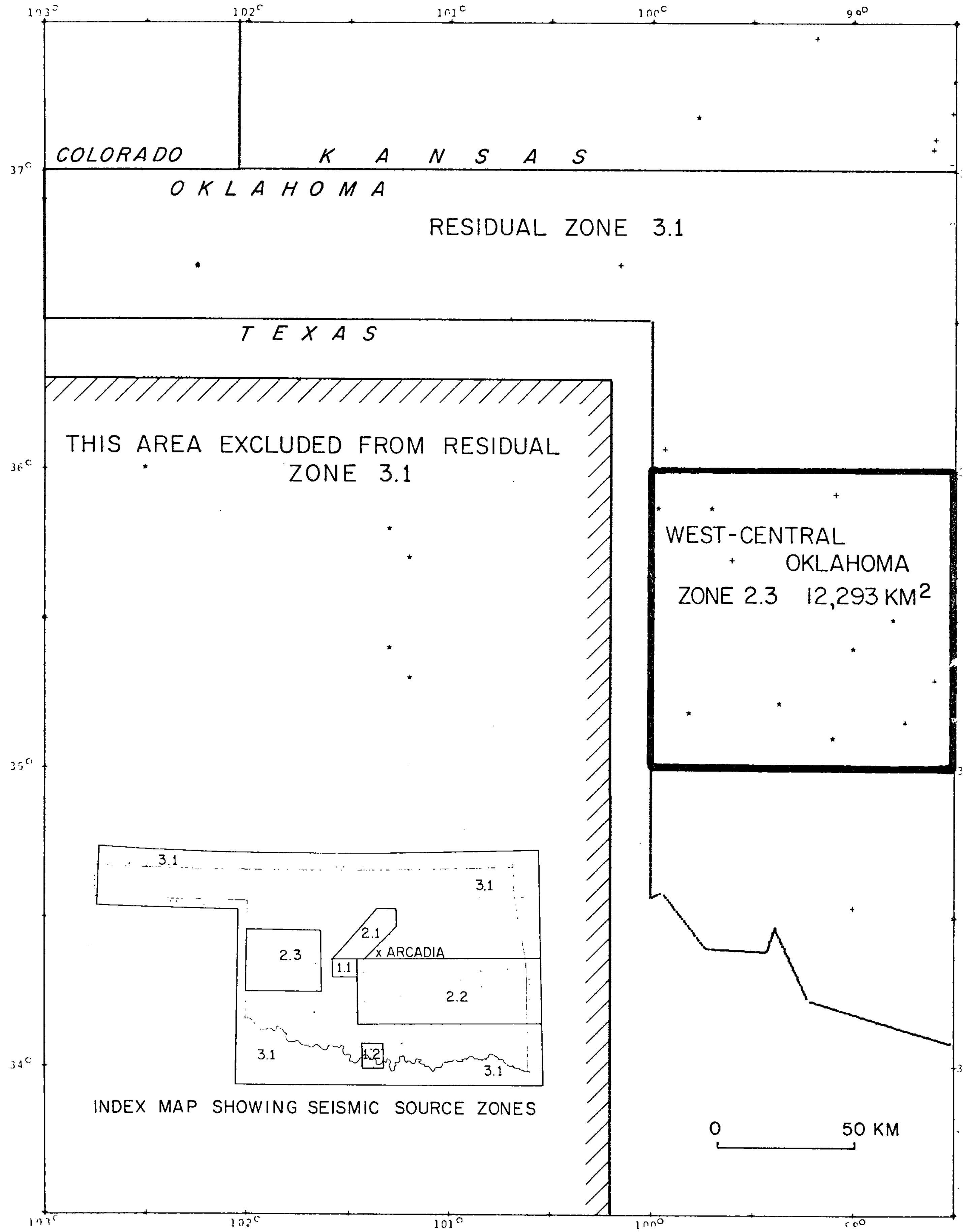

Fig. 12a. Seismic-source zones for western Oklahoma and adjacent states.

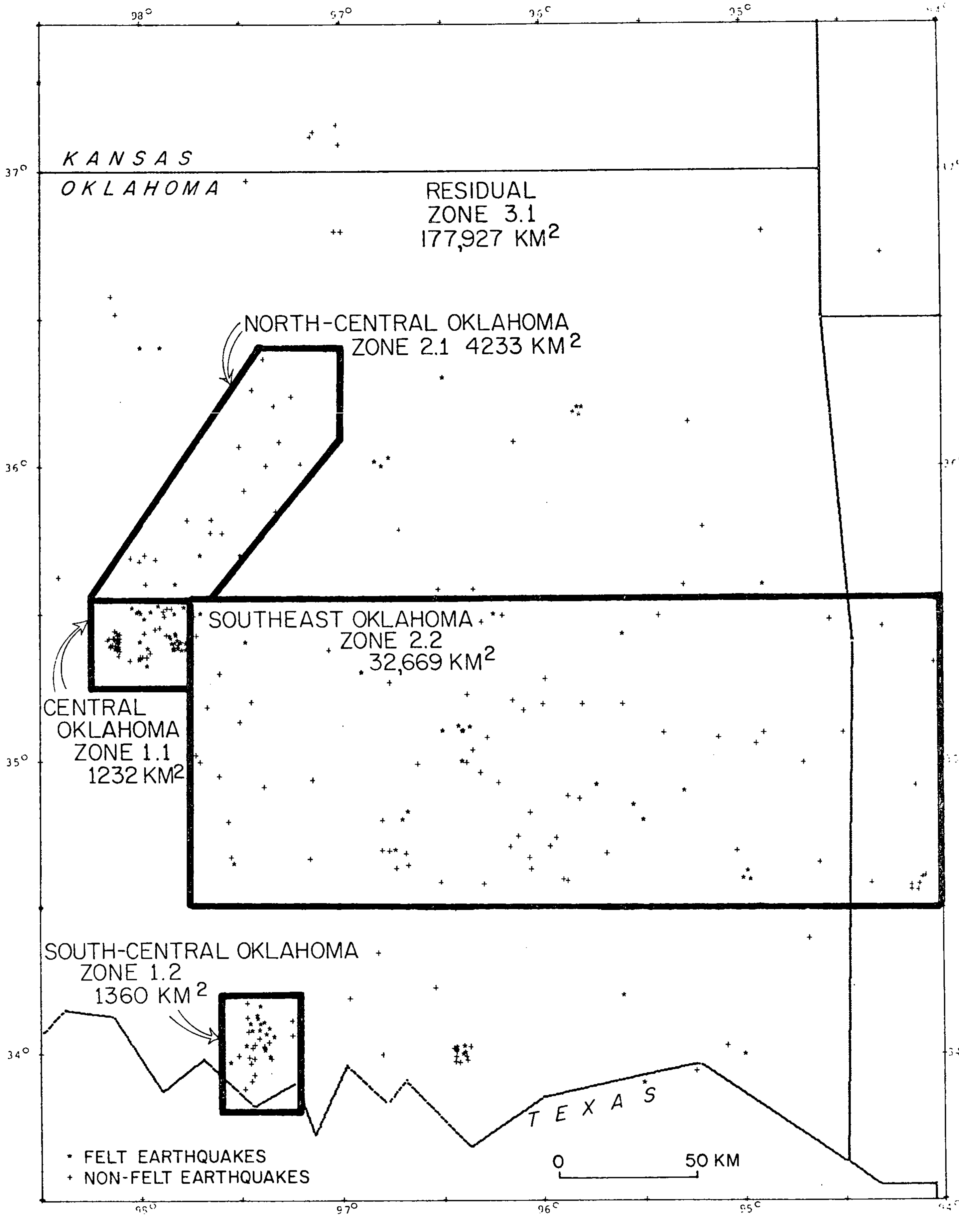

Fig. 12b. Seismic-source zones for eastern Oklahoma and adjacent states.

Table 5. Seismic source zones of Oklahoma and surrounding areas.

Zone name	Zone number	Area (km^2)	Boundaries (Given as latitude and longitude of each straight-line intersection starting at the most north-easterly and proceeding clockwise)
Central Oklahoma	1.1	1,232.4	35.55N 97.75W 35.25N 97.75W 35.25N 98.25W 35.55N 98.25W 35.55N 97.75W
South-central Oklahoma	1.2	1,359.8	34.2 N 97.2 W 33.8 N 97.2 W 33.8 N 97.6 W 34.2 N 97.6 W 34.2 N 97.2 W
North-central Oklahoma	2.1	4,232.8	36.4 N 97.0 W 36.1 N 97.0 W 35.55N 97.65W 35.55N 98.25W 36.4 N 97.4 W 36.4 N 97.0 W
Southeastern Oklahoma	2.2	32,668.9	35.55N 94.0 W 34.5 N 94.0 W 34.5 N 97.75W 35.55N 97.75W 35.55N 94.0 W
West-central Oklahoma	2.3	12,292.7	36.0 N 98.5 W 35.0 N 98.5 W 35.0 N 100.0 W 36.0 N 100.0 W 36.0 N 98.5 W
Residual	3.1	177,927.4	37.5 N 94.0 W 33.5 N 94.0 W 33.5 N 100.2 W 36.3 N 100.2 W 36.3 N 103.0 W 37.5 N 103.0 W 37.5 N 94.0 W Excluding area inside zone 1.1, 1.2, 2.1, 2.2, 2.3.

Table 6. Equations estimating largest magnitude (M) that will occur with frequency of f per year per 1,000 km^2 of source zone. (For zone 1.1, frequency is f per year for entire zone, which is 1,232 km^2 in area. Numbers following ± indicate 95% confidence limits.)

Zone 1.1 Central Oklahoma

$$M = 2.7241 \pm 0.049893 - (0.87951 \pm 0.048971) \log(f)$$

Zone 2.1 North-central Oklahoma

$$M = 1.8241 \pm 0.019184 - (0.86024 \pm 0.018579) \log(f)$$

Zone 2.2 Southeast Oklahoma

$$M = 1.1716 \pm 0.052239 - (0.99229 \pm 0.026765) \log(f)$$

Zone 2.3 West-central Oklahoma

$$M = 1.5062 \pm 0.21077 - (0.72025 \pm 0.090866) \log(f)$$

Zone 3.1 Residual

$$M = -0.27607 \pm 0.13897 - (1.2692 \pm 0.057652) \log(f)$$

DIRECTION OF STUDY FOR FY 1981

The following goals have been established for the 1981 fiscal year:

1. Complete the detailed gravity and magnetic study for parts of Canadian, Oklahoma, and Logan Counties.

2. Begin compiling, at a scale of 1:1,000,000, information, such as earthquake, aeromagnetic and structure, and geology, for the four-state (Iowa, Nebraska, Kansas, and Oklahoma) project area.

3. Finish the preparation of plates, at a scale of 1:500,000, for inclusion in the final report to be submitted at the end of fiscal year 1981. A separate plate or plates will be prepared with the following information: (a) bedrock geologic map, (b) three structure-contour maps, (c) aeromagnetic map, (d) contour map of top of the Precambrian basement, (e) earthquake map, and (f) detailed gravity map.

4. Complete the installation of a five-station array, using the DR-100 portable trigger-digital systems, in the El Reno area in western Canadian County.

REFERENCES CITED

Arbenz, K. J., 1956, Tectonic map of Oklahoma, showing surface structural features: Oklahoma Geol. Survey Map GM-3, scale 1:750,000.

Barrett, Christopher, 1980, A gravity and magnetic study of the Kingfisher anomaly, north-central Oklahoma: University of Oklahoma M.S. thesis, 45 p.

Cordell, L., and Henderson, R. G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer: Geophysics, v. 33, no. 4, p. 596-601.

Denison, R. E., 1966, Basement rocks in adjoining parts of Oklahoma, Kansas, and Arkansas: University of Texas, Austin, Ph.D. dissertation, 292 p.

Geodata International, Inc., 1976, Aerial radiometric and magnetic survey Oklahoma City National topographic map, Oklahoma: U.S. Energy Research and Development Administration, v. 1 and v. 2, GJBX-34 (76).

Jones, V. L., and Lyons, P. L., 1964, Vertical-intensity magnetic map of Oklahoma: Oklahoma Geol. Survey Map GM-6, scale 1:750,000.

Jordan, Louise, 1962, Geologic map and section of pre-Pennsylvanian rocks in Oklahoma: Oklahoma Geol. Survey Map GM-5, scale 1:750,000.

Kisvarsanyi, E. B., 1980, Granite ring complexes and Precambrian hot-spot activity in the St. Fancois terrane, Midcontinent region, United States: Geology, v. 8, no. 1, p. 43-47.

Lawson, J. E., Jr., 1980, Expected earthquake ground motion parameters of the Arcadia, Oklahoma dam site: U.S. Army Corps of Engineers, Tulsa District, contract P.O. No. DACW 56-80-M-0660, 41 p.

Lawton, D. L., and Palmer, D. F., 1978, Enhancement of linear features by rotational exposure: Journal of Photogrammetric Engineering and Remote Sensing, v. 44, No. 9, p. 1185-1190.

Luza, K. V., DuBois, R. L, Lawson, J. E., Jr., Foster, P., and Koff, L., 1978, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma: U.S. Nuclear Regulatory Commission, NUREG/CR-0050, 67 p.

Luza, K. V., and Lawson, J. E., Jr., 1979, Seismicity and tectonic relationships of the Nemaha Uplift in Oklahoma, part II: U.S. Nuclear Regulatory Commission, NURET/CR-0875, 81 p.

Luza, K. V., and Lawson, J. E., Jr., 1980, Seismicity and tectonic relationships of the Nemah Uplift in Oklahoma, part III: U.S. Nuclear Regulatory Commission, NUREG/CR-1500, 70 p.

Lyons, P. L., 1964, Bouguer gravity-anomaly map of Oklahoma: Oklahoma Geol. Survey Map GM-7, scale 1:750,000.

Santiago, D. J., 1979, A gravity and magnetic study of the Medford anomaly north-central Oklahoma: University of Oklahoma, M.S. thesis, 105 p.

Shoup, R. C., 1980, Correlation of landsat lineaments with geologic structures, north-central Oklahoma: University of Oklahoma, M.S. thesis, 123 p.

Talwani, M., 1965, Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape: Geophysics v. 30, no. 5, p. 797-817.

Texas Instruments Incorporated, 1978, Aerial radiometric and magnetic reconnaissance survey of portions of the great plains and central lowlands: Department of Energy, v. 1 and v. 2-M, GJBX-100 (78).

Wheeler, R. R., 1960, The structural map of the Midcontinent from Denver to the east Texas Gulf Coast: Dallas, Texas. Scale 1 inch = 6 miles. (Central series, consisting of 3 sheets, covers Oklahoma from T. 24 N. southward in to north Texas).