NUREG/CR-3109

Seismicity and Tectonic Relationships of the Nemaha Uplift in Oklahoma
Part V

Final Report

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The University of Oklahoma

Prepared for
U.S. Nuclear Regulatory
Commission

OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

Open-File Report OF 1-83

SEISMICITY AND TECTONIC RELATIONSHIPS OF THE NEMAHA UPLIFT IN OKLAHOMA
PART V
(Final Report)

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Manuscript Completed: September 1982
Date Published: February 1983

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Prepared for
Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Under Contract No. NRC 04-76-0314
NRC FIN B5967

ABSTRACT

The Nemaha Ridge is composed of a number of crustal blocks typically 3 to 5 miles (5 to 8 km) wide and 5 to 20 miles (8 to 32 km) long. Structure-contour maps prepared of the top of the Viola Formation (Ordovician), the base of the Pennsylvanian, and the top of the Oswego Formation (Middle Pennsylvanian) 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.

A detailed study of the Oklahoma City Uplift suggests that a number of the Nemaha-related faults were developed in pre-Mississippian time. Many of these faults exhibit both increasing and decreasing displacements from early to late Paleozoic time. However, the displacement for most of the Oklahoma City faults took place between the end of Oswego time and the end of Hunton time.

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. An interpretation of Precambrian lithologic relationships suggests that central Oklahoma was uplifted between late Precambrian and early Cambrian time. Perhaps zones of weakness, which developed from this uplift, were reactivated during the Early Pennsylvanian orogeny to form the main axis of the Nemaha Ridge.

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 may correlate with some of the earthquake-epicentral 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 second gravity study was completed for Canadian County and vicinity. Preliminary interpretation of the data suggests faulting within the basement near observed earthquake activity.

A total-intensity aeromagnetic map for the Enid and Oklahoma City 1° by 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 data on the aeromagnetic map.

A regional seismograph network was established to supplement existing seismological capability. The Oklahoma Geophysical Observatory (TUL); seven semipermanent, volunteer-operated seismograph stations; and three radiolink stations constitute the network.

A local earthquake-location program, named HYPERCUBE, was developed. It is used to calculate individual and average magnitudes of up to four types: m3Hz, mbLg, mbeus, and MDUR. A duration-magnitude formula, which gives magnitudes consistent with Nuttli's m3Hz and mbLg scales, was developed. The magnitude-duration scale, which uses the following equation,

$$\mathrm{MDUR} = -1.49 + 1.86 \log (\mathrm{DUR}),$$

is used for local and regional earthquakes recorded at Oklahoma seismograph stations.

From 1897 through 1976, Oklahoma has had approximately 128 known earthquakes. After the network became operational in late 1977, 255 additional earthquakes were detected in Oklahoma (through 1981).

The pre-1977 earthquake data, when combined with the 1977-81 earthquake data indicate at least one seismic trend in north-central Oklahoma. There appears to be a 25-mile-wide (49-km) and 90-mile-long (145-km) zone that extends northeastward from 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 earthquake-epicentral data exhibit three other seismic trends. 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. 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 last general area of earthquake activity lies along and north of the Ouachita front in southeastern Oklahoma. The earthquake activity forms a diffuse, broad pattern and appears to be unrelated to known Paleozoic faults.

A study of earthquake distribution and intensity values in Oklahoma led to the development of a seismic-source 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.

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*Reduced from original 1:500,000-scale map submitted to the U.S. Nuclear Regulatory Commission. Ozalid copy available for sale from the Oklahoma Geological Survey.

**Reduced from original 1:750,000-scale map submitted to the U.S. Nuclear Regulatory Commission. Ozalid copy available for sale from the Oklahoma Geological Survey.

PREFACE

This is the final report of studies performed under contract number NRC 04-76-0314 from the U.S. Nuclear Regulatory Commission. This project is part of the U.S. Nuclear Regulatory Commission's Nemaha Uplift Seismotectonic Project. The Kansas, Nebraska, and Iowa Geological Surveys have conducted similar studies in their respective states.

SUMMARY

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) 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 (fig. 5a, 5b). Except for a few localities, surface geologic relationships offer very 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 (figs. 7-9).

Data from more than 20,000 wells were used to construct these structure-contour maps. Three horizons were selected: the top of the Viola Formation (Ordovician), the base of the Pennsylvanian, and the top of the Oswego Formation (Middle Pennsylvanian System). These units were selected because they have been penetrated by a large number of boreholes and because they are easily recognizable on electric logs.

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.

A detailed study of the Oklahoma City Uplift by Koff (1978) suggests that a number of the Nemaha-related faults were developed in pre-Mississippian time. Many of these faults exhibit both increasing and decreasing displacements from early to late Paleozoic time. However, the displacement for most of the Oklahoma City faults took place between the end of Oswego time and the end of Hunton time.

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. 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 (fig. 17a, 17b). 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.

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. 18). 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.

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 trying 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 Uraniuim Resource Evaluation (NURE) data by Noel F. Rasmussen (fig. 22). 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 Central Oklahoma metamorphics (low), the Tulsa Mountains (high), and the Greenleaf and Osage Islandmaxima (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 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. Parts two and three consist of seven semipermanent, volunteer-operated seismograph stations and three radiolink stations. The signals from the three radiolink stations are recorded on five drum recorders at the observatory.

Each semipermanent station consists of a Geotech S-13 short-period vertical seismometer and a Sprengnether MEQ-800B unit including amplifier, filters, ink-recording unit, and temperature-compensated crystal-oscillator counter (clock) to record minutes and hours. The installation of this equipment usually requires 2 days. During the first day, the tank vault is installed in the field. The amplifier-filter-recorder-clock system and a WWV radio are installed in a protected area. The recorder and clock are activated, and while the recorder is recording a straight line, the volunteer operator is instructed in record changing, labeling, radio-time-mark recording, and clock corrections. During the remainder of the first day, a four-wire shielded cable is buried a few inches deep going from the building housing the recorder to the tank vault. At the end of the first day, the volunteer is again instructed in record changing by removing the record, which by then has several hours of straight lines and time marks on it. A new record is mounted to run overnight. On the second day, the tank vault is finished and the seismometer is installed, and all record-changing procedures and seismic recording commence. A supply of recording paper, ink, and stamped mailing tubes for weekly mailing of records is left.

In general, the volunteer's ability, without technical training, to operate a seismograph station has exceeded our expectations. Unfortunately, the amount of major maintenance has also exceeded our expectations. This maintenance is most frequently related to damage to the MEQ-800B timing system, which is usually caused by nearby lightning strikes.

In addition to the seven semipermanent stations, three radio-telemetry seismographs, linked to the Oklahoma Geophysical Observatory, are used to act as part of the overall network for earthquake detection. Each radiolink system consists of one Geotech S-13 seismometer and one Monitron and (or) Emheiser Rand telemetry unit. The telemetry unit amplifies the seismometer output and uses this output to frequency-modulate an audiotone. A 500-milliwatt, crystal-controlled transmitter limits the line-of-sight transmission to 50 miles (80 km). The signals from the radio-telemetry stations are recorded at the Oklahoma Geophysical Observatory.

The El Reno area, site of numerous earthquakes, was selected for detailed microearthquake studies. A five-station array, using Sprengnether DR-100 portable trigger-digital systems, was installed in December 1980 and July 1981.

In a typical installation, a DR-100 unit is placed in a pump house, where it is well grounded and connected to AC power. A WWVB antenna, which is attached to a 6-foot (2-m) galvanized pipe driven into the ground near the pump house, is connected via cable to each unit. A two-wire shielded cable 200 to 980 feet (60 to 300 m) or more in length is laid on top of the ground. The cable is connected to a 4.5-Hz vertical geophone that is buried from 4 to 12 inches (10 to 30 cm) deep. Volunteers are asked to do little more than change tapes weekly, and the tapes are mailed to the Observatory for processing.

A local earthquake-location program, named HYPERCUBE, was developed. It is used to calculate individual and average magnitudes of up to four types: m3Hz, mbLg, mbeus, and MDUR. All the output data are formatted into a 4,000-byte buffer set up to be the image of an 8.5- by 11-inch page with margins. The operator can print this buffer any number of times on a thermal printer and (or) impact printer and can archive the buffer in a magnetic-tape file.

A magnitude-duration formula, which gives magnitudes consistent with Nuttli's m3Hz and MbLg scales, was developed. An alternate magnitude scale was needed where data were insufficient to calculate a m3Hz or mbLg magnitude, particularly with small-magnitude earthquake events. The magnitude-duration scale, which uses the following equation,

$$\mathrm{MDUR} = -1.49 + 1.86 \log (\mathrm{DUR}),$$

is used for local and regional earthquakes recorded at Oklahoma seismograph stations.

A computer-based catalog was used to print earthquake information in page-sized format. Information for each earthquake includes date, origin time, county, intensity, magnitude, location, focal depth, and references.

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. The 1977-81 earthquake-location information is printed in table 7. Figure 34a and b 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. 38). 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 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 (fig. 24).

The earthquake epicentral data produce 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. The faulting has resulted in 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.

With the possible exception of the earthquakes along the northern front of the Ouachita Mountains, it was not possible to correlate Oklahoma earthquakes with recognized geologic features. Therefore, 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. These zones, in order of decreasing seismic activity, embrace certain areas herein referred to as central Oklahoma (zone 1.1), south-central Oklahoma (zone 1.2), north-central Oklahoma (zone 2.1), southeastern Oklahoma (zone 2.2), west-central Oklahoma (zone 2.3), and residual (an area that encompasses all remaining parts of the State, zone 3.1). Except for zone 1.2, a magnitude-frequency relationship was developed for each zone. Furthermore, the data can be used to calculate horizontal acceleration and horizontal ground velocity for any given site within Oklahoma.

INTRODUCTION

The U.S. Nuclear Regulatory Commission has established rigorous guidelines that must be adhered to before a permit to construct a nuclear-power plant is granted to an applicant. Local as well as regional seismicity and structural relationships play an integral role in the final design criteria for nuclear-power plants. This requires that a value for the maximum expectable seismic event be assigned at a proposed site. The existing historical record of seismicity is inadequate in a number of areas of the Midcontinent region because of the lack of instrumentation and (or) the sensitivity of the instruments deployed to monitor earthquake events. This inadequacy has made it necessary to rely on the delineation of major tectonic provinces that are based on broad regional structure and associated seismicity. The delineation of tectonic provinces that accurately reflect the potential magnitude of seismic events is an important cost-risk factor in assigning design criteria for nuclear-power plants.

King (1951), Hadley and Devine (1974), and others have categorized the geologic regions of the United States into tectonic provinces. The largest of these tectonic provinces is the Central Stable Province. This province extends from the western margin of the Appalachian Plateau to the eastern edge of the Rocky Mountain Uplift and from the Gulf Coastal Plain to Northern Canada. Compared to the Appalachian tectonic province, the Central Stable Region has displayed little tectonic activity since Late Pennsylvanian time. The historical record of faulting and seismicity has been limited, with a notable exception being the New Madrid, Missouri, area, which includes adjacent areas in Kentucky, Tennessee, and Illinois. Nevertheless, the entire region is so large that despite the broad-scale picture of relative historical stability, there is within it considerable geologic diversity and sufficient seismic history to require a moderately high seismic classification for nuclear-power-plant siting.

Six years ago the U.S. Nuclear Regulatory Commission 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. The Midcontinent Geophysical Anomaly 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 Oklahoma Geological Survey, in cooperation with the geological surveys of Kansas, Nebraska, and Iowa, conducted 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, was intended to provide data to be used to design 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.

This report summarizes Oklahoma's project results for the past 5 years and the project progress for the 5th year (January 1, 1981, through December 31, 1981). Progress summaries for fiscal years 1977, 1978, 1979, and 1980 were published as NUREG/CR-0050 (Luza and others, 1978), NUREG/CR-0875 (Luza and Lawson, 1979), NUREG/CR-1500 (Luza and Lawson, 1980), and NUREG/CR-2439 (Luza and Lawson, 1981, respectively.

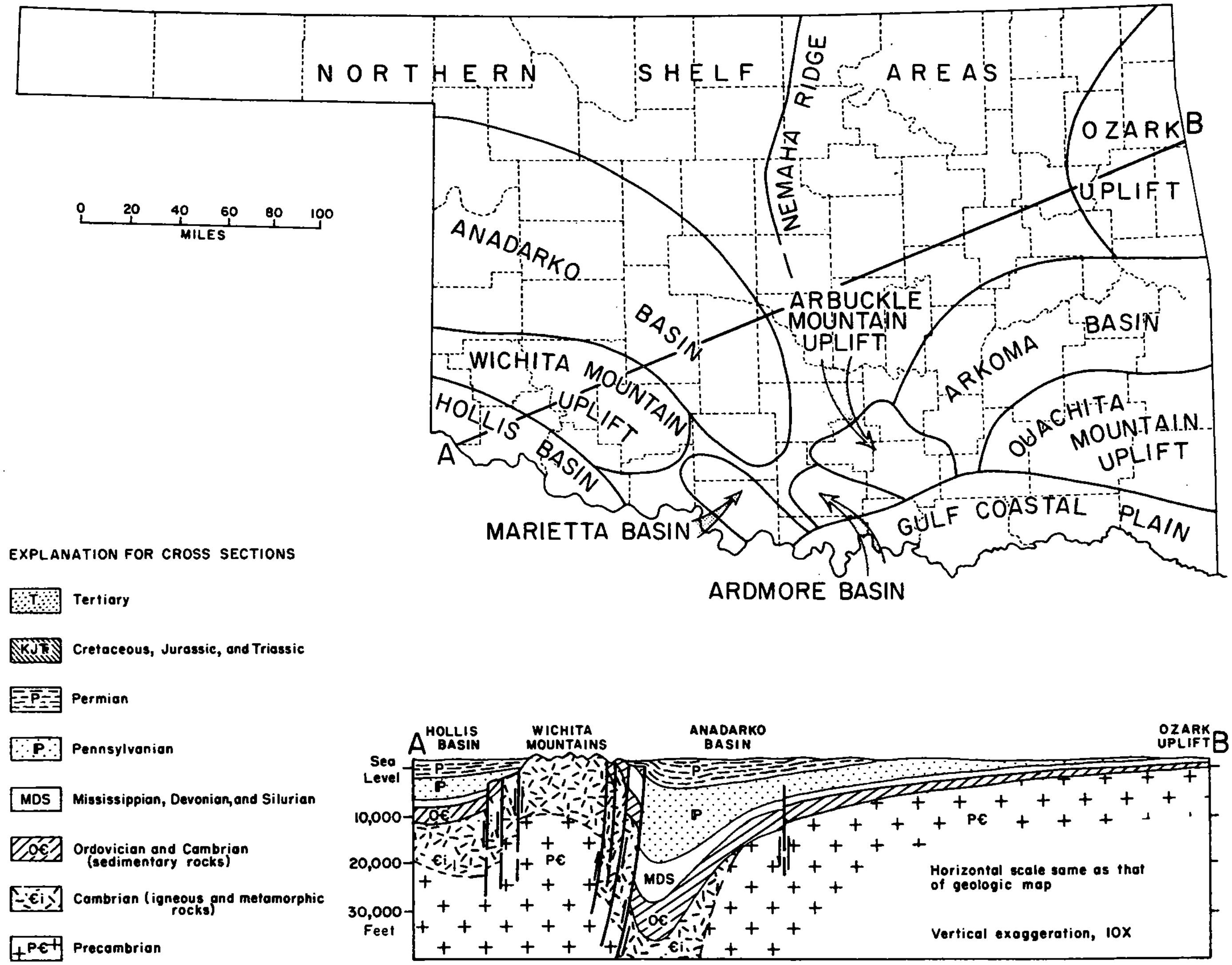


Fig. 1. Major geologic and tectonic provinces of Oklahoma.

GEOLOGY

Regional Geology

The Midcontinent region contains a number of structural features (fig. 2). The tectonic events vary in age from the oldest basement rock, 1.3 billion years, through the Paleozoic and ending with the close of the Permian, about 225 million years ago. Included are at least 30 separate tectonic events in the Paleozoic, of which 14 are regionally significant (Ham and Wilson, 1967). The regional Paleozoic disturbances are chiefly of Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian age. All these disturbances are epeirogenic except those of the Pennsylvanian and Early Permian, which are orogenic in southern Oklahoma and in the craton-bordering Ouachita system.

Over most of the central craton the Paleozoic tectonic record is characterized generally by episodes of marine sedimentation that were terminated by episodes of uplift, gentle folding, erosion, and partly by the overlap of younger strata upon unconformable surfaces. The Salina and Forest City Basins, which contain 4,000 (1,220 m) to 10,000 feet (3,050 m) of sediment, are examples of relatively shallow intracratonic basins.

Along the southern border of the craton, north of the Ouachita system, is the Arkoma Basin, which contains as much as 25,000 feet (7,625 m) of sediment. A transverse belt, locally called the Wichita-Amarillo trend, as well as the Arbuckle Mountains, developed in middle Paleozoic time. This area is one of intense folding and uplift associated with longitudinal faults at least 400 miles (640 km) long with vertical displacements of at least 15,000 feet (4,575 m). North of the Wichita Mountains is the Anadarko Basin, which was the site of almost continuous deposition from Late Cambrian through Permian time. The thickest sediments are estimated to be greater than 45,000 feet (13,725 m).

Another structural feature, the Nemaha Ridge or Uplift, is common to the states of Oklahoma, Kansas, and Nebraska. This uplift developed mainly during the Pennsylvanian Period as a number of small crustal blocks that were raised sharply along the axis of the uplift. The uplifted crustal blocks making up the Nemaha Ridge typically are 3 to 5 miles (5-8 km) wide and 5 to 20 miles (8-32 km) long and are bounded by faults on the east and (or) west side (Huffman, 1959). Only in northern Kansas and southeastern Nebraska is faulting exposed at the surface. This fault is locally referred to as the Humboldt Fault.

Middle Pennsylvanian (Desmoinesian) strata overlie Devonian or older units on many of the uplifted blocks that make up the Nemaha Uplift in Oklahoma. The missing rock record over the uplifted blocks has contributed to a more generalized structural-history interpretation than, perhaps, is desired. A generalized map of pre-Pennsylvanian rocks in Oklahoma is shown in figure 3. The greatest thickness of Mississippian strata, 20,000 feet (6,100 m), is in the Ouachita province. The strata are characterized by alternating beds of sandstone and shale and are Meramecian in age. In western Oklahoma

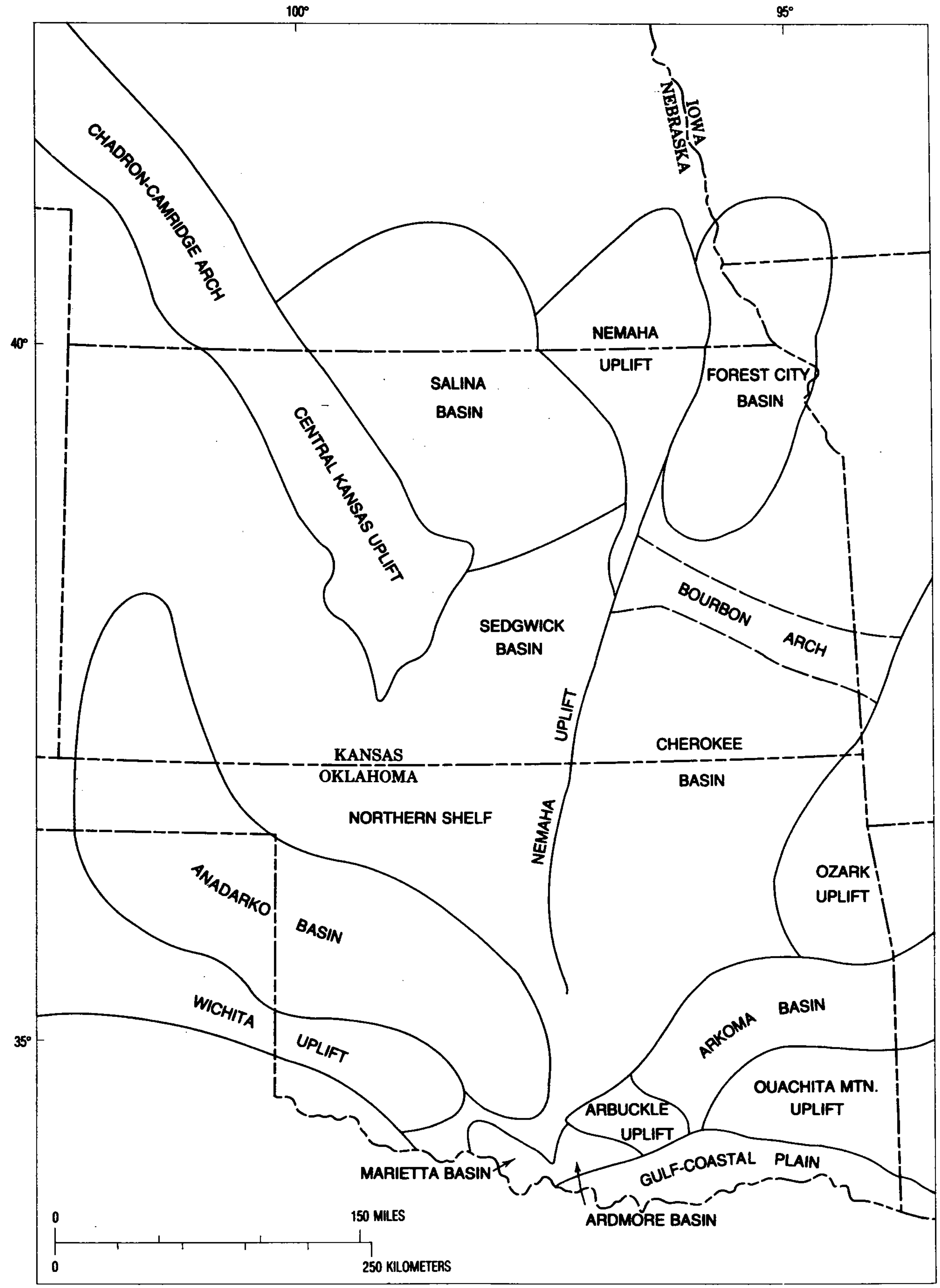


Fig. 2. Major geologic and tectonic provinces of the Midcontinent.

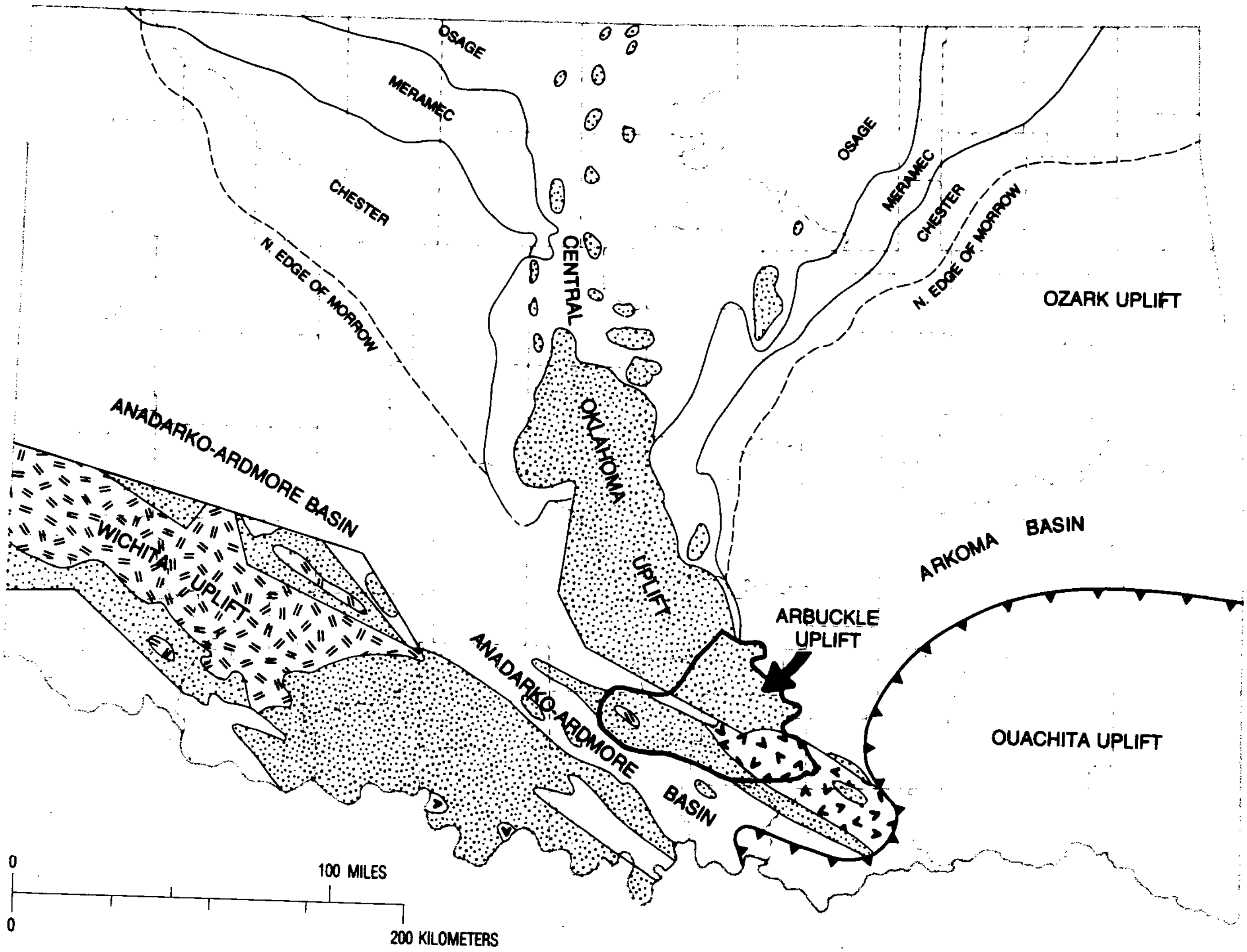


Fig. 3. Pre-Pennsylvanian paleogeologic map of Oklahoma (exclusive of the Panhandle) showing rocks below Pennsylvanian in subsurface (modified from Jordan, 1962). Stippled areas denote Devonian through Late Cambrian; pattern in Wichita Uplift region denotes Middle Cambrian intrusive and flow rocks; V pattern represents Precambrian granite.

within the Anadarko Basin, Mississippian units are primarily carbonate rocks 1,500 (460 m) to more than 3,500 feet (1,070 m) thick. In northern Oklahoma, the Chesterian and (or) Meramecian units have been removed by pre-Pennsylvanian erosion. The remaining Meramecian or Osagean rocks are principally cherty carbonate units ranging in thickness from 200 to 600 feet (61-183 m). Early Pennsylvanian rocks, Morrowan and Atokan, are absent over north-central Oklahoma. Middle and upper Desmoinesian strata were probably the first units to completely cover the uplifted Nemaha Ridge fault blocks since the Mississippian.

Regional Surface Geology

The surface geology that overlies the Nemaha Uplift region was compiled on the Enid and Oklahoma City 1^{o} x 2^{o} Quadrangles at a scale of 1:250,000. The geologic information was recompiled at a scale of 1:500,000 and is displayed in figure 5a and b. Outcrop patterns and stratigraphic nomenclature were derived from a synthesis of work done by Fay (1971a, 1971b, 1972), Bingham and Moore (1975), and Bingham and Bergman (1980).

The surface rocks in the vicinity of the Nemaha Uplift consist mainly of Middle to Upper Pennsylvanian strata and Lower Permian red beds (figs. 4, 5a, 5b). The rock units generally trend north-south and dip westward at 90 feet or less per mile.

Rock units that belong to the Cabaniss Group (Middle Pennsylvanian) are the oldest rocks exposed in the mapped area (fig. 5a, 5b). The Cabaniss Group can be divided into the Thurman Sandstone (near the base), the Stuart Shale, and the Senora Formation. The Thurman Sandstone consists mainly of medium-grained silty sandstone with cherty conglomerate at the base. Only a few feet (1 m) is exposed in the southeastern corner of the mapped area. The Stuart Shale, which overlies the Thurman, is composed mostly of laminated clayey shale with minor amounts of silty sandstone. The thickness ranges from 80 to 180 feet (24-55 m). Above the Stuart is the Senora Formation, which is about 500 to 950 feet (150-290 m) thick. This unit consists mainly of fine-grained micaceous sandstone and shale and contains coal beds locally.

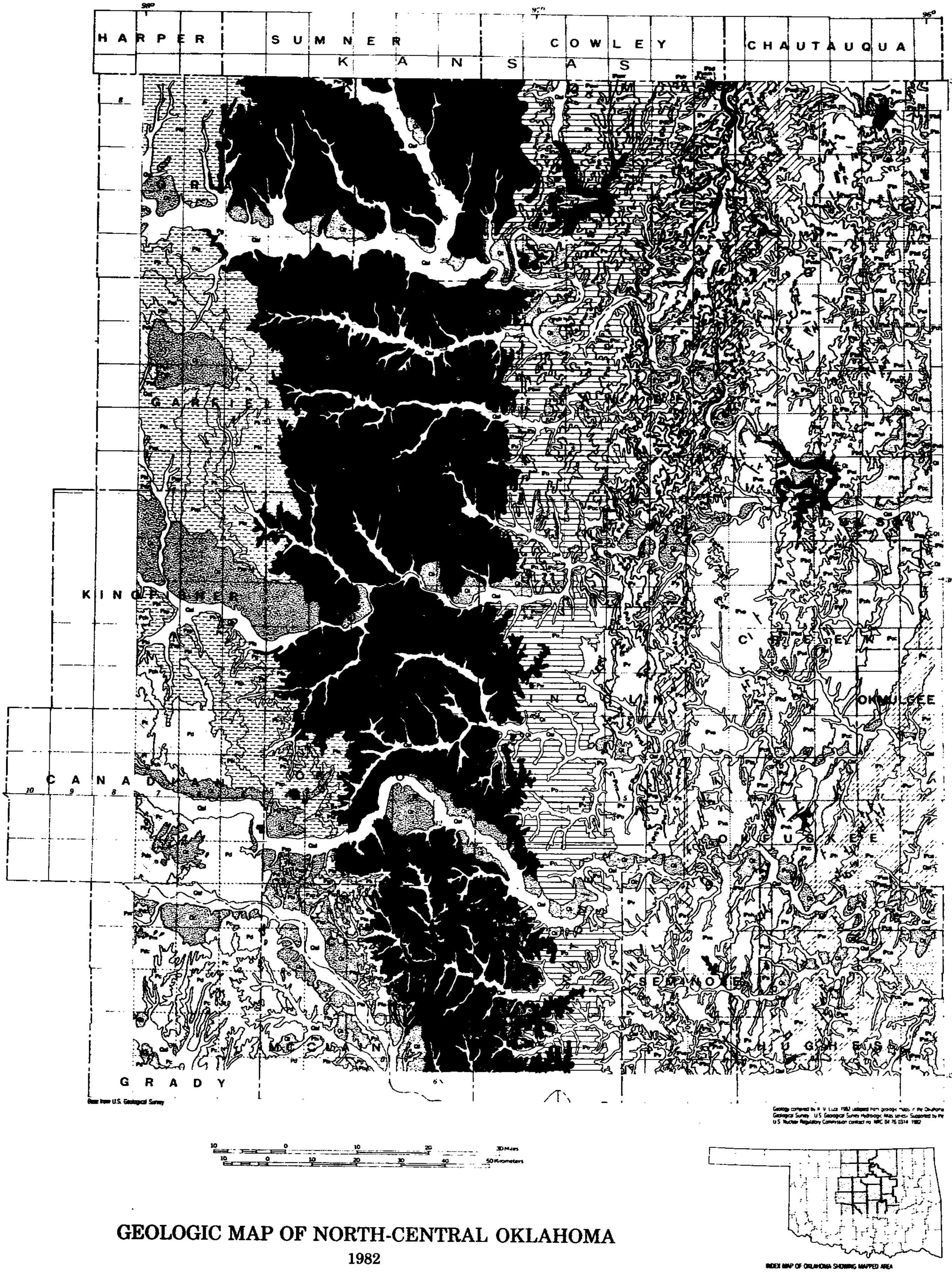
Above the Cabaniss Group is the Marmaton Group, which consists of an 800- to 1,600-foot (240-480-m) sequence of interbedded shale and sandstone. The Calvin Sandstone, Wetumka Shale, Wewoka Formation, and Holdenville Shale are the principal units that compose the Marmaton Group. These units form an outcrop pattern approximately 18 miles (29 km) wide extending 48 miles (77 km) in a northeast-southwest direction across the southeastern corner of the study area (fig. 5a, 5b).

The Skiatook Group (lower Missourian) overlies the Marmaton Group. The principal formations that make up this group are the Seminole, Coffeyville, and Nellie Bly. The dominant lithologies are shale, buff-colored, fine- to medium-grained sandstone, and thin limestone beds. Coal seams occur in the upper part of the Seminole Formation. These units, which are exposed in the southeastern part of the study area, form an outcrop belt 6 to 12 miles (9.5-19 km) wide and about 80 miles (130 km) long. The thickness ranges from 300 to 1,400 feet (92-427 m).

Upper Missourian rock units are included in the Ochelata Group, which overlies the Skiatook Group. The Belle City, Hilltop, Dewey, Chanute, Wann, Barnsdall, and Tallant are the principal units that make up the Ochelata Group. Alternating layers of fine- to medium-grained sandstone and shale and interbedded fine-grained calcareous sandstone and limestone are the principal lithologies. The thickness ranges from less

SYSTEM	SERIES	GROUP	FORMATION
PERMIAN	Custerian(?)		Marlow
	Cimarronian	El Reno	Dog Creek Blaine Flowerpot Cedar Hills
		Hennessey	Bison Salt Plains Kingman Fairmont
		Sumner	Garber Wellington
?—? PENNSYLVANIAN	Gearyan(?)	Oscar Vanoss	Interbedded sandstone, shales and limestone
	Virgilian	Ada Vamoosa	
	Missourian	Ochelata	Tallant Barnsdall Wann Chanute Dewey
		Skiatook	Nellie Bly Coffeyville Seminole
	Desmoinesian	Marmaton	Holdenville Wewoka Wetumka Calvin
		Cabaniss	Senora Stuart Thurman

Fig. 4. Generalized geologic section for north-central Oklahoma.



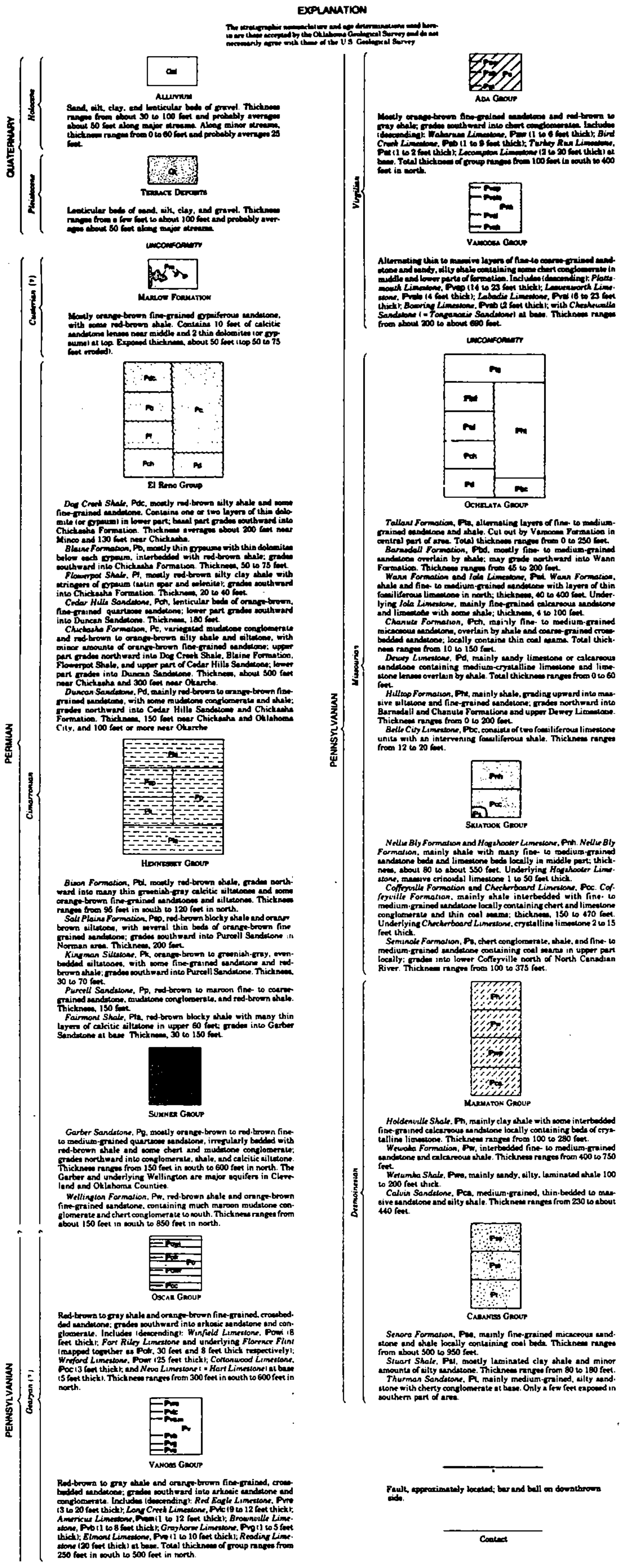
Base from U.S. Geological Survey

Geology compiled by R. V. Luza 1982 (adapted from geologic maps of the Oklahoma Geological Survey, U.S. Geological Survey Hydrologic Atlas series). Supported by the U.S. Nuclear Regulatory Commission contract no. NRC 04 76 0314 1982

INDEX MAP OF OKLAHOMA SHOWING MAPPED AREA

GEOLOGIC MAP OF NORTH-CENTRAL OKLAHOMA
1982

Fig. 5a. Geologic map of north-central Oklahoma (reduced from original 1:500,000-scale map).



EXPLANATION

The stratigraphic nomenclature and age determinations used herein are those accepted by the Oklahoma Geological Survey and do not necessarily agree with those of the U.S. Geological Survey

ALLUVIUM

Sand, silt, clay, and lenticular beds of gravel. Thickness ranges from about 30 to 100 feet and probably averages about 50 feet along major streams. Along minor streams, thickness ranges from 0 to 60 feet and probably averages 25 feet.

TERRACE DEPOSITS

Lenticular beds of sand, silt, clay, and gravel. Thickness ranges from a few feet to about 100 feet and probably averages about 50 feet along major streams.

UNCONFORMITY

MARLOW FORMATION

Mostly orange-brown fine-grained gypsiferous sandstone, with some red-brown shale. Contains 10 feet of calcitic sandstone lenses near middle and 2 thin dolomites (or gypsums) at top. Exposed thickness, about 50 feet (top 50 to 75 feet eroded).

El Reno Group

Dog Creek Shale, Pdc, mostly red-brown silty shale and some fine-grained sandstone. Contains one or two layers of thin dolomite (or gypsum) in lower part; basal part grades southward into Chickasha Formation. Thickness averages about 200 feet near Minco and 130 feet near Chickasha.

Blaine Formation, Pb, mostly thin gypsums with thin dolomites below each gypsum, interbedded with red-brown shale; grades southward into Chickasha Formation. Thickness, 50 to 75 feet.

Flowerpot Shale, Pf, mostly red-brown silty clay shale with stringers of gypsum (satin spar and selenite); grades southward into Chickasha Formation. Thickness, 20 to 40 feet.

Cedar Hills Sandstone, Pch, lenticular beds of orange-brown, fine-grained quartzose sandstone; lower part grades southward into Duncan Sandstone. Thickness, 180 feet.

Chickasha Formation, Pc, variegated mudstone conglomerate and red-brown to orange-brown silty shale and siltstone, with minor amounts of orange-brown fine-grained sandstone; upper part grades northward into Dog Creek Shale, Blaine Formation, Flowerpot Shale, and upper part of Cedar Hills Sandstone; lower part grades into Duncan Sandstone. Thickness, about 500 feet near Chickasha and 300 feet near Okarche.

Duncan Sandstone, Pd, mainly red-brown to orange-brown fine-grained sandstone, with some mudstone conglomerate and shale; grades northward into Cedar Hills Sandstone and Chickasha Formation. Thickness, 150 feet near Chickasha and Oklahoma City, and 100 feet or more near Okarche

HENNESSEY GROUP

Bison Formation, Pbi, mostly red-brown shale, grades northward into many thin greenish-gray calcitic siltstones and some orange-brown fine-grained sandstones and siltstones. Thickness ranges from 95 feet in south to 120 feet in north.

Salt Plains Formation, Psp, red-brown blocky shale and orange-brown siltstone, with several thin beds of orange-brown fine-grained sandstone; grades southward into Purcell Sandstone in Norman area. Thickness, 200 feet.

Kingman Siltstone, Pk, orange-brown to greenish-gray, even-bedded siltstones, with some fine-grained sandstone and red-brown shale; grades southward into Purcell Sandstone. Thickness, 30 to 70 feet.

Purcell Sandstone, Pp, red-brown to maroon fine- to coarse-grained sandstone, mudstone conglomerate, and red-brown shale. Thickness, 150 feet.

Fairmont Shale, Pfa, red-brown blocky shale with many thin layers of calcitic siltstone in upper 60 feet; grades into Garber Sandstone at base. Thickness, 30 to 150 feet.

SUMNER GROUP

Garber Sandstone, Pg, mostly orange-brown to red-brown fine- to medium-grained quartzose sandstone, irregularly bedded with red-brown shale and some chert and mudstone conglomerate; grades northward into conglomerate, shale, and calcitic siltstone. Thickness ranges from 150 feet in south to 600 feet in north. The Garber and underlying Wellington are major aquifers in Cleveland and Oklahoma Counties.

Wellington Formation, Pw, red-brown shale and orange-brown fine-grained sandstone, containing much maroon mudstone conglomerate and chert conglomerate to south. Thickness ranges from about 150 feet in south to 850 feet in north.

OSCAR GROUP

Red-brown to gray shale and orange-brown fine-grained, crossbedded sandstone; grades southward into arkosic sandstone and conglomerate. Includes (descending): *Winfield Limestone*, ℙow (8 feet thick); *Fort Riley Limestone* and underlying *Florence Flint* (mapped together as ℙofr, 30 feet and 8 feet thick respectively); *Wreford Limestone*, ℙowr (25 feet thick); *Cottonwood Limestone*, ℙoc (3 feet thick); and *Neva Limestone* (= *Hart Limestone*) at base (5 feet thick). Thickness ranges from 300 feet in south to 600 feet in north.

VANOSS GROUP

Red-brown to gray shale and orange-brown fine-grained, crossbedded sandstone; grades southward into arkosic sandstone and conglomerate. Includes (descending): *Red Eagle Limestone*, ℙvre (3 to 20 feet thick); *Long Creek Limestone*, ℙvlc (9 to 12 feet thick); *Americus Limestone*, ℙvam (1 to 12 feet thick); *Brownville Limestone*, ℙvb (1 to 8 feet thick); *Grayhorse Limestone*, ℙvg (1 to 5 feet thick); *Elmont Limestone*, ℙve (1 to 10 feet thick); *Reading Limestone* (20 feet thick) at base. Total thickness of group ranges from 250 feet in south to 500 feet in north.

ADA GROUP

Mostly orange-brown fine-grained sandstone and red-brown to gray shale; grades southward into chert conglomerates. Includes (descending): *Wakarusa Limestone*, ℙaw (1 to 6 feet thick); *Bird Creek Limestone*, ℙab (1 to 9 feet thick); *Turkey Run Limestone*, ℙat (1 to 2 feet thick); *Lecompton Limestone* (2 to 20 feet thick) at base. Total thickness of group ranges from 100 feet in south to 400 feet in north.

VAMOOSA GROUP

Alternating thin to massive layers of fine-to coarse-grained sandstone and sandy, silty shale containing some chert conglomerate in middle and lower parts of formation. Includes (descending): *Plattsmouth Limestone*, ℙvsp (14 to 23 feet thick); *Leavenworth Limestone*, ℙvsle (4 feet thick); *Labadie Limestone*, ℙvsl (6 to 23 feet thick); *Bowring Limestone*, ℙvsb (2 feet thick); with *Cheshewalla Sandstone* (= *Tonganoxie Sandstone*) at base. Thickness ranges from about 200 to about 690 feet.

UNCONFORMITY

OCHELATA GROUP

Tallant Formation, ℙta, alternating layers of fine- to medium-grained sandstone and shale. Cut out by Vamoosa Formation in central part of area. Total thickness ranges from 0 to 250 feet.

Barnsdall Formation, ℙbd, mostly fine- to medium-grained sandstone overlain by shale; may grade northward into Wann Formation. Thickness ranges from 45 to 200 feet.

Wann Formation and Iola Limestone, ℙwi. *Wann Formation*, shale and fine- to medium-grained sandstone with layers of thin fossiliferous limestone in north; thickness, 40 to 400 feet. Underlying *Iola Limestone*, mainly fine-grained calcareous sandstone and limestone with some shale; thickness, 4 to 100 feet.

Chanute Formation, ℙch, mainly fine- to medium-grained micaceous sandstone, overlain by shale and coarse-grained crossbedded sandstone; locally contains thin coal seams. Total thickness ranges from 10 to 150 feet.

Dewey Limestone, ℙd, mainly sandy limestone or calcareous sandstone containing medium-crystalline limestone and limestone lenses overlain by shale. Total thickness ranges from 0 to 60 feet.

Hilltop Formation, ℙht, mainly shale, grading upward into massive siltstone and fine-grained sandstone; grades northward into Barnsdall and Chanute Formations and upper Dewey Limestone. Thickness ranges from 0 to 200 feet.

Belle City Limestone, ℙbc, consists of two fossiliferous limestone units with an intervening fossiliferous shale. Thickness ranges from 12 to 20 feet.

SKIATOOK GROUP

Nellie Bly Formation and Hogshooter Limestone, ℙnh. *Nellie Bly Formation*, mainly shale with many fine- to medium-grained sandstone beds and limestone beds locally in middle part; thickness, about 80 to about 550 feet. Underlying *Hogshooter Limestone*, massive crinoidal limestone 1 to 50 feet thick.

Coffeyville Formation and Checkerboard Limestone, ℙcc. *Coffeyville Formation*, mainly shale interbedded with fine- to medium-grained sandstone locally containing chert and limestone conglomerate and thin coal seams; thickness, 150 to 470 feet. Underlying *Checkerboard Limestone*, crystalline limestone 2 to 15 feet thick.

Seminole Formation, ℙs, chert conglomerate, shale, and fine- to medium-grained sandstone containing coal seams in upper part locally; grades into lower Coffeyville north of North Canadian River. Thickness ranges from 100 to 375 feet.

MARMATON GROUP

Holdenville Shale, ℙh, mainly clay shale with some interbedded fine-grained calcareous sandstone locally containing beds of crystalline limestone. Thickness ranges from 100 to 280 feet.

Wewoka Formation, ℙw, interbedded fine- to medium-grained sandstone and calcareous shale. Thickness ranges from 400 to 750 feet.

Wetumka Shale, ℙwe, mainly sandy, silty, laminated shale 100 to 200 feet thick.

Calvin Sandstone, ℙca, medium-grained, thin-bedded to massive sandstone and silty shale. Thickness ranges from 230 to about 440 feet.

CABANISS GROUP

Senora Formation, ℙse, mainly fine-grained micaceous sandstone and shale locally containing coal beds. Thickness ranges from about 500 to 950 feet.

Stuart Shale, ℙst, mostly laminated clay shale and minor amounts of silty sandstone. Thickness ranges from 80 to 180 feet.

Thurman Sandstone, ℙt, mainly medium-grained, silty sandstone with cherty conglomerate at base. Only a few feet exposed in southern part of area.

Fault, approximately located; bar and ball on downthrown side.

Contact

Fig. 5b. Explanation for geologic map (reduced from original 1:500,000-scale map).

than 100 feet (30 m) in the southern part of the study area to more than 1,000 feet (300 m) near the Kansas border.

Virgilian-age sediments are divided into the Vamoosa Group, unconformably overlying the Ochelata Group, and the Ada Group. The Vamoosa Group consists of alternating thin to massive layers of fine- to coarse-grained sandstone and sandy, silty shale containing some cherty conglomerates. Several limestone units, 1 to 20 feet (.3-6 m) thick, occur within the Vamoosa Group. The thickness ranges from about 200 feet (61 m) or less in the southern part of the study area to about 700 feet (214 m) near the Kansas border. Exposures of the Vamoosa Group produce an outcrop pattern 4 to 12 miles (6-18 km) wide, extending north-south across the east-central part of the mapped area (fig. 5a, 5b).

The Vamoosa Group is overlain by the Ada Group. The Ada Group consists mostly of orange-brown, fine-grained sandstone and red-brown to gray shale that grades southward into chert conglomerates. Several limestone units, 1 to 20 feet (.3-6 m) thick, occur within the section. The total thickness of the group ranges from 100 feet (30 m) in the south to 400 feet (120 m) in the north, which is reflected by the narrow outcrop pattern, 3 to 12 miles (5-20 km) wide, displayed on the geologic map (fig. 5a, 5b).

Uppermost Pennsylvanian(?) sediments (considered by some to be lowermost Permian), which belong to the Vanoss and Oscar Groups, overlie the Ada Group in north-central Oklahoma. The Vanoss and Oscar Groups are composed of red-brown to gray shale and orange-brown, fine-grained cross-bedded sandstone that grades southward into arkosic sandstone and conglomerate. Numerous limestone beds, 1 to 20 feet (.3-6 m) thick, occur throughout the section. The total thickness of the Vanoss Group ranges from 250 feet (76 m) in the south to 500 feet (150 m) in the north, whereas the thickness of the Oscar Group ranges from 300 feet (90 m) in the south to 600 feet (180 m) in the north.

Lower Permian sediments of the Sumner Group overlie those of the Oscar Group in north-central Oklahoma. The Sumner Group, composed of the Wellington and Garber Formations, forms a north-south outcrop pattern 40 miles (64 km) wide near the Kansas border to 20 miles (32 km) wide near the southern edge of the mapped area (fig. 5a, 5b). The Wellington Formation consists of red-brown shale and orange-brown, fine-grained sandstone that contains much maroon mudstone conglomerate and chert conglomerate to the south. The thickness ranges from about 150 feet (45 m) in the south to 850 feet 255 m) in the north. The Garber Sandstone is composed mostly of orange-brown to red-brown, fine- to medium-grained quartzose sandstone, irregularly bedded with red-brown shale and some chert and mudstone conglomerate that grades northward into conglomerate, shale, and calcareous siltstone. The thickness ranges from 150 feet (45 m) in the south to 600 feet (180 m) in the north. The Garber and Wellington Formations are the principal units that overlie the main axis of the Nemaha Uplift in Kay, Grant, Garfield, Kingfisher, Oklahoma, and Cleveland Counties.

The Hennessey Group, which consists mostly of red-brown shale and orange-brown, fine-grained sandstone and siltstone, overlies the Sumner Group. The Fairmont, Purcell, Kingman, Salt Plains, and Bison are the principal formations that make up this group. The thickness ranges from 350 to 550 feet (107-168 m). Principal exposures of the Hennessey Group occur in the western and northwestern parts of the mapped area (fig. 5a, 5b).

The El Reno Group overlies the Hennessey. The main formations that constitute the El Reno Group are the Cedar Hills, Flowerpot, Blaine, and Dog Creek. The thickness ranges from 350 to 500 feet (107-150 m). The dominant lithologies include red-brown silty shale, orange-brown, fine-grained sandstone, orange-brown siltstone, and mudstone conglomerate. Exposures of the El Reno Group occur in the southwestern part of the mapped area (fig. 5a, 5b).

The Marlow Formation, in the lower part of the Whitehorse Group, overlies rocks of the El Reno Group. The Marlow consists mostly of orange-brown, fine-grained sandstone. The exposed thickness is about 50 feet (15 m). A few isolated outcrops occur in the southwestern part of the area (fig. 5a, 5b).

Pleistocene deposits are represented by 50 to 100 feet (15-30 m) of gravel, sand, silt, and clay, which occur as terraces adjacent to major streams. Alluvium, present only within the stream channels, was deposited as lenticular beds of intercalated sand, silt, clay, and gravel. Deposits are as thick as 120 feet (37 m) but probably average about 25 feet (7.5 m) along major streams. Along minor streams, thicknesses range from a few to about 50 feet (15 m) but also average only about 25 feet (7.5 m).

Subsurface Geology

Except for a few localities, surface geologic relationships offer very 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 a series of structure-contour maps of key stratigraphic horizons. The area contoured was expanded to include all of the area within the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles.

Three horizons were selected for structure-contour mapping: the top of the Viola Formation (Ordovician), the base of the Pennsylvanian, and the top of the Oswego Formation (Middle Pennsylvanian) (see fig. 6 for relative stratigraphic positions). These units were selected because they have been penetrated by a large number of boreholes and because they are easily recognizable on electric logs.

The term Viola was applied by Taff (1902) to limestones that crop out near the former village of Viola, Johnston County, Oklahoma. Subsequent work by Wengerd (1948) subdivided the Viola into four lithologic members and gave formation rank to an overlying limestone, the Fernvale, now called the Welling (Amsden, 1979). The Viola Formation consists of dense, fine-grained, cherty, even-bedded limestone. The overlying Welling is a coarsely crystalline, fossiliferous limestone that rests disconformably on the Viola Limestone. For this project, the structure-contour map represents the top of the Viola Group or Viola Limestone which includes the Welling Formation as well as the underlying Viola, because these two units are most often grouped together on drillers logs (fig. 7).

The Viola conformably overlies the Simpson Group. The Sylvan Shale, which consists of light-gray to gray-green, slightly calcareous, pyritic shale, rests conformably on top of the Viola Group. Regional isopach studies by Huffman (1959) and others indicate a maximum thickness of 1,500 feet (460 m) for the Viola in the Anadarko-Ardmore Basins. The unit thins northward to about 200 feet (61 m) in southern Kansas. The Viola has been removed by erosion in northern Oklahoma and along the uplifted features associated with the Nemaha Ridge.

The structure map of the base of Pennsylvanian strata represents an unconformable surface (fig. 8). Most of the Upper Mississippian strata were eroded prior to the

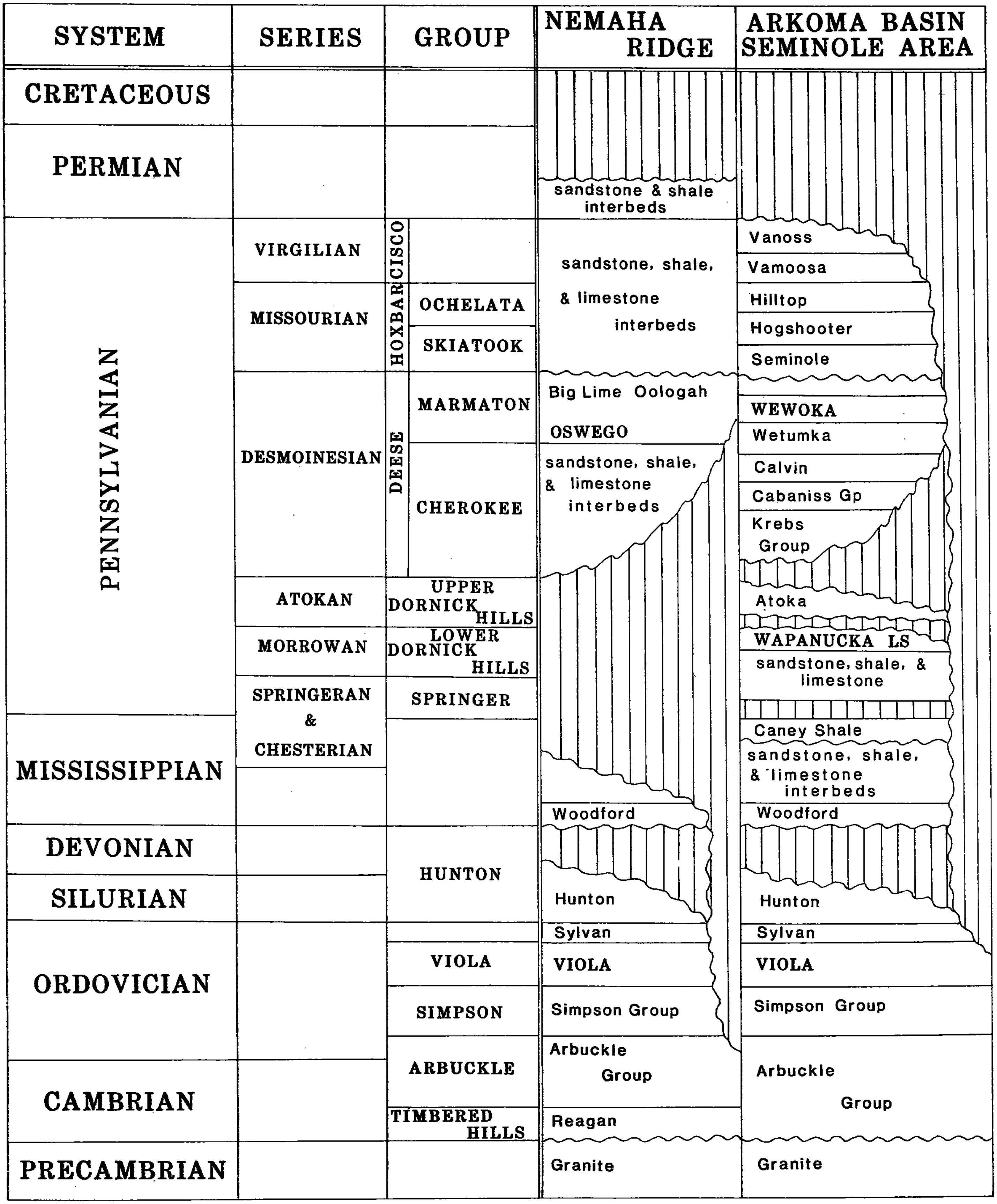


Fig. 6. Generalized subsurface geologic section for north-central Oklahoma.

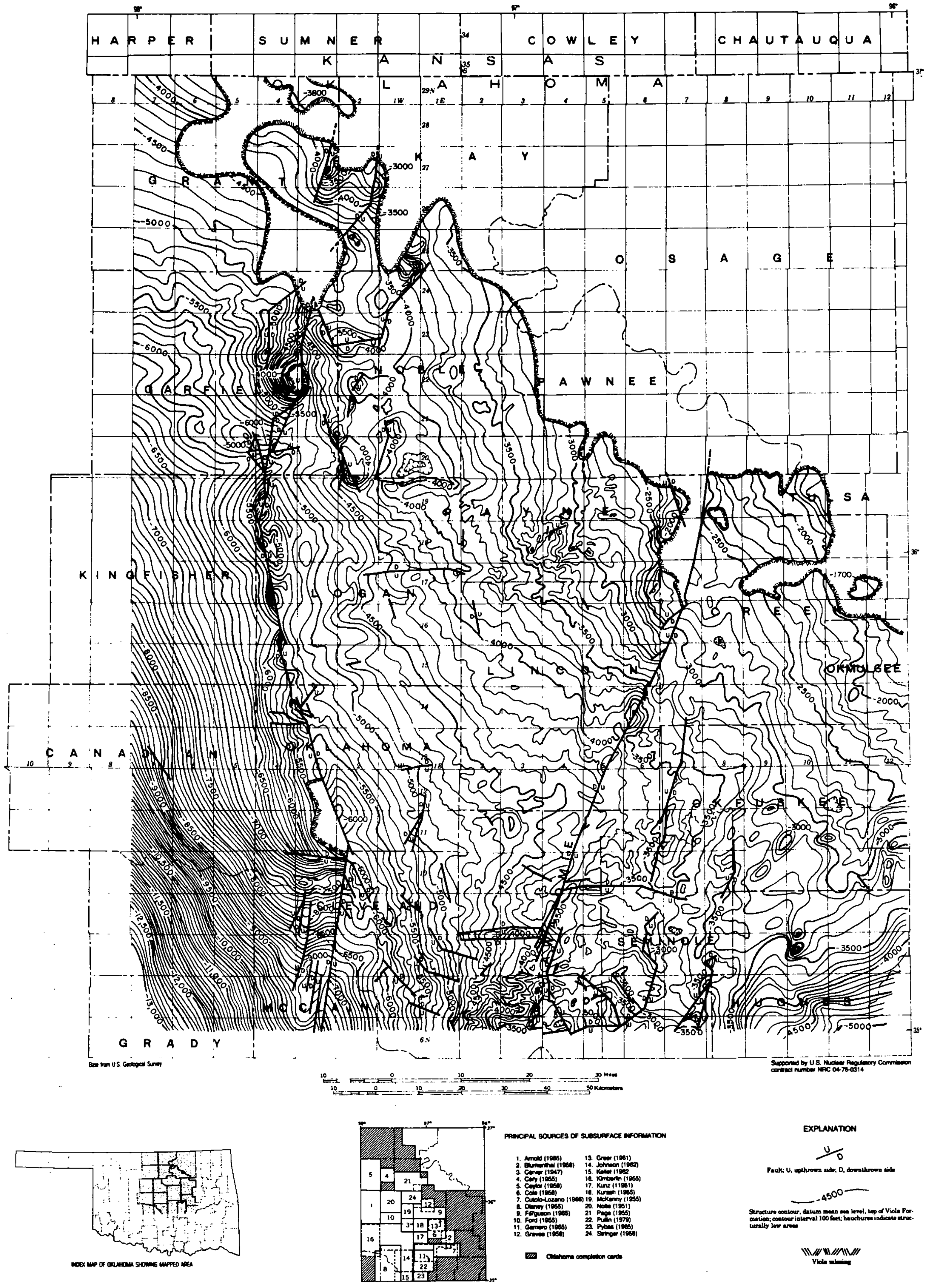


Fig. 7. STRUCTURE-CONTOUR MAP OF TOP OF VIOLA FORMATION IN NORTH-CENTRAL OKLAHOMA (reduced from original 1:500,000-scale map).

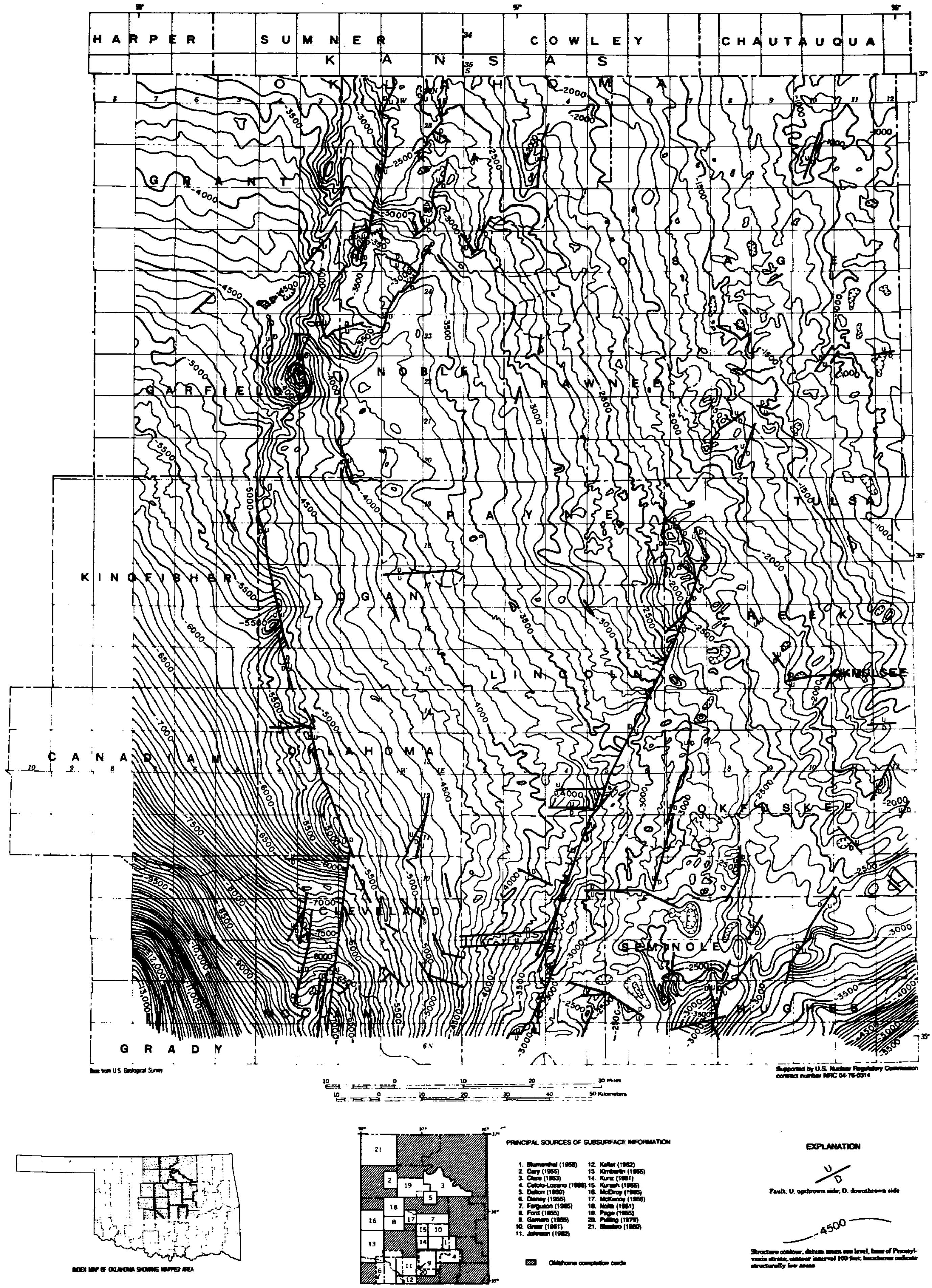


Fig. 8. **STRUCTURE-CONTOUR MAP OF BASE OF PENNSYLVANIA STRATA IN NORTH-CENTRAL OKLAHOMA** (reduced from original 1:500,000-scale map).

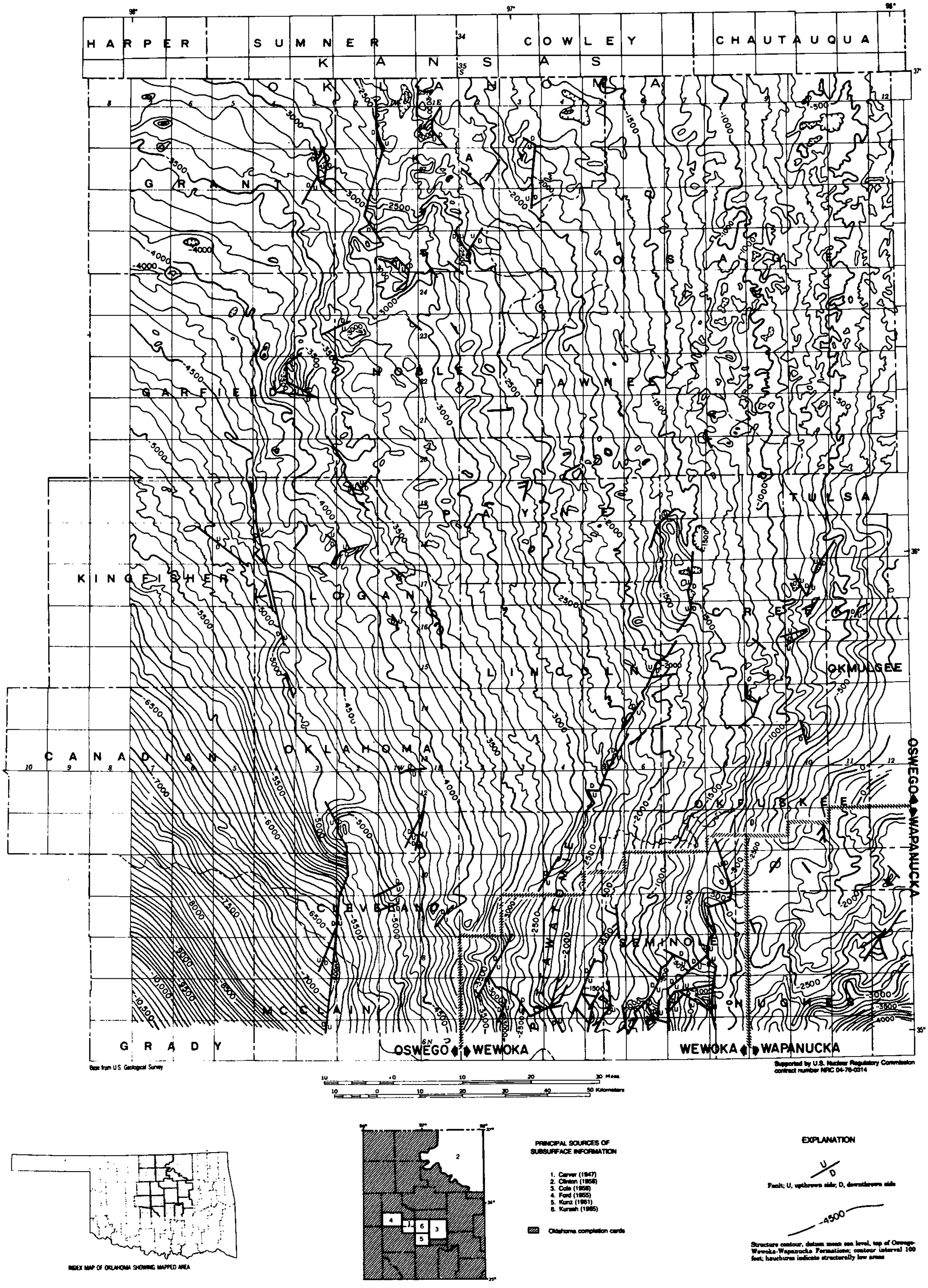


Fig 9. STRUCTURE-CONTOUR MAP OF TOP OF OSWEGO-WEWOKA-WAPANUCKA FORMATIONS (reduced from original 1:500,000-scale base).

deposition of Pennsylvanian sediments. The principal geologic formations that basal Pennsylvanian sedimentary rocks rest upon include the Hunton Group, the Woodford Shale, the Mayes Limestone, and the Caney Shale. The Ordovician and older formations generally occur beneath the Pennsylvanian in the major uplifted areas, such as the Oklahoma City Uplift. The pre-Pennsylvanian unconformity surface is relatively flat, and therefore generally reflects pre-Pennsylvanian structure (Pulling, 1979).

The top of the Oswego Limestone (Middle Pennsylvanian) was also chosen as a reference horizon because it is continuous laterally in north-central Oklahoma, easily recognizable on electric logs, and most often reported on Oklahoma completion cards.

The Oswego Limestone is the lowermost formation of the Marmaton Group. It is equivalent to the Fort Scott Formation and is an informal subsurface name widely used in Oklahoma. The Oswego is fairly uniform in thickness (50 to 80 feet; 15 to 25 m) and gradually thins southward, where it interfingers with interbedded sandstones and shales. In the Arkoma Basin, the Oswego thins abruptly along a line from T. 10 N., R. 9 E., into interbedded sandstones and shales of the Wewoka Formation. The top of the Wewoka was used as a mapping horizon principally in Pottawatomie and Seminole Counties. In the southeastern part of the area, the top of the Wapanucka Limestone was used as a mapping horizon because it is the youngest widespread limestone in the Arkoma Basin (see fig. 9).

Permian deltaic deposits composed of fine-grained sandstone, siltstone, and shale overlie Pennsylvanian strata in central Oklahoma. Very few electric logs exist for the Permian units in central Oklahoma. Because of the lack of continuous marker beds in the Permian as well as the poor subsurface control, we did not attempt to construct structure-contour maps of any of the Permian formations in this area.

Data from more than 20,000 wells were used to construct the three structure-contour maps. Information from Oklahoma completion cards (scout tickets) was used to supplement data from unpublished and published reports (figs. 7-9). Elevation tops for each unit were posted on 1:250,000-scale AMS maps and contoured. These data were adjusted to fit information from published and unpublished sources. After the final adjustments were made, all data were recompiled at a reduced scale of 1:500,000.

The structure-contour maps (figs. 7-9) reveal essentially two complex fault patterns. The westernmost pattern is related to the Nemaha Uplift. This fault pattern is dominated by several discontinuous uplifts such as the Oklahoma City, Lovell, Garber, and Crescent. 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. These blocks are generally bounded by near vertical faults on the east side that are downthrown to the east. These features form a fault zone that extends from Oklahoma City in a northwesterly direction to T. 18 N., R. 3 W. In this region, 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.

To illustrate some of the results of our subsurface investigations, we have selected a six-township area in central Oklahoma for more detailed discussion (figs. 10-12). We

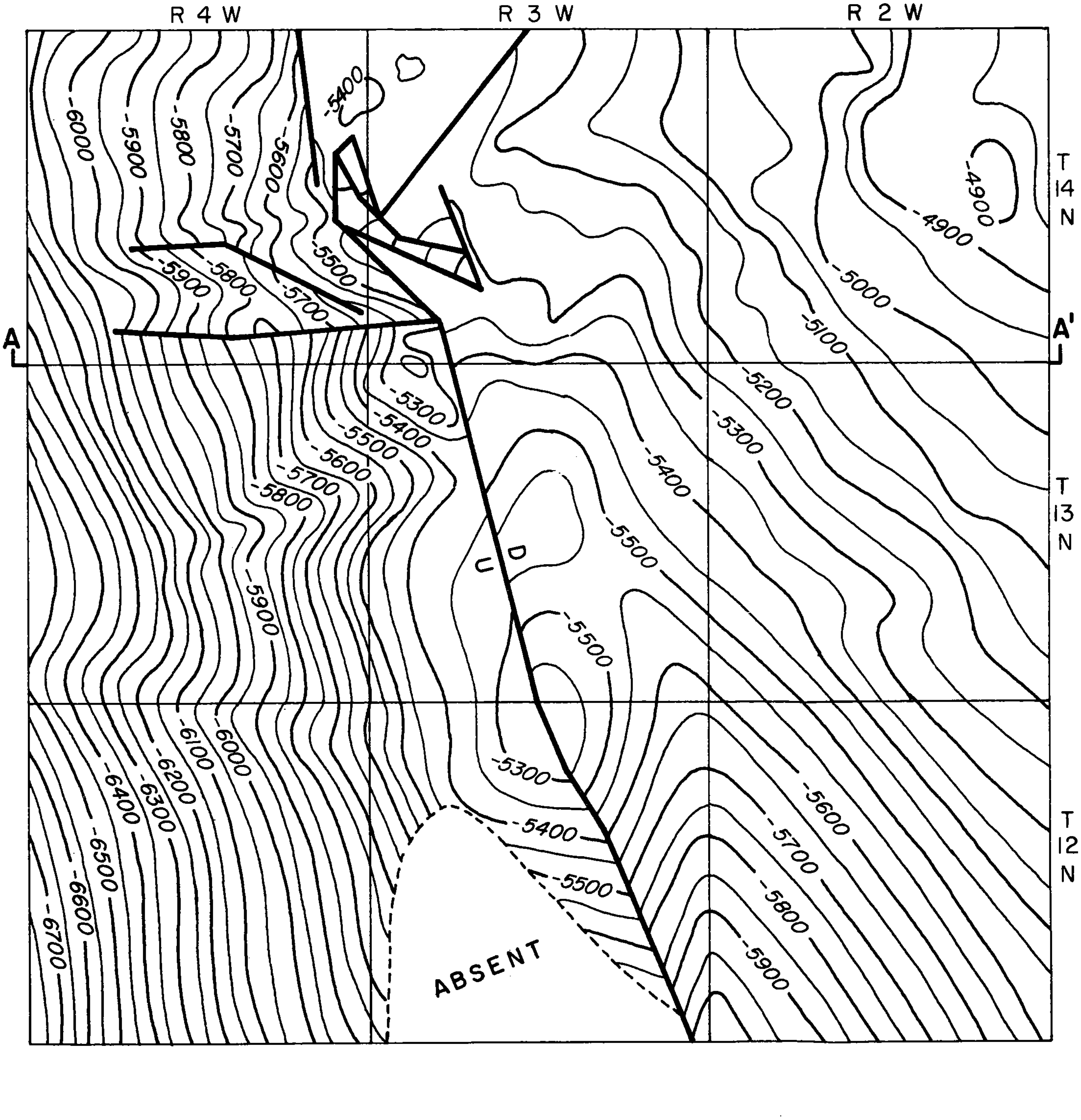


Fig. 10. Structure map, in feet, of top of Viola Formation in vicinity of Oklahoma City. Contour interval is 50 feet.

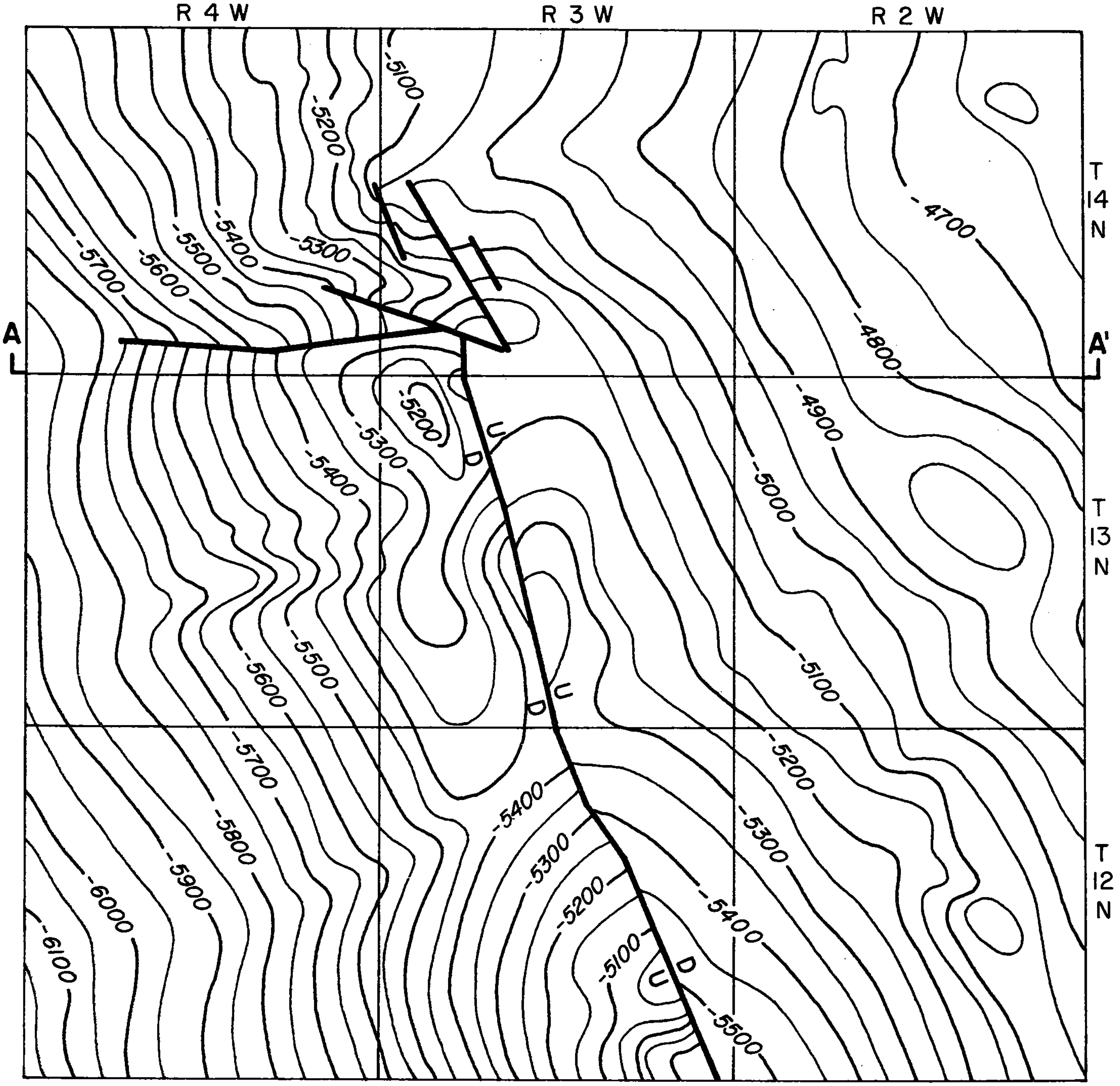


Fig. 11. Structure map, in feet, of base of Pennsylvanian System in vicinity of Oklahoma City. Contour interval is 50 feet.

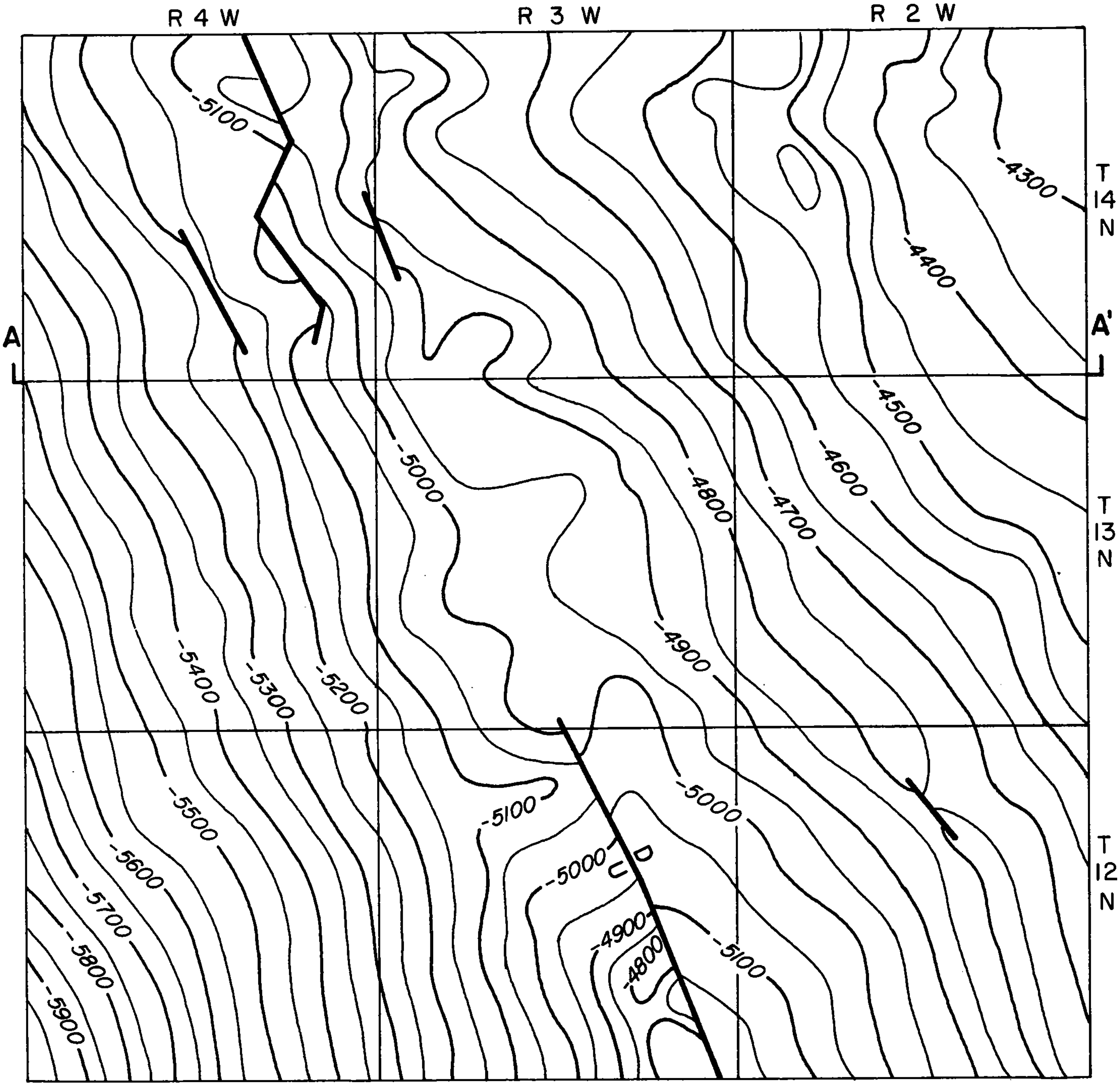


Fig. 12. Structure map, in feet of top of Oswego Formation in vicinity of Oklahoma City. Contour interval is 50 feet.

have also prepared a series of schematic cross sections that illustrate the geologic and tectonic history of this area (fig. 13).

The structure-contour maps reveal a complex fault pattern and geologic history in this area. The fault pattern is less complex higher in the geologic section, as shown by comparing the structure at the top of the Viola to that at the top of the Oswego (figs. 10-12). This is especially evident in T. 14 N., R. 3 W., where faults present in the Viola are absent in the shallower Oswego. Another major fault zone extends from T. 13 N., R. 3 W., through T. 12 N., R. 3 W. The northern part of this nearly vertical fault zone can be traced through the Viola up to the base of the Pennsylvanian, but it is not present in Middle Pennsylvanian (Oswego) strata. However, the southern part of this fault zone does cut Middle Pennsylvanian rocks, and there it shows two episodes of fault movement (Early and Middle Pennsylvanian). The Permian strata above the Oswego appear to be unaffected by faulting in this area.

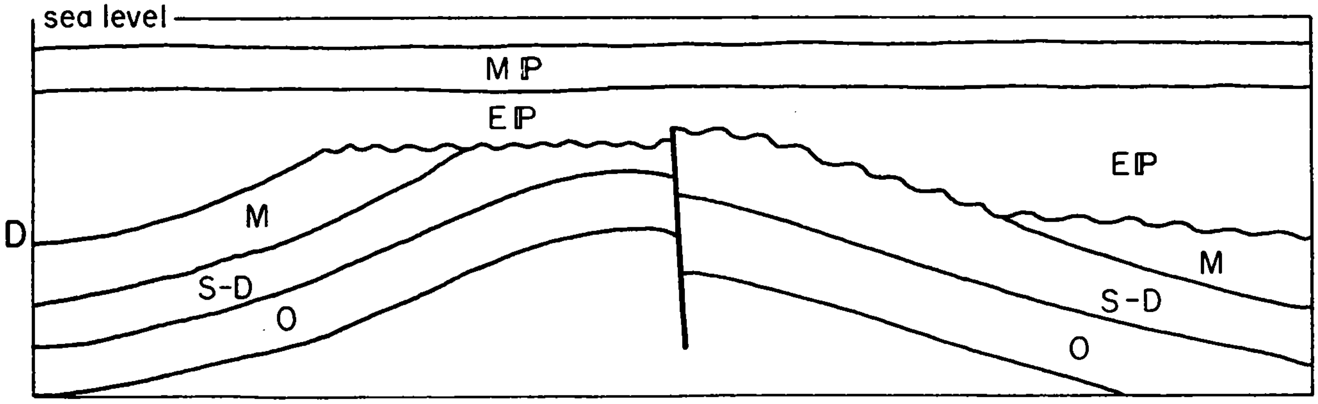
It can be demonstrated that the west block in the study area (fig. 13) was uplifted in Late Mississippian or Early Pennsylvanian time and that the Mississippian, Devonian, Silurian, and Ordovician strata were truncated during this episode of uplift and erosion. Early Pennsylvanian sediments then were deposited across the truncated blocks, and these sediments, in turn, were faulted along some of the preexisting Nemaha faults. However, the direction of movement was reversed, and the west block moved downward compared to the east block. Middle Pennsylvanian and Early Permian strata show no evidence of fault movement in this area.

A detailed subsurface study near the Oklahoma City Uplift, which typifies a number of uplifted features in central Oklahoma, was completed by Koff (1978). Koff, who utilized drill-hole information from approximately 1,100 wells, constructed several structure-history cross sections and paleostructure maps of the Arbuckle-Simpson interface in order to reconstruct the structural history of this region with emphasis on the origin of the structural elements as well as fault displacements.

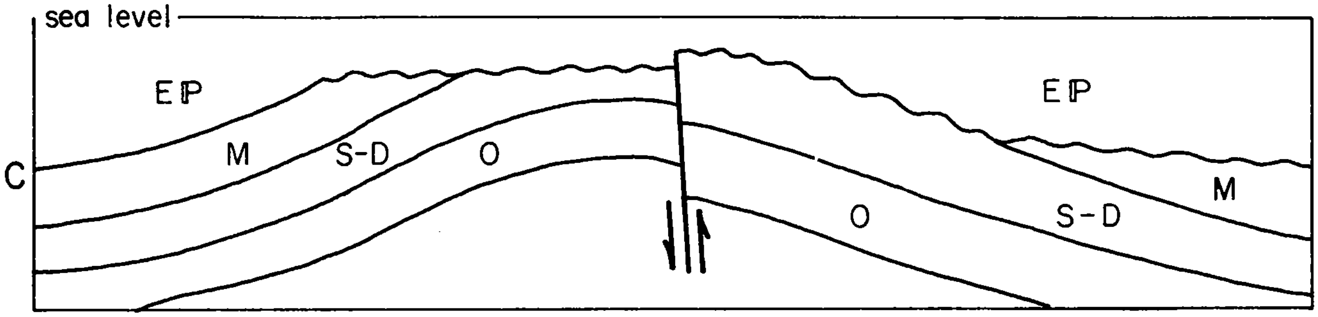
Koff's interpretation of the data resulted in the delineation of eight fault zones that can be grouped into two distinct categories based on the nature of displacements (fig. 14). Category 1, which includes the Oklahoma City and McClain County Fault zones (faults *A* and *B*, fig. 14), contains faults of constantly increasing displacement from early to late Paleozoic time. For example, the Oklahoma City Fault displacement was 1,700 feet (536 m) by the end of Oswego deposition and has now reached 2,300 feet (726 m) (figs. 15, 16). Category 2 faults, of which there are six, exhibit both increasing and decreasing displacements from early to late Paleozoic (figs. 15, 16). Except for faults *F* and *H*, more than 65 percent of the maximum total offset achieved on the faults occurred by the end of Oswego time (fig. 15).

The second major structural feature occurs in the east-central part of the study area. This feature was called the Wilzetta Fault by Cole (1969), Pulling (1979), and others. This fault feature was probably named after the Wilzetta Oil Field, discovered in 1934 and located in T. 13 N., R. 5 E., in southeastern Lincoln County. The Wilzetta Fault extends north-northeast diagonally across Pottawatomie, Lincoln, and western Creek Counties. This fault zone marks the westward extension of the Seminole-Cushing Ridge, which trends in a north-northeast direction and plunges northward away from the Pauls Valley Uplift (Pulling, 1979).

The Seminole-Cushing Ridge may have originated in Middle Devonian time, when a major epeirogeny occurred. The general uplift from the northeast may have given rise to southeastward dip in the Hunton and older rocks. Major folding took place during



END MIDDLE PENNSYLVANIAN



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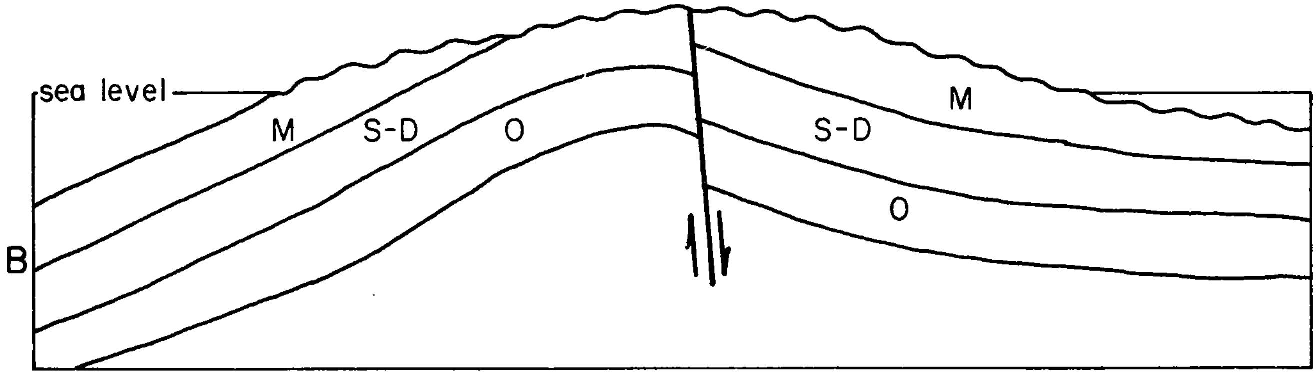
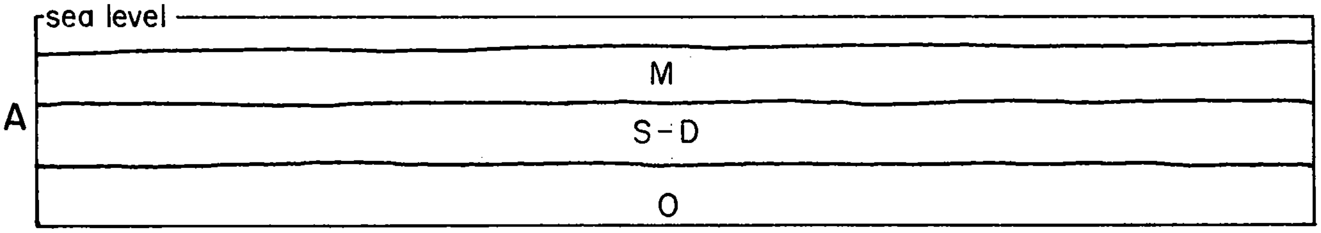


EARLY PENNSYLVANIAN



LATE MISSISSIPPIAN

Fig. 13. Schematic cross-sections at A-A' (see figs. 9-11 for location) illustrating geologic and tectonic history of this area. A, lower Paleozoic strata prior to uplift; B, uplift and erosion during Early Pennsylvanian time; C, fault movement is reversed; and D, Middle Pennsylvanian strata are unaffected by faulting.

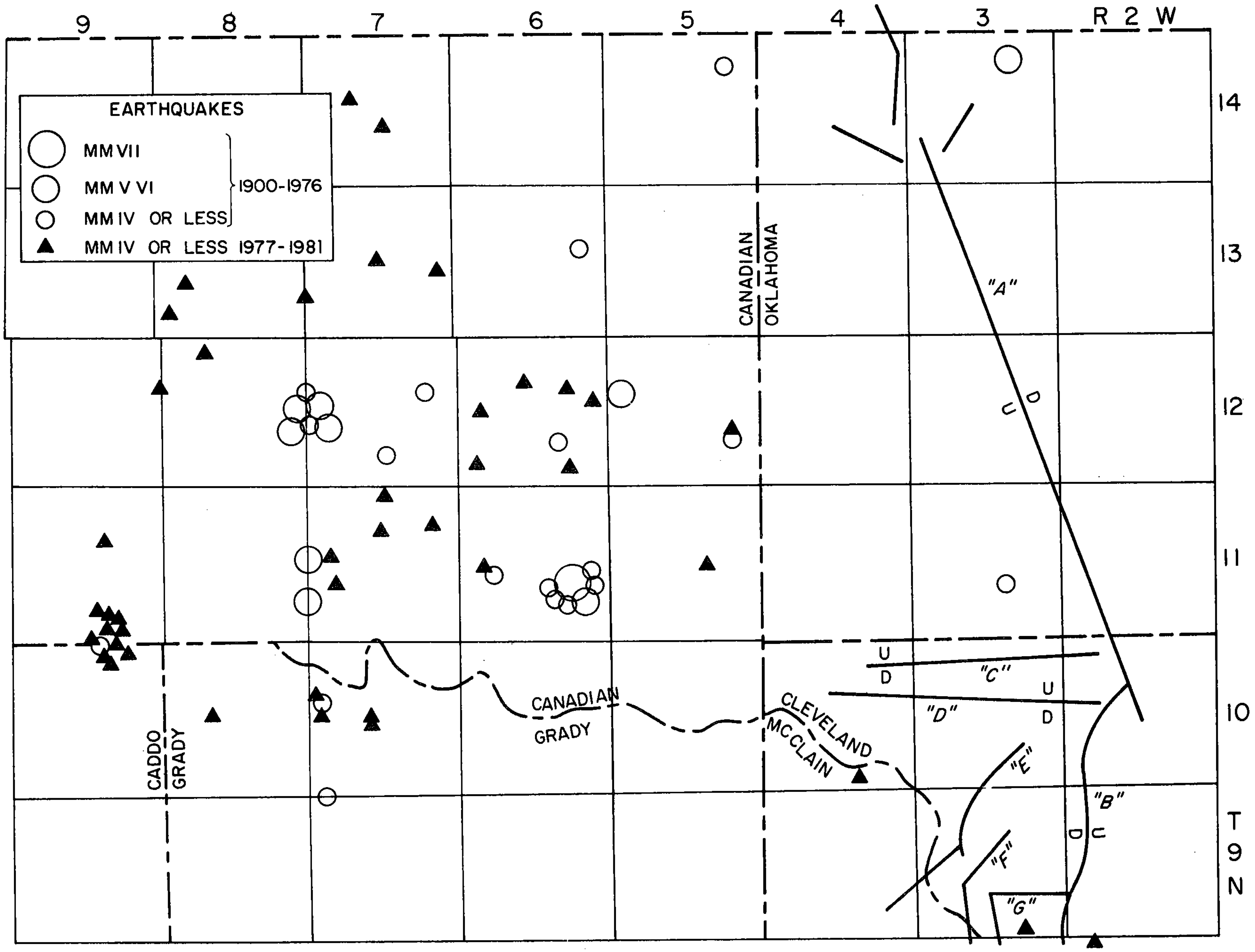
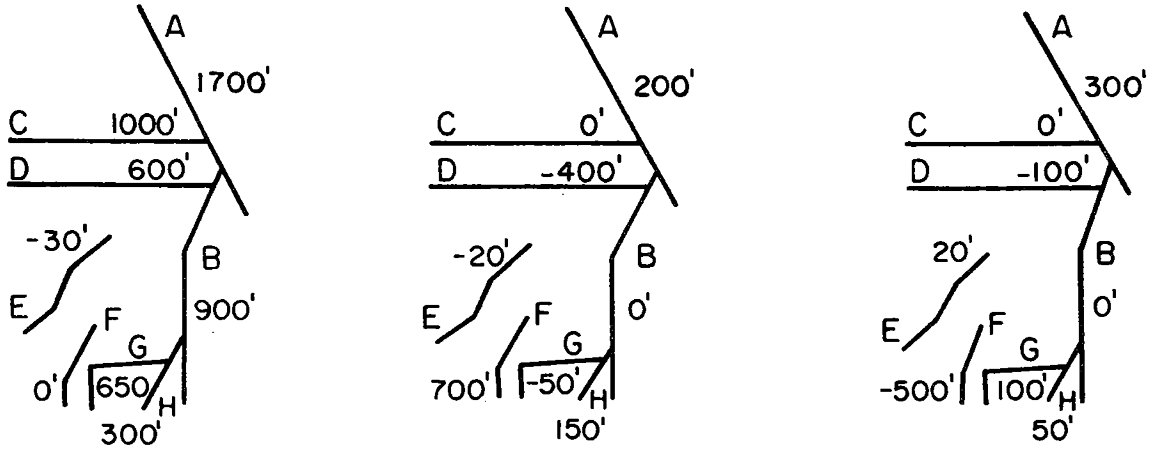


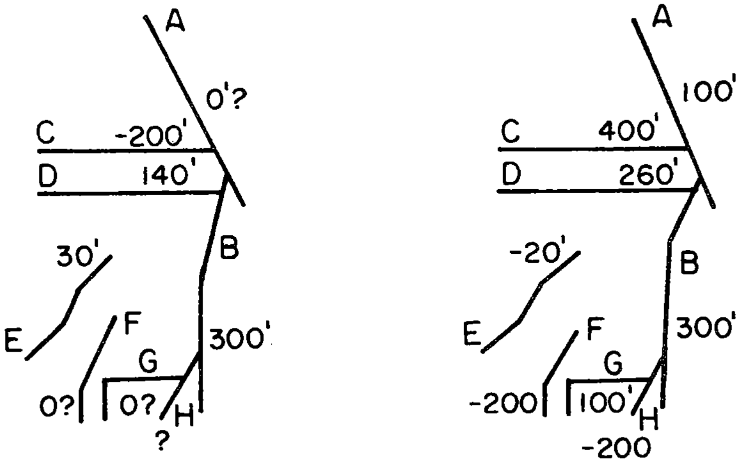
Fig. 14. Relationship of subsurface structures, identified by Koff (1978), to known earthquake epicenters.

SYSTEM	TIME	DEPOSITIONAL SEQUENCE	A	B	C	D	E	F	G	H
PRESENT			2300	1900	1300	700	100	100	800	500
PERMIAN	225									
	270	FORAKER	?	1600	900	540	150	?	?	?
PENNSYLVANIAN	280	OREAD	2200	1300	1100	400	120	300	700	700
	285	CHECKERBOARD	1900	1300	1100	500	100	800	600	650
	290	OSWEGO	1700	1300	1100	900	120	100	650	300
	305									
MISSISSIPPIAN	320									
DEVONIAN	345	HUNTON	?	400	100	300	150	100		
SILURIAN	400									
ORDOVICIAN	430	SYLVAN			0-50		150	100		
		VIOLA								
		SIMPSON GROUP			150		150			
CAMBRIAN U M	500	ARBUCKLE GROUP								

Fig. 15. Chart showing net maximum displacement of faults. Time is shown in millions of years; fault displacement is in feet.



(A) HUNTON-OSWEGO (B) OSWEGO-CHECKERBOARD (C) CHECKERBOARD—OREAD



(D) OREAD-FORAKER (E) FORAKER-PRESENT

Fig. 16. Net differences of fault displacements for selected time-depositional intervals in Oklahoma City area.

the Wichita Orogeny in post-Mississippian, pre-Desmoinesian time. The formation of northeast-southwest-trending structures, such as the Wilzetta Fault, is probably related to the Wichita Orogeny. Renewed movement along the Wilzetta Fault and slight uplift of the Seminole-Cushing Ridge occurred during Cherokee deposition as well as afterward (Pulling, 1979).

The Nemaha Ridge in northern Oklahoma, in Grant, Kay, Garfield, and Noble Counties, is composed of a number of discontinuous uplifted features 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 trends southeastward toward Oklahoma City (see fig. 8). Koff's study of the Oklahoma City Uplift, the southernmost extension of the Nemaha Ridge, and its associated fault features suggests that a number of the Nemaha-related faults were developed in pre-Mississippian time. Many of these faults exhibit both increasing and decreasing displacements from early to late Paleozoic time. However, the displacement for most of the Oklahoma City faults took place between the end of Oswego time and the end of Hunton time.

In Koff's (1978) detailed study of the Oklahoma City Uplift, an attempt was made to determine if there was a correlation with the subsurface structures and historical earthquakes (fig. 14). Unfortunately, the lack of subsurface control in Canadian County did not permit the construction of the detailed structure and isopach maps that are needed to make correlation studies.

Basement Rocks in Central Oklahoma

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 land surface near the Kansas border and is about 8,000 feet (2,440 m) deep near Oklahoma City. The most systematic basement-rock study that embraces the Nemaha Ridge area was done by Denison (1966, 1981), who examined and described samples from more than 220 wells that penetrated Precambrian rocks in adjoining parts of Oklahoma, Kansas, Missouri, and Arkansas. Twenty-five isotopic-age determinations were made on 20 samples of basement rocks from wells and outcrop.

The basement rocks in central Oklahoma are characterized by four igneous terranes, three granitic and one volcanic (fig. 17a, 17b). The basis for this characterization was petrographic examination of samples collected from 56 wells that penetrated the basement in this area and eight isotopic-age determinations. The isotopic ages range from 1,150 to 1,270 million years, and these dates, when considered with analytical variations, indicate a main period of thermal activity about 1,200 million years ago.

Denison (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. The Washington Volcanic Group consists principally of rhyolite porphyry, andesite, and metarhyolite. The subcrop beneath Paleozoic sediments forms two subparallel bands in the northeastern and southeastern parts of central Oklahoma (fig. 17a, 17b). Rhyolite, which exhibits relict welded-tuff textures, is the dominant lithologic unit in this group, whereas the metarhyolite is present in broad areas around the margins of the rhyolite.

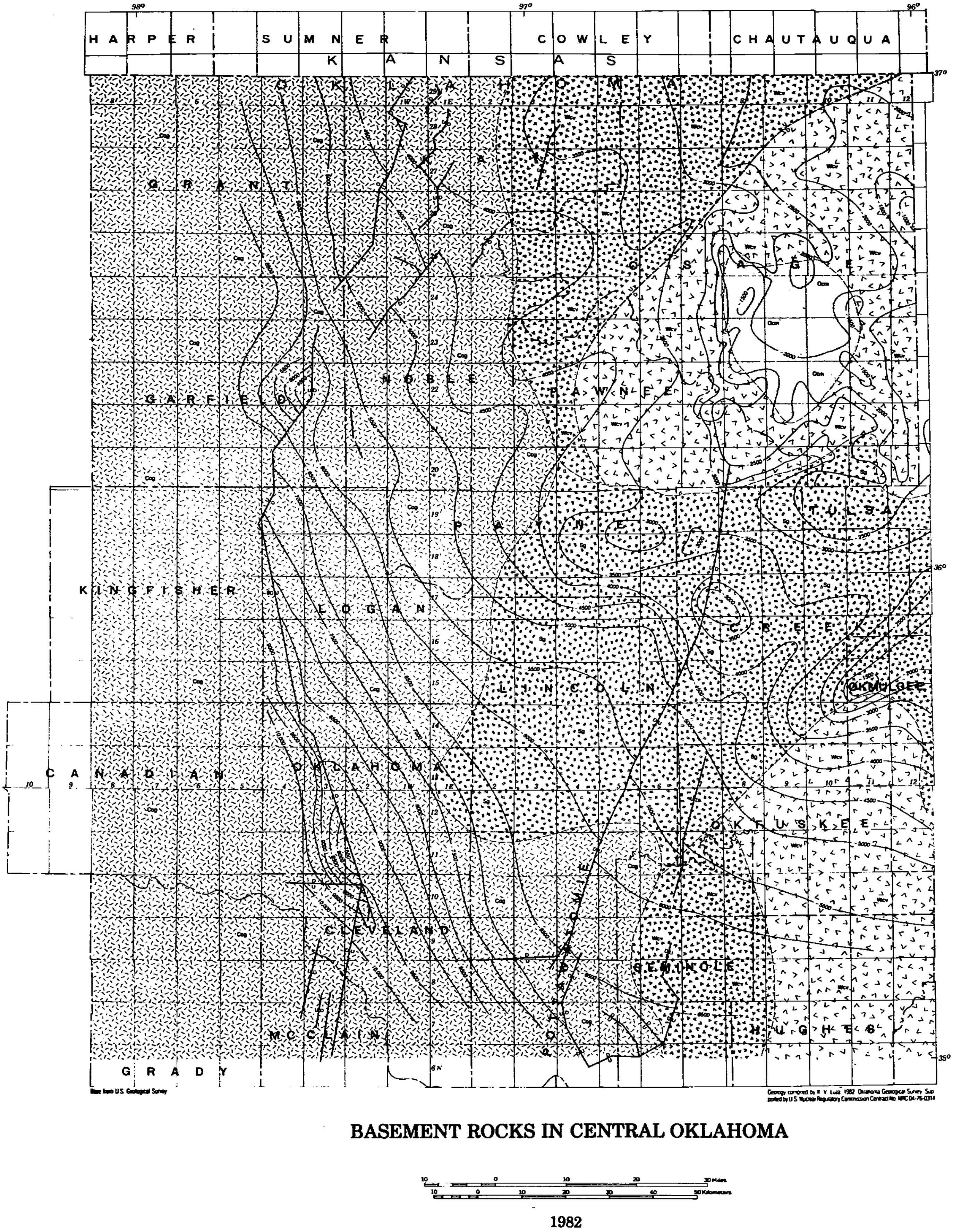


Fig. 17a. Basement-rock map of central Oklahoma (reduced from original 1:500,000-scale map).

EXPLANATION

Cog

Central Oklahoma Granite Group

Medium- to coarse-grained plutonic rock composed of microcline, quartz, sodic plagioclase, hornblende, and chloritized biotite with minor amounts of sphene, magnetite-ilmenite, apatite, zircon, and fluorite; locally sheared, particularly near fault zones, and intruded by diabase.

Ocm

Osage County Microgranite

Hypabyssal intrusive rock composed of phenocrysts of perthite and quartz in a fine-grained matrix characterized by rod-like quartz intergrown with perthite; primary biotite appears to be deuterically altered to chlorite.

Sg

Spavinaw Granite Group

Micrographic granite porphyries composed of perthite, plagioclase, and quartz phenocrysts in a fine-grained matrix of quartz and feldspar; some plagioclase crystals are altered to a mixture of sericite-clay-zeolite-epidote.

Wcv

Washington County Volcanic Group

Chiefly porphyritic rhyolite containing phenocrysts of perthite, sodic plagioclase, and quartz; the groundmass probably consists of quartz-feldspar intergrowths and/or devitrification products; the rhyolite is converted to metarhyolite near the contact with the Central Oklahoma Granite Group.

Inferred contact

U
D

Inferred fault (from lower Paleozoic structure—contour data); U, upthrown side; D, downthrown side; dashed where existence uncertain

6000

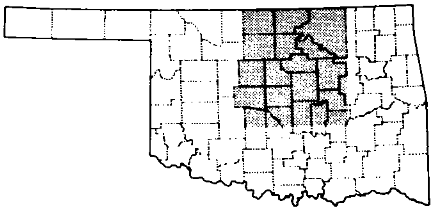
Structure contour; interval, 500 ft.; datum is mean sea level

Sources of Information:

Denison, R.E., 1981, Basement rocks in northeastern Oklahoma; Oklahoma Geological Survey Circular 84, 88 p.

Jordan, Louise, 1962, Geologic map and section of pre-Pennsylvanian rocks in Oklahoma, showing surface and subsurface distribution: Oklahoma Geological Survey map GM-5, scale 1:750,000.

Luza, K. V., and Lawson, J. E. Jr. 1981, Seismicity and tectonic relationships of the Nemaha Uplift, part III: Oklahoma Geological Survey Special Publication 81–3, 70 p.



INDEX MAP OF OKLAHOMA SHOWING MAPPED AREA

Fig. 17b. Explanation for basement-rock map (reduced from original 1:500,000-scale map).

The Spavinaw Granite Group is present in subcrop along a broad, presediment arch extending from southwestern Missouri into Oklahoma. The rocks in this group generally show micrographic and porphyritic textures. The homogeneity in composition and texture, coupled with erosional patterns, suggests that this unit was intruded into the Washington volcanic unit, perhaps as a sill.

A second intrusive rock, the Osage Microgranite, is the most distinctive and uniform rock type in the province. The subcrop extends over a 320-square-mile (830-km^2) area in Osage County. The microgranite is porphyritic and has a distinctive texture characterized by rod-like quartz crystals. Denison (1981) suggested that the microgranite probably was intruded between layers of the Washington Volcanic Group.

The youngest basement-rock unit in central Oklahoma is the Central Oklahoma Granite Group. This unit consists of a medium- to coarse-grained plutonic rock composed of microcline, quartz, sodic plagioclase, hornblende, and chloritized biotite. Adjacent rock units appear to be metamorphosed near the contact with the Central Oklahoma Granite Group, thus attesting the younger age of this unit.

There appears to have been no igneous or metamorphic activity following the 1,200-million-year-old intrusions in central Oklahoma. The 700-million-year interval between the last igneous activity and deposition of the earliest Paleozoic (Late Cambrian) sediments must have been characterized by uplift and by a considerable amount of erosion, particularly in central Oklahoma.

There are few borehole penetrations into basement rock in central Oklahoma. Therefore, basement-rock lithologies, contact relationships, and structural interpretations in the vicinity of the Nemaha Uplift are highly interpretive (fig. 17a, 17b). Regional contact relationships suggest that the Central Oklahoma Granite must have intruded into several kilometers of overlying rock, namely the Washington Volcanic Group. The intruded rocks are not present above the Central Oklahoma Granite in the vicinity of the Nemaha Ridge. Perhaps this region was uplifted between late Precambrian to Early Cambriantime. Subaerial erosion probably was a primary factor that contributed to the removal of the overlying volcanic units before deposition of Middle Cambrian sediments. Perhaps zones of weakness, which developed from the initial uplift (late Precambrian to Early Cambrian), were reactivated during the Early Pennsylvanian Orogeny to form the main axis of the Nemaha Ridge.

Landsat Imagery Study

Most major geologic structures in north-central Oklahoma can be defined only by a detailed subsurface analysis. An attempt was made to relate linear and (or) curvilinear features, identified on Landsat imagery, to geologic structure.

The study area, which encompasses approximately 13,000 square miles (33,672 km^2), includes Oklahoma City near the southeastern corner and Great Salt Plains near the northwestern corner (see fig. 18 for approximate location). The 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.

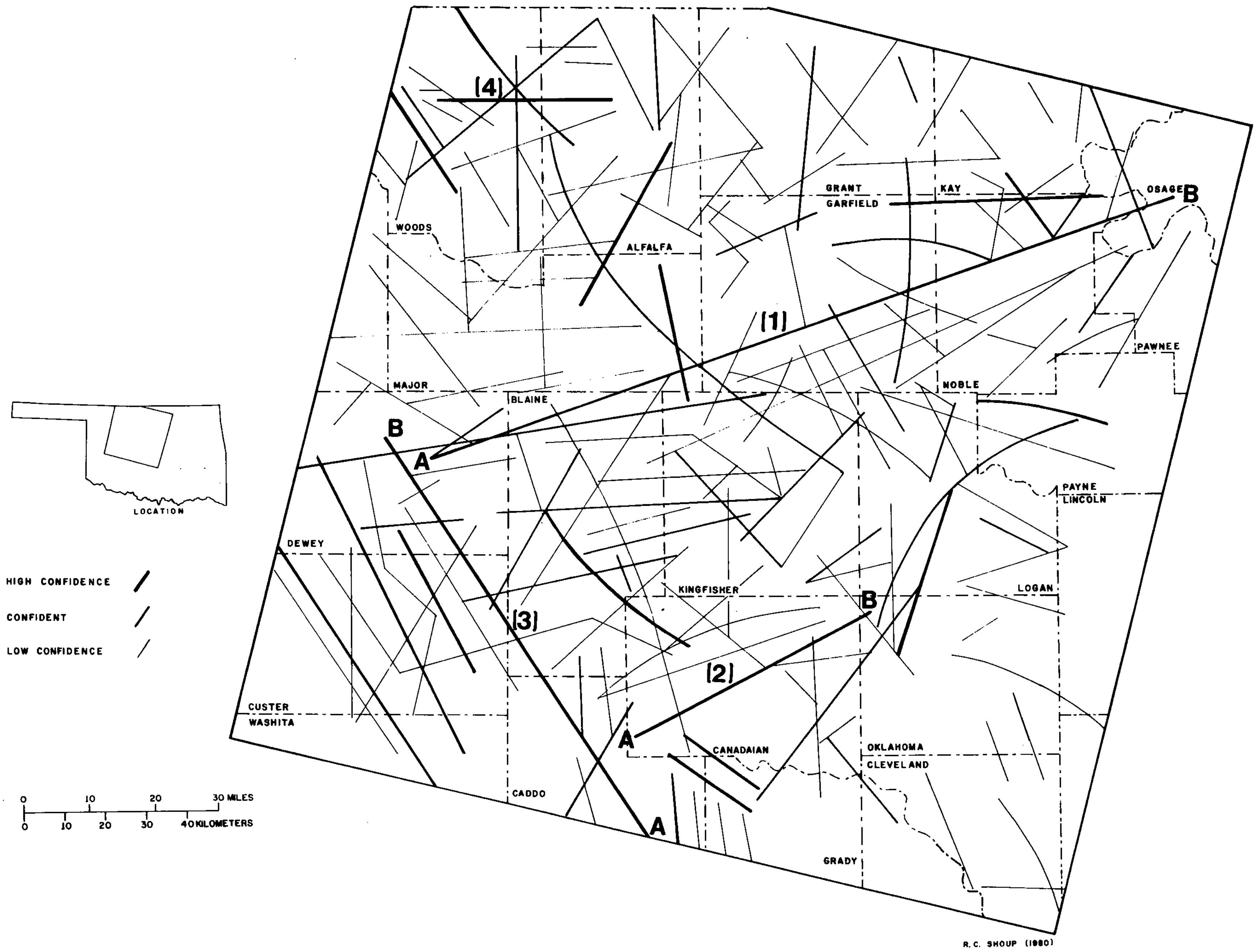


Fig. 18. Lineament map for north-central Oklahoma. Three categories of lineaments (high, confident, and low) are portrayed on map (Shoup, 1980). Detailed studies include (1) trans-Oklahoma lineament, (2) El Reno lineament, (3) Oklahoma-Louisiana lineament, and (4) Woods County lineaments.

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. 18). 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° 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 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. 18). 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 tonal 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 in 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 expresssed 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 30 to 150 feet (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-southwestward-plunging anticlinal 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 orientation 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 follows 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 (-1,617 m) in T. 15 N., R. 4 W., to -11,300 feet (-3,447 m) in T. 12 N., R. 8 W. The dip is fairly consistent at 250 feet per mile (47 m/km), and the strike through 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 (-1,373 m) in T. 15 N., R. 4 W., to -8,000 feet (-2,440 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), 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 1½ 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, 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 imagery 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.

GRAVITY AND MAGNETICS

Kingfisher and Medford Maxima

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. 19 for regional gravity map). It was hoped that more detailed information would give better insight into 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 total-field magnetometer were used to collect the data. Data were corrected for instrumental and diurnal variations and elevation, and a Bouger gravity-anomaly map (fig. 20) 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 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

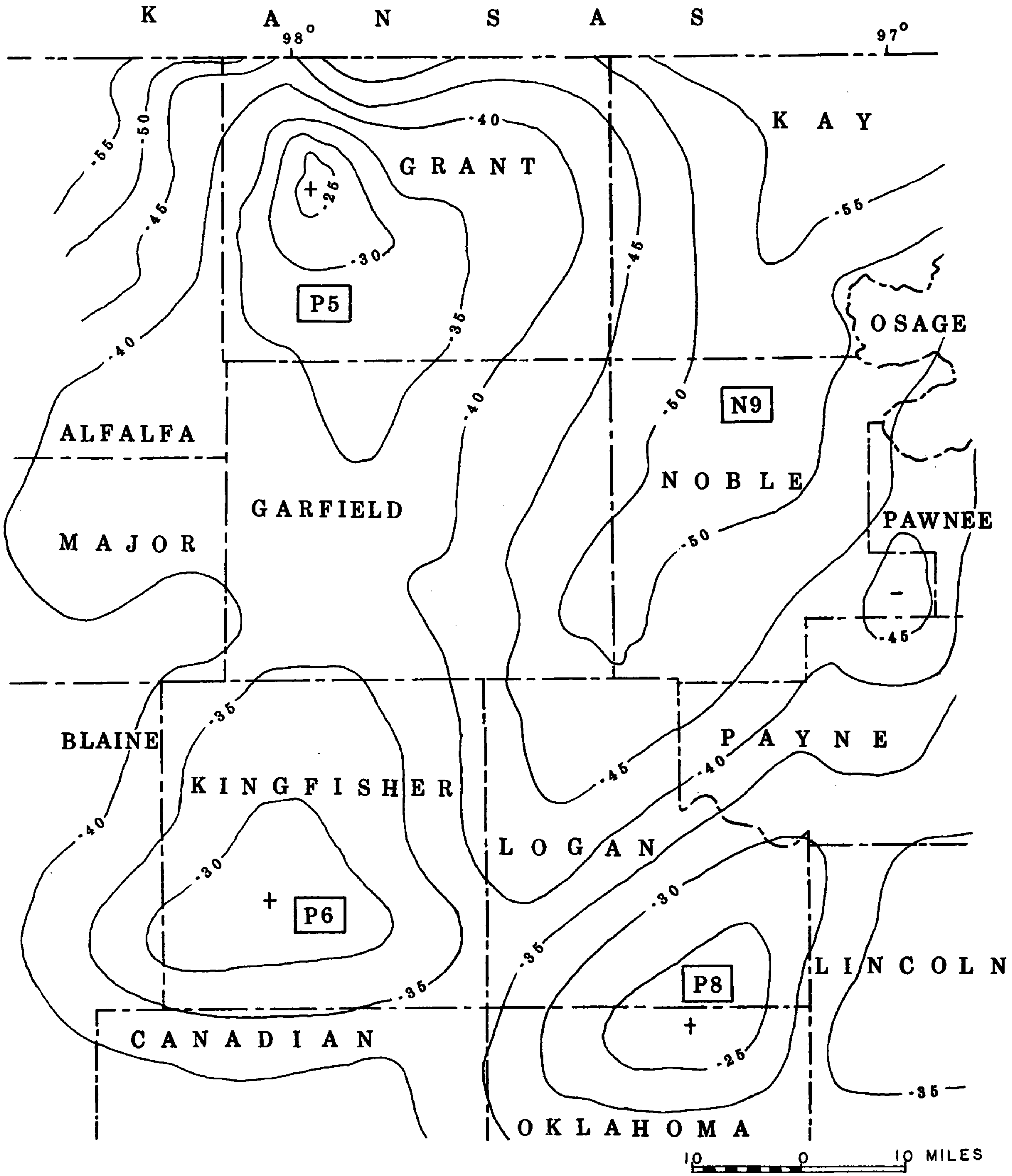


Fig. 19. Gravity anomalies: Medford maximum (P5), Kingfisher maximum (P6), Edmond maximum (P8), and granite ridge mimimum (N9), identified by Lyons (1964). Countour interval is 5 milligals.

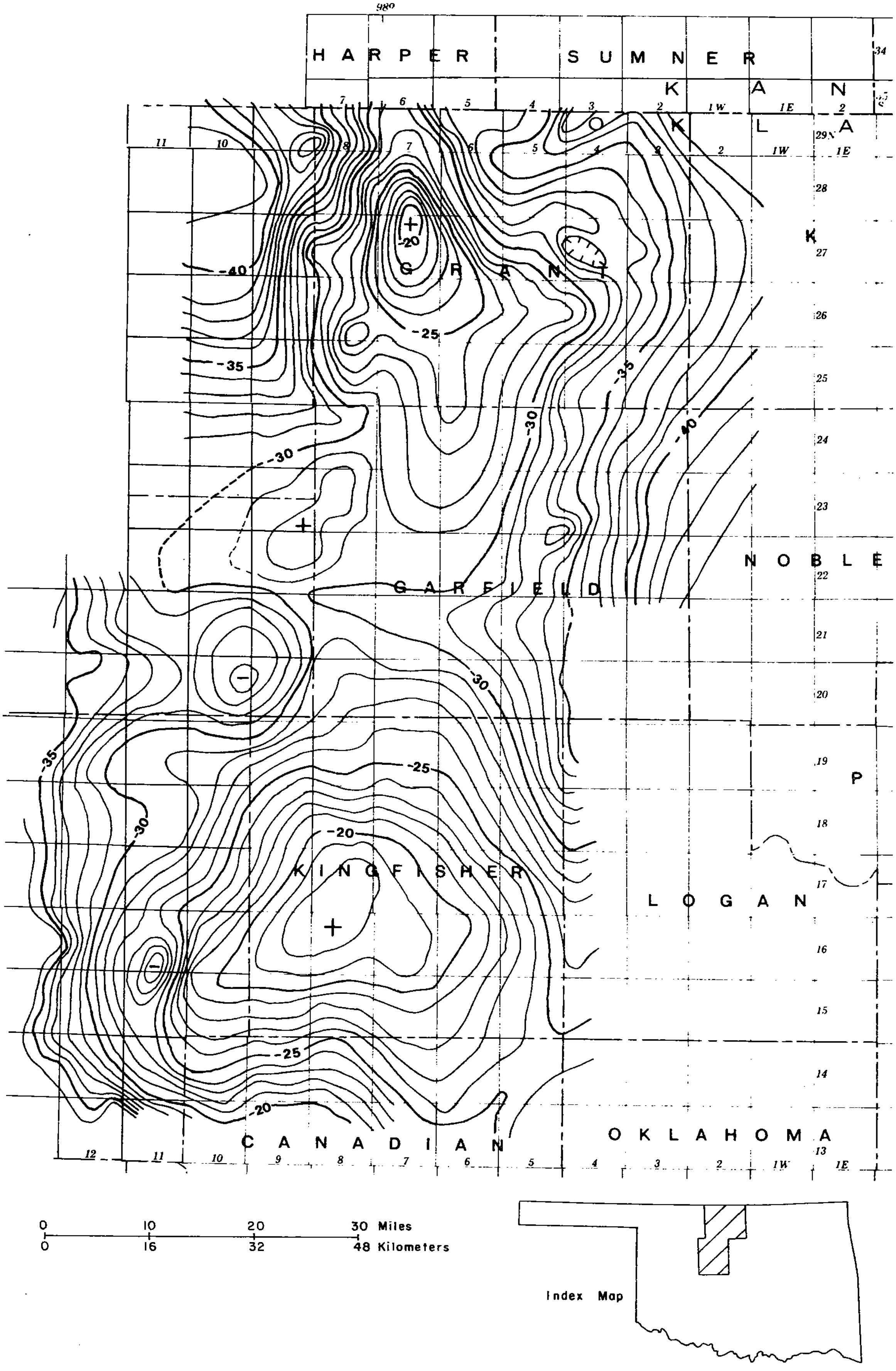


Fig. 20. Bouguer gravity-anomaly map of north-central Oklahoma. Modified from Barrett (1980) and Santiago (1979). Contour interval is 1 milligal.

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 x 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.

Edmond Maximum

In 1980, a third gravity and magnetic study was initiated. The study area included Canadian County, site of numerous earthquakes, and the Edmond maximum (fig. 19).

Hayden (1982) established 301 gravity and magnetic stations in Canadian County and parts of Caddo, Oklahoma, Cleveland, Lincoln, Payne, and Logan Counties. Stations were spaced 3 miles (14.8 km) apart around the periphery of each 36-square-mile (93 km^2) township. Data were corrected for instrumental and diurnal variations and elevation, and a Bouguer gravity-anomaly map (fig. 21) and a total-intensity magnetic-anomaly map were constructed. A vertical-prism-styled modeling algorithm (Cordell and Henderson, 1968) was used to interpret the gravity data. The Bouguer and magnetic data were superimposed in order to define coanomalous units, which further aided in the interpretation. A coanomalous unit is one that contains two or more areally coincident geophysical anomalies (Watkins, 1964).

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. On the other hand, the crust underlying the southwestern quadrant, 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.

The pattern of geophysical anomalies in the northeastern quadrant reflects not only structural heterogeneity (Nemaha Fault system) but intrabasement compositional variations. The gravity and magnetic lows in the northeastern quadrant may be

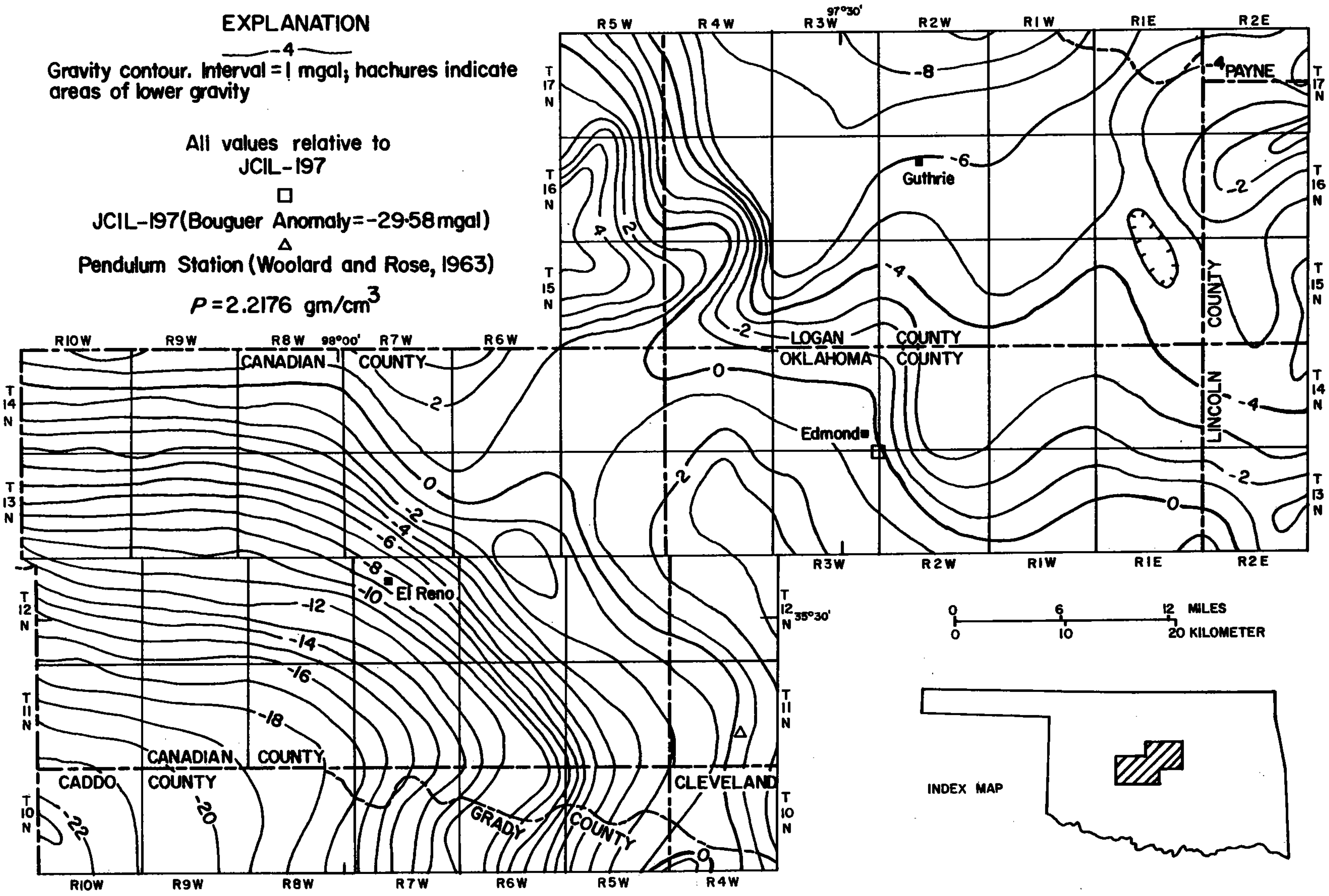


Fig. 21. Bouguer gravity-anomaly map of Canadian County and vicinity (modified from Hayden, 1982).

attributable to (1) lithological variations in the basement rocks, (2) sedimentary rocks draping over the basement uplift, and (or) (3) both. Conversely, the isolated gravity and magnetic highs over the Nemaha structures are interpreted to be (1) structural relief over the Nemaha Uplift and (or) (2) intrasedimentary density and susceptibility contrasts resulting from erosion.

No large magnetic anomalies dominate the southwestern quadrant. Significant gradient changes in the magnetic data along a northwest-southeast trend suggest faulting within the basement. A two-dimensional analysis of the Bouguer gravity data also indicates a fault-like structure in the southwest region. The structure appears to be a step discontinuity within the basement complex and trends northwest-southeast. The structure is about 22,300 feet (6.8 km) deep, which places the top of the anomalous body below the basement surface.

The feature in the southwestern quadrant occurs in close proximity to the observed earthquake activity. Furthermore, the basement discontinuity closely parallels the shelf-Anadarko Basin interface. Since this region does not appear to be in isostatic equilibrium, perhaps the crust is trying to attain equilibrium. As a possible consequence of this process, earthquakes occur along this discontinuity.

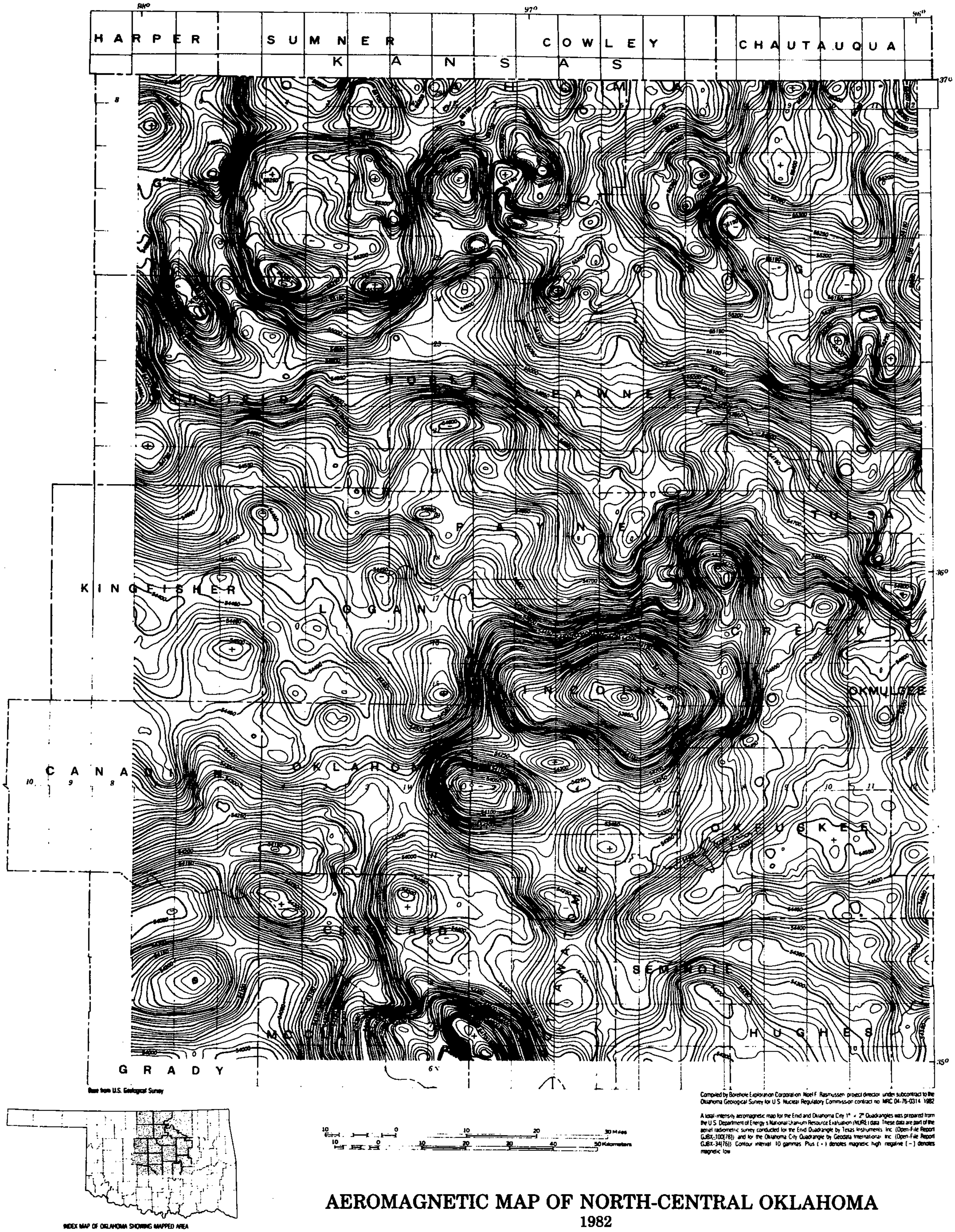
Aeromagnetic Survey

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 (fig. 22). 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 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 type. 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



Compiled by Borehole Exploration Corporation, Noel F. Rasmussen, project director, under subcontract to the Oklahoma Geological Survey for U.S. Nuclear Regulatory Commission contract no. NRC 04-76-0314. 1982

A total-intensity aeromagnetic map for the Enid and Oklahoma City 1° × 2° Quadrangles was prepared from the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) data. These data are 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)). Contour interval 10 gammas. Plus (+) denotes magnetic high; negative (−) denotes magnetic low.

AEROMAGNETIC MAP OF NORTH-CENTRAL OKLAHOMA
1982

Fig. 22. Aeromagnetic map of north-central Oklahoma (reduced from original 1:500,000-scale map).

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 23.

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 handpicked from the displayed profile without damaging the real signals.

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

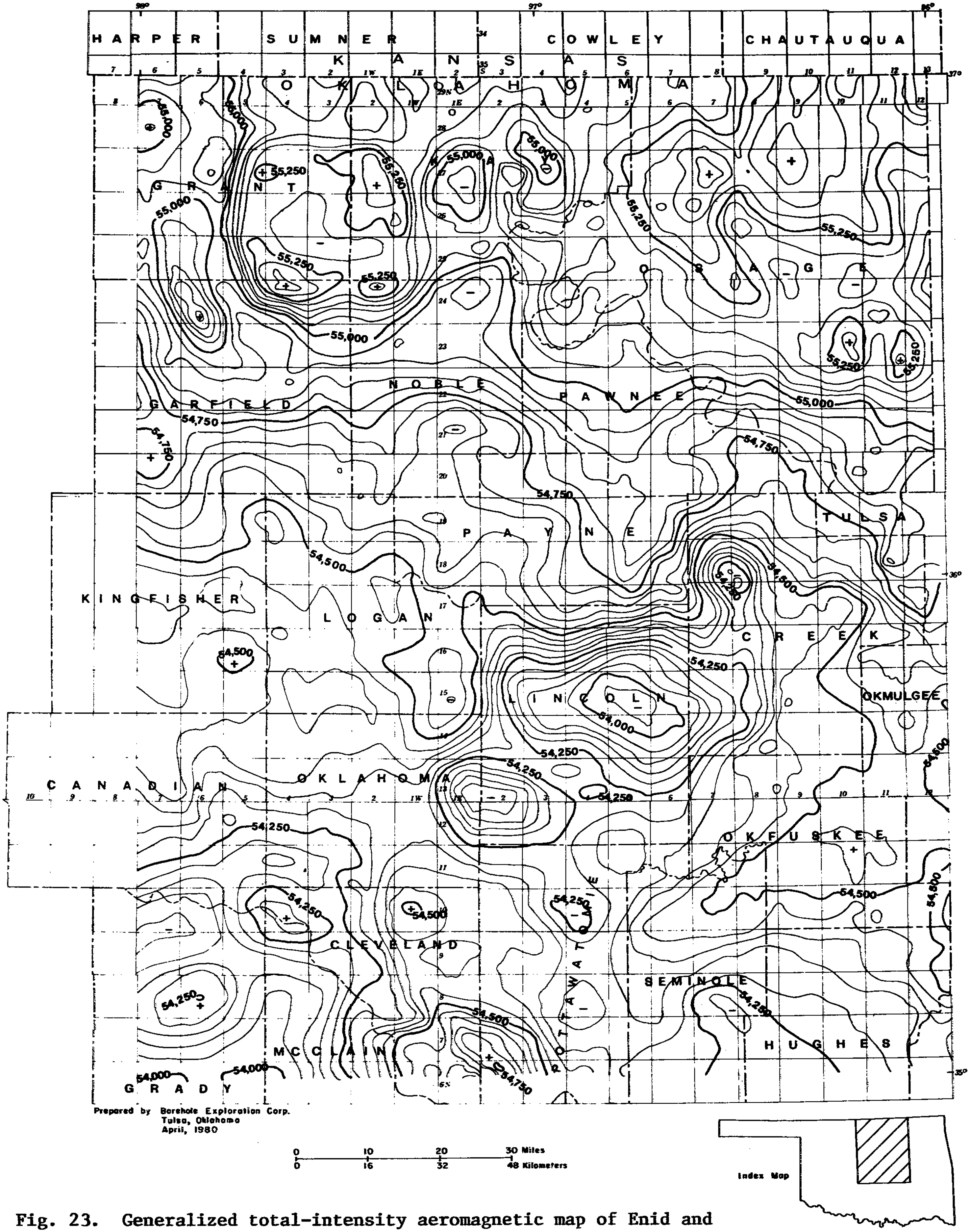
1. A constant value was added to all grid points to increase the datum so that the magnetic values were nearly matched.
2. A plot of the grid values for both quadrangles was made.
3. The values were hand contoured.
4. The magnetic values were adjusted to match at the quadrangle boundaries; the new values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

<u>Interpretation.</u>—The magnetic data were used to prepare an interpretive map that shows high and low magnetic anomalies, fault patterns, and basement-rock lithologies (fig. 24). Many of the features displayed on the map correspond with the previously known basement structures and lithologies. The following is a more 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 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 lithologic 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 area 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



Prepared by Borehole Exploration Corp.
Tulsa, Oklahoma
April, 1980

Fig. 23. Generalized total-intensity aeromagnetic map of Enid and Oklahoma City 1° x 2° Quadrangles. Contour interval is 50 gammas.

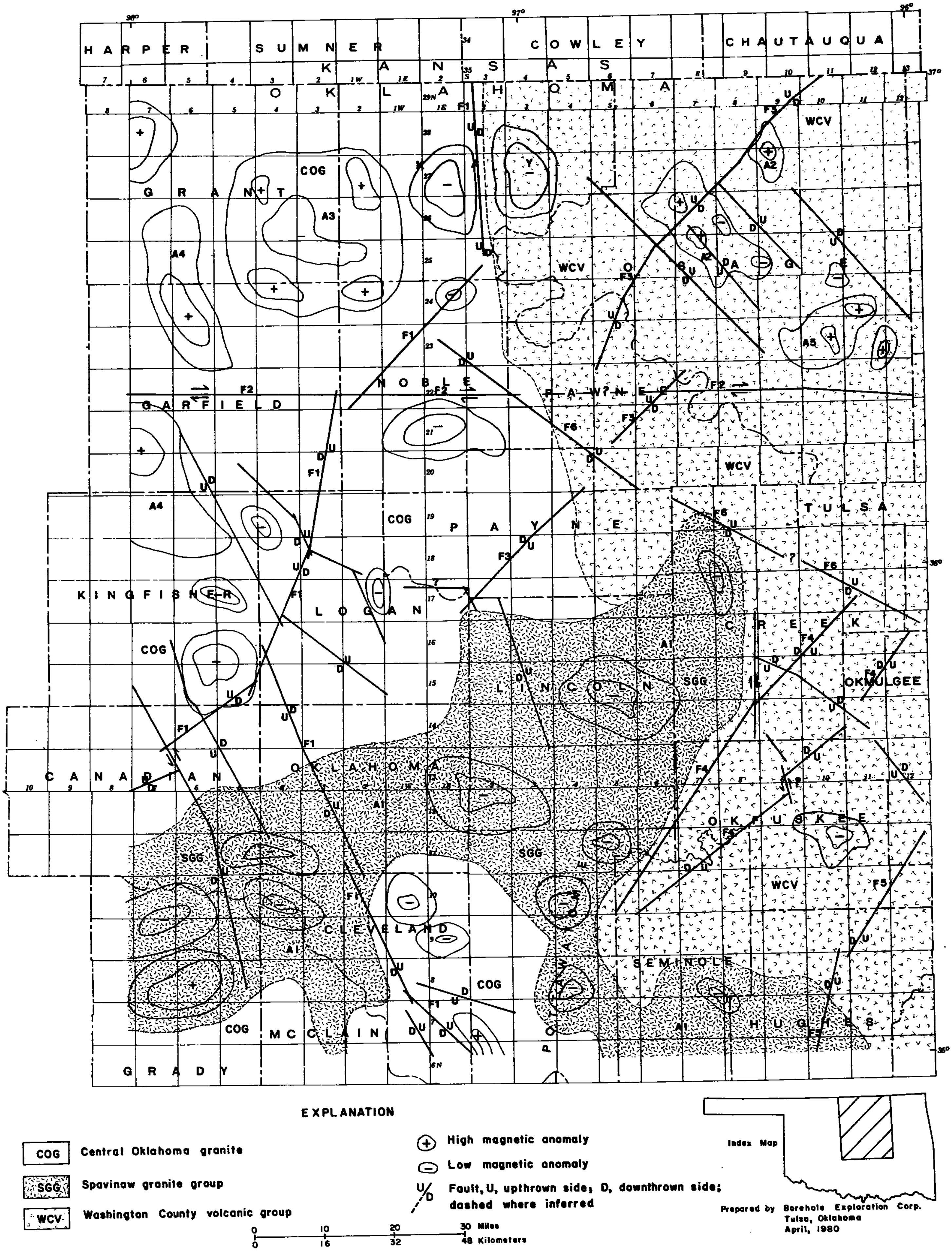


Fig. 24. Interpretive map showing high and low magnetic anomalies, fault patterns, and basement-rock lithologies.

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 resistant 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 offsest 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 Volcanic Group (rhyolite flows).

Concluding Remarks.—Interpretation of the magnetic data from the Oklahoma City and Enid Quadrangles has yielded results consisting of lithologic contacts, magnetic highs and lows, and fault patterns shown by map symbols in figure 24. A summary of the major conclusions that resulted from this study is listed below.

1. Three lithologic units are clearly defined by the change in the magnetic intensity on the aeromagnetic map (fig. 23). They include the Washington 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.

SEISMOLOGY

Introduction

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 additional seismograph stations would greatly improve earthquake detection for Oklahoma. Perhaps the earthquake data, when used in conjunction with the geologic, gravity, and magnetic information, may lead to an understanding of the causes of past and future seismicity.

The Oklahoma network of seismograph stations consists of three distinct parts. One part is the Oklahoma Geophysical Observatory (TUL). The Observatory, located near Leonard, Oklahoma, in southern Tulsa County, operates seven seismometers, three long period and four short period. The seismometers are located in a vault detached from the main building. 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 constitute parts two and three of Oklahoma's regional network. The signals from the three radiolink stations are recorded on five drum recorders at the observatory,

Semipermanent Stations

In our initial site-analysis study, which incorporated earthquake-detection levels, we proposed to install eight seismometers in such a way as to include detailed coverage of the entire Nemaha Ridge as well as most of the remaining area of Oklahoma (table 1; fig. 25). This network of seismograph stations would allow the following capabilities: (a) marginal detection of all m3Hz 1.7 earthquakes, (b) reliable detection of all m3Hz 2.0 earthquakes, (c) marginal location of all m3Hz 1.8 earthquakes, and (d) reliable detection of all m3Hz 2.1 earthquakes. It was anticipated that the maximum detection capability of the network would overlap into Kansas, and provide, with the Kansas and Nebraska networks, continuous coverage of the Nemaha Ridge area. Our qualitative experience suggests that detection and location have been about 0.1 magnitude units better than listed in table 1 for Oklahoma. The present Kansas and Nebraska network stations, which varied considerably from the proposed seismic network (fig. 25), were concentrated in eastern Kansas and southeastern Nebraska. During actual network operation, all of eastern Kansas would be at level 1, with western Kansas at level 4. Southeastern Nebraska may be only at level 3 because several stations were intermittent and were in areas of moderately high cultural noise.

To determine the performance of the Oklahoma Network, the cumulative number of all Oklahoma earthquakes of a given magnitude or greater were tabulated for the four-year period 1978-81. The 1977 earthquake data were omitted because network stations were being established as late as September 1977. During this four-year period, 228 located earthquakes had a calculated m3Hz magnitude. The cumulative numbers

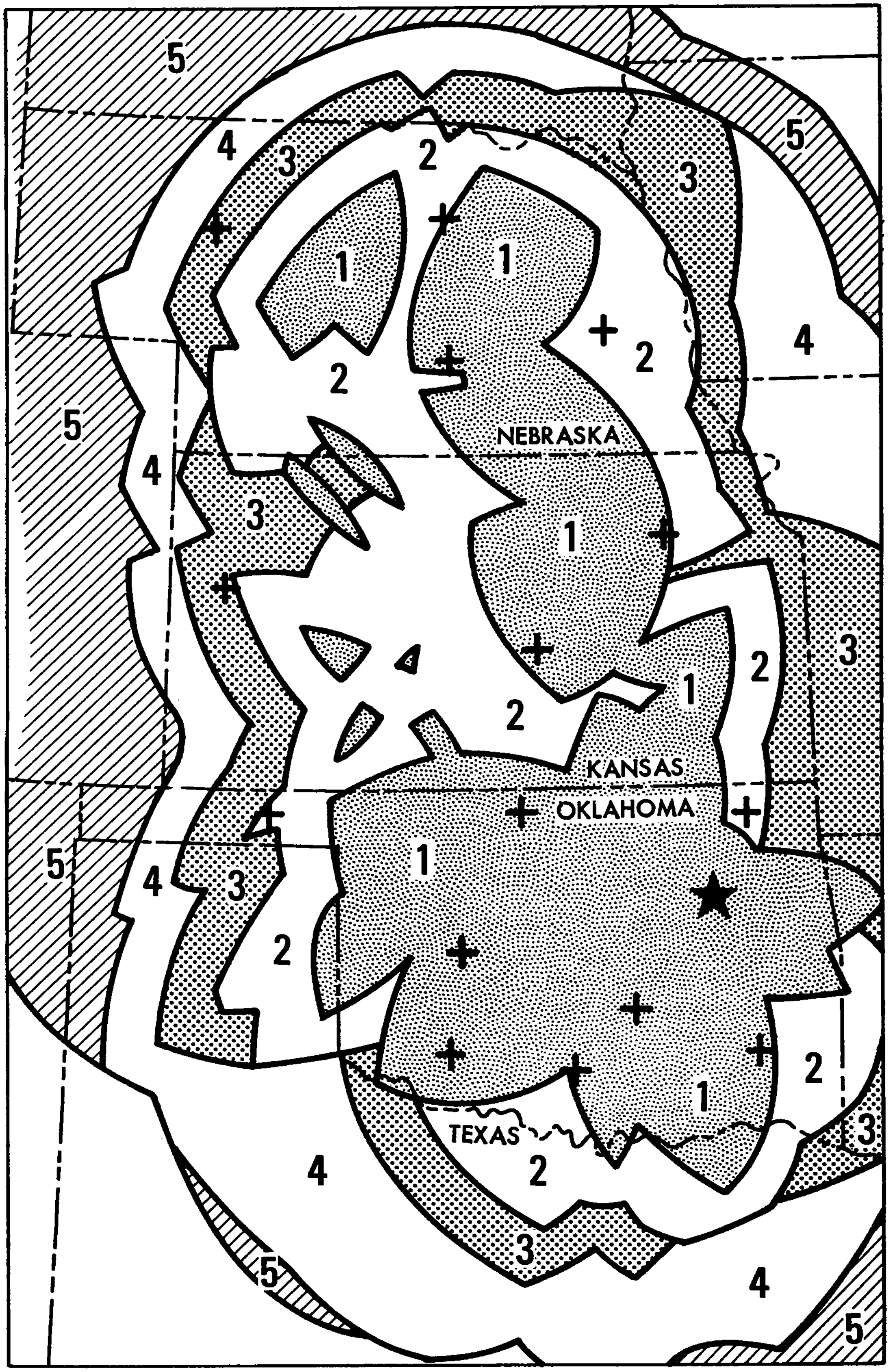


Fig. 25. Map of proposed seismic network, showing levels of coverage defined in table 1. Semipermanent stations proposed are shown by + symbols, and Oklahoma Geophysical Observatory at Leonard is indicated by ★.

Table 1. Levels of coverage for high-pass vertical (HPZ) seismograph network

Level no.	Maximum distance to one station	Maximum distance to each of two other stations	Smallest magnitude m3Hz earthquake detected		Smallest magnitude m3Hz earthquake located	
			Marginal	Reliable	Marginal	Reliable
1	150 km	200 km	1.7	2.0	1.8	2.1
2	200 km	250 km	1.8	2.1	1.9	2.2
3	250 km	300 km	1.8	2.2	2.0	2.3
4	320 km	350 km	2.0	2.3	2.1	2.4
5	300 km	350 km	2.0	2.3	No location capability	

are plotted on figure 26. The log-cumulative number vs. magnitude graph follows the expected straight line from about m3Hz 1.9 to m3Hz 3.0. This strongly suggests that all earthquakes of m3Hz 1.9 or greater in Oklahoma were detected and located. At m3Hz 1.5, the graph indicates that 450 earthquakes were expected; however, only 228 were detected and located. Thus, at m3Hz 1.5, about 50 percent of the earthquakes that probably occurred were detected and located. If we consider 50 percent location "marginal," all of Oklahoma was at coverage level 1 or better as defined by table 1.

The other magnitudes—mbLg (168 earthquakes) and MDUR (232 earthquakes)—were similarly plotted. They showed no significant difference in detection and location levels. The cumulative number of m3Hz-magnitude earthquakes for one limited area (Canadian County) were plotted on figure 26. The location levels for Canadian County are similar to those for all of Oklahoma.

Operator-Selection Process.—Door-to-door or telephone inquiries were made to prospective volunteer operators who lived near each potential seismograph area. The selection process was based on the following criteria: (1) location within the area at a site relatively free of cultural noise with bedrock near the surface if possible; (2) agreement to locate a seismometer vault on their own or their employers' property (with appropriate permission); (3) an inside place for the amplifier-filter-recorder-clock system and the WWV time-signal receiver; and, (4) utilizing their own services for changing and labeling seismographs and correcting the clock, as closely as possible on a 365-day-per-year basis. We did not attempt to work with high schools, junior colleges, or four-year colleges because they generally do not have sites of low cultural noise.

In cases where the prospective volunteer operator was an employee of the Oklahoma State Park system or the Oklahoma Forestry Service, the prospective volunteer was contacted first to avoid any possibility of a supervisor's imposing seismograph operation as a work-related duty.

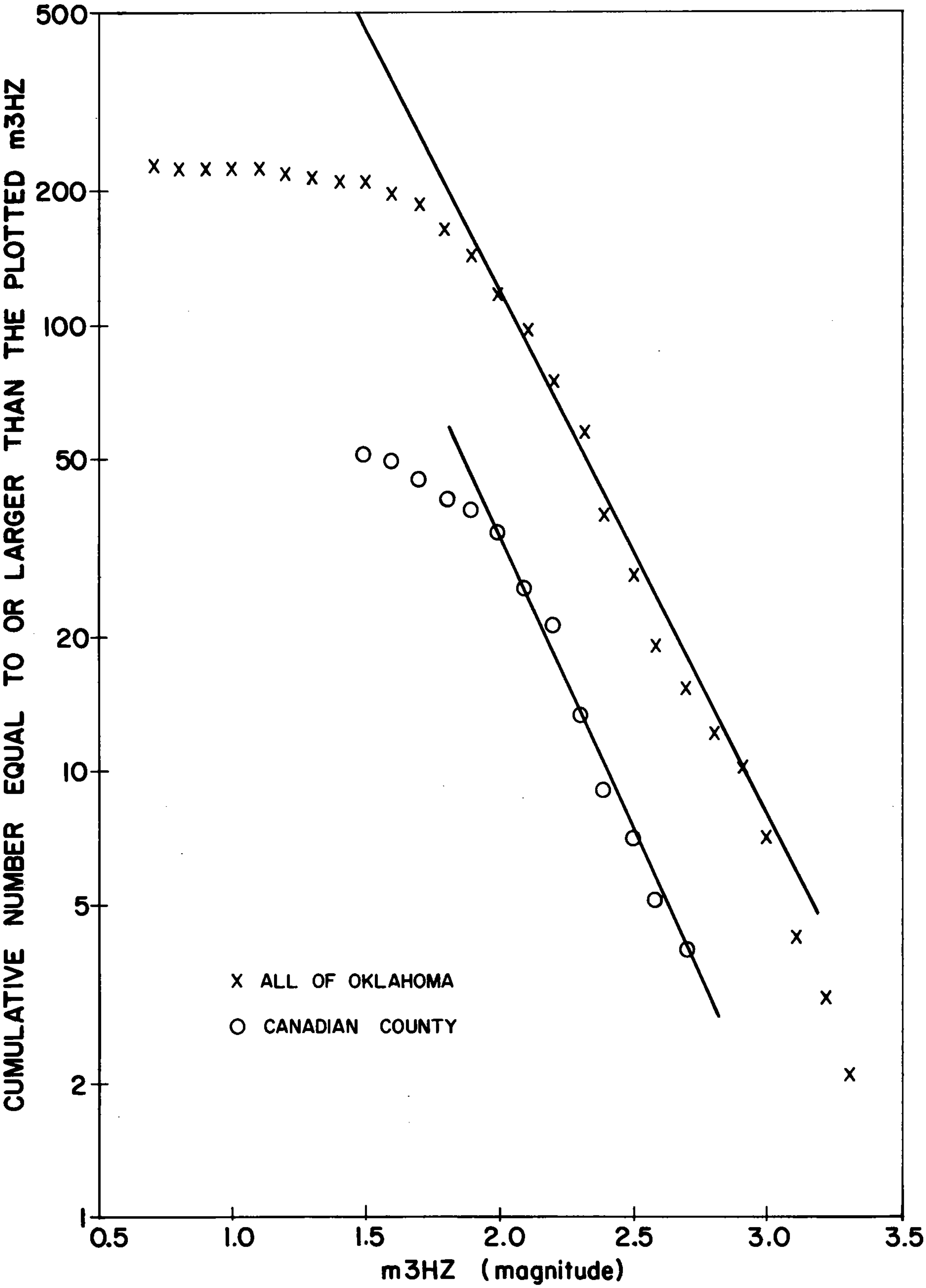


Fig. 26. Log-cumulative-frequency vs. magnitude for earthquakes recorded January 1, 1978, to December 31, 1981.

Equipment.—For the volunteer-operated stations, the following basic equipment is used:

1. Amplifier-filter-recorder-clock: Portable "microearthquake systems" were chosen, not for their portability per se, but because they were a cost-effective way to obtain a timing system, amplifier, and recorder in one convenient, easy-to-install package. We evaluated the Sprengnether MEQ-800B and an engineering model of the Geotech Portacorder, without the timing system. The Sprengnether unit was chosen as satisfactory. The Portacorder had a number of disadvantages, which may have been partly due to its being an early engineering model. Also, the Portacorder timing system was not available for evaluation in 1977.

2. Seismometer: The final system was designed to have a peak magnification near 10 Hz, but it was desirable also to have significant magnification at 1 Hz and below to record teleseismic P-waves. Because the seismometer acts as a mechanical high-pass filter, a relatively low natural-frequency seismometer was desirable. A seismometer with relatively high output was desirable to maximize the signal/electronic noise ratio. The Geotech S-13 with a 629 volt-second/meter generator constant, and a natural frequency adjustable to as low as 0.75 Hz, was selected.

3. Time-signal-radio receiver: In order to have an audio time for the aid of the volunteer operators, it was decided to use high-frequency WWV instead of the very low-frequency WWVB transmissions. We found only one portable WWV receiver, the Kinemetrics WWVT, to evaluate. It was satisfactory, providing clearly audible voice-announcements of UTC through the unfiltered speaker output, simultaneously with the second "ticks" through a 1,000-Hz bandpass filter, for direct recording on the drum.

Seismometer-output curves for various damping and free-period values were convolved with sensitivity curves for various filter combinations on the Sprengnether MEQ-800B recorder by graphically adding the ordinates on log-log graph paper. This produced a large family of curves for the complete seismograph system. The curves in figure 27 were chosen. These curves resulted from a seismometer natural frequency of 0.77 Hz, damping 0.5 critical, recorder "low" filter switched "OUT" (the "OUT" position actually selects a high pass filter with a 6 dB/octave rolloff down 3 dB at 0.1 Hz) and the "high" filter switched to "10 Hz" (low pass filter with about 6 dB/octave rolloff down 3 dB at 10 Hz). The clipping level was always set at its maximum value of 25-mm-peak trace amplitude. Steady-state harmonic calibration confirmed that overall system response was within 5 percent of the expected response. Any recording trace speed below 60 mm/min was rejected as giving insufficient time resolution. Afterseveral days of recording at 60, 120, and 240 mm/min, it was decided that 120 or 240 mm/min forced the lines so close together (½mm, ¼mm) that the magnification would be restricted to a value that could hamper event detection. It did not seem practical to improve the magnification-time-resolution tradeoff by asking volunteers to change records at intervals of less than 24 hours.

Several modifications were made to the Sprengnether MEQ-800B unit. A terminal strip was mounted on the outside of the unit and wired in parallel to the five-pin seismometer plug. The terminal strip simplified installation and maintenance in semi-permanent indoor locations. Also, the 10-second timing mark produced by the clock at 000000 to 000010 and 120000 to 120010 UTC was used to produce four daily DC step-calibration pulses through the seismometer calibration coil. Lightning protection was added to the power supply and the seismometer line.

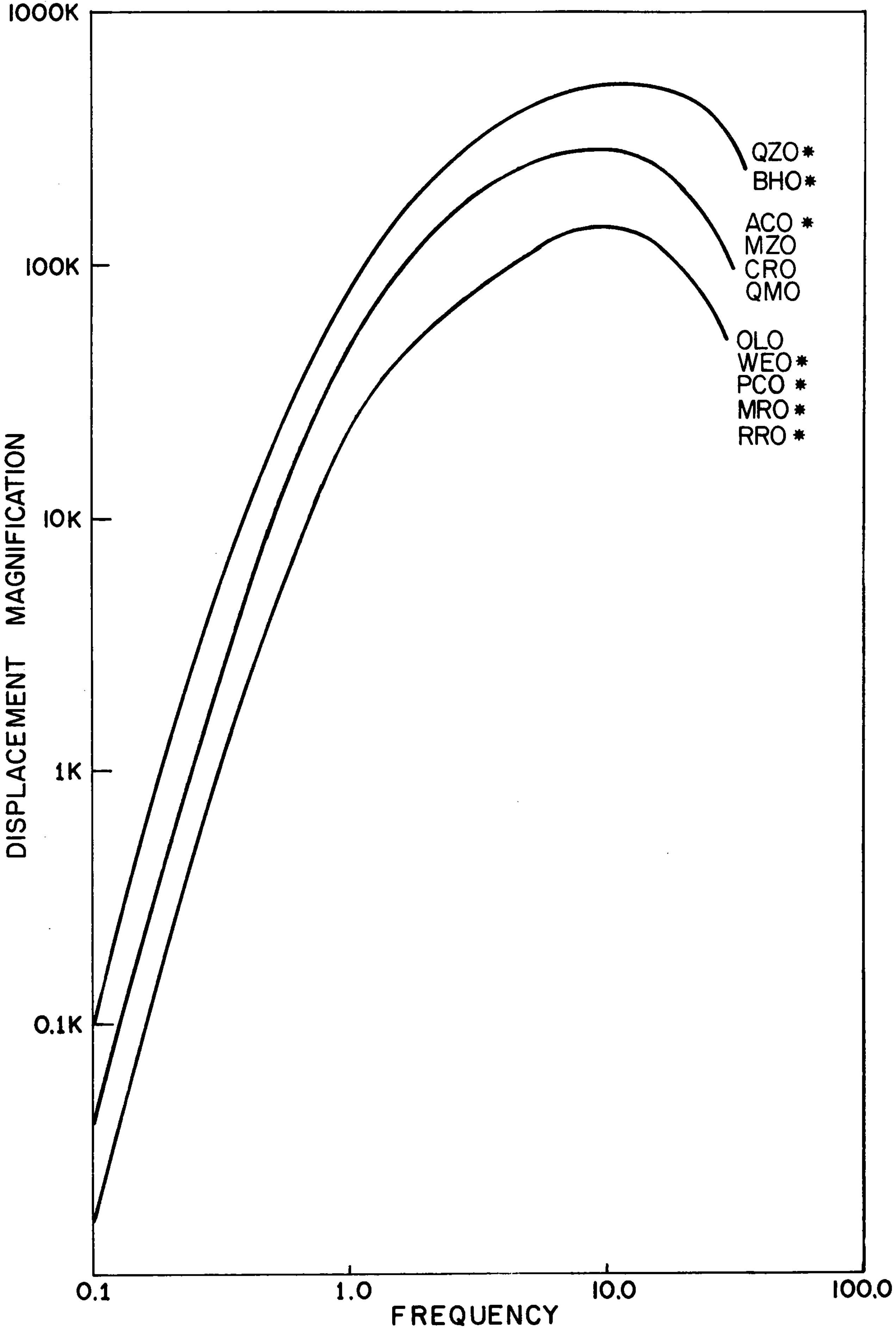


Fig. 27. Frequency vs. displacement-magnification curves for volunteer-operated network stations. (* Operating Stations.)

Installation.—If an enthusiastic volunteer was found in the target area, and if the location offered by the volunteer appeared to be reasonably remote from local sources of cultural ground noise, the station was installed and the volunteer trained. Installation usually required two days. On the first day, a tank vault to house the seismometer was constructed in the field, and the concrete was left to harden overnight (fig. 28). The amplifier-filter-recorder-clock system and the WWV ratio were installed in a protected area. The recorder and clock were activated, and with the recorder recording a straight line, the volunteer was instructed in record changing, labeling, radio-time-mark recording, and clock corrections. During the remainder of the day, a four-wire shielded cable, which connected the recorder to the seismometer, was buried a few inches deep. At the end of the first day the volunteer was again instructed in record changing by removing the record, which by then had had several hours of straight lines and time marks recorded. A new record was mounted to run overnight. On the second day the tank vault was finished and the seismometer was installed and all connections completed. The volunteer again reviewed the record-changing procedure, and seismic recording commenced. A copy of Bulletin 16, Instructions for Volunteer Cooperating Scientists—Operation of Portable Seismograph Stations, (University of Oklahoma Earth Sciences Observatory, 1977), a supply of recording paper and ink, and stamped mailing tubes for weekly mailing of records were left. The volunteer was asked to phone us collect if any malfunction occurred. Most of the volunteers subsequently recruited and trained one or more neighbors to change records during vacations or unexpected absences.

The coordinates and elevation of each seismometer were determined from field measurements, with tape and Brunton compass, to the nearest point or structure easily identifiable on a U.S. Geological Survey 1:24,000-scale topographic map (table 2). A station-location map is shown in figure 29. Each station was subjectively rated according to its usefulness or contribution to the program (table 2). The rating system uses letter designations, A through D, which have the following meanings:

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.

In general, the volunteers' ability, without technical training, to operate seismograph stations has exceeded our expectations. Unfortunately, the amount of major maintenance required has also exceeded our expectations. This maintenance is most frequently related to MEQ-800B timing-system failure, which we are not attributing to the volunteer operators and which are generally caused by lightning effects.

We have studied, in particular, the accuracy of timing on the volunteer-station records. At the beginning of each record, the volunteers record both timing-system second ticks and filtered ticks from the WWV receiver. In our tests with a high-accuracy time-base oscilloscope to measure intervals, we found that the radio and timing-system marks are separate on the record if they are more than 50 milliseconds apart. When they are separated by more than 16 milliseconds, but less than 50 milli-

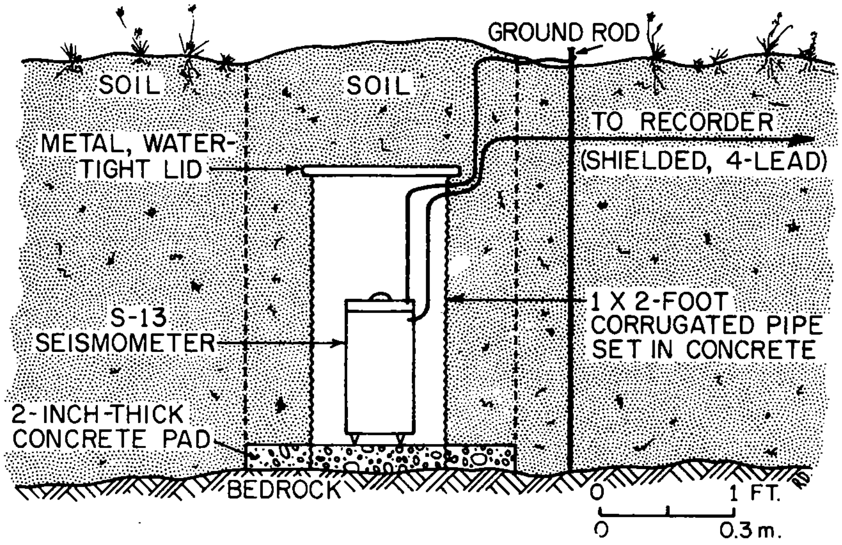


Fig. 28. S-13 seismometer installation.

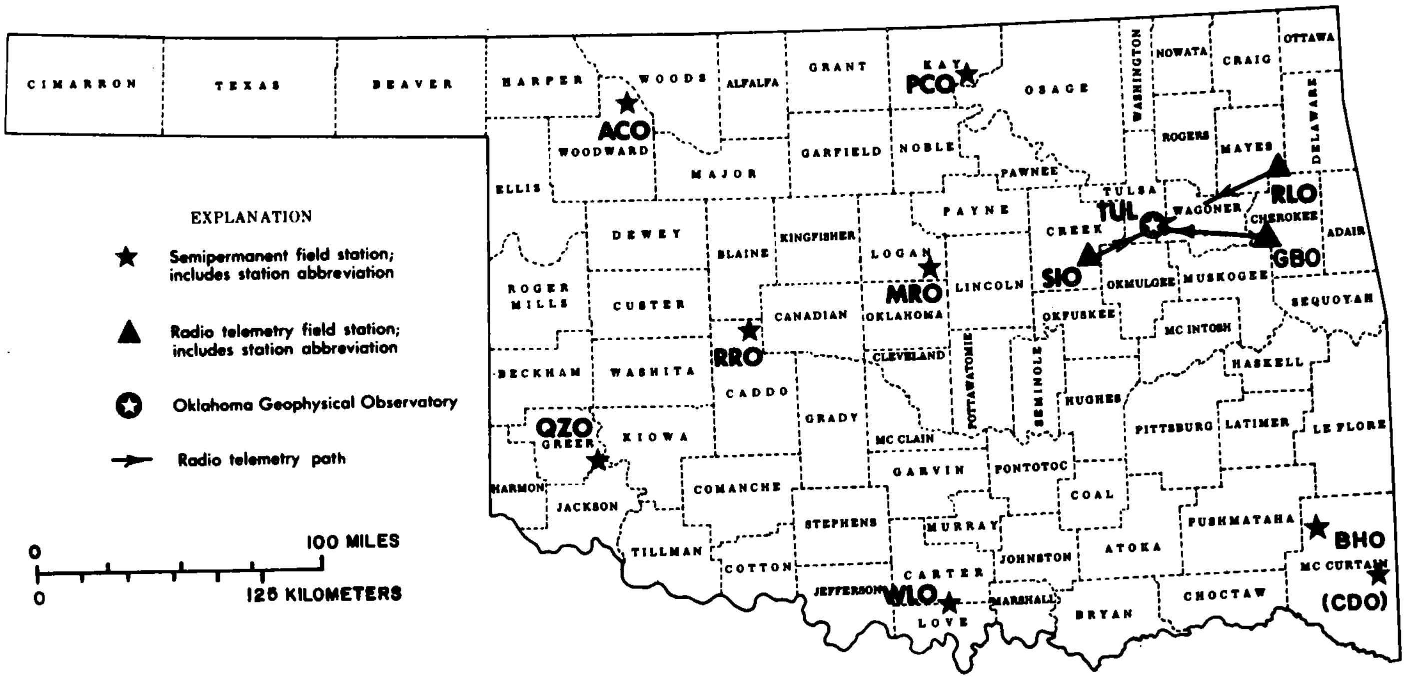


Fig. 29. Active seismograph stations in Oklahoma.

Table 2. 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		Quality and continuity operation	Ground noise
						At time of installation	In final network configuration		
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 (CLOSED) Greer County	34.892917	99.307056	479	J. Briley 770729-810311	(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. (CLOSED)	34.190378	94.77254	230	Jim Martin 800801	(A)	(A)	(B)	(B)
QZO	Quartz Mt. St. Park Greer Co.	34.905167	99.305317	488	Jim Cole 810320	A	A	B	A
BHO	Bethel McCurtain Co.	34.380800	94.867264	143	G/A Henderson 810330	A	A	A	A

* 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.

seconds, a single mark only appears each second, but it is no higher than the clock or radio mark alone. At less than 16 milliseconds' separation, the mark made each second is twice as high as the clock or radio mark alone. If the volunteers find this doubly high mark, they do not set the clock, and if the marks are not of double height, they advance or retard the clock until the marks do become doubly high.

The "fine time" on incoming records is checked by looking at the clock and radio marks. Usually the volunteers have to advance or retard the clock every three or four days. Almost never do the marks actually separate to indicate a 50-millisecond error. "Coarse time" (e.g., the correct second, minute, and hour) is verified. For the second, it is verified by looking for the 29th- and/or 59th-second marks, which are omitted by WWV. The hour and minute are easily verifiable on most records by two or three teleseismic P-wave arrivals, which are compared with TUL seismograms and to those from other net stations. As a final check, the minutes are numbered across the top of the seismogram, and the hour marks are labeled. The volunteers' labeling of the first recorded minute mark, their labeling of the last recorded minute mark, and the position of the 10-second-long timing-system marks at 000000 and 120000 are checked for agreement. We feel that the combination of the visible hour-minute-second UTC time display in LED decimal digits, and the voice on the radio giving each UTC minute, helps the volunteers to keep track of the UTC time easily without any added confusion of converting between their local time and UTC.

Maintenance problems have been particularly severe with the MEQ-800B clock. Clock malfunctions have usually required that the recorder unit be exchanged and the clock removed and sent to the manufacturer. Unfortunately, the drum will not even rotate when the clock is not operating, and this prevents recording without time marks; a record without time marks might yield usable Sg-Pg intervals, however. Originally, eight net stations were planned, seven using NRC-funded equipment and one using University of Oklahoma-purchased equipment. It has been necessary to keep the eighth MEQ-800B as a spare to exchange for malfunctioning units.

Radiolink Stations

Originally we had planned to have three high-frequency vertical seismometers radiolinked to the Oklahoma Geophysical Observatory for extended directional capability of the observatory. The extension of directional capability was based on the assumption that the maximum radiolink distance would be 12.5 miles (20 km). Later, in our study of the theory and practice of VHF radiolinks, we discovered that the maximum distance could approach 31 to 50 miles (50 to 80 km). It was then decided that the radiolinks would be spaced to serve as additional network stations rather than simply to confer "directional capability."

Site Selection.—Three radiolink transmitting sites are placed as far from the Oklahoma Geophysical Observatory as path conditions permit. We chose to use a single, permanent receiving tower for all three radiolinks. This was determined to be the most cost effective for this network to maximize the height of the single receiving tower. The receiving tower is a Rhon 45G, guyed to Rohn 45PSF specifications, which allow for 100 mile/hour (160 km/hour) winds. The tower was set 1,200 feet (336 m) from the main observatory building for two purposes: (1) to prevent vibrating guy wires from producing ground noise near the underground vault housing the observatory seismometers, and (2) to gain 30 feet (10 m) of topographic elevation. The tower is 120 feet (36 m) high. A 10-foot (3-m) vertical pipe, attached to the top of the tower, has three 11-element Uda-Yagi receiving beams mounted at 120 (36 m), 125 (38 m), and 130 feet (39 m) above ground level.

The first radiolink transmitting site, Rose Lookout (RLO), is at a state forestry lookout tower 47 miles (76 km) northeast of the Oklahoma Geophysical Observatory (fig. 29). This site was chosen because it was (1) one of the farthest points in any direction with a line-of-sight path to the observatory and (2) one of the areas of lowest cultural activity in the State.

The State Forestry Service permitted us to use its 40-foot-high (12 m) tower to attach an 11-element Uda-Yagi transmitting beam. Also, we were able to place the electronics in a secure location inside the lookout tower cab, where 110 VAC was available. The seismometer tank vault was placed in a massive chert in a bramble-choked corner of the State Forestry Service property, and a buried cable connected the seismometer, about 250 feet (75 m) from the lookout tower, to the electronics. The tower is remotely located at the end of a rough, unimproved road. Cultural noise is limited to two to four vehicle arrivals and departures per day, and an occasional mowing of the lawn covering part of the Forestry Service property.

A second radiolink station, near Slick, Oklahoma (SIO), was installed July 12, 1978 (fig. 29). This station, which is located on a wooded hill in the middle of the 16-square-mile (41 km^2) Jackson Ranch and is accessible by a series of winding dirt trails that can be driven over only during dry weather, is in an extremely quiet location.

Line-of-sight restrictions and cultural-noise problems led to the installation of the third radiolink station in a less than ideal location with respect to overall network configuration. The site is on privately owned property about 25 miles (40 km) south-southwest of RLO radiolink station. This site, northeast of Fort Gibson, Cherokee County, has a 34-mile (55-km) line-of-sight path to TUL (fig. 29). The station, which is named GBO (Fort Gibson), began operation on July 19, 1979. It has an 11-element Uda-Yagi transmitting antenna on top of a 30-foot (9-m) telescoping portable tower.

Equipment.—Geotech S-13 seismometers, set to 0.77-Hz natural frequency and 0.5 times critical damping, are used as transducers in both the regional net and the radiolink seismic installations. The 215-220-MHz telemetry band was selected for the radiolinks.

Initially, Emheiser Rand radiolink equipment was selected for each station. Each radiolink consists of four modules. The SVP 250M, a seismic-amplifier voltage-controlled oscillator (VCO), amplifies the seismometer output and uses it to frequency-modulate an audio tone. It affects the responses of the overall seismograph system by including bandpass filter rolling off 12 dB per octave outside 0.1 Hz and 30 Hz. The SDT 2000 is a 100-milliwatt crystal-controlled transmitter whose RF carrier is frequency-modulated by the audio signal from the VCO. The 100-mw level was chosen as being compatible with both line-of-sight transmission to 50 miles (80 km) and beyond and operation for long periods on batteries as required. Seven-element and five-element Uda-Yagi antennas were used for transmitting and receiving, respectively with RG8U foam dielectric coax used for low loss at P-band (220-225-MHz) frequencies. The SDR 8200 crystal-controlled receiver, with a sensitivity of 0.5 to 1 microvolt for 20-dB quieting, recovers the audio signal. The audio signal is carried from the receivers in a shed at the base of the receiving tower to the discriminators in the observatory by 1,200 feet (366 m) of aerial telephone cable. The SDC 2500M discriminator converts the audio-signal frequency fluctuations to a voltage output. The discriminator affects the overall system response by incorporating a two-pole low-pass filter, which is down 3 dB at 25 Hz. The voltage output is amplified by a Geotech AR-311 amplifier and recorded by a Geotech RV-301B helicorder at 90 mm/minute trace speed. Because of the limited audio bandwidth ($\underline{+}$125 Hz from audio-center frequency), as many as eight channels could be multiplexed on one RF carrier. The Emheiser Rand transmitters were eventually replaced with 500-mw Monitron transmitters, and the receivers have been replaced with Monitron receivers. In all cases, replacement was made only when the Emheiser Rand unit was destroyed by lightning.

The network stations, when combined with the seismic equipment at the Oklahoma Geophysical Observatory (TUL) and the radiolinked stations, enable us to exceed our capabilities to detect and locate earthquakes as specified earlier and as defined in the proposal. As previously discussed, the network appears to be capable of detecting and locating all Oklahoma earthquakes of magnitude 1.9 and above, and 50 percent of all Oklahoma earthquakes of magnitude 1.5 to 1.8.

Microearthquake Array

The El Reno area, in central Canadian County, was selected for a detailed microearthquake study. 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 (1.6 km) north of Pleasant View Cemetery. The final two stations were installed on July 22 and 23, 1981 (table 3; fig. 30). These stations 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 the number of that station in the immediate locale. For example, MNER1 is near Minco (MN), is part of the El Reno array (E), and is the first station installed near Minco (1).

Table 3. Stations in El Reno array on December 31, 1981

Name	Abbreviation	Symbol	Latitude (°N)	Longitude (°W)	Opening date
Shell Creek	SCE 1	S	35.438507	97.813971	Dec. 17, 1980
Minco	MNE 1	M	35.330972	97.891114	Dec. 18, 1980
Pleasant View	PVE 1	P	35.440365	97.896780	Dec. 31, 1980
Union City	UCE 1	U	35.422204	98.029665	July 22, 1981
John's Creek	JCE 1	J	35.581219	97.900337	July 23, 1981

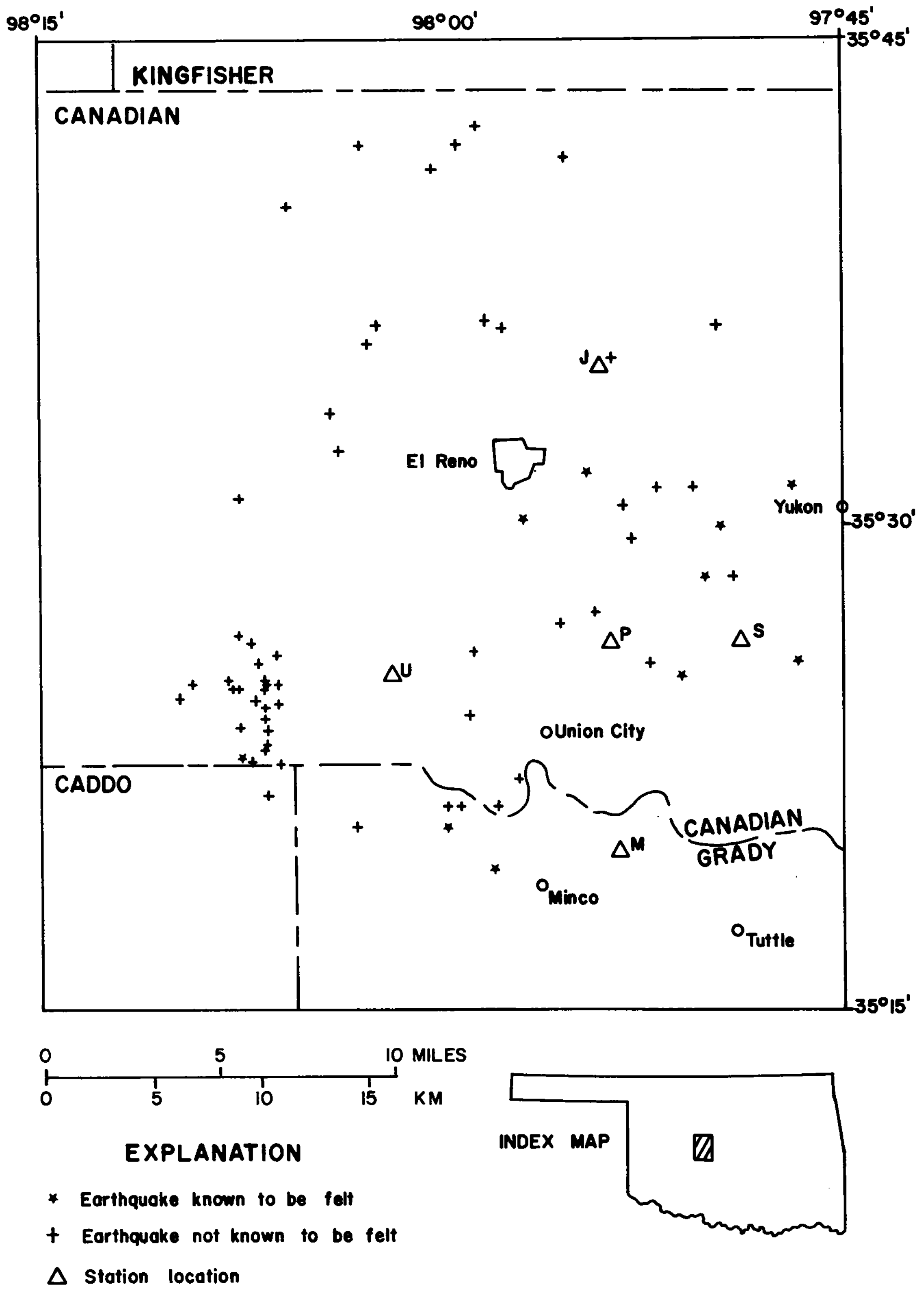


Fig. 30. Stations in the El Reno digital array (P, S, M, U, J) on December 31, 1981, with earthquake data for 1977-1981.

In a typical installation, a modified Sprengnether DR-100 unit is placed in a pump house, where it is well grounded and connected to AC power (Luza and Lawson, 1980, 1981). An active WWVB antenna is placed on a 6-foot (2-m) long galvanized pipe driven into the ground near the pump house. A two-wire shielded cable 200 to 980 feet (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 can pass), to a 4.5-Hz vertical geophone that is buried from 4 to 12 inches (10 to 30 cm) 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 houses where they can be serviced easily on a daily basis. Because the volunteers need only to service the digital units weekly, these units were placed in well houses or any remote buildings 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 percent 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 percent 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.

Figure 30 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. It is anticipated 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 currently 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.

The DR-100 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).

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.

Two stations, MNE1 and SCE1, recorded a large number of very close and extremely small earthquakes, i.e., distances of 2 miles (3 km) or less from the station and magnitudes of about 0.1.

During the report period, there was only one earthquake recorded by a triggered digital station that was also recorded by any other seismograph stations. On July 11, 1981, an mbLg 3.5 earthquake in Garvin County triggered SCE1, that was 39 miles (63 km) from the epicenter. This earthquake was recorded by eight Oklahoma analog recording stations, by five Kansas stations, and one Texas station.

There appear to be several factors that limited the number of recordings by these stations. They are listed below, with possible remedies:

> Problem 1 - difficulty of monitoring down time without continuous recording. Remedy: send in tapes more often than once a week and play them back immediately to detect station status.
>
> Problem 2 - unit not recording because it is filled with recordings due to noise triggers. Remedies: (a) send in tapes more often than once a week, (b) lower sampling rate to increase number of events per tape (this was done; the sample rate was dropped from 100 samples per second to 50 per second), (c) have dial-up telephone capability in which tape contents could be dumped daily to a central location (would avoid continuous telephone line but would require much equipment development), (d) shorten time recorded per event (this was considered an unfavorable tradeoff), (e) select quieter locations (in this particular area we were not able to discover quieter potential sites), (f) limit recording to nighttime hours (would require considerable equipment modification), (g) have more sophisticated trigger, with digital triggering algorithms in a microprocessor rather than an analog short-term/long-term average ratio trigger (there are existing units that would do this but at a cost increase of 50 percent or even 100 percent), (h) increase recording density (an expensive retrofit has become available for these particular units).
>
> Problem 3 - limited number of earthquakes in the area of interest during the time period involved. Remedy: none.
>
> Problem 4 - earthquakes, even very near ones that have highly emergent P-waves, will not trigger unit unless trigger level ratio is so low that there are continuous noise triggers. Remedy: this problem had been anticipated and was partially alleviated by extending shift registers to the maximum length to permit unit to trigger on S and still record P.

In general it was felt that the most desirable remedy was more frequent changing of tapes. It was not felt that frequent maintenance visits would be useful, as many problems are only detectable at play-back time.

One outstanding feature of our modified system was the excellent timing available from digital recording of WWVB in addition to the system clock.

In future microearthquake studies, we feel that these same modified units would serve well, particularly if the retrofit controller to double recording density was added, and the tapes were changed several times per week.

Data Analysis

An HP-9825T programmable calculator and 9866B line printer were installed at the Oklahoma Geophysical Observatory. The HP-9825T has an interpretive compiler that is resident in about 64K bytes of static semiconductor RAROM (random-access read-only memory). Also, 16K bytes of dynamic semiconductor RARWM (random-access read-write memory) are available for programs and data. The interpretive compiler uses a language called "HPL" by the manufacturer. The "HPL" language includes almost all instructions available in PL1 (and hence all FORTRAN IV instructions). It also includes considerable string-manipulating capability, which uses string instructions similar to those found in some versions of the BASIC language. A NMOS-16 bit microprocessor, which cycles at 11 megahertz, consists of the usual ALU (arithmetic logic unit) plus an input-output controller that allows DMA (direct memory access), two priority-level interrupts, and an extended math chip that manipulates numbers in BCD (binary coded decimal) form.

Peripherals built into the mainframe include a 2-track magnetic-tape cassette with 250K-byte capacity, a light-emitting diode display, and a 16-character-column thermal printer. The 96-6866B line printer uses a 5-wide, 7-high dot matrix to produce a 97-character set. It prints on thermal paper, up to 200 80-character lines per minute.

The programmable calculator's capabilities were extended by increasing the dynamic semiconductor RARWM (random-access read-write memory) from 16K to 64K bytes. Also, a second printer, HP model 9871A, has been added. The 9871A is actually a 132-character-wide printer-plotter controlled by its own 16-bit microprocessor backed by a 32K-bit RAROM (random-access read-only memory) and a 1,024-bit RARWM. The 16-bit microprocessor receives instructions from the 9825T desktop computer via an IEEE-488 bus (HP model HP-IB). The bus is interfaced with the desktop computer by an HP 98034A interface, which has its own 8-bit microprocessor backed with a 4,096-bit RAROM. A 1.2-megabyte disc file has also been added.

Six programs were developed for the HP-9825T to store and process all teleseismic and local arrival time and amplitude data. These programs perform the following functions:

1. Accepts from seismogram reader the year, date (month-day), and station abbreviation that applies to all data entered until a new year and/or month-day and/or station are entered, and provides on the 16-column printer a posting of the last entered year, month-day, or station.
2. Accepts from the seismogram reader a string of arrival-time/amplitude data and checks them as extensively as possible for syntax errors (e.g., ePc 0862239 is an invalid sequence, because the minute exceeds 59).
3. The last three digits of a first arrival are entered as millimeters and tenths; if the station records at a trace speed other than 60 mm/min, or if an extra

symbol indicates a TUL non-60 mm/min seismogram, the last three digits are rescaled to represent seconds and deciseconds.

4. Enters all amplitudes as peak-to-peak trace amplitude in millimeters; depending on the period of the wave and on the response curve used, the amplitudes are rescaled to center-to-peak ground amplitude in nanometers (SP) or micrometers (LP); in the case of TUL an extra character is used to indicate which seismogram the amplitude was measured on.
5. Displays and/or prints the last entry for the reader.
6. Provides a visual review for all or any event data in current file to allow rapid editing.
7. Stores accumulated data on tape to await the next reading session.
8. Prints phase/amplitude bulletin giving all accumulated data sorted chronologically for each station or prints P/PKP arrival bulletin giving first arrivals only, sorted chronologically and clustered into groups of arrivals probably representing one earthquake.
9. Archives material appearing in one set of bulletins on archive-tape file and prints archive record slip.
10. Maintains a file of all information available on stations in Oklahoma, Kansas, and Nebraska; prints station-coordinate tables and address-telephone tables; and produces magnetic-tape files with selected station data for other programs.
11. Maintains and prints a map of Oklahoma stations.
12. Locates local and regional earthquakes.
13. Produces bulletin giving location, magnitudes, and station data for local and near-regional earthquakes.

One output example includes a station list for Oklahoma, Kansas, Nebraska, and Iowa as well as stations in the surrounding states that have, in the past, detected some phases from earthquakes in the four states. Other examples are a P/PKP arrival bulletin and a phase/amplitude bulletin (see Luza and others, 1978).

Earthquake Location

A program named HYPERCUBE, with four versions—2, 3, 4, and 9—was developed to locate local earthquakes (Luza and Lawson, 1979). This program systematically moves the earthquake-origin point (a point in space-time specified by four parameters: origin time, latitude, longitude, and depth) to a location that would give the minimum average value of the absolute weighted residuals. The average residual value (R) is calculated from the formula

$$R = \frac{\sum_{i=1}^{n} \text{abs}\,(Ri)\ Wi}{\sum_{i=1}^{n} Wi},$$

where n is the number of arrival phases, Ri is the residual (observed minus computed) of phase i, and Wi is the weight applied to phase i. This value is calculated for the trial origin point and 80 points surrounding it in space time. The 80 points consist of all possible combinations of the four parameters, of the parameters plus a certain time or space step, and of the parameters minus a time or space step. This gives three values for each parameter, which may be combined in 81 ways. Since this 81-point array is a parallelopiped in 4-space, the program was named HYPERCUBE. Strictly speaking, the array is not a cube, because time steps are not comparable to spatial steps. Even the spatial steps are not equal. The latitude and longitude steps are usually taken equal in terms of degrees, making them unequal in kilometers (at 36° N, 1° of latitude is 69 miles, 111.1 km, while 1° of longitude is only 45.2 miles, 72.7 km). Also, the depth steps are usually an order of magnitude smaller than latitude and longitude steps.

Each phase is entered as a separate piece of data with either a default weight of 1.0 or a given weight of 0.0 or greater. The phase identifier must include one of the following kernals: PG, P1; P*, PB, P2; PN, P3; P?; SG, S1; S*, SB, S2; SN, S3; S?. This nomenclature assumes a velocity model of two layers over a half space. Waves traveling in the first layer have the suffix G ("granitic") or 1; those refracted critically in the second layer have suffixes of *, B ("basaltic"), or 2; and those refracted critically in the half-space (assumed to be the upper mantle) have suffixes of N or 3. The ? suffix indicates that the travel-time subroutine should select the earliest arrival for a given distance (only versions 4 and 9 accept the ? suffix). The ? is replaced with the suffix of the selected phase, and during each iteration the suffix is changed if the movement of the trial origin point makes a different phase earlier. In all cases the model of Nuttli and others (1969) has been used for epicentral locations. The travel-time subroutine, in HYPERCUBE versions 2 and 3, is a full-ray-tracing program that can utilize as many as nine layers over a half-space; it can easily be dimensioned for more than nine layers. Version 9 is even shorter and more restrictive. It calculates only for a hypocentral depth of 16,405 feet (5 km).

After the individual phases are entered, the initial trial origin point is assigned the following parameters in order (a, b, c; b and c being default values):

1. Origin time
   a. Time entered manually
   b. Time calculated from non-zero weighted Pg and Sg recorded at one station (if Pg and Sg are recorded at more than one station, an average is calculated)
   c. Time of arrival of earliest phases reported

2. Depth
   a. Depth entered manually
   b. 5 km

3. Latitude
   a. Latitude entered manually
   b. Latitude of station with earliest arriving phase

4. Longitude
    a. Longitude entered manually
    b. Longitude of station with earliest arriving phase

Any of the steps for the parameters can be entered manually. If they are not entered, the following default values are taken:

Δ Origin time — 10 seconds
Δ Latitude — 1.0°
Δ Longitude — 1.0°
Δ Depth — 5.0 km (restrained depth)

R (average of absolute value of weighted residuals) is then calculated for the first 81-point hypercube. If the minimum R is at the center of the cube, the cube's dimensions (the parameter steps) are each halved, and the smaller cube with the same center is used in the next calculation. If R is at any point except the center, the next cube is the same size with its center at the point of minimum R of the last cube. The ending criteria have been varied, but most calculations have been simply run until the cube has halved nine times. Figure 31 shows a high-level flow chart of the HYPERCUBE programs.

After the ending criteria are met, the residuals for each phase and the hypocenter parameters are printed. The operator can selectively change any phase or hypocenter data and run the program again. If the location is considered final, the HYPERCUBE program, regardless of the version used, is overlayed with the HYPERCUBE OUTPUT program called from a disc. This program accepts comments, amplitudes, and periods of Pn and Sg phases and durations. It calculates individual and average magnitudes of up to four types: m3Hz, mbLg, mbeus, MDUR. All the output data are formatted into a 4000-byte buffer set up to be the image of an 8½-inch x 11-inch page with margins. The operator can print this buffer any number of times on a thermal printer and (or) an impact printer and can archive the buffer in a magnetic-tape file.

The HYPERCUBE program, version 2, uses a full ray-tracing travel-time subroutine and is heavily documented with comments. Owing to the many comments, it could bestored but not executed, at least not before the system RARWM was extended from 16K to 64K bytes. Version 3 as well as versions 4 and 9 are largely stripped of comments, with the line numbers mostly coinciding with those of documented version 2. In many places, the other versions have a blank line or lines to replace the comments in the reference version. Version 4 has a much shortened travel-time subroutine. Version 9 has an even shorter travel-time subroutine, and it always calculates with depth fixed at 5 km. Also, version 9 replaces the cosine function in the distance subroutine with a fast table look-up and interpolation. Because the number of distances and travel times calculated is (assuming the depth parameter is retained) 270 times the number of non-zero weighted phases, any increased speed in these subroutines is very important. The use of table look-up for cosine, and a few other shortcuts, make the location time 43 percent less for version 9 than for version 4.

One early problem was operator misidentification of phases; the Pn and Pg phases required repeated runs for one earthquake. This was largely alleviated in versions 4 and 9 of the HYPERCUBE by allowing a first arrival to be identified simply as P? or S?, with the program selecting the earliest existing phase.

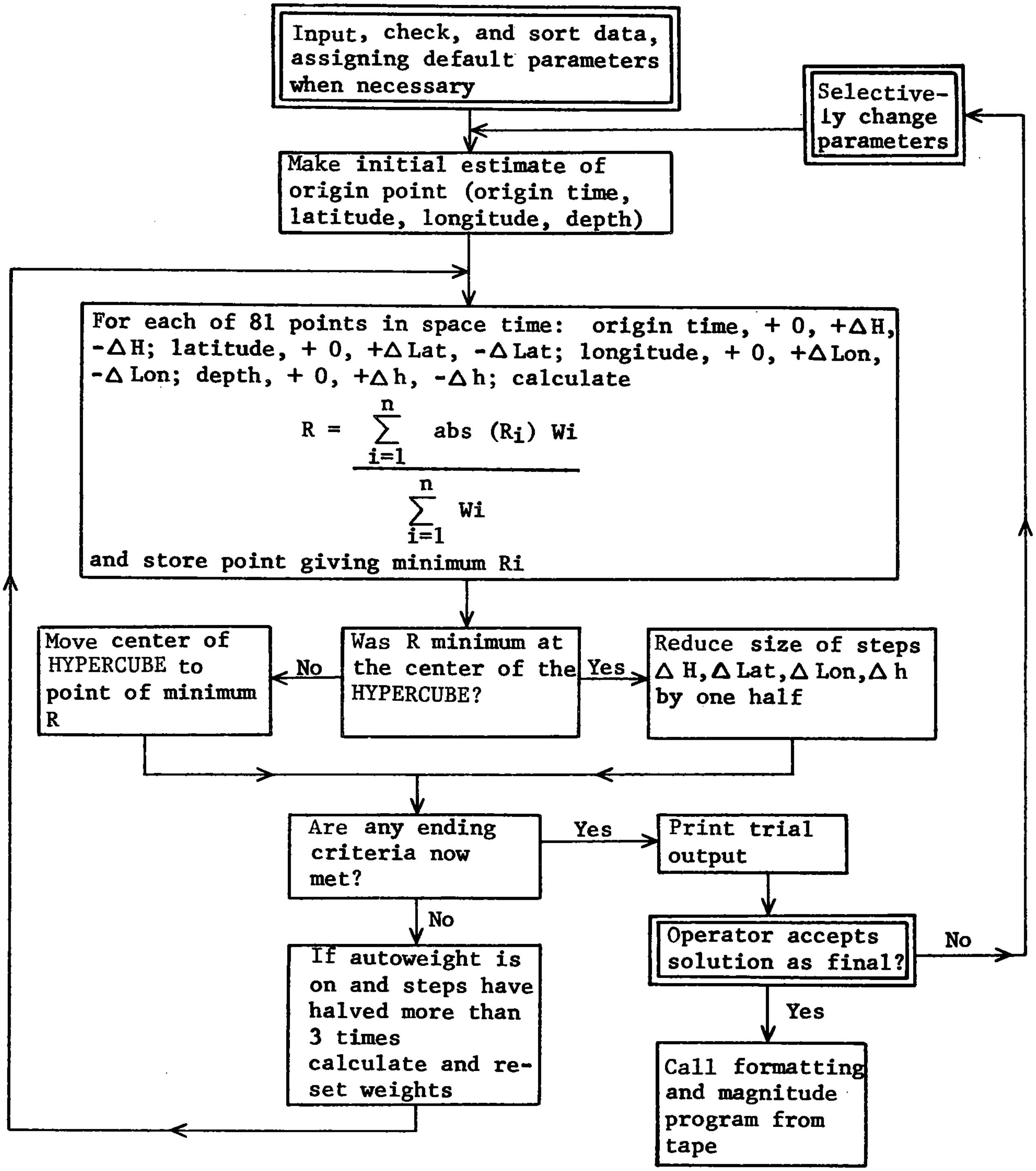


Fig. 31. High-level flow chart of HYPERCUBE. Interactive processes are shown in double box.

Another problem that caused repeated runs was the necessity to decrease the weight of some arrivals with large 2- to 4-second residuals and to eliminate entirely, or else weight to zero, those phases with residuals so large as to make their identification doubtful. An autoweighting subroutine was added to alleviate this problem. It must either be switched on at the time of data entry or else be left off by default. The autoweights are assessed only after the search cube has been halved four times. If applied earlier, with the cube still some distance from the hypocenter, all phases would be downweighted to nearly zero. After trying several exponential weighting functions with little success, a function was chosen that gives weight, 1.0, for any residual of 1 second or less; it weights others as the reciprocal of the square of the amount by which the residuals exceed 1 second. This function is expressed as follows:

$$Wi = 1.0 \text{ if } |Ri| \leq 1.0$$

$$Wi = \frac{1}{(Ri-1)^2} \text{ if } |Ri| > 1.0 \text{ .}$$

Each program has at its end a subroutine called SEARCH. This is used to print all lines in the program itself with any given characters or words. This is a great aid in program maintenance. Tracing, for example, all calls for a given subroutine is a long, error-prone visual process that requires tens of minutes for programs like HYPERCUBE and will exceed 400 lines. The SEARCH subroutine runs 30 seconds or less per search. The SEARCH subroutine also has a map mode that prints all lines having one or more of the following:

1. Subroutine or function call, e.g.: cll 'DELTA' (A, B, C).
2. A label that could possibly be used as a subroutine entry, e.g.: "DELTA."
3. Subroutine or function return, e.g.: "ATLED": ret p3.
4. Beginning of a for-next loop, e.g.: for A = -5 to 15 by 0.5.
5. End of a for-next loop, e.g.: next A.

The map mode does not have "gto" statements, because it is assumed that no well-structured program should have a gto (same as GO TO in Fortran). With a few deliberate exceptions, all gto statements in HYPERCUBE advance control over only a few lines within one program module. A statement such as gto + 3 (alternately jmp + 3) can be used to jump ahead three lines. However, gto 320 (go to line 320) is never used in HYPERCUBE, and a statement like gto DELTA is used sparingly and then only within one program module, or it is used to jump from the beginning of the program to the main module.

The results of locating 12 Kansas and Nebraska earthquakes calculated by Don Steeples (personal communication) using program HYPO71 (revised 11/25/73), and Steeples' own four-layer over a half-space model were compared with the HYPERCUBE results. In general, if the azimuthal gap of no station coverage was less than 180° and the nearest station was closer than 62 miles (100 km) to the hypocenter, the two programs calculated locations with 984 to 9,843 feet (0.3 to 3.0 km) of each other. However, for earthquakes far outside the network (gap usually more than 200°, nearest station not closer than 200 km), the differences were 6 to 37 miles (10 to 60 km).

In almost all located events, all stations were several times farther from the epicenter than the likely depth of the event. This made the locations highly indeterminate at depth, which in practice was most often restrained to an arbitrary 3 miles (5 km). This was done so often that HYPERCUBE version 9 was written. Version 9 uses 3 miles (5 km) as the fixed depth of the hypocenter.

Earthquake Magnitude

Magnitudes of local (epicentral great circle distance, Δ , is less than or equal to 186 miles, 300 km) and regional (distance range of 186 to 621 miles, 300 to 1,000 km) earthquakes recorded at Oklahoma seismograph stations have been calculated, whenever possible, on two scales developed by Otto Nuttli. One magnitude scale, m3Hz for epicentral distances of 6.83 to 137.86 miles (11 to 222 km), is determined from the following equation:

$$m3Hz = -1.63 + .87\log(\Delta) + \log(A/T), \qquad (1)$$

where Δ is great-circle distance from epicenter to station, in km; A is center-to-peak ground amplitude of maximum sustained (3 cycles or more) vertical motion, Sg, measured at a frequency near 3 hertz, in nanometers; and T is period in seconds of cycles from which A is measured (Zollweg, 1974). The other magnitude scale, Nuttli's mbLg, is defined thus:

$$mbLg = -1.09 + .90\log(\Delta) + \log(A/T) \qquad (2)$$

for epicentral distances of 34.53 to 276.35 miles (55.6 to 445 km); and for epicentral distances of 276.35 to 2,086.56 miles (445 to 3,360 km) this equation:

$$mbLg = -3.10 + 1.66\log(\Delta) + \log(A/T) \qquad (3)$$

is used (Nuttli, 1973). The symbols in equations (2) and (3) are the same as in equation (1), except that the sustained ground amplitude is measured at frequencies near 1 hertz.

Evernden's (1967) mbeus magnitude is also calculated when Pn waves are clearly recorded at distances exceeding 124.20 miles (200 km). However, mbeus could be calculated only for three of the 13 earthquakes used in this study, so it will not be discussed further.

A number of earthquakes near Wilson, south-central Oklahoma, recorded at station WLO, cannot have magnitudes assigned on the m3Hz scale for one or more of the following reasons:

1. Sg is clipped at WLO, so its amplitude cannot be measured.

2. The Sg-Pg interval is not clear enough to calculate the distance, or else the distance is too small (Δ<11 km) to apply the m3Hz formula.

3. The earthquake is not recorded at any other station, or it is recorded only at CRO, which is too far away from WLO (259 km) to apply the m3Hz formula.

A smaller number of earthquakes near Ponca City in the Nemaha Uplift area recorded at station PCO cannot be assigned m3Hz for the same reasons. When these earthquakes are large enough to be recorded at the other stations, the seismograph-frequency response at all stations except TUL (with multiple frequency responses) prevents 1-hertz waves from being recorded and thus prevents the use of mbLg.

Several studies (Real and Teng, 1973; Herrmann, 1975; Bakun and Lindh, 1977) discussed the use of signal duration to calculate magnitudes. Aki and Chouet (1975) gave strong theoretical and empirical evidence that the coda, upon which signal duration chiefly depends, is a result of backscattering of Sg waves by lithospheric inhomogeneities in the region surrounding the seismometer. They suggested that the inhomogeneities that caused scattering may have dimensions in the range of 0.1 to 1.0 km, with seismic-wave velocities differing from the enclosing rock by "a few percent." Aki and Chouet found that the ambient seismic noise is also dependent on the inhomogeneities that cause Sg backscattering. Thus, even at noisier sites, the backscattering of Sg will be more intense, so that the coda will remain visible above the noise. Aki and Chouet (1975) suggested that this effect makes coda length nearly independent of receiver site. A magnitude-duration scale applicable to Oklahoma would be useful for smaller events and also as an additional and rapidly measurable parameter for estimating magnitude of any local and regional earthquakes. Initial experiments with magnitude-duration relationships used in California gave values of magnitude nearly one unit greater than m3Hz or mbLg.

Accordingly, a study was undertaken to find a formula for magnitude calculated from duration, which would give magnitudes consistent with m3Hz and mbLg.

Vertical-ground-motion amplitudes of Sg at 3 Hz and 1 Hz were calculated from measurements on one or more of three seismograms at station TUL and verical motion seismographs located at eight single-seismograph sites in Oklahoma. These amplitudes were used in calculating m3Hz and mbLg. Durations were measured on one seismogram (HPZ) at TUL and on seismograms from the eight other sites. Each seismograph is operated at a sufficiently high magnification for the ambient background noise to be continuously visible. The characteristics of the seismographs used are given in table 4.

Durations were measured as the time in seconds between the arrival of Pg and the point at which the coda amplitude had decreased to twice the amplitude of the ambient background noise. If for any reason (e.g., trains near station OLO) the ambient background noise was temporarily higher than the normal 24-hour ambient background at that station, the duration was not measured from that seismogram. A visual semi-quantitative estimation of the predominant coda frequency was made, and the ambient background-noise amplitude at the approximate frequency of the coda was measured at one or more points several minutes after the coda ceased to be visible. This measurement was made with a 20-power magnifier with a scale etched in 0.1-mm intervals. The magnifier was then slid slowly along the trace from the point of background-noise measurement in a direction toward the coda until the peak-to-peak trace (in millimeters) was twice the ambient-noise peak-to-peak trace (in millimeters). This point was marked and the duration read by measuring from this point to the Pg arrival.

The 3-Hz and 1-Hz amplitudes and the duration were input as data in the local hypocenter-locating program, HYPERCUBE. HYPERCUBE calculated individual station values of m3Hz and mbLg according to equations (1) and (2). The value of m3Hz or mbLg for the earthquake was the arithmetic mean of the station values. HYPERCUBE also calculated the common (base 10) logarithm of duration for individual stations, and the value of log (DUR) for the earthquake was the arithmetic mean of log (DUR) from individual stations.

Table 4. Characteristics of vertical seismographs used in calculating m3Hz, mbLg, and measuring duration

Station Abbrev.	Seismograph Mnemonic	Displacement magnification			Peak magnification	Used to calculate		
		1 Hz	3Hz	10Hz	occurs at	mbLg	m3Hz	DUR
TUL	HPZ	45k	170k	220k	10-20 Hz		X	X
TUL	SPZ	100k	65k	40k	1.7 Hz	(X)	(X)	
TUL	SPNBZ	200k	39k	3k	1.0 Hz	X		
RLO	HPZ	25k	170k	500k	18 Hz			X
CRO, MZO, QMO	HPZ	48k	152k	280k	10 Hz		X	X
ACO, OLO	HPZ	24k	76k	140k	10 Hz		X	X
PCO, WLO	HPZ	12k	38k	70k	10 Hz		X	X

(X) = occasionally.
SPZ = short-period vertical.
HPZ = high-pass vertical.
SPNBZ = short-period narrow-band vertical.

The previously described measurements were carried out for 13 earthquakes occurring in Oklahoma, Kansas, Arkansas, Texas, and Missouri between Nov. 26, 1977, and March 5, 1978. Their locations along with m3Hz, mbLg, and log (DUR), are given in table 5 and figure 32. Both m3Hz and mbLg were not calculated for every earthquake in the table. From the data in table 5, three least-squares relationships, equations (4), (5), and (6), were calculated by methods given in Lapin (1975). The mbLg and m3Hz magnitudes and logarithms of the durations in seconds are plotted in figure 33, along with lines given by equations (4), (5), and (7). The ± values, after the coefficients, are Student's T 95 percent confidence limits calculated by the method of Hyans and Philpot (1971). The least-squares relations are:

$$\begin{aligned} \text{mbLg} &= -1.377 \pm 1.249 + (1.755 \pm 0.6130)\log(\text{DUR}) \\ (n &= 12 \text{ earthquakes}), \end{aligned} \tag{4}$$

$$\begin{aligned} \text{m3Hz} &= -1.596 \pm 1.337 + (1.961 \pm 0.6802)\log(\text{DUR}) \\ (n &= 10 \text{ earthquakes}), \end{aligned} \tag{5}$$

$$\begin{aligned} \text{mbLg} &= 0.04098 \pm 0.9196 + (0.9419 \pm 0.3914)\text{m3Hz} \\ (n &= 9 \text{ earthquakes}). \end{aligned} \tag{6}$$

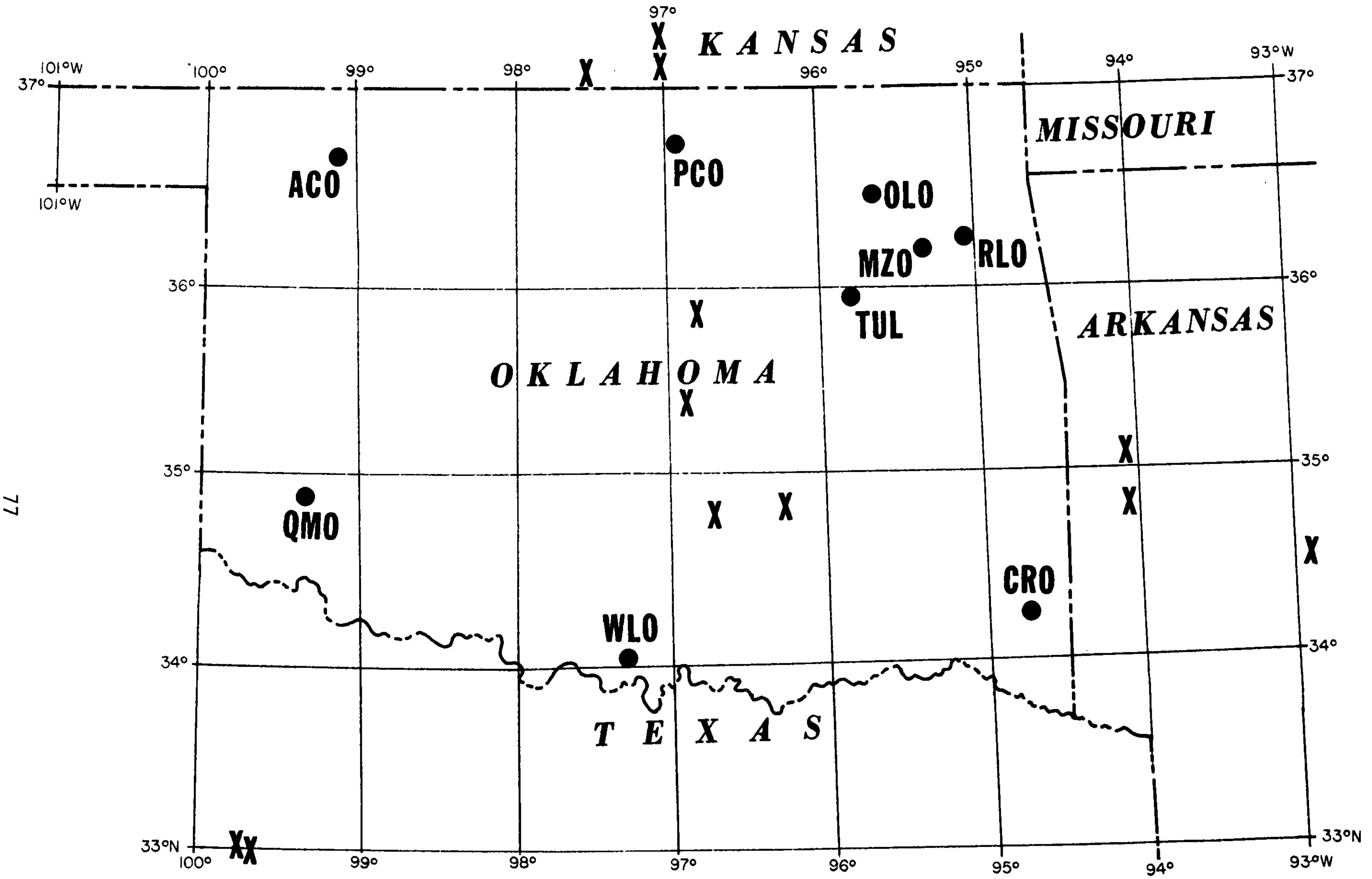


Fig. 32. Seismograph stations (●) and earthquakes (X) used to determine duration magnitudes.

Table 5. Earthquakes used to calculate m3Hz and mbLg magnitudes and measure duration

Date	Location	m3Hz	mbLg	log (DUR)	DUR
Nov. 26, 1977	34.4°N 92.8°W near Malvern, Ark.	2.85	2.85	2.24	2.68
Nov. 27, 1977	33.0°N 100.6°W near Rotan, Texas		2.32	2.22	2.64
Nov. 28, 1977	33.1°N 97.8°W near Rotan, Texas		2.77	2.39	2.96
Dec. 8, 1977	34.4°N 96.7°W Canadian Co., Okla.	2.26	2.01	1.85	1.95
Dec. 14, 1977	34.7°N 96.7°W Pontotoc Co., Okla.	2.30	2.09	2.14	2.49
Dec. 16, 1977	37.2°N 97.0°W near Arkansas City, Kan.	1.70	1.81	1.79	1.84
Dec. 20, 1977	37.2°N 97.0°W near Arkansas City, Kan.		1.81	1.73	1.73
Jan. 8, 1978	35.8°N 97.7°W Kingfisher Co., Okla.	2.16	1.98	1.97	2.17
Jan. 8, 1978	37.1°N 97.4°W near Caldwell, Kansas	1.55		1.58	1.45
Feb. 10, 1978	34.7°N 96.2°W Coal County, Oklahoma	2.02	1.53	1.76	1.78
Feb. 11, 1978	36.5°N 94.1°W near Cassville, Missouri	1.99	1.99	1.89	2.03
Mar. 3, 1978	35.1°N 94.1°W Hughes Co., Oklahoma	2.49	2.12	2.08	2.38
Mar. 5, 1978	34.7°N 95.1°W Latimer Co., Oklahoma	3.06	2.87	2.25	2.70

Note: The log duration (in seconds) is used to calculate a duration magnitude, MDUR (see equation 7).

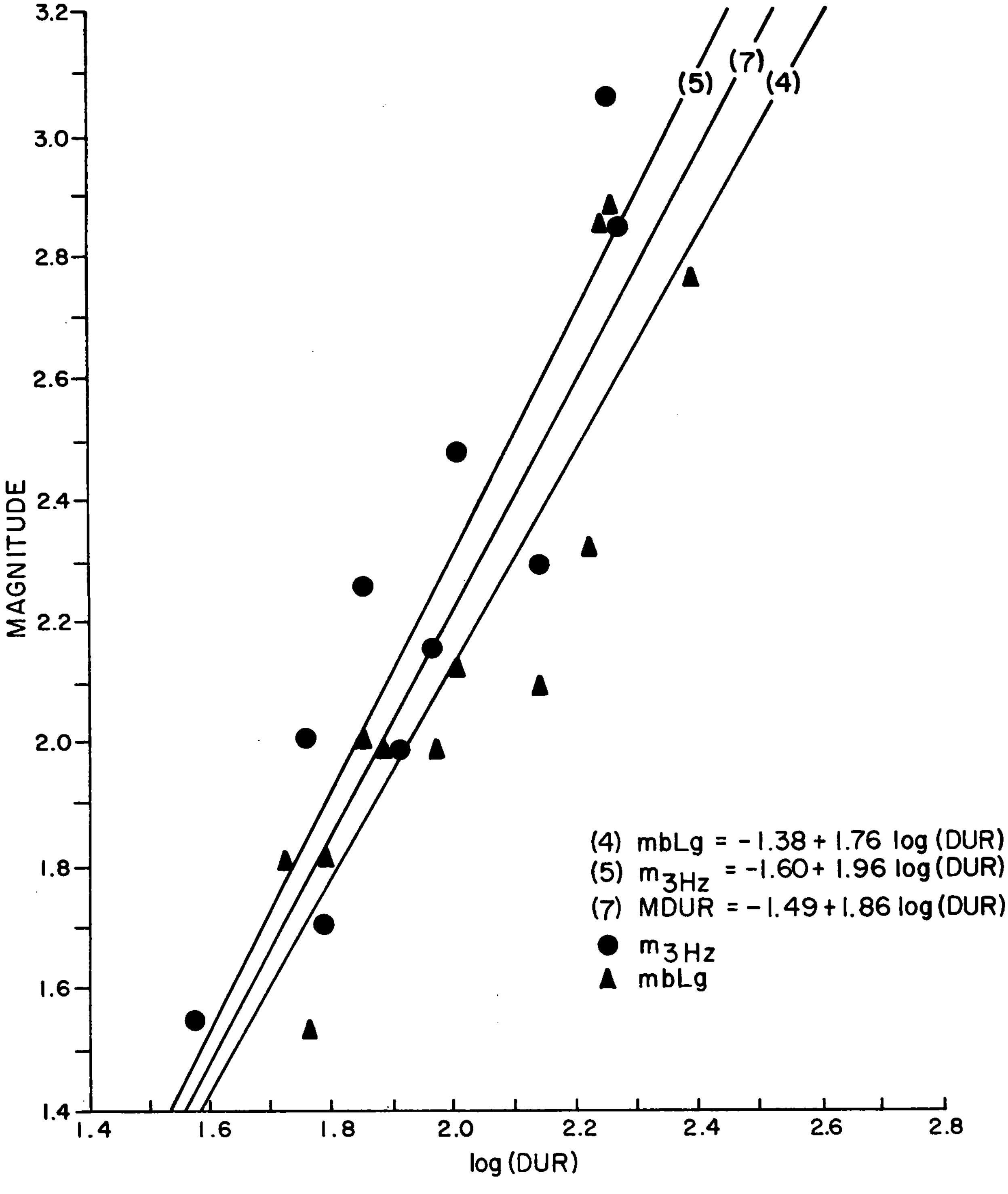


Fig. 33. Log(DUR) vs. magnitude data from table 5. Equation (7) represents an average of equations (4) and (5).

Because the Student's T 95 percent confidence intervals of the parameters in equations (4) and (5) overlap considerably, it was felt that one equation could represent a magnitude duration (MDUR) consistent with both mbLg and m3Hz:

$$MDUR = -1.49 + 1.86\log(DUR). \qquad (7)$$

Accordingly, equation (7) was adopted for use as a magnitude duration for local and regional earthquakes recorded at Oklahoma seismograph stations.

A number of published magnitude-duration formulas differ considerably from equation (7). It is interesting to note that the published equation resembling (7) more closely than any we could find was Herrmann's (1975):

$$mb = 1.68 \pm 0.87 + (1.96 \pm 0.37)\log(DUR) + (0.00190 \pm 0.00188)\Delta\,, \qquad (8)$$

where Δ is in km. This was calculated for a geological setting (Ozark Uplift, Missouri, station GRV, Greenville) for which mbLg and m3Hz are also considered valid. GRV also has a frequency response similar to that of the Oklahoma stations, and Herrmann's measurements were made from the P arrival to the disappearance of the coda into the noise level. The distance term used by Herrmann in equation (8) and by some other authors is very small. Our present data did not seem to be capable of defining such a term if it exists in our setting. We also noted that the 19 earthquakes used by Herrmann in defining equation (8) were in the range $2.5 \le mb \le 4.5$, which is larger than almost our entire data set.

The seismograph response seems to have a limited influence on duration, especially as higher frequencies are progressively removed. The TUL VSPZ (very narrow band, peaked at 16 Hz) gave similar durations to the various HPZ (wider band, peaked at about 10 Hz) seismographs. However, the TUL SPNBZ (very narrow band, peaked at about 1 Hz) gave notably shorter duration.

We have some indication that there may be a quantifiable site factor, with duration at very quiet locations like CRO and RLO exceeding those at less quiet locations. We do not have sufficient data to know if this difference is systematic enough to allow a "site correction" to be added to equation (7), which will be used for calculating Oklahoma duration magnitudes until such time as an accumulation of data will allow one or more of the following modifications:

1. A change in the parameters of equation (7).

2. Addition of a seismometer-site correction.

3. Addition of a distance term.

4. Addition of a magnitude-dependent term.

5. Addition of a seismograph-passband-dependent term to allow use of durations measured from seismographs (e.g., the TUL SPNBZ) with radically different responses from those used in this study.

Earthquake Catalog

A computer-based catalog was used to print earthquake information in page-size format. Information for each earthquake includes date, origin time, county, intensity, magnitude, location, focal depth, and references.

The date and time are given in UTC (Coordinated Universal Time). The first two digits refer to the hour on a 24-hour clock. The next two digits refer to the minute, and the remaining digits are the seconds. To convert to local Central Standard Time, subtract 6 hours.

Three magnitude scales—mbLg (Nuttli), m3Hz (Nuttli), and MDUR (Lawson)—were used to report earthquake magnitude. Each magnitude scale was established to accommodate specific criteria, such as the distance from the epicenter, as well as the availability of certain seismic data.

For earthquake epicenters located from 6.83 to 137.86 miles (11 km to 222 km) from a seismograph station, Otto Nuttli developed the m3Hz magnitude scale (Zollweg, 1974). This magnitude is derived from the following expression:

$$m3Hz = \log(A/T) - 1.63 + 0.87\log(\Delta), \qquad (1)$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Sg waves, near 3 hertz in frequency, measured in nanometers; T is the period of the Sg waves measured in seconds; and Δ is the great-circle distance from epicenter to station measured in kilometers.

Otto Nuttli's (1973) earthquake magnitude, mbLg, for seismograph stations located between 34.53 and 276.35 miles (55.6 and 445 km) from the epicenter, is derived from the following equation:

$$mbLg = \log(A/T) - 1.09 + 0.90\log(\Delta). \qquad (2)$$

Where seismograph stations are located between 276.35 and 2,086.56 miles (445 and 3,360 km) from the epicenter, mbLg is defined as

$$mbLg = \log(A/T) - 3.10 + 1.66\log(\Delta), \qquad (3)$$

where A is the maximum center-to-peak vertical-ground-motion amplitude sustained for three or more cycles of Sg waves, near 1 hertz in frequency, measured in nanometers; T is the period of Sg waves measured in seconds; and Δ is the great-circle distances from station to epicenter measured in kilometers.

The MDUR magnitude scale was developed by Lawson (1978) for earthquakes in Oklahoma and adjacent areas. It is defined as

$$MDUR = 1.86\log(DUR) - 1.49, \qquad (4)$$

where DUR is the duration or difference, in seconds, between the Pg-wave arrival time and the time the final coda amplitude decreases to twice the background-noise amplitude. If the Pn wave is the first arrival, the interval between the earthquake-origin time and the decrease of the coda to twice the background-noise amplitude is measured instead.

The depth to the earthquake hypocenter is measured in kilometers. For most Oklahoma earthquakes the focal depth is unknown. In almost all Oklahoma events, the stations are several times farther from the epicenter than the likely depth of the event. This makes the locations indeterminate at depth, which usually requires that the hypocenter depth be restrained to an arbitrary 5 km for purposes of computing latitude, longitude, and origin time. All available evidence indicates that no Oklahoma hypocenters have been deeper than 9 to 12 miles (15 to 20 km).

All network-located earthquakes from January 1, 1977, to December 31, 1981, inclusive, are printed in table 7. Locations by the Kansas Geological Survey also have been included in the catalog. The events are sorted in strict chronological order. If the earthquake is located by both the Oklahoma Geophysical Observatory and the Kansas Geological Survey, the location with the earliest origin time is printed first. Figure 34a and 34b shows the distribution of all known Oklahoma earthquakes.

Earthquake Distribution

On December 31, 1981, 42 seismograph stations were operating in Oklahoma, Kansas, Nebraska, and Iowa. The map in figure 35 shows operating stations on January 1, 1982. During 1981, 77 earthquakes were located by the Oklahoma Geophysical Observatory and the Kansas Geological Survey. By state, they were distributed as shown in table 6. The complete catalog listing of all earthquake locations from 1977 through 1981 is given in table 7. The locations of the 1981 earthquake event are shown in figure 36. For comparison, figure 37 shows all earthquakes located from January 1, 1977, through December 31, 1981, a 5-year period.

Table 6. Earthquake distribution by state, 1981

State	Number located by Oklahoma Geophysical Observatory	Number located by Kansas Geological Survey
Oklahoma	57	1
Kansas	2	5
Nebraska	-	7
Missouri	1	1
Texas	5	-
Arkansas	3	-
Tennessee	1	-

Table 7. Oklahoma Geophysical Observatory regional earthquake catalog, January 1, 1977 through December 31, 1981.

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1977 FEB 4	205229.28	OK LOVE	2		1.9		34.065	97.370	5.0R	O
1977 FEB10	012816.26	OK LOVE	2		2.0		34.065	97.370	5.0R	O
1977 MAR 3	140816.52	OK NOBLE		1.9	1.6		36.263	97.437	5.0R	O
1977 MAR 9	162108.06	OK COAL		2.1		2.0	34.588	96.511	5.0R	O
1977 MAR12	210419.63	OK SEMINOLE		2.5	2.3	2.7	34.994	96.625	5.0R	O
1977 MAR26	213712.59	OK LOVE	3		2.4		34.065	97.370	5.0R	O
1977 APR28	023056.12	OK PAYNE		2.0	1.8	2.1	36.009	97.201	5.0R	O
1977 MAY22	121504.65	OK NOBLE		1.5	1.4	1.3	36.240	97.246	5.0R	O
1977 JUN 2	232909.35	AR POLK				3.4	34.587	94.118	10.0R	O
1977 JUN 2	233512.16	AR MONTGOMERY		2.8	2.6	2.7	34.601	93.898	10.0R	O
1977 JUN 2	234049.92	AR POLK		1.1		1.3	34.587	94.358	10.0R	O
1977 JUN 3	000654.23	AR POLK		1.5		1.5	34.612	94.087	10.0R	O
1977 JUN 3	001457.11	AR SCOTT		1.2		1.2	34.921	94.135	10.0R	O
1977 JUN 3	013546.79	AR POLK		1.0		1.6	34.587	94.118	10.0R	O
1977 JUN 3	014700.92	AR POLK		0.7		0.3	34.587	94.118	10.0R	O
1977 JUN 3	022927.91	AR POLK		0.8		0.9	34.587	94.118	10.0R	O
1977 JUN 3	075814.55	AR POLK		0.7		0.7	34.587	94.118	10.0R	O
1977 JUN 3	081627.94	AR POLK		2.3	2.1	2.4	34.650	93.931	10.0R	O
1977 JUN 7	230120.66	TX SCURRY			3.5	3.2	32.858	100.774	4.5R	O
1977 JUN 8	005128.76	TX SCURRY			2.3	2.9	32.858	100.774	4.5R	O
1977 JUN16	020246.56	OK LOVE			2.0	1.8	34.041	97.358	5.0R	O
1977 JUN16	222424.13	OK LOVE				1.8	33.909	97.444	5.0R	O
1977 JUN17	033705.66	TX NOLAN			2.5	3.0	32.346	100.401	5.0R	O
1977 JUN30	230321.99	OK JOHNSTON		2.8	2.5	2.1	34.193	96.958	5.0R	O
1977 JUL 9	202359.38	AR SEBASTIAN		2.4	2.0	2.6	35.337	94.040	5.0R	O
1977 JUL10	083909.29	OK OKFUSKEE		2.0	1.6	2.0	35.476	96.304	5.0R	O
1977 AUG10	001118.19	OK GARVIN		1.6	1.9	1.9	34.677	97.546	5.0R	O
1977 AUG18	103425.21	NE GREELEY				2.5	41.415	98.468	5.0	K
1977 AUG18	103426.61	NE HOWARD			2.7		41.139	98.581	5.0R	O
1977 SEP12	023630.06	OK CHOCTAW		2.5		2.4	33.947	95.243	5.0R	O
1977 SEP26	015510.63	OK LOVE			1.7	1.4	33.987	97.346	5.0R	O
1977 SEP29	071901.13	OK NOBLE		2.1		2.1	36.394	97.072	5.0R	O
1977 OCT 6	003608.35	OK KINGFISHER		1.8	2.1	1.7	35.820	97.767	5.0R	O
1977 NOV 3	110020.27	TX BOWIE		2.2	2.3	2.1	33.384	94.130	5.0R	O
1977 NOV25	172609.91	KS WOODSON		2.2			37.958	95.864	5.0R	O
1977 NOV26	041818.24	AR HOT SPRING	4	2.8	2.8	2.7	34.427	92.884	14.0R	O
1977 NOV27	204818.82	TX SCURRY			2.3	2.6	32.862	100.676	5.0R	O
1977 NOV28	014052.87	TX SCURRY			2.8	3.0	33.022	100.842	5.0R	O
1977 DEC 1	130434.20	NE RED WILLOW	3			2.3	40.309	100.367	5.0	K
1977 DEC 1	130435.41	NE FRONTIER			2.4		40.408	100.303	5.0R	O
1977 DEC 1	132238.57	NE RED WILLOW	3			2.4	40.209	100.298	5.0R	K
1977 DEC 1	132242.16	NE DAWSON			2.7		40.732	99.846	5.0R	O
1977 DEC 8	194740.22	OK CANADIAN		2.3	2.0	2.0	35.449	97.927	5.0R	O
1977 DEC16	061227.28	KS COWLEY				2.0	37.158	97.004	12.2	K
1977 DEC16	061227.97	KS COWLEY		1.7	1.8	1.8	37.160	97.017	5.0R	O
1977 DEC20	075639.36	KS COWLEY				2.3	37.127	97.030	5.0	K
1977 DEC20	075640.45	KS COWLEY			1.8	1.7	37.095	97.007	5.0R	O
1978 JAN 8	041633.56	OK KAY		1.5		1.5	36.971	97.463	5.0R	O
1978 JAN 8	041634.39	KS COWLEY				1.8	37.077	97.067	5.0R	K

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1978 JAN 8	101917.65	OK LOGAN		2.1	2.0	2.2	35.824	97.642	5.0R	O
1978 JAN11	213203.88	KS WABAUNSEE				1.6	38.868	96.201	0.4	K
1978 JAN11	213204.61	KS WABAUNSEE					38.876	96.235	5.0R	O
1978 JAN12	201524.67	MO ATCHISON					40.356	95.450	5.0R	O
1978 JAN12	201528.00	NE NEMAHA				1.7	40.300	95.800	5.0R	K
1978 JAN27	112537.56	KS NEMAHA					39.890	95.995	5.0R	O
1978 JAN27	112537.65	KS NEMAHA				2.4	39.836	95.974	9.0	K
1978 FEB 3	002547.62	NE RED WILLOW				2.4	40.032	100.333	5.0R	K
1978 FEB 3	002549.04	NE RED WILLOW			2.7	2.3	40.078	100.321	5.0R	O
1978 FEB10	064202.39	OK COAL		2.1	1.5	1.9	34.712	96.157	5.0R	O
1978 FEB11	175901.36	MO MC DONALD		2.0	2.0	2.1	36.725	94.300	5.0R	O
1978 FEB14	010938.64	OK LOGAN		1.7		1.7	35.777	97.585	5.0R	O
1978 FEB21	111248.11	OK TILLMAN		2.5	2.2	2.0	34.535	99.003	5.0R	O
1978 MAR 3	022437.28	OK HUGHES		2.5	2.1	2.4	35.086	96.278	5.0R	O
1978 MAR 5	144650.48	OK LE FLORE		3.1	2.9	2.7	34.699	95.033	7.0R	O
1978 MAR 9	063050.82	OK LOVE	2		2.6	2.5	34.010	97.378	5.0R	O
1978 APR 2	213248.08	OK ATOKA		2.5	2.3	2.5	34.635	96.057	5.0R	O
1978 APR11	014902.17	AR FRANKLIN		1.9		1.9	35.558	93.759	5.0R	O
1978 APR11	074335.37	AR VAN BUREN		2.0		2.2	35.542	92.869	5.0R	O
1978 APR11	085102.43	OK PITTSBURG		1.7		1.8	34.693	95.681	5.0R	O
1978 APR13	023531.16	AR VAN BUREN			1.8	2.4	35.539	92.625	5.0R	O
1978 APR13	034350.76	OK JOHNSTON		1.9	2.0	1.9	34.351	96.820	5.0R	O
1978 APR14	232738.29	KS MARSHALL				1.9	39.814	96.395	1.2	K
1978 APR14	232738.60	KS MARSHALL					39.838	96.385	5.0R	O
1978 APR19	142054.06	OK TULSA		1.5		1.1	36.088	96.136	5.0R	O
1978 APR20	081304.00	OK COAL		1.7		1.6	34.586	96.293	5.0R	O
1978 APR22	101450.34	AR POLK		2.0	1.9	2.1	34.572	93.977	5.0R	O
1978 MAY 1	225913.38	OK MC CURTAIN		2.1	2.2	2.2	34.400	94.673	5.0R	O
1978 MAY 4	043552.89	OK OKFUSKEE		1.3		1.5	35.588	96.345	5.0R	O
1978 MAY 7	160620.45	NE CHERRY	5		3.9	3.7	42.310	101.716	5.0R	O
1978 MAY17	231115.65	OK CANADIAN	1	2.1	2.3	2.0	35.525	97.910	5.0R	O
1978 MAY18	001922.43	OK CANADIAN	3	2.5	2.7	2.6	35.502	97.949	5.0R	O
1978 MAY18	003217.57	OK CANADIAN	2	2.2	2.1	2.1	35.601	97.828	5.0R	O
1978 MAY19	003937.46	OK MC CLAIN		1.7	2.0	1.9	35.135	97.503	5.0R	O
1978 MAY19	062732.70	OK LOGAN		1.8		1.4	36.002	97.367	5.0R	O
1978 MAY20	015343.36	KS DECATUR				2.3	39.998	100.333	5.0	K
1978 MAY20	015344.70	NE RED WILLOW			2.8	2.5	40.110	100.320	5.0R	O
1978 MAY22	042835.06	KS WABAUNSEE				2.3	39.135	96.292	8.9	K
1978 MAY22	042835.73	KS WABAUNSEE			1.9		39.138	96.295	5.0R	O
1978 MAY28	091900.22	OK HUGHES		2.1	0.9	1.8	35.213	96.144	5.0R	O
1978 JUN16	114656.29	TX SCURRY	F		4.7	3.8	32.961	100.794	5.0R	O
1978 JUN16	115333.15	TX GARZA			3.4		33.067	101.193	5.0R	O
1978 JUN22	051015.54	OK DEWEY		2.0		2.2	35.923	99.089	5.0R	O
1978 AUG 3	003537.09	OK BEAVER		2.3	2.1	2.4	36.689	100.162	5.0R	O
1978 AUG 6	042856.83	OK ELLIS		3.0	2.2	2.6	36.073	99.935	5.0R	O
1978 AUG 6	042859.41	OK ROGER MILLS					36.005	99.454	0.5	K
1978 AUG 8	120748.69	OK CARTER		2.3	2.2	1.9	34.127	97.463	5.0R	O
1978 AUG26	145751.99	OK CARTER				1.4	34.178	97.463	5.0R	O
1978 SEP 8	051606.60	OK MAYES				1.4	36.155	95.275	5.0R	O
1978 SEP14	080618.59	NE LINCOLN				2.2	40.896	100.367	5.0	K

Table 7. (continued)

DATE	(UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1978	SEP14	080620.96	NE FRONTIER			2.9		40.426	100.326	5.0R	O
1978	SEP26	211717.72	OK CANADIAN		2.2	2.2	2.2	35.519	97.866	5.0R	O
1978	SEP27	015603.81	OK CANADIAN		2.2	2.1	2.2	35.519	97.843	5.0R	O
1978	SEP27	205603.75	OK LOVE		2.4		1.9	33.883	97.477	5.0R	O
1978	OCT31	120529.14	AR CRAWFORD		1.8		2.1	35.458	94.297	5.0R	O
1978	NOV 1	084459.88	KS WASHINGTON				1.6	39.860	97.349	5.0	K
1978	NOV 1	084500.10	KS WASHINGTON					39.883	97.352	5.0R	O
1978	DEC 4	230614.14	KS KIOWA		2.6		2.5	37.449	99.179	5.0R	O
1978	DEC 4	230614.64	KS BARBER				2.2	37.340	98.640	0.5	K
1978	DEC 4	230620.98	KS LANE					38.492	100.440	5.0R	O
1978	DEC 4	230623.20	KS SHERIDAN				2.3	39.138	100.455	5.0	K
1978	DEC 8	111853.92	OK ATOKA		2.0	1.8	1.7	34.676	96.063	5.0R	O
1978	DEC10	134102.12	MO CARROLL				2.0	39.477	93.259	5.0	K
1978	DEC10	134108.16	MO CARROLL			2.4	2.3	39.351	93.525	5.0R	O
1978	DEC19	020028.87	OK HASKELL		1.2	1.7	1.7	35.086	95.125	5.0R	O
1978	DEC27	220030.02	OK LOVE		2.0		1.9	33.996	97.512	5.0R	O
1978	DEC28	053032.43	OK LOVE		1.4	1.9	1.5	34.080	97.462	5.0R	O
1978	DEC28	135409.81	OK LOVE		1.9	2.1	1.9	33.991	97.456	5.0R	O
1979	JAN 3	000339.23	AR JOHNSON		1.8	2.0	1.8	35.557	93.468	5.0R	O
1979	JAN 7	044524.35	AR YELL				2.1	34.912	93.215	5.0R	O
1979	JAN 8	113542.99	OK ALFALFA		2.0	2.1	1.9	36.579	98.146	4.7	O
1979	JAN24	034200.85	KS NEMAHA				1.5	39.619	96.082	5.0	K
1979	JAN24	034201.30	KS NEMAHA					39.634	96.094	5.0R	O
1979	JAN24	051546.35	OK LOVE		1.4		1.5	33.985	97.434	5.0R	O
1979	JAN24	052532.00	OK LOVE		1.8	2.1	1.9	34.022	97.381	5.0R	O
1979	JAN28	102409.34	OK SEQUOYAH		1.4		1.7	35.483	94.568	5.0R	O
1979	JAN29	192010.40	OK MC CLAIN		2.4	2.6	2.3	34.916	97.383	5.0R	O
1979	FEB 1	123132.28	OK PITTSBURG		1.8	1.7	2.1	34.830	96.062	5.0R	O
1979	FEB 4	165559.96	OK GARVIN		2.6	2.5	2.6	34.672	97.157	5.0R	O
1979	FEB 5	142340.05	OK HUGHES		2.2	1.8	2.2	35.177	96.092	5.0R	O
1979	FEB10	195603.61	KS JACKSON				1.7	39.265	95.905	4.0	K
1979	FEB10	195603.86	KS JACKSON					39.257	95.891	5.0R	O
1979	FEB25	192944.18	MO HOWARD				1.9	39.134	92.671	5.0	K
1979	MAR 1	034218.77	OK LOVE		1.9	2.0	1.8	33.969	97.446	5.0R	O
1979	MAR 9	114743.48	KS SUMNER				1.7	37.140	97.167	1.2	K
1979	MAR 9	114744.77	KS COWLEY		1.6			37.137	97.135	5.0R	O
1979	MAR 9	124318.77	KS SUMNER				1.8	37.169	97.160	2.0	K
1979	MAR 9	124320.22	KS SUMNER		1.9	1.9	1.8	37.121	97.148	5.0R	O
1979	MAR13	232922.56	OK CANADIAN	2	1.7			35.421	97.851	5.0R	O
1979	MAR14	031056.83	OK CANADIAN	4	2.0	1.9	1.8	35.498	97.826	5.0R	O
1979	MAR14	040243.05	OK LOGAN		1.4		1.5	35.781	97.650	5.0R	O
1979	MAR14	043715.27	OK CANADIAN	5	2.2	2.2	2.1	35.519	97.781	5.0R	O
1979	MAR15	103810.48	OK CANADIAN		1.6		1.6	35.689	97.923	5.0R	O
1979	MAR16	123817.42	OK ALFALFA		2.0	1.9	2.0	36.517	98.123	5.0R	O
1979	MAR18	172539.66	OK CANADIAN		1.6		1.5	35.377	98.100	5.0R	O
1979	MAR18	173309.23	OK CANADIAN				0.8	35.410	98.115	5.0R	O
1979	MAR18	173516.41	OK CANADIAN				1.0	35.410	98.115	5.0R	O
1979	MAR18	173951.71	OK CANADIAN		1.5		1.3	35.410	98.115	5.0R	O
1979	MAR18	174431.59	OK CANADIAN		1.6		1.4	35.410	98.115	5.0R	O

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1979 MAR18	175252.20	OK GRADY		1.8		1.5	35.344	98.053	5.0R	O
1979 MAR18	175536.84	OK CANADIAN		1.6		1.1	35.384	98.110	5.0R	O
1979 MAR18	180717.57	OK CANADIAN		2.1	2.0	1.8	35.439	98.118	5.0R	O
1979 MAR18	181453.81	OK CANADIAN		1.9	1.7	1.5	35.410	98.116	5.0R	O
1979 MAR18	183036.85	OK CANADIAN		2.3	2.3	2.0	35.418	98.108	5.0R	O
1979 MAR18	184629.65	OK CANADIAN		1.9	2.0	1.6	35.443	98.126	5.0R	O
1979 MAR18	185723.95	OK CANADIAN		2.0	2.0	1.8	35.416	98.130	5.0R	O
1979 MAR18	191350.60	OK CANADIAN		2.4	2.4	1.9	35.418	98.155	5.0R	O
1979 MAR18	193021.23	OK CANADIAN		2.2	2.2	1.8	35.418	98.101	5.0R	O
1979 MAR18	194157.26	OK CANADIAN		2.2	2.0	1.8	35.406	98.110	5.0R	O
1979 MAR18	200530.54	OK CANADIAN		2.7	2.5	2.0	35.416	98.110	5.0R	O
1979 MAR18	202411.90	OK CANADIAN		2.3		1.8	35.420	98.110	5.0R	O
1979 MAR18	204419.47	OK CANADIAN	3	2.9	2.9	2.5	35.379	98.124	5.0R	O
1979 MAR18	210741.09	OK CANADIAN		2.0	1.8	1.5	35.429	98.114	5.0R	O
1979 MAR18	211654.63	OK CANADIAN		1.9	1.8	1.3	35.379	98.118	5.0R	O
1979 MAR18	214210.54	OK CANADIAN		2.4	2.5	2.1	35.394	98.108	5.0R	O
1979 MAR18	220820.53	OK CANADIAN		2.1	1.9	1.7	35.396	98.126	5.0R	O
1979 MAR18	224217.44	OK CANADIAN		2.0	1.9	1.5	35.416	98.126	5.0R	O
1979 MAR18	231901.29	OK CARTER	3	2.5	2.3	2.2	34.100	97.448	5.0R	O
1979 MAR18	234039.22	OK CANADIAN		2.2	2.0	1.7	35.433	98.102	5.0R	O
1979 MAR19	005432.65	OK CANADIAN		2.1	2.0	1.7	35.408	98.102	5.0R	O
1979 MAR19	034255.14	OK CANADIAN		2.5	2.5	2.3	35.400	98.110	5.0R	O
1979 MAR21	045556.19	OK HUGHES		1.8	1.2	1.7	35.043	96.349	5.0R	O
1979 MAR23	013148.66	OK LOVE				1.3	34.034	97.430	5.0R	O
1979 MAR23	060139.99	OK LOVE				1.8	34.022	97.440	5.0R	O
1979 MAR23	075737.46	OK CADDO		1.9	1.8	1.7	35.361	98.108	5.0R	O
1979 MAR23	084114.13	OK CANADIAN		2.0	1.9	1.9	35.387	98.108	5.0R	O
1979 MAR23	104354.67	OK CANADIAN		1.5		0.9	35.605	97.974	5.0R	O
1979 MAR23	172602.40	OK CANADIAN		2.1		1.8	35.411	98.163	5.0R	O
1979 APR 1	122910.76	OK CANADIAN		1.8	1.7	1.9	35.420	98.132	5.0R	O
1979 APR 8	224610.41	NE KEARNEY				2.4	40.969	98.564	0.7	K
1979 APR22	092252.46	OK LINCOLN		1.6		1.8	35.789	96.711	5.0R	O
1979 MAY 8	112334.88	OK LOGAN		2.1	1.9	2.2	35.923	97.480	5.0R	O
1979 MAY12	215641.18	OK MC CLAIN		2.1	1.9	2.3	35.301	97.601	5.0R	O
1979 MAY22	034923.77	OK LOVE	3	1.8	1.9	2.0	34.027	97.470	3.7R	O
1979 MAY23	173008.30	OK LOVE			2.2	2.0	34.055	97.405	3.4R	O
1979 JUN 1	110001.61	OK NOBLE		1.6	1.4	1.1	36.207	97.330	5.0R	O
1979 JUN 3	050622.10	KS CLOUD				2.2	39.444	97.788	12.9	K
1979 JUN 6	161621.91	NE RED WILLOW	3			2.5	40.144	100.348	1.0	K
1979 JUN 7	073935.56	OK BECKHAM	3	3.2	2.9	3.0	35.187	99.812	5.0R	O
1979 JUN12	111311.88	NE NEMAHA				1.8	40.406	96.054	2.1	K
1979 JUN15	050823.60	KS WASHINGTON				1.9	39.840	97.220	5.0	K
1979 JUN19	044956.95	OK PITTSBURG		1.9	1.4	2.0	34.715	95.965	5.0R	O
1979 JUN19	045313.53	OK PITTSBURG		1.8		1.9	34.746	95.932	5.0R	O
1979 JUN25	073022.45	KS BUTLER				1.6	38.016	97.005	2.1	K
1979 JUN26	130410.23	KS JACKSON				2.0	39.296	96.016	9.0	K
1979 JUN30	204641.34	KS WASHINGTON	4			3.1	39.937	97.274	5.0	K
1979 JUN30	211007.27	KS WASHINGTON				1.4	39.908	97.292	5.0	K
1979 JUL 1	070016.28	OK LOVE		1.9	1.8	2.0	34.028	97.383	5.0R	O
1979 JUL 1	195934.14	KS WASHINGTON				2.0	39.952	97.286	5.0	K

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1979 JUL 4	034521.29	OK CANADIAN		2.3	2.3	2.2	35.705	97.978	5.0R	O
1979 JUL 7	011533.23	OK PITTSBURG		2.4	1.6	2.1	34.879	95.814	5.0R	O
1979 JUL13	074813.44	OK MC CURTAIN		1.3		1.8	34.033	95.087	5.0R	O
1979 JUL14	183226.81	KS ROOKS				2.1	39.526	99.256	12.6	K
1979 JUL16	000348.18	NE RED WILLOW	3			2.7	40.168	100.287	5.0	K
1979 JUL16	013420.32	NE RED WILLOW	3			2.5	40.193	100.345	5.0	K
1979 JUL16	052701.42	NE RED WILLOW				1.3	40.191	100.333	9.1	K
1979 JUL16	060809.89	NE RED WILLOW				1.5	40.189	100.346	11.1	K
1979 JUL16	070556.02	NE RED WILLOW				1.1	40.200	100.332	7.1R	K
1979 JUL24	022406.27	OK LOGAN		2.8	2.5	2.5	36.070	97.506	5.0R	O
1979 JUL24	041646.09	NE RED WILLOW				2.2	40.208	100.433	0.9	K
1979 JUL24	080446.26	NE PHELPS				1.9	40.466	99.623	0.9	K
1979 JUL25	031537.27	OK LOVE	5		2.7	2.3	33.967	97.549	5.0R	O
1979 JUL31	191105.62	OK PAYNE		2.4	2.5	1.9	36.086	97.305	5.0R	O
1979 AUG 2	041621.66	NE RED WILLOW				2.5	40.172	100.357	0.8	K
1979 AUG 2	104632.55	KS GEARY				2.2	38.930	96.563	18.2	K
1979 AUG 3	052940.63	TX SCURRY			2.6		32.851	100.737	5.0R	O
1979 AUG 3	102911.63	OK CANADIAN		2.0	1.9	1.7	35.683	98.005	5.0R	O
1979 AUG 9	000414.86	OK LOVE		1.8	2.4	2.0	33.930	97.432	5.0R	O
1979 AUG13	110947.65	NE RED WILLOW				1.7	40.113	100.502	1.5	K
1979 AUG14	235931.37	NE RED WILLOW				1.5	40.173	100.343	1.8	K
1979 AUG15	064553.87	NE RED WILLOW				1.5	40.145	100.339	1.5	K
1979 AUG15	160707.14	NE RED WILLOW				1.3	40.142	100.441	1.2	K
1979 AUG16	072712.82	OK MC CLAIN		1.7	1.9	1.7	34.953	97.602	5.0R	O
1979 AUG19	015807.85	OK CLEVELAND		2.4	2.2	2.1	35.203	97.445	5.0R	O
1979 AUG31	080011.70	NE RED WILLOW	4			2.2	40.139	100.337	1.5	K
1979 SEP 4	074011.97	OK GARVIN		2.2	2.3	2.1	34.799	97.557	5.0R	O
1979 SEP 5	023848.48	OK CANADIAN		1.7	1.9	1.5	35.429	97.871	5.0R	O
1979 SEP 5	040434.49	OK CANADIAN		1.8	1.8	1.5	35.427	97.717	5.0R	O
1979 SEP 9	000022.19	KS JACKSON				1.5	39.391	95.892	5.0	K
1979 SEP13	004922.97	OK BECKHAM	4	3.3	3.4	3.1	35.217	99.362	14.5R	O
1979 SEP13	021951.28	OK WASHITA		1.9		2.1	35.380	99.360	14.5R	O
1979 SEP15	034225.39	OK CANADIAN		1.8		1.7	35.493	97.882	5.0R	O
1979 SEP15	140119.38	OK GRADY		2.0	1.9	1.9	35.369	97.952	5.0R	O
1979 SEP16	060453.11	OK GRADY		1.7		1.6	35.355	97.997	5.0R	O
1979 SEP16	062758.42	OK CANADIAN		1.7		1.5	35.435	97.981	5.0R	O
1979 SEP16	104205.85	OK CANADIAN		2.0	2.0	1.9	35.455	97.905	5.0R	O
1979 SEP16	110700.23	OK GRADY		1.9	1.8	1.8	35.355	97.989	5.0R	O
1979 SEP16	155720.84	OK GRADY	4	2.5	2.5	2.2	35.343	97.997	5.0R	O
1979 SEP16	221642.17	OK GRADY		2.1	1.9	1.9	35.355	97.966	5.0R	O
1979 SEP17	143809.60	OK HASKELL		1.6	1.8	1.7	35.063	94.937	5.0R	O
1979 SEP17	204150.53	OK GRADY	4	2.6	2.5	2.3	35.320	97.968	5.0R	O
1979 OCT 6	110851.92	OK PITTSBURG		1.5		1.6	34.887	95.873	5.0R	O
1979 OCT19	161725.83	KS BARBER				2.0	37.061	98.607	5.1	K
1979 OCT19	161726.68	KS BARBER		2.2		2.3	37.077	98.605	5.0R	O
1979 OCT19	211228.05	KS BARBER				1.8	37.090	98.588	5.0	K
1979 OCT19	211228.33	KS BARBER		1.9		1.9	37.113	98.599	5.0R	O
1979 OCT21	072907.55	OK COAL		2.3	2.2	2.4	34.502	96.432	5.0R	O
1979 NOV 7	055409.84	OK CANADIAN		2.1		1.9	35.510	97.888	5.0R	O
1979 NOV11	102657.33	OK CANADIAN		2.2	1.9	2.1	35.695	98.050	5.0R	O

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1979 NOV16	055015.60	OK HUGHES				1.3	35.285	95.987	5.0R	O
1979 NOV19	045843.40	NE FURNAS				1.5	40.248	100.046	13.6R	K
1979 NOV27	091036.79	OK BLAINE		3.3	3.3	2.9	35.630	98.408	5.0R	O
1979 NOV29	220231.21	NE RED WILLOW				1.9	40.163	100.361	3.2	K
1979 DEC 7	141708.19	KS REPUBLIC				2.1	39.694	97.619	0.2	K
1979 DEC 9	231258.66	OK LOVE	3	2.9	2.5	2.4	33.988	97.353	5.0R	O
1979 DEC10	082514.82	OK HUGHES		1.8	1.5	2.0	34.965	96.307	5.0R	O
1979 DEC14	132009.02	OK MC CLAIN		1.8	1.9	1.8	35.187	97.664	5.0R	O
1979 DEC15	073015.17	KS BARBER		1.9		1.7	37.199	98.513	5.0R	O
1979 DEC15	073015.53	KS BARBER				1.7	37.090	98.471	0.5	K
1979 DEC16	123737.49	OK WASHITA		2.5		2.2	35.158	98.741	5.0R	O
1979 DEC20	145826.81	OK NOBLE		2.1		1.9	36.367	97.379	5.0R	O
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

Table 7. (continued)

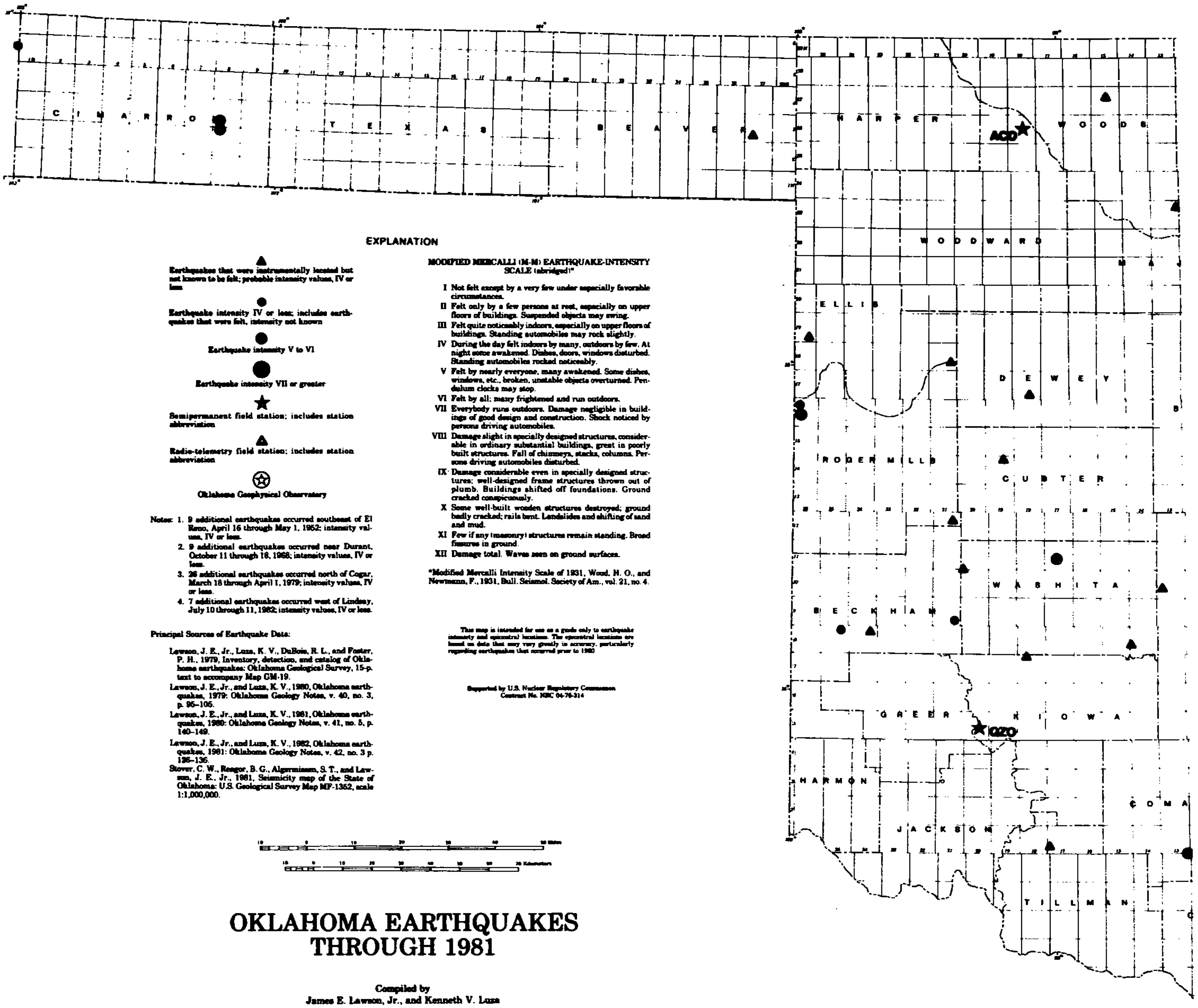
DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1980 SEP 7	002233.40	KS CLOUD				1.5	39.589	97.715	8.3	K
1980 SEP 7	015014.23	OK CLEVELAND		1.9		2.2	34.953	97.258	5.0R	O
1980 SEP 7	080620.87	OK PITTSBURG		1.6	1.4	1.8	34.680	95.840	5.0R	O
1980 OCT 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 NOV 9	145305.86	KS JACKSON				1.0	39.265	95.953	12.9	K
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
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	033409.68	OK ALFALFA				2.1	36.539	98.157	2.8	K
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
1981 JAN 4	173408.46	OK CANADIAN		2.3	2.2	2.2	35.664	98.097	5.0R	O
1981 FEB 4	033819.08	OK CREEK		1.8	1.5	1.8	35.661	96.388	5.0R	O
1981 FEB17	055302.87	KS OSBORNE				1.8	39.379	98.737	8.7	K
1981 FEB18	123347.61	OK MC CLAIN		2.0	2.0	2.1	34.902	97.491	5.0R	O
1981 FEB20	022029.71	OK CUSTER		2.4	2.2	2.3	35.707	99.202	5.0R	O
1981 MAR 8	144708.15	OK CANADIAN		1.9	1.9	1.9	35.593	98.047	5.0R	O
1981 MAR 8	154057.01	OK CANADIAN		2.2	2.4	2.3	35.601	97.961	5.0R	O
1981 MAR13	124216.68	NE DAWSON				2.4	40.891	99.695	5.0R	K
1981 MAR20	050948.17	NE RED WILLOW				1.9	40.172	100.327	1.8	K
1981 MAR25	072219.27	OK MC CLAIN		1.7	2.0	2.0	34.925	97.412	5.0R	O
1981 APR20	181813.48	NE NANCE				2.4	41.357	97.828	5.0R	K
1981 APR25	040722.32	OK POTTAWATOMIE		1.7	1.5	2.0	35.117	96.903	5.0R	O
1981 APR27	000403.25	OK OKMULGEE		2.0		2.1	35.602	95.882	5.0R	O
1981 APR27	075108.11	OK POTTAWATOMIE		1.6		1.7	35.293	96.916	5.0R	O
1981 APR29	085900.80	AR JOHNSON				1.9	35.761	93.556	5.0R	O
1981 MAY 5	112954.68	OK ATOKA			1.9	2.1	34.560	95.828	5.0R	O
1981 MAY 8	133017.39	TX GARZA				2.2	32.212	101.511	5.0R	O
1981 MAY15	051352.00	OK CANADIAN		1.9	1.7	1.9	35.473	97.817	5.0R	O
1981 MAY17	040538.36	AR SEARCY			1.9	2.1	35.839	92.517	5.0R	O

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1981 MAY25	225018.68	MO OREGON	F		2.7		36.746	91.623	5.0R	O
1981 MAY30	090710.35	MO PLATTE				1.9	39.361	94.860	0.5	K
1981 JUN 9	014632.79	TX SHELBY	F		3.2		31.992	94.321	5.0R	O
1981 JUN10	160523.14	OK PONTOTOC		2.1	1.7	1.9	34.714	96.684	5.0R	O
1981 JUN17	050224.82	OK GRANT		1.9		1.9	36.675	97.625	5.0R	O
1981 JUN20	051651.44	KS ELLSWORTH				1.8	38.712	98.379	11.9	K
1981 JUN26	185502.20	NE PLATTE				2.7	41.517	97.633	4.2	K
1981 JUL 1	224330.07	OK MC CLAIN		2.3	2.5	2.7	34.953	97.550	5.0R	O
1981 JUL 8	025629.89	OK GARFIELD		1.4			36.513	97.557	5.0R	O
1981 JUL 8	032830.93	OK CANADIAN		1.7	1.7	1.7	35.602	98.041	5.0R	O
1981 JUL 8	064115.11	KS WABAUNSEE				1.7	39.085	96.034	5.0R	K
1981 JUL 9	010039.96	OK CANADIAN		1.7	1.9	1.7	35.558	98.069	5.0R	O
1981 JUL 9	062028.29	OK CANADIAN		1.6	1.7	1.5	35.539	98.065	5.0R	O
1981 JUL 9	224711.10	OK MC CLAIN		2.3		2.4	34.955	97.651	5.0R	O
1981 JUL10	031656.10	OK CANADIAN		1.5		1.4	35.514	98.128	5.0R	O
1981 JUL10	072311.90	OK MC CLAIN		1.6	1.7	1.8	34.930	97.624	5.0R	O
1981 JUL10	223918.45	OK GARVIN		1.8	2.3	1.6	34.544	97.283	5.0R	O
1981 JUL11	191424.90	OK GRADY		1.0			34.853	97.732	5.0R	O
1981 JUL11	192107.63	OK GRADY		1.7	1.9	1.8	34.858	97.719	5.0R	O
1981 JUL11	192639.20	OK GRADY		0.9			34.853	97.732	5.0R	O
1981 JUL11	192807.25	OK GRADY		1.1			34.853	97.732	5.0R	O
1981 JUL11	193038.19	OK GRADY		1.0			34.853	97.732	5.0R	O
1981 JUL11	193453.98	OK GRADY		1.2			34.853	97.732	5.0R	O
1981 JUL11	193638.40	OK GRADY		0.9			34.853	97.732	5.0R	O
1981 JUL11	194447.96	OK MC CLAIN		1.9	1.9	1.9	34.870	97.669	5.0R	O
1981 JUL11	200429.21	OK GRADY		1.8	1.9	1.8	34.919	97.724	5.0R	O
1981 JUL11	200657.63	OK GRADY		2.1	2.4	2.3	34.868	97.724	5.0R	O
1981 JUL11	201923.72	OK GRADY	2	2.0	2.2	2.2	34.881	97.751	5.0R	O
1981 JUL11	210921.84	OK GRADY	5	2.9	3.5	3.0	34.853	97.732	5.0R	O
1981 JUL12	042649.04	OK GRADY		1.5	1.6	1.5	34.776	97.676	5.0R	O
1981 JUL12	182925.53	OK MC CLAIN		1.9	2.2	1.8	34.947	97.427	5.0R	O
1981 JUL14	040815.36	OK OKFUSKEE		0.7			35.418	96.604	5.0R	O
1981 JUL15	183133.83	OK GARVIN		2.0	2.3	1.9	34.537	97.350	5.0R	O
1981 JUL17	124157.77	NE PLATTE				1.9	41.568	97.313	5.0R	K
1981 JUL20	095331.08	OK MC CLAIN		1.9	2.0	2.1	34.971	97.411	5.0R	O
1981 JUL25	000431.72	OK OSAGE		1.6		1.5	36.693	96.904	5.0R	O
1981 JUL26	042303.72	OK NOBLE		1.7		1.8	36.224	97.232	5.0R	O
1981 JUL31	232425.91	OK LATIMER		1.7		2.0	34.709	95.222	5.0R	O
1981 AUG 1	015844.50	KS RICE				2.7	38.343	97.931	10.0R	K
1981 AUG 1	015845.38	KS MC PHERSON		3.0	2.8	2.7	38.297	97.861	5.0R	O
1981 AUG 2	004318.84	AR JOHNSON		1.7	1.9	1.7	35.608	93.510	5.0R	O
1981 AUG 7	115342.05	TN CROCKETT	F		3.8		35.948	89.154	5.0R	O
1981 SEP 6	175254.93	OK WOODS		2.3		2.2	36.480	98.531	5.0R	O
1981 SEP17	193100.46	OK JOHNSTON		2.3		1.9	34.481	96.823	5.0R	O
1981 SEP28	113607.58	OK ROGER MILLS		1.2		1.8	36.015	99.400	5.0R	O
1981 OCT 1	040620.41	AR JOHNSON		1.7	2.4	2.1	35.509	93.544	5.0R	O
1981 OCT 9	215425.58	NE HOWARD				2.5	41.264	98.698	5.0R	K
1981 OCT24	053542.27	OK PITTSBURG		1.3		1.7	35.167	95.777	5.0R	O
1981 NOV 5	164722.06	OK CANADIAN		2.1	2.0	1.9	35.677	97.982	5.0R	O
1981 NOV 6	123642.00	TX CHEROKEE			3.3		31.979	95.194	5.0R	O

Table 7. (continued)

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
1981 NOV 6	192825.31	OK PONTOTOC		2.0		2.2	34.676	96.682	5.0R	O
1981 NOV 9	093655.47	OK GARVIN		1.9	1.7	1.9	34.796	97.480	5.0R	O
1981 NOV10	200402.08	TX COKE				2.3	32.000	100.674	5.0R	O
1981 NOV12	005939.29	OK CREEK		1.1		1.6	35.668	96.479	5.0R	O
1981 NOV27	010826.13	KS PRATT				2.0	37.475	98.849	5.0R	K
1981 NOV27	010827.57	KS BARBER		2.1	2.2	2.1	37.042	98.943	5.0R	O
1981 NOV29	005705.48	TX MONTAGUE		1.9	1.9	2.1	33.647	97.817	5.0R	O
1981 DEC 4	031307.34	OK GRADY		1.8	2.0	1.9	35.195	97.691	5.0R	O
1981 DEC 4	053140.01	OK MC CLAIN		2.0	2.2	2.1	35.137	97.659	5.0R	O
1981 DEC 8	062042.00	NE GOSPER				2.2	40.447	99.744	5.0R	K
1981 DEC 9	215003.65	OK COMANCHE		1.8		2.1	34.608	98.465	5.0R	O
1981 DEC17	052253.76	OK GRADY		2.2	2.0	2.1	35.132	97.852	5.0R	O
1981 DEC17	054454.21	OK GARFIELD				2.4	36.397	97.594	10.6	K
1981 DEC17	054454.70	OK GARFIELD		2.7	2.9	2.6	36.387	97.661	5.0R	O
1981 DEC19	024953.21	OK LOVE		1.2		1.8	33.948	97.495	5.0R	O



EXPLANATION

▲ Earthquakes that were instrumentally located but not known to be felt; probable intensity values, IV or less

● Earthquake intensity IV or less; includes earthquakes that were felt, intensity not known

● Earthquake intensity V to VI

● Earthquake intensity VII or greater

★ Semipermanent field station; includes station abbreviation

▲ Radio-telemetry field station; includes station abbreviation

⍟ Oklahoma Geophysical Observatory

Notes:
1. 9 additional earthquakes occurred southeast of El Reno, April 16 through May 1, 1952; intensity values, IV or less.
2. 9 additional earthquakes occurred near Durant, October 11 through 16, 1968; intensity values, IV or less.
3. 26 additional earthquakes occurred north of Cogar, March 18 through April 1, 1979; intensity values, IV or less.
4. 7 additional earthquakes occurred west of Lindsay, July 10 through 11, 1982; intensity values, IV or less.

Principal Sources of Earthquake Data:

Lawson, J. E., Jr., Luza, K. V., DuBois, R. L., and Foster, P. H., 1979, Inventory, detection, and catalog of Oklahoma earthquakes: Oklahoma Geological Survey, 15-p. text to accompany Map GM-19.

Lawson, J. E., Jr., and Luza, K. V., 1980, Oklahoma earthquakes, 1979: Oklahoma Geology Notes, v. 40, no. 3, p. 95–106.

Lawson, J. E., Jr., and Luza, K. V., 1981, Oklahoma earthquakes, 1980: Oklahoma Geology Notes, v. 41, no. 5, p. 140–149.

Lawson, J. E., Jr., and Luza, K. V., 1982, Oklahoma earthquakes, 1981: Oklahoma Geology Notes, v. 42, no. 3 p. 126–136.

Stover, C. W., Reagor, B. G., Algermissen, S. T., and Lawson, J. E., Jr., 1981, Seismicity map of the State of Oklahoma: U.S. Geological Survey Map MF-1352, scale 1:1,000,000.

MODIFIED MERCALLI (M-M) EARTHQUAKE-INTENSITY SCALE (abridged)*

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings. Standing automobiles may rock slightly.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, doors, windows disturbed. Standing automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken, unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction. Shock noticed by persons driving automobiles.
VIII	Damage slight in specially designed structures, considerable in ordinary substantial buildings, great in poorly built structures. Fall of chimneys, stacks, columns. Persons driving automobiles disturbed.
IX	Damage considerable even in specially designed structures; well-designed frame structures thrown out of plumb. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed; ground badly cracked; rails bent. Landslides and shifting of sand and mud.
XI	Few if any (masonry) structures remain standing. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces.

*Modified Mercalli Intensity Scale of 1931, Wood, H. O., and Newmann, F., 1931, Bull. Seismol. Society of Am., vol. 21, no. 4.

This map is intended for use as a guide only to earthquake intensity and epicentral locations. The epicentral locations are based on data that may vary greatly in accuracy, particularly regarding earthquakes that occurred prior to 1960

Supported by U.S. Nuclear Regulatory Commission
Contract No. NRC 04-76-314

OKLAHOMA EARTHQUAKES
THROUGH 1981

Compiled by
James E. Lawson, Jr., and Kenneth V. Luza
1982

Fig. 34a. Oklahoma earthquakes, through 1981, for western Oklahoma (reduced from original 1:750,000-scale map).

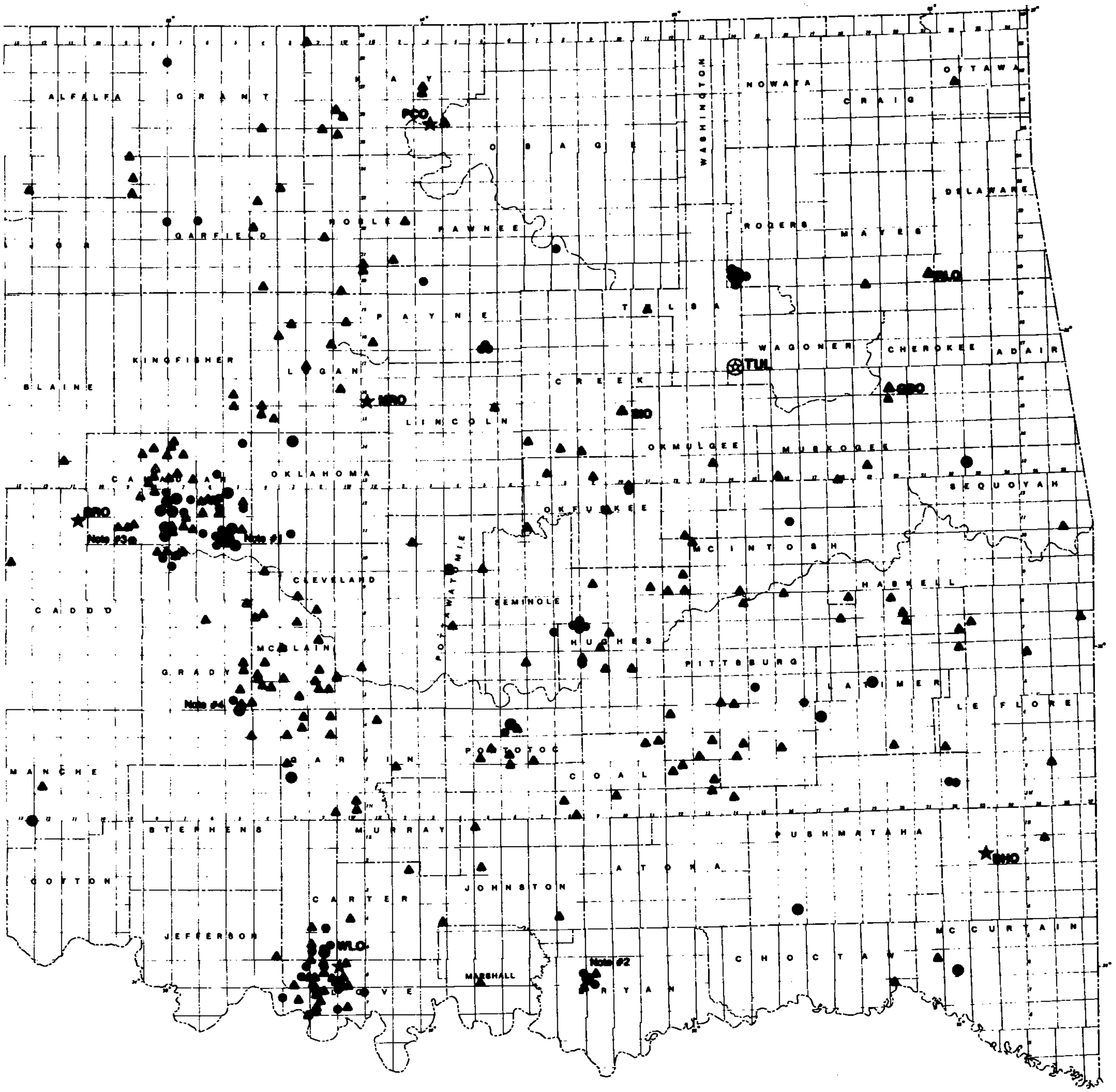


Fig. 34b. Oklahoma earthquakes, through 1981, for eastern Oklahoma (reduced from original 1:750,000-scale map).

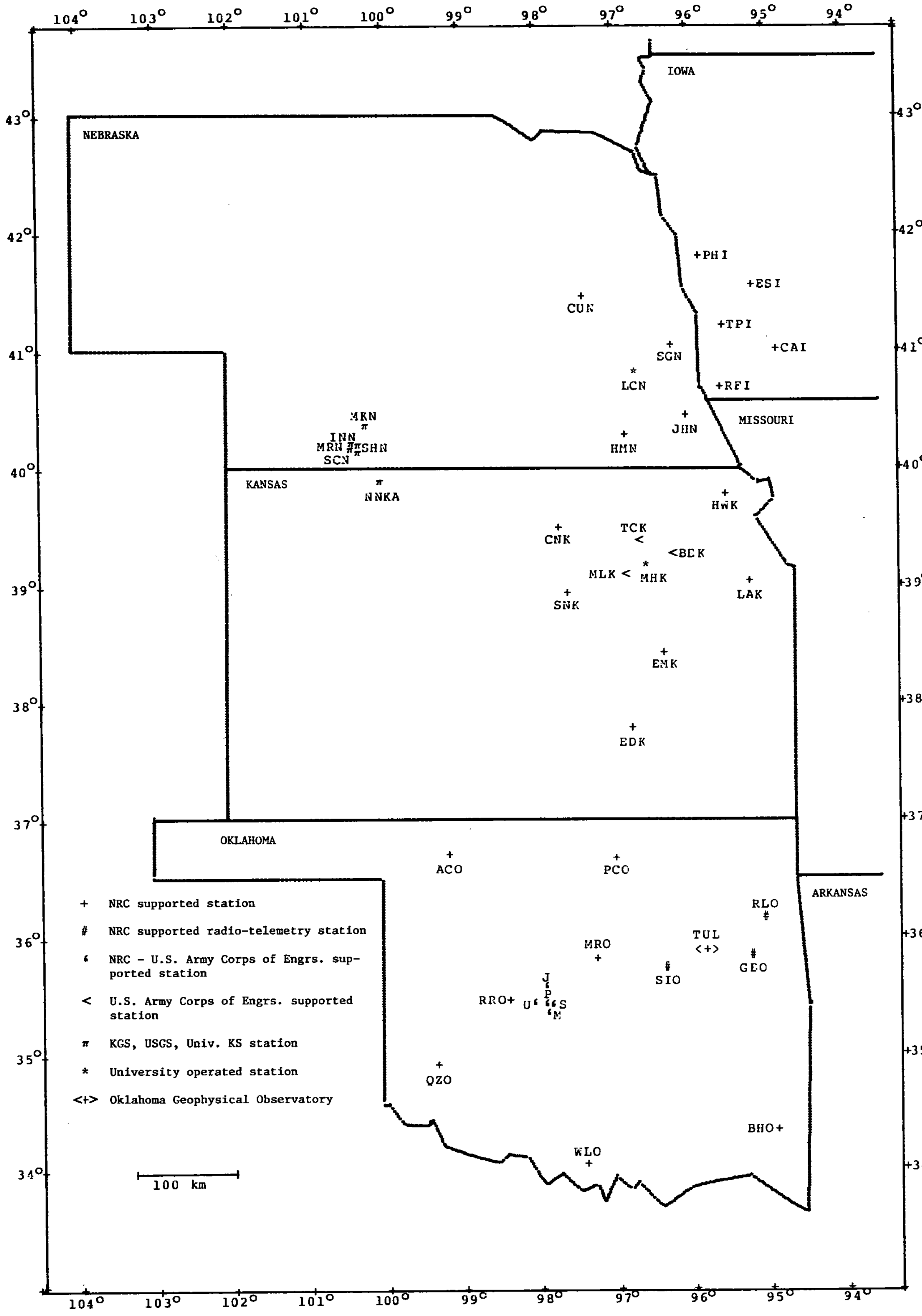


Fig. 35. Seismograph stations operating in Oklahoma, Kansas, Nebraska, and western Iowa, January 1, 1982.

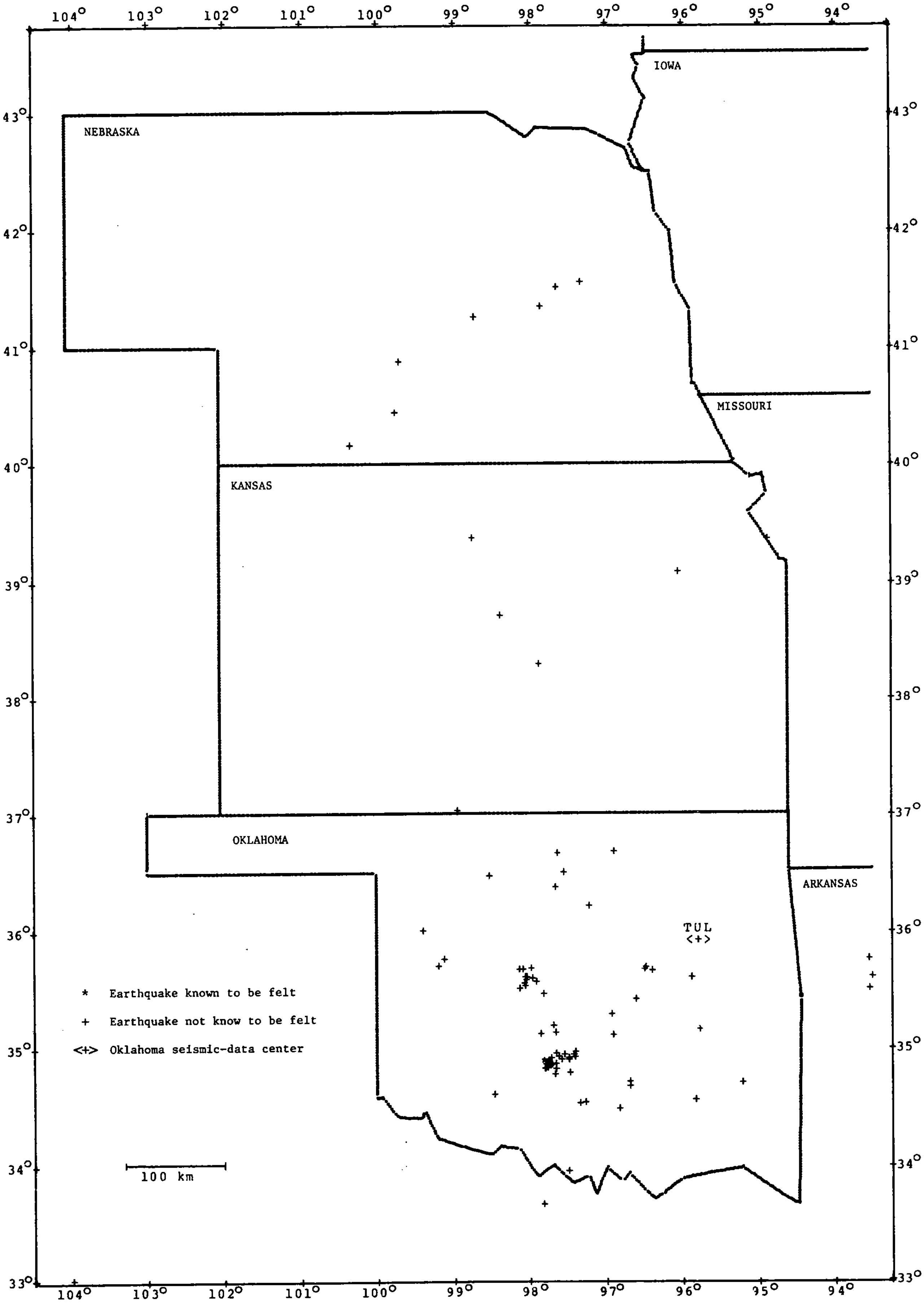


Fig. 36. Earthquake distribution for western Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, January 1-December 31, 1981.

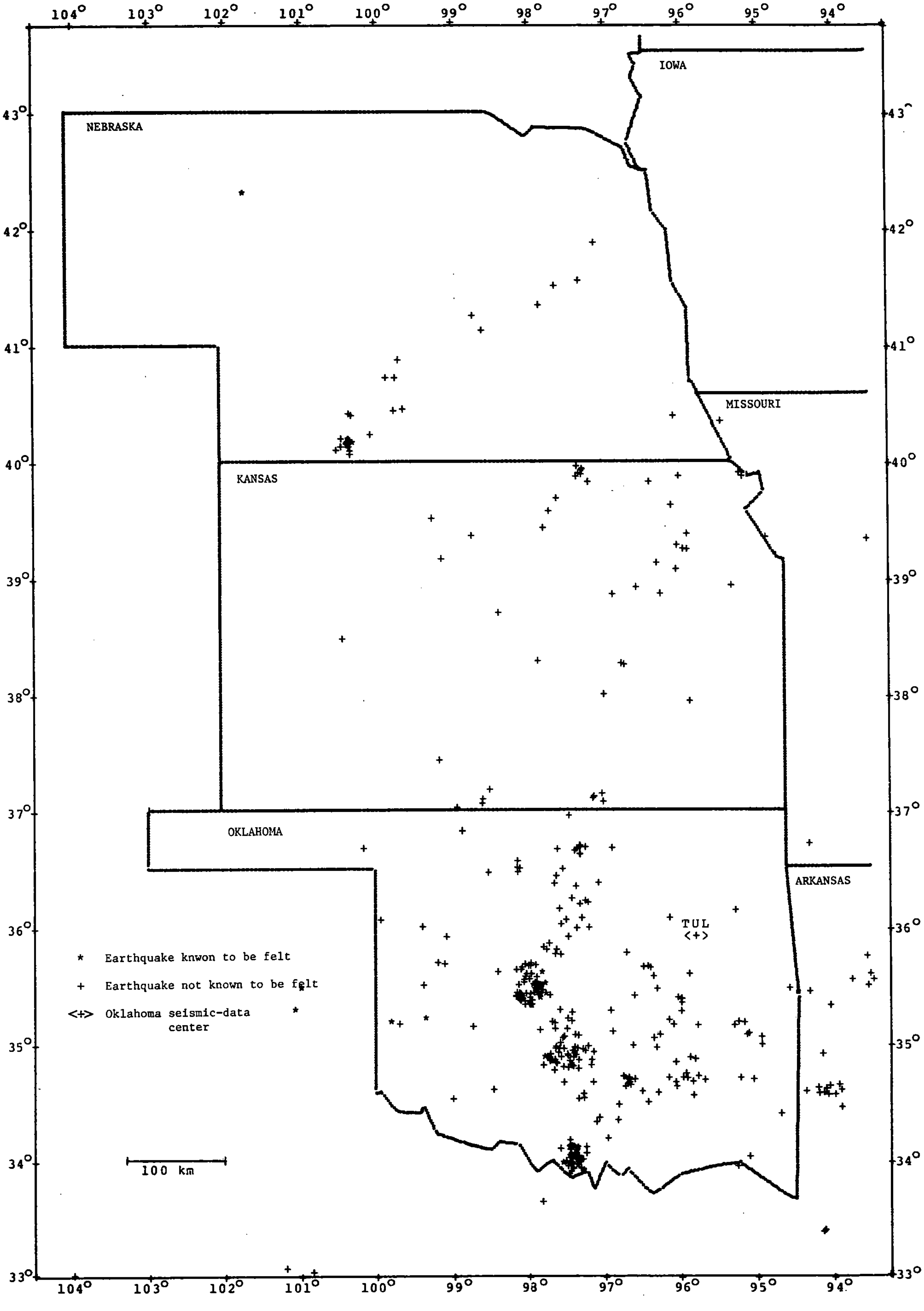


Fig. 37. Earthquake distribution for western Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, January 1, 1977, through December 31, 1981.

In 1981, 57 Oklahoma earthquakes were located by the Oklahoma Geophysical Observatory staff. Magnitude values range from a low of 1.0 (MDUR) in Grady County to a high of 2.9 (MDUR) in Grady County. The listing represents only those earthquakes that could be located by using three or more seismograph records. Two earthquakes were reported felt by people living in the vicinity of an earthquake epicenter. The felt areas for the above earthquakes are probably restricted to a few tens of square kilometers away from the epicentral location. A summary of these events is listed in table 8.

Table 8. Earthquakes that were reported felt in Oklahoma, 1981

Event	Date and origin time (UTC)[a]		Nearest city	County	Intensity (MM)[b]
361	Jul 11	201923.72	Bradley	Grady	II
362	Jul 11	210921.84	Bradley	Grady	V

[a] UTC refers to Coordinated Universal Time, formerly Greenwich Mean Time.
[b] Modified Mercalli (MM) earthquake-intensity scale.

The earthquake activity culminated with felt earthquakes having mbLg magnitudes of 2.2 and 3.5. The last earthquake of the swarm, which was the largest of the year, was felt with MM intensity IV in Bradley, Erin Springs, and Lindsay. Three km west of Lindsay, where pictures were knocked off a wall, the intensity reached MM V. The McClain-Grady-northern Garvin County region was the site of the greatest earthquake activity in 1981, even without counting the July 11 swarm.

Nine earthquakes occurred in Canadian County in 1981. None of these events was reported felt. Three earthquakes that occurred in Garfield and Grant Counties plot in close proximity to the Nemaha Uplift structures. In 1981, the first known earthquakes occurred in Custer County (February 20) and Osage County (July 25). Thus far, 58 Oklahoma counties have had at least one earthquake within their boundaries.

The 1981 earthquake epicentral data, when combined with previous earthquake data, producd at least four seismic trends worthy of discussion. One trend is in north-central Oklahoma (fig. 38). The pre-1977 earthquake data (circles) and the 1977-81 earthquake data (triangles) are shown in figure 38. There appears to be a 25-mile-wide (40-km) and 90-mile-long (145-km) earthquake zone that extends northeastward from near El Reno toward Perry (Noble County). Most of the earthquakes within this zone have occurred in the vicinity of the El Reno-Mustang area, which has been the site of numerous earthquakes since 1908. Ten of the 1981 earthquakes plot within this zone. Prior to installation of the statewide earthquake-station network, more than one-half of the known Oklahoma earthquakes occurred in the vicinity of El Reno. However, after the El Reno earthquake of 1952, magnitude 5.5 (mb), no earthquakes were reported for this region until 1978.

The correlation of historical and recent earthquake activity to known structural features remains unclear. Some fault features that cut pre-Pennsylvanian rocks, which

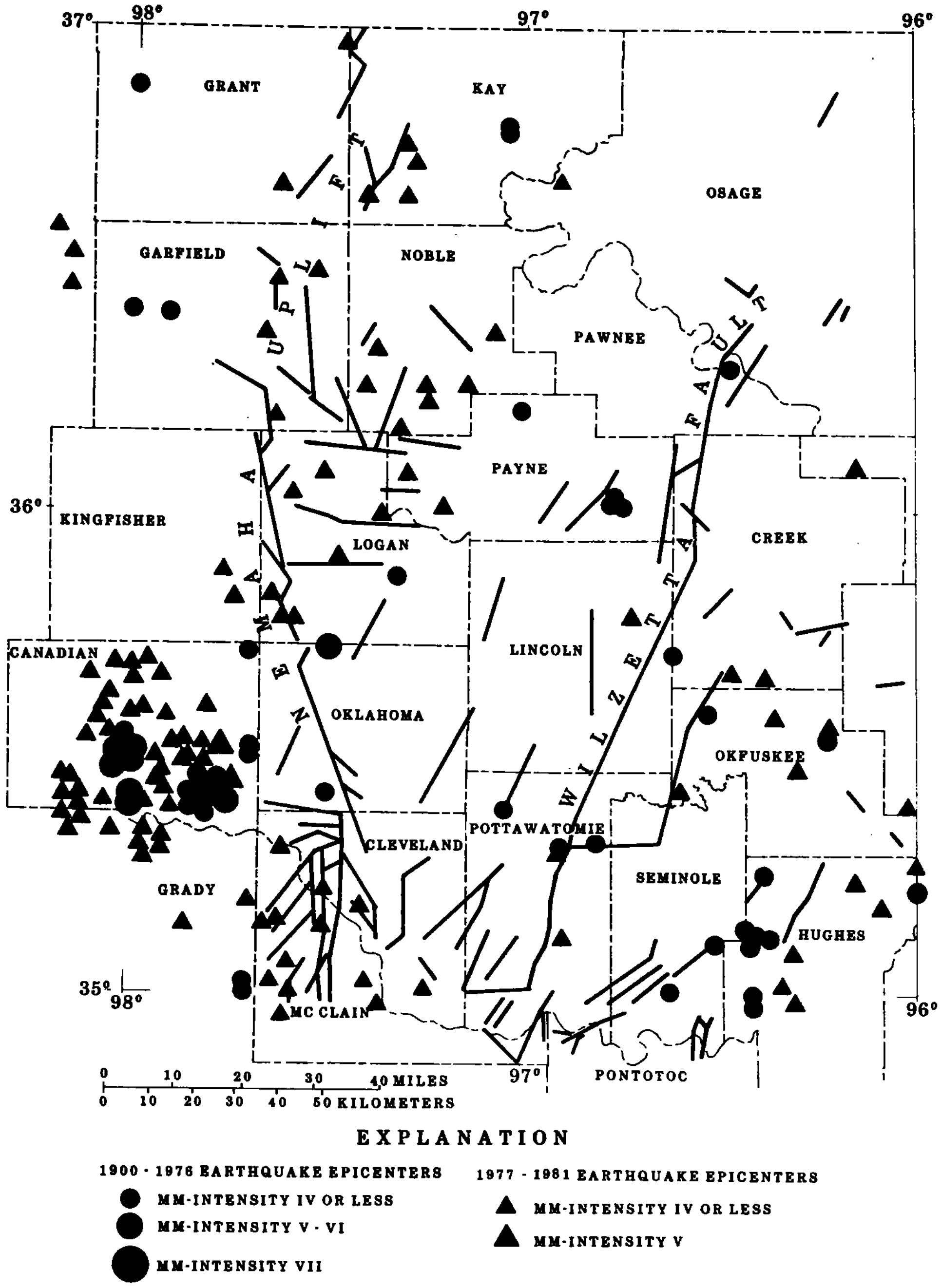


Fig. 38. Distribution of faults that cut pre-Pennsylvanian strata, and earthquake epicenters for north-central Oklahoma (Wheeler, 1960; Jordan, 1962; unpublished reports).

were compiled from Jordan (1962), Wheeler (1960), and unpublished reports, are shown in figure 38. 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 appears to be more active than the middle and northern parts. The recent as well as the historic earthquake data seem to support this observation. The installation of a five-seismograph-station array was completed in 1981 southeast of El Reno. It was hoped that additional earthquake data, such as focal-depth determinations, could be gained from these network stations.

A second trend is situated between Norman and Pauls Valley. Twenty-four earthquakes were instrumentally located in this region. This trend closely parallels the McClain County Fault Zone, which is about 25 miles wide and 37 miles long (40 by 60 km). Perhaps this very complex fault zone, which contains numerous subparallel faults, is the southernmost extension of the Nemaha Uplift.

In south-central Oklahoma, earthquakes are concentrated in the Wilson area, Carter and Love Counties. Only one earthquake was located in this region in 1981. In the past, this area has also been the site of numerous small earthquakes. A fourth general area of earthquake activity lies along and north of the Ouachita front (Arkoma Basin) in southeastern Oklahoma. Three 1981 earthquakes, with (DUR) magnitudes that range from 1.7 to 2.1, were instrumentally detected in this region.

Oklahoma Seismic-Source Zones

With the possible exception of the earthquakes along the northern front of the Ouachita Mountains, it was not possible to correlate Oklahoma earthquakes with recognized geologic features. It was therefore decided to divide Oklahoma into seismic-source zones, which were based only on earthquake occurrence. The zones were drawn with the following three criteria:

1. Using network-located earthquakes (1977-79) only, each zone should show a relatively uniform density of earthquakes.
2. Historical earthquakes (pre-1977), some of which were only felt and some of which were located with the aid of Oklahoma Geophysical Observatory seismographs and occasionally with seismographs outside Oklahoma, either must define the same apparent zone or, in areas with too few historic earthquakes, must appear not to contradict the zone boundaries.
3. Both historical and network-located earthquakes must lie along the same line on a graph of log cumulative frequency vs. magnitude.

These criteria were 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), southeastern Oklahoma (zone 2.2), west-central Oklahoma (zone 2.3), and residual (an area that encompasses all remaining parts 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. Table 9 gives the descriptive names, zone numbers, areas, and precise boundaries of the zones.

Table 9. Seismic source zones of Oklahoma and surrounding areas

Zone name	Zone number	Area (km^2)	Boundaries[a]	
			Latitude °N	Longitude °W
Central Oklahoma	1.1	1,232.4	35.55	97.75
			35.25	97.75
			35.25	98.25
			35.55	98.25
			35.55	08.75
South-central Oklahoma	1.2	1,359.8	34.2	97.2
			33.8	97.2
			33.8	97.6
			34.2	97.6
			34.2	97.2
North-central Oklahoma	2.1	4,232.8	46.3	97.0
			36.1	97.0
			35.55	97.65
			35.55	98.25
			36.4	97.4
			36.4	97.0
Southeastern Oklahoma	2.2	32,668.9	35.55	94.0
			34.5	94.0
			34.5	97.75
			35.55	97.75
			35.55	94.0
West-central Oklahoma	2.3	12,292.7	36.0	98.5
			35.0	98.5
			35.0	100.0
			36.0	100.0
			36.0	98.5
Residual	3.1	177,927.4	37.5	94.0
			33.5	100.2
			36.3	100.2
			36.3	103.0
			37.5	103.0
			37.5	94.0
			Excluding area inside zones 1.1, 1.2, 2.1, 2.2, 2.3)	

[a] Given as latitude and longitude of each straight-line intersection, starting at the most northeasterly and proceeding clockwise.

The six zones are shown in figure 39 a and b along with the earthquakes located from 1977 through 1981. There is a clustering of earthquakes crossing the western boundary of zone 2.2. When the zones are shown with only the 1981 earthquakes (fig. 40a, 40b), it is apparent that much of this clustering is very recent. Another zone will probably have to be defined for this area, but for two or three years more earthquake locations are needed to clarify whether this area should be separated from zone 2.2 or whether the western boundary of zone 2.2 should simply be expanded westward.

For each zone except 1.2, a magnitude-frequency relationship was developed. These relations are given in table 10. 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.

Table 10. Equations estimating largest magnitude (M) that will occur with frequency of f per year per 1,000 km^2 of source zone

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 - Southeastern 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

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

Note: 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.

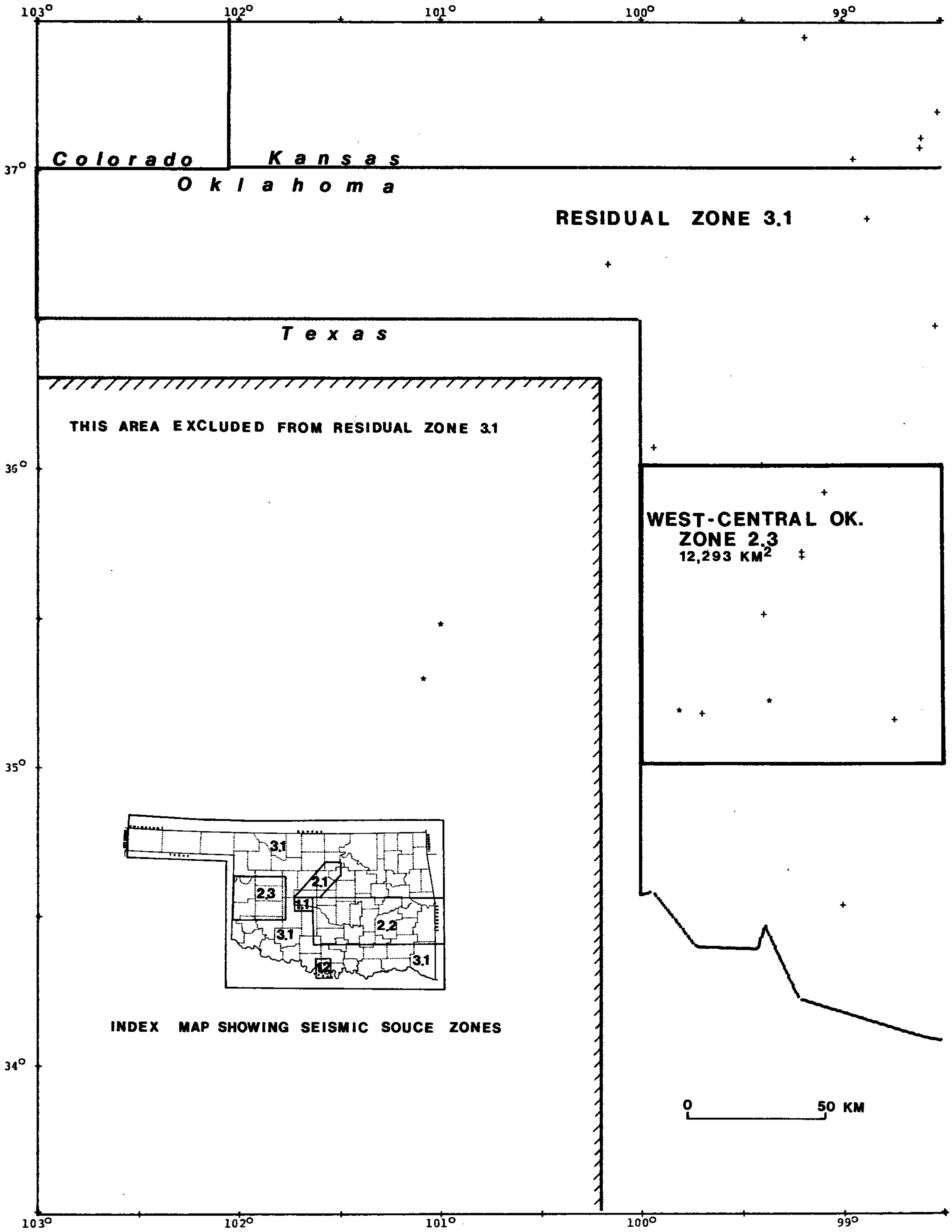


Fig. 39a. Seismic-source zones for western Oklahoma and adjacent states; 1977 through 1981 earthquake data.

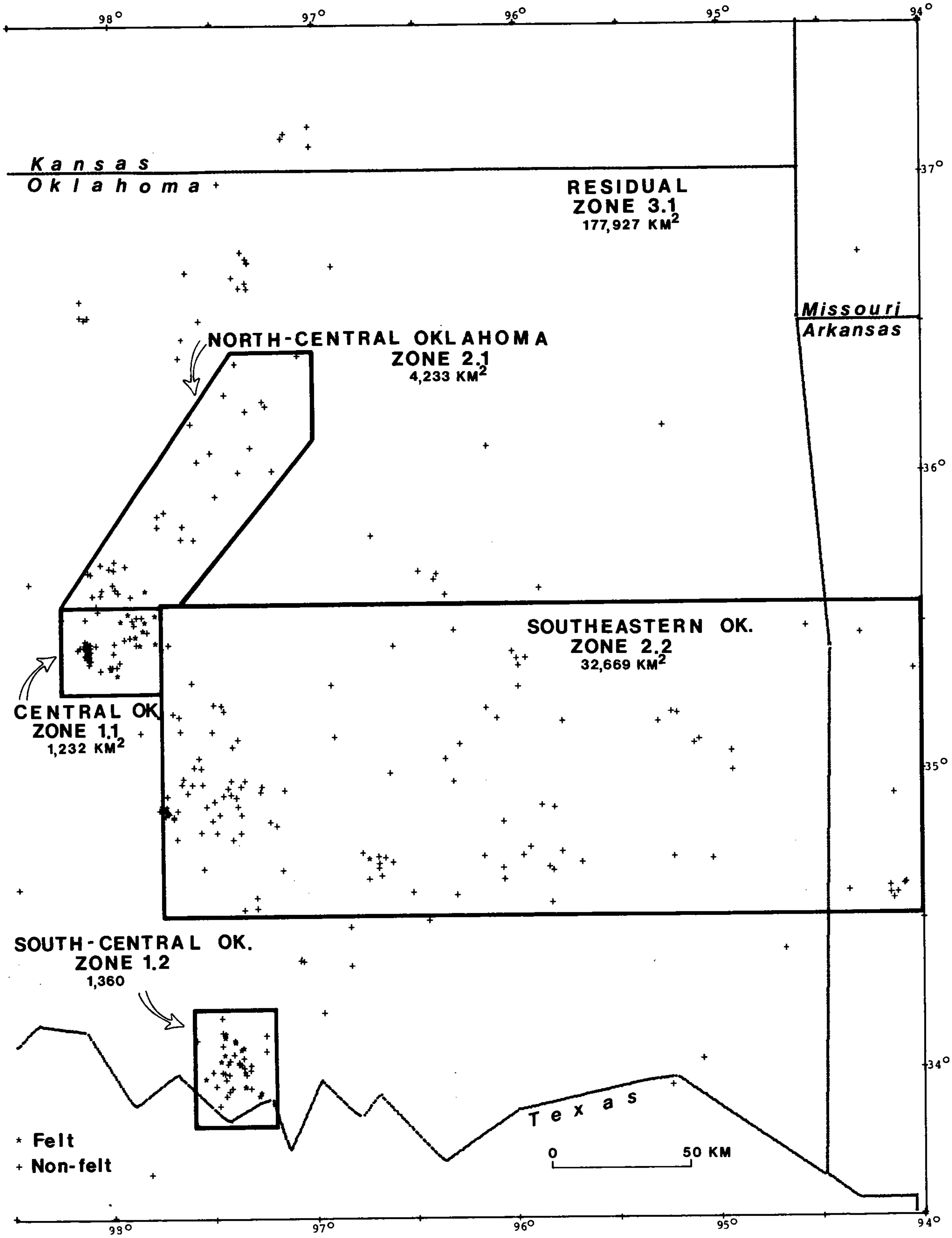


Fig. 39b. Seismic-source zones for eastern Oklahoma and adjacent states; 1977 through 1981 earthquake data.

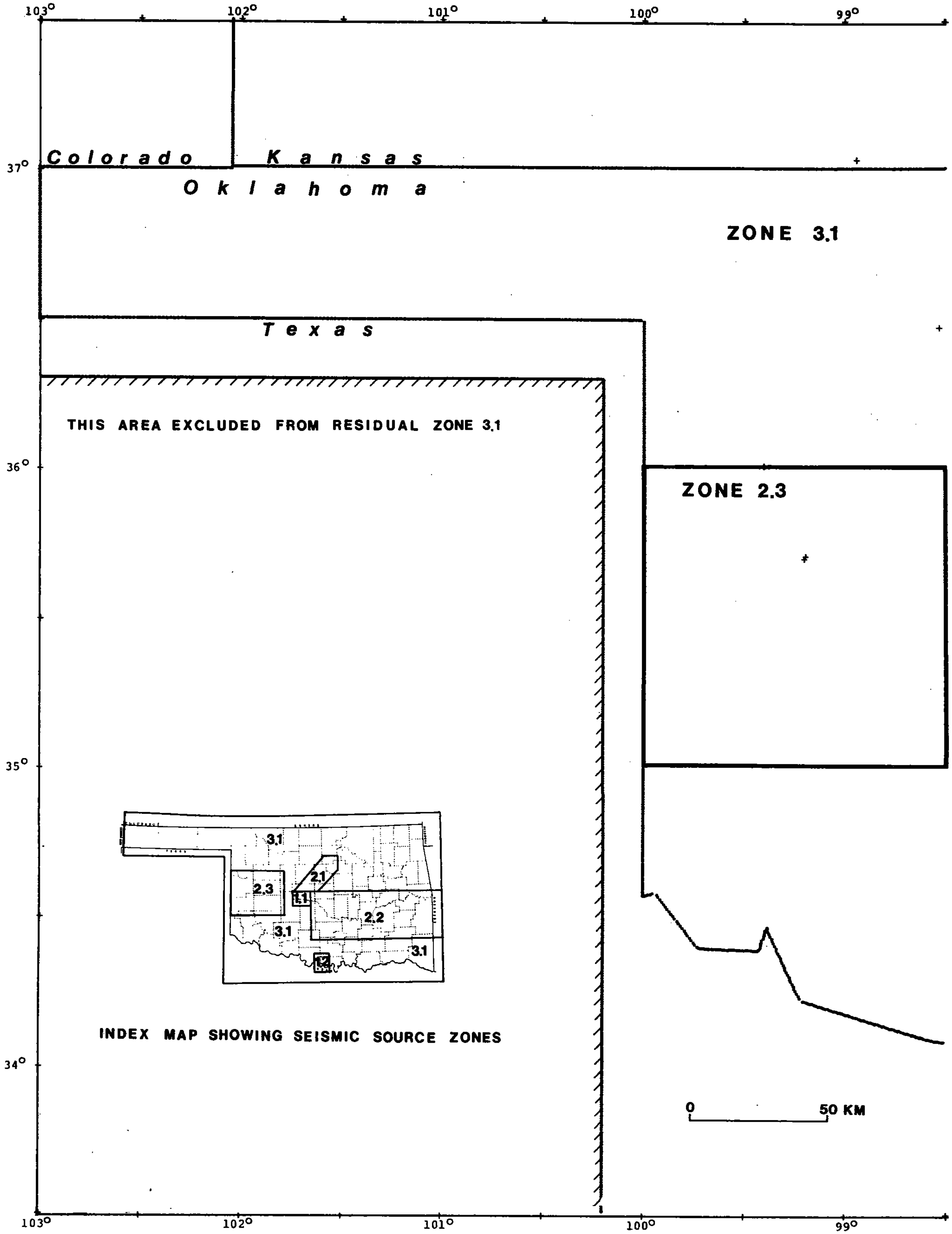


Fig. 40a. Seismic-source zones for western Oklahoma and adjacent states; 1981 earthquake data.

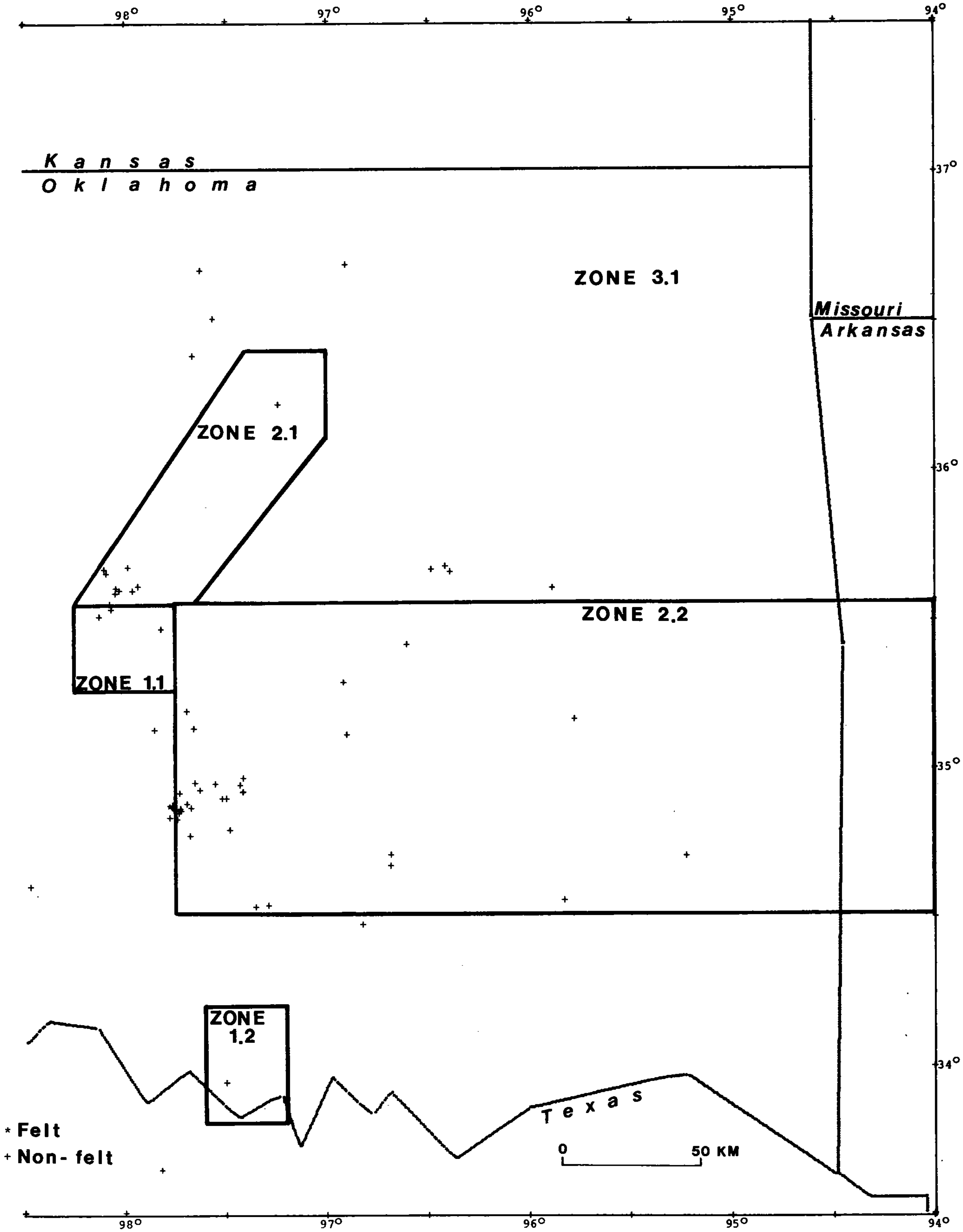


Fig. 40b. Seismic-source zones for eastern Oklahoma and adjacent states; 1981 earthquake data.

DISCUSSION

Six years ago (1976) the principal objectives of the Nemaha study were as follows:

1. Synthesize and analyze all available geologic, seismic, and other 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.

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. The geologic, aeromagnetic, and seismological information are displayed in figures 5, 7-9, 17, 22, and 34.

The subsurface studies reveal that the Nemaha Ridge consists of several uplifted crustal blocks. These blocks are typically 3 to 5 miles (5 to 8 km) wide and 5 to 20 miles (8 to 32 km) long and are generally bounded by near-vertical faults.

An important aspect of this investigation was to ascertain whether or not there is a correlation between the Nemaha Uplift structures and the earthquake activity in north-central Oklahoma. From 1897 through 1976, Oklahoma has had approximately 128 known earthquakes. More than half of these earthquakes occurred in north-central Oklahoma. Since 1976, 255 additional earthquakes were located in Oklahoma.

The pre-1977 earthquake data, when combined with the 1977-81 earthquake data, produce at least one seismic trend in north-central Oklahoma (fig. 38). 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 observation.

Koff's (1978) detailed study of the Oklahoma City Uplift attempted to determine if there was a correlation with subsurface structures and historical earthquakes in the El Reno-Mustang area (fig. 14). Unfortunately, the lack of subsurface control in Canadian County did not permit the construction of detailed structure and isopach maps needed for correlation studies.

Most of the earthquakes in Canadian County occur 18 to 24 miles (30 to 40 km) west of the Nemaha structures. The focal depths of most of these earthquakes range between 2.5 to 3.7 miles (4 to 6 km). In the vicinity of Oklahoma City, the Nemaha faults extend almost vertically for at least 2 miles (3.2 km) below the surface. Therefore, it does not seem plausible that the Nemaha structures are directly related to most of the earthquake activity in Canadian County.

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. Hayden's (1982) gravity study in western Canadian County and vicinity suggests that the Anadarko Basin is not in isostatic equilibrium. Perhaps the Anadarko Basin is still undergoing some form of isostatic adjustment, which may be one of the mechanisms responsible for some of the earthquake activity near the basin margins.

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 (fig. 24).

The earthquake epicentral data produce 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. The faulting has resulted in 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 oil-field 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.

Earthquake focal depths and fault-plane solutions would be quite useful in the evaluation of earthquake mechanisms. Unfortunately, Oklahoma earthquakes have very shallow focal depths. The network spacing did not permit accurate depth determinations, except in a few instances. A five-station array was established in Canadian County in order to gather focal-depth information. However, the earthquakes recorded on the network stations were not of sufficient magnitude to trigger on more than one station. The network was temporarily closed because of insufficient results. However, the network could be reactivated if an earthquake, similar in size and magnitude to the El Reno event, were to occur.

All objectives, with the exception of a seismotectonic-province map and the identification of definite earthquake-source mechanisms, were achieved. After considerable amount of 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. As an alternative to a seismotectonic map, we prepared a seismic-source-zone map for Oklahoma (fig. 39a, b).

On the basis of patterns of historical earthquakes and network-located earthquakes, Oklahoma was divided into six seismic-source zones. The zones were based on consistent pattern of earthquake occurrences. For each seismic-source zone, a maximum expected earthquake magnitude for a given time interval can be computed. Furthermore, horizontal acceleration and horizontal ground velocity, which may be expected at a specific site for a given time interval from earthquakes within a source zone, can be determined.

A principal assumption used in this concept is that future seismicity, for as long as 2,000 years, will follow the spatial and temporal patterns of the last 80 years. This assumption should be rated fair to poor. The July 27, 1980, earthquake northeast of Lexington, Kentucky, which had a magnitude of 5.3 (Oklahoma Geophysical Observatory, mbLg), occurred in an area essentially free of historical seismicity. The method used in the source-zone study would have assigned extremely low risk to this area. However, the 1952 earthquake near El Reno, Oklahoma, having a magnitude of 5.0, was preceded by earthquakes (as early as 1908) and followed by earthquakes (as late as 1981). In more active seismic areas of the world, particularly at lithospheric-plate boundaries, causative geologic structures might be identifiable. But even in such cases, past seismicity is relied upon to define which of these structures may be active.

We have made good progress toward the identification of earthquake-prone areas in Oklahoma. Earthquake-source mechanisms, focal-depth determination, and fault-plane solutions remain elusive. It will take several years of recording and locating small-magnitude earthquakes before some definite seismic trends are established. Apparently, many of the earthquake-generating structures are deeply buried. More sophisticated techniques, such as seismic-reflection profiles, in-situ stress analyses, and micro-earthquake arrays, will be needed to solve the source-mechanism problem.

ACKNOWLEDGMENTS

Many individuals assisted in various phases of this project. George A. Laguros, Phillip R. Sanders, Brent L. Seaton, and William D. Fishman assisted in the collection and compilation of the geological and geophysical data. T. J. Nagengast, L. R. Koff, and T. C. Axtmann collected and interpreted the subsurface data. Christopher Barrett, J. M. Hayden, and D. J. Santiago conducted gravity and magnetic surveys in central and north-central Oklahoma. The linear-enhancement study was completed by Robert C. Shoup. Noel F. Rasmussen and associates prepared an aeromagnetic map with interpretation for north-central Oklahoma. Special appreciation is extended to the numerous volunteers who have operated our seismograph field stations.

We appreciate the excellent cooperation and assistance provided by Neil B. Steuer and Jerry Harbour.

REFERENCES CITED

Adi, Ketti, and Chouet, Bernard, 1975, Origin of coda waves: source, attenuation, and scattering effects: Journal of Geophysical Research, v. 80, p. 3322-3342.

Amsden, T. W., 1979, Welling Formation, new name for Upper Ordovician unit in eastern Oklahoma (formerly called "Fernvale"): Am. Assoc. Pet. Geologists Bull., v. 63, p. 1135-1138.

Arnold, B. M., Sr., 1956, The subsurface geology of Kingfisher County, Oklahoma: Univ. of Oklahoma M.S. thesis, 84 p.

Bakun, W. H., and Lindh, A. G., 1977, Local magnitudes, seismic moments, and coda durations for earthquakes near Oroville, California: Bulletin of the Seismological Society of America, v. 67, p. 615-629.

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

Bingham, R. H., and Bergman, D. L., 1980, Reconnaissance of the water resources of the Enid Quadrangle, north-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 7, scale 1:250,000, 4 sheets.

Bingham, R. H., and Moore, R. L., 1975, Reconnaissance of the water resources of the Oklahoma City Quadrangle, central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 4, scale 1:250,000, 4 sheets.

Blumenthal, Morris, 1958, Subsurface geology of the Prague-Paden area, Lincoln and Okfuskee Counties, Oklahoma: Shale Shaker Digest II, p. 155-170.

Carver, G. E., Jr., 1947, A subsurface study of the northeast Arcadia-Coon Creek area, Oklahoma and Logan Counties, Oklahoma: Univ. of Oklahoma M.S. thesis, 59 p.

Cary, L. W., 1955, Subsurface geology of the Garber area, Garfield County, Oklahoma: Shale Shaker Digest I, p. 384-403.

Caylor, J. W., 1958, Subsurface geology of western Garfield County, Oklahoma: Shale Shaker Digest II, p. 202-220.

Clare, P. H., 1963, Petroleum geology of Pawnee County, Oklahoma: Oklahoma Geol. Survey Circ. 62, 62 p.

Clinton, R. D., 1958, The geology of the Osage Country: Shale Shaker Digest II, p. 325-337.

Cole, J. A., 1958, Subsurface geology of east-central Lincoln County, Oklahoma: Shale Shaker Digest II, p. 79-96.

Cole, J. G., 1969, Cherokee Group, east flank of the Nemaha Ridge (parts 1 and 2): Shale Shaker Digest VI, p. 75-99.

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.

Cutolo-Lozano, F. J., 1966, Subsurface stratigraphic analysis of northern Seminole County and portions of Pottawatomie and Okfuskee Counties, Oklahoma:. Univ. of Oklahoma M.S. thesis, 61 p.

Dalton, D. V., 1960, The subsurface geology of northeast Payne County, Oklahoma: Univ. of Oklahoma M.S. thesis, 69 p.

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

Denison, R. E., 1981, Basement rocks in northeastern Oklahoma: Oklahoma Geological Survey Circular 84, 84 p.

Disney, R. W., 1955, A subsurface study of the pre-Pennsylvanian rocks of Cleveland and McClain Counties, Oklahoma: Shale Shaker Digest I, p. 53-64.

Evernden, J. F., 1967, Magnitude determination at regional and near-regional distances in the United States: Bulletin of the Seismological Society of America, v. 57, p. 591-639.

Fay, R. O., 1971a, Geology of Region 8, in Appraisal of the water and related land resources of Oklahoma, Region eight: Oklahoma Water Resources Board Publication 34, p. 17-25.

Fay, R. O., 1971b, Geology of Region 9, in Appraisal of the water and related land resources of Oklahoma, Region nine: Oklahoma Water Resources Board Publication 36, p. 17-32.

Fay, R. O., 1972, Geology of Region 10, in Appraisal of the water and related land resources of Oklahoma, Region ten: Oklahoma Water Resources Board Publication 40, p. 19-29.

Ferguson, D. B., 1965, Subsurface geology of northern Lincoln County, Oklahoma: Shale Shaker Digest IV, p. 448-458.

Ford, W. J., 1955, The subsurface geology of southwest Logan County, Oklahoma: Shale Shaker Digest I, p. 327-343.

Gamero, G. A., 1965, Subsurface stratigraphic analysis of northern Pottawatomie County, Oklahoma: Univ. of Oklahoma M.S. thesis, 52 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).

Graves, J. M., 1958, Subsurface geology of a portion of Lincoln and Payne Counties, Oklahoma: Shale Shaker Digest II, p. 1-22.

Greer, J. K., 1961, Subsurface geology of east-central Lincoln County, Oklahoma: Univ. of Oklahoma M.S. thesis, 67 p.

Hadley, J. B., and Devine, J. F., 1974, Seismotectonic map of the eastern United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-620, 8 p., 3 sheets.

Ham, W. E., and Wilson, J. L., 1967, Paleozoic epeirogeny and orogeny in the central United States: American Journal of Science, vol. 265, p. 332-407.

Hayden, J. M., 1982, A gravity and magnetic investigation of a microseismically active area in central Oklahoma: Univ. of Oklahoma M.S. thesis, in preparation.

Herrmann, R. B., 1975, The use of duration as a measure of seismic moment and magnitude: Bulletin of the Seismological Society of America, v. 65, p. 899-913.

Huffman, G. G., 1959, Pre-Desmoinesian isopachous and paleogeologic studies in central midcontinent region: Am. Assoc. Pet. Geologists Bull., v. 43, p. 2541-2574.

Hyans, L., and Philpot, J., 1971, A tutorial on linear regression in blood banking: Transfusion, v. 11, p. 47-58.

Johnson, R. K., 1962, Subsurface geology of northeast Cleveland County, Oklahoma: Shale Shaker Digest III, p. 15-30.

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 Geological Survey Map GM-5, scale 1:750,000.

Kellet, C. R., 1962, Subsurface geology of the Purcell area, Cleveland and McClain Counties, Oklahoma: Shale Shaker Digest III, p. 317-347.

Kimberlin, Z. G., 1955, The subsurface geology of Canadian County, Oklahoma: Shale Shaker Digest I, p. 419-433.

King, P. B., 1951, The tectonics of middle North America - east of the Cordilleran system: Princeton University Press, Princeton, N.J., 203 p.

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

Koff, L. R., 1978, Tectonics of the Oklahoma City Uplift, central Oklahoma: Univ. of Oklahoma M.S. thesis, 64 p.

Kunz, H. E., 1961, Subsurface geology of southwestern Lincoln County, Oklahoma: Univ. of Oklahoma M.S. thesis, 71 p.

Kurash, G. E., Jr., 1965, Subsurface geology of west-central Lincoln County, Oklahoma: Shale Shaker Digest IV, p. 366-389.

Lapin, Lawrence, 1975, Statistics meaning and method: Harcourt, Brace, Jovanovich, Inc., 591 p.

Lawson, J. E., Jr., Luza, K. V., DuBois, R. L., and Foster, P. H., 1969, Earthquake map of Oklahoma (with accompanying text): Oklahoma Geol. Survey Map GM-19, 15 p., map scale 1:750,000.

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.

Lawson, J. E., Jr., and Luza, K. V., 1981, Oklahoma earthquakes, 1981: Oklahoma Geology Notes, v. 42, p. 126-137.

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, NUREG/CR-0875, 81 p.

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

Luza, K. V., Lawson, J. E., Jr., 1981, Seismicity and tectonic relationships of the Nemaha Uplift in Oklahoma, part IV: U.S. Nuclear Regulatory Commission NUREG/CR-2439, 52 p.

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

McElroy, M. N., 1965, Isopach and lithofacies study of the Desmoinesian Series of north-central Oklahoma: Shale Shaker Digest IV, p. 1-18.

McKenny, J. W., 1955, Subsurface geology of northeastern Logan County, Oklahoma: Shale Shaker Digest I, p. 149-166.

Nolte, C. J., 1951, Geology of the subsurface formations of northern Logan County, Oklahoma: Univ. of Oklahoma M.S. thesis, 47 p.

Nuttli, O. W., Stauder, W., and Kisslinger, Carl, 1969, Travel-time tables for earthquakes in the central United States: Earthquake Notes, Eastern Section, Seismological Society of America, v. 40, n. 4, p. 19-28.

Nuttli, O. W., 1973, Seismic wave attenuation and magnitude relations for Eastern North America: Journal of Geophysical Research, v. 78, p. 876-885.

Page, K. G., 1955, The subsurface geology of southern Noble County, Oklahoma: Shale Shaker Digest I, p. 448-456.

Pulling, D. M., 1979, Subsurface stratigraphic and structural analysis, Cherokee Group, Pottawatomie County, Oklahoma: Shale Shaker, v. 29, no. 6, p. 124-137; v. 29, no. 7, p. 148-158.

Pybas, G. W., 1965, Petroleum geology of southwestern Pottawatomie County, Oklahoma: Shale Shaker Digest IV, p. 390-405.

Real, C. R., and Teng, Ta-Liang, 1973, Local Richter magnitude and total signal durations in southern California: Bulletin of the Seismological Society of America, v. 63, p. 1809-1827.

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.

Stanbro, G. E., 1960, A subsurface study of the "Cherokee" Group, Grant County and a portion of Alfalfa County, Oklahoma: Univ. of Oklahoma M.S. thesis, 34 p.

Stover, C. W., Resagor, B. G., Algermissen, S. T., and Lawson, J. E., Jr., 1981, Seismicity map of the State of Oklahoma: U.S. Geological Survey Miscellaneous Field Studies Map MF-1352, scale 1:1,000,000.

Stringer, C. P., Jr., 1958, Subsurface geology of western Payne County, Oklahoma: Shale Shaker Digest II, p. 258-273.

Taff, J. A., 1902, Description of the Atoka quadrangle (Indian Territory): U.S. Geol. Survey Atlas, Folio 79, 8 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).

United States Earthquakes, Annual publication of: U.S. Dept. of Commerce, Coast and Geodetic Survey, 1928 through 1968; NOAA National Ocean Survey for 1969; NOAA Environmental Data Service for 1970-72; and U.S. Dept. of Commerce, NOAA, and U.S. Dept. of Interior, Geological Survey, for 1973 to present.

University of Oklahoma Earth Sciences Observatory, 1977, Instructions for volunteer cooperating scientists—operation of portable seismograph stations, Bull. 16, 14 p.

Watkins, J. S., 1964, Regional geological implications of the gravity and magnetic fields of a part of eastern Tennessee and southern Kentucky: U.S. Geological Survey Professional Paper 516A, 17 p.

Wengerd, S. A., 1948, Fernvale and Viola limestones of south-central Oklahoma: Am. Assoc. Pet. Geologists Bull., v. 32, p. 2183-2253.

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 into north Texas.)

Wood, H. O., and Neumann, F., 1931, Modified Mercalli intensity scale of 1931: Seismological Society of America Bulletin, v. 21, p. 277-283.

Zollweg, J. E., 1974, A preliminary study of the seismicity of the central United States, 1963-1974: St. Louis University, unpublished undergraduate paper, 15 p.

NRC FORM 335
(11-81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-3109

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Seismicity and Tectonic Relationships of the Nemaha Uplift in Oklahoma--Final Report

5. DATE REPORT COMPLETED

MONTH	YEAR
December	1982

DATE REPORT ISSUED

MONTH	YEAR
February	1983

6. *(Leave blank)*

7. AUTHOR(S)
K. V. Luza and J. E. Lawson, Jr.

8. *(Leave blank)*

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Oklahoma Geological Survey
The University of Oklahoma
Norman, Oklahoma 73019

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
B5967

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Earth Sciences Branch
Division of Health, Siting, and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

13. TYPE OF REPORT
Final Technical

PERIOD COVERED *(Inclusive dates)*

14. *(Leave blank)*

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(200 words or less)*

The Nemaha Ridge is composed of a number of crustal blocks typically 3 to 5 miles (5 to 8 km) wide and 5 to 20 miles (8 to 32 km) long. Structure-contour maps prepared of the top of the Viola Formation, the base of the Pennsylvanian, and the top of the Oswego Formation 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. A detailed study of the Oklahoma City Uplift suggests that a number of the Nemaha-related faults were developed in pre-Mississippian time. Many of these faults exhibit both increasing and decreasing displacements from early to late Paleozoic time. However, the displacement for most of the Oklahoma City faults took place between the end of Oswego time and the end of Hunton Time. A regional seismograph network was established to supplement existing seismological capability. The Oklahoma Geophysical Observatory (TUL); seven semipermanent, volunteer-operated seismography stations; and three radiolink stations constitute the network. From 1897 through 1976 Oklahoma has had approximately 128 known earthquakes. After the network became operational in 1977, 255 additional earthquakes were detected in Oklahoma (through 1981). A study of earthquake distribution and intensity values in Oklahoma led to the development of a seismic-source map for Oklahoma and parts of the adjacent states.

17. KEY WORDS AND DOCUMENT ANALYSIS

Seismicity
Nemaha Uplift
Oklahoma
Kansas
gravity
network

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$