NUREG/CR-1500

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

Prepared by K.V. Luza, J.E. Lawson, Jr.

The University of Oklahoma

Prepared for
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ABSTRACT

Structure-contour maps of the top of the Viola Formation (Ordovician), base of the Pennsylvanian, and top of the Oswego Formation (Middle Pennsylvanian) were completed for the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles.

From October 1, 1978, to December 31, 1979, approximately 149 earthquakes in Oklahoma, Kansas, Nebraska, and nearby areas were located. Approximately 29 seismograph stations (19 NRC supported) were operational for the entire reporting period. Two additional stations, CAI in southwestern Iowa and GBO in eastern Oklahoma, became operational late in calendar year 1979.

Detailed gravity and magnetic studies were completed for the Kingfisher and Medford maxima, north-central Oklahoma. An aeromagnetic map was prepared for the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles from NURE data. Seismological studies included (1) a microearthquake study near Wilson, Oklahoma, (2) frequency-magnitude evaluation of the Wilson microearthquake data, and (3) magnitude determinations from earthquake felt-area reports for 25 historical Oklahoma earthquakes.

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SUMMARY

The Oklahoma Geological Survey's geological and geophysical investigations of the Nemaha Uplift continued in FY 1979. The principal emphasis of the geological investigations thus far has been on the construction of a series of structure-contour maps of key stratigraphic horizons. These horizons include the top of the Viola Formation (Ordovician), the base of the Pennsylvanian, and the top of the Oswego Formation (Middle Pennsylvanian). In conjunction with this program, a detailed study of the Oklahoma City Uplift, the southernmost extension of the Nemaha Uplift, was completed.

The Nemaha Ridge in northern Oklahoma 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 abruptly changes direction, with the principal trend being northwest-southeast. Koff's (1978) study of the Oklahoma City Uplift, the southernmost extension of the Nemaha Ridge, and related fault features suggests that a number of the Nemaha-related faults were developed in pre-Mississippian time. Many of the faults exhibit both increasing and decreasing displacements from early to late Paleozoic time. However, most of the displacement for the Oklahoma City faults took place between the end of Oswego and the end of Hunton time.

The correlation between historical and recent earthquake activity with the Nemaha Uplift structures remains unclear. The pre-1977 earthquake data, when combined with 1977-1979 earthquake data, define a zone of earthquakes 25 miles (40 km) wide and 87 miles (140 km) long. This zone begins near El Reno and extends northeastward to Perry, Oklahoma, and cuts diagonally across the main axis of the Nemaha Uplift. Uncertainty still exists in what this earthquake zone represents. The southern terminus of this zone

appears to be more active than the middle and northern parts of the trend. The recent as well as the historical earthquake data seem to support this observation.

Detailed gravity and magnetic surveys were completed in the vicinity of the Medford and Kingfisher maxima, north-central Oklahoma. Preliminary conclusions indicated that the gravity and magnetic anomalies in this area may be related to the Greenleaf anomaly of Kansas and the Midcontinent gravity high. These anomalies may represent intra-basement intrusions of several bodies of denser, very likely mafic-rich material. Possibly the causative bodies of the Medford and Kingfisher anomalies represent an initial or pre-rift stage of the rift development during which no actual emplacement of an axial-dike system or the development of a definite spreading axis took place. The adjoining area to the south and east--Canadian, Oklahoma, and Logan Counties--is planned for detailed gravity and magnetic surveys this summer. This area includes most of the earthquake activity in north-central Oklahoma as well as the Edmond maximum and part of the granite-ridge minimum.

A total-field magnetic map for the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles was prepared from the National Uranium Resources Evaluation (NURE) data. A separate map for each AMS quadrangle (1:250,000 scale) was prepared with a 10-gamma contour interval. The data are being recompiled on a 1:500,000-scale base map with a 50-gamma contour interval.

From October 1, 1978, to December 31, 1979, approximately 149 earthquakes in Oklahoma, Kansas, Nebraska, and nearby areas were located. By state, they are distributed as follows: 101 in Oklahoma, 24 in Kansas, 18 in Nebraska, three in western Arkansas, two in western Missouri, and one in north Texas. Station coverage was relatively uniform over this time period. Approximately 29 seismograph stations (19 NRC supported) were operational for the entire reporting period. Two additional stations, CAI in southwestern Iowa and GBO in eastern Oklahoma, became operational late in calendar year 1979.

Over one-half (54) of the Oklahoma earthquakes reported in 1979 occurred within the El Reno-Perry zone. On March 13-18, 1979, a swarm of 26 earthquakes occurred northeast of Cogar, Oklahoma (Caddo-Canadian Counties). A second swarm of nine earthquakes, during September 15-17, 1979, occurred near Minco, Oklahoma (Grady-Canadian Counties). An earthquake map of Oklahoma (earthquakes shown through 1978) was published in 1979 (Lawson and others, 1979).

Data from over 400 microearthquakes in the Wilson area (Love-Carter Counties) were studied to determine the relationship between earthquake frequency and earthquake magnitude. Long-term-earthquake data plots were compared with earthquake-swarm data plots. The comparison indicated that the short-term earthquake-seismicity level was in good agreement with the regional, long-term earthquake-seismicity level. Data obtained from an earthquake swarm that occurred on June 23, 1978 indicated a one-day seismicity level 224 times greater than the long-term seismicity level. This increase in microearthquake activity in the Wilson area may be related, in part, to oil-field-reservoir-stimulation techniques, such as hydraulic fracturing.

Four portable microearthquake systems, Sprengnether DR-100 units, were field tested over a 2-month period in the Wilson area. Many logistical and operational lessons were learned. We plan to install a seven-station array near the El Reno area this summer.

An attempt was made to determine magnitude from some of Oklahoma's historical-earthquake felt-area reports. Values of mbLg for seven earthquakes were calculated from Oklahoma Geophysical Observatory seismograms. These values were compared to mb values obtained by using Nuttli and Zollweg's (1974) empirical formula that relates felt area to magnitude. The Nuttli-Zollweg formula appears to be a reasonable equation for relating mbLg magnitude to felt area for Oklahoma earthquakes, especially for magnitude 3 earthquakes and greater. Therefore, mbLg magnitudes were calculated for 25 Oklahoma earthquakes that have had felt areas reported (Docekal, 1970). These data were incorporated into a computerized catalog of Oklahoma earthquakes.

GEOLOGICAL INVESTIGATIONS

Introduction

The Oklahoma Geological Survey, in cooperation with the Kansas, Nebraska, and Iowa Geological Surveys, is conducting a 5-year investigation of the seismicity and tectonic relationships of the Nemaha Uplift and associated geologic features in the Midcontinent (fig. 1). This investigation, which began in October of 1976, is intended to provide data that can be used to better design large-scale structures, such as dams, high-rise buildings, and nuclear power plants, as well as to provide the necessary information to evaluate insurance rates in the Midcontinent.

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

Structure-Contour Program

To better understand 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° x 2° 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. 2 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

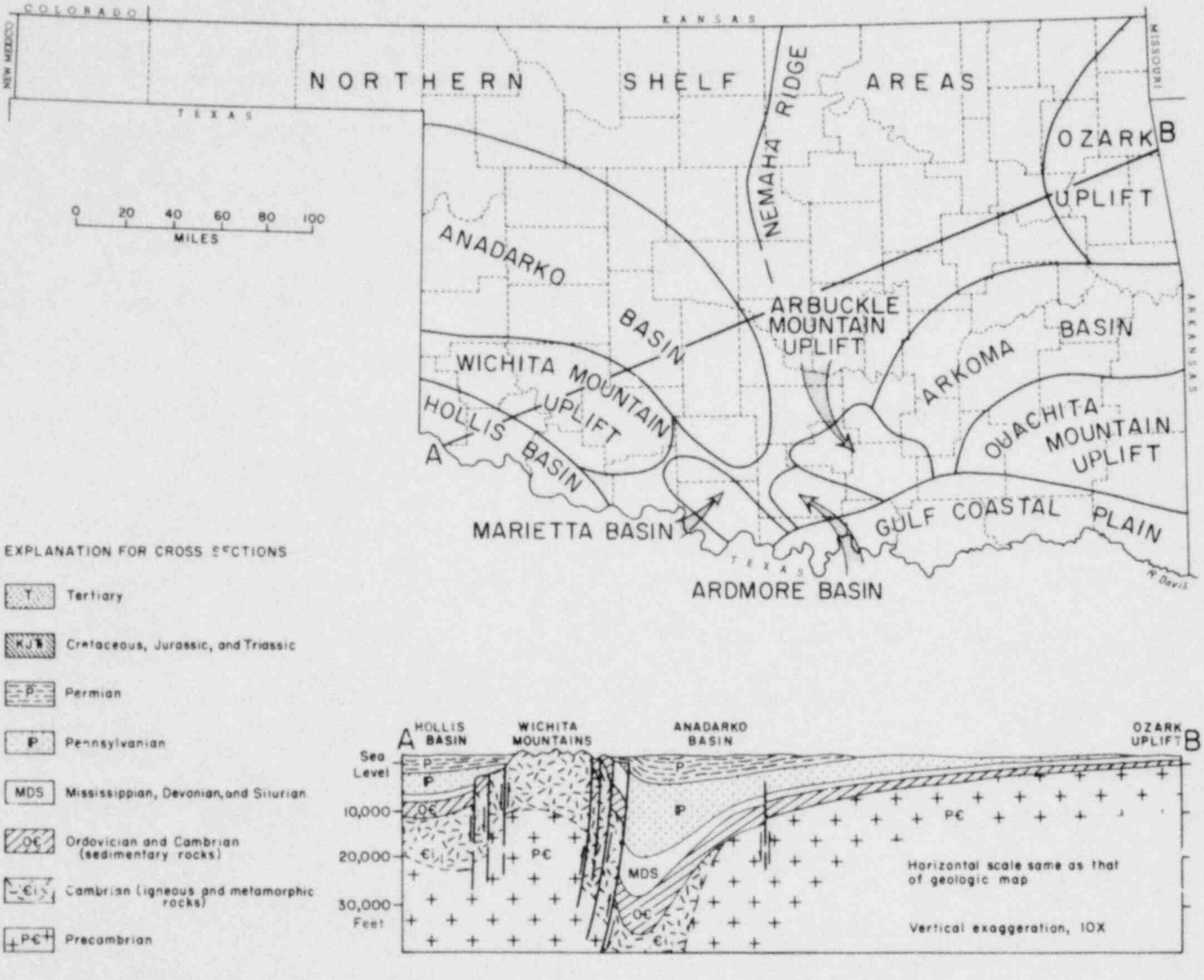


Fig. 1. Major geologic and tectonic provinces of Oklahoma.

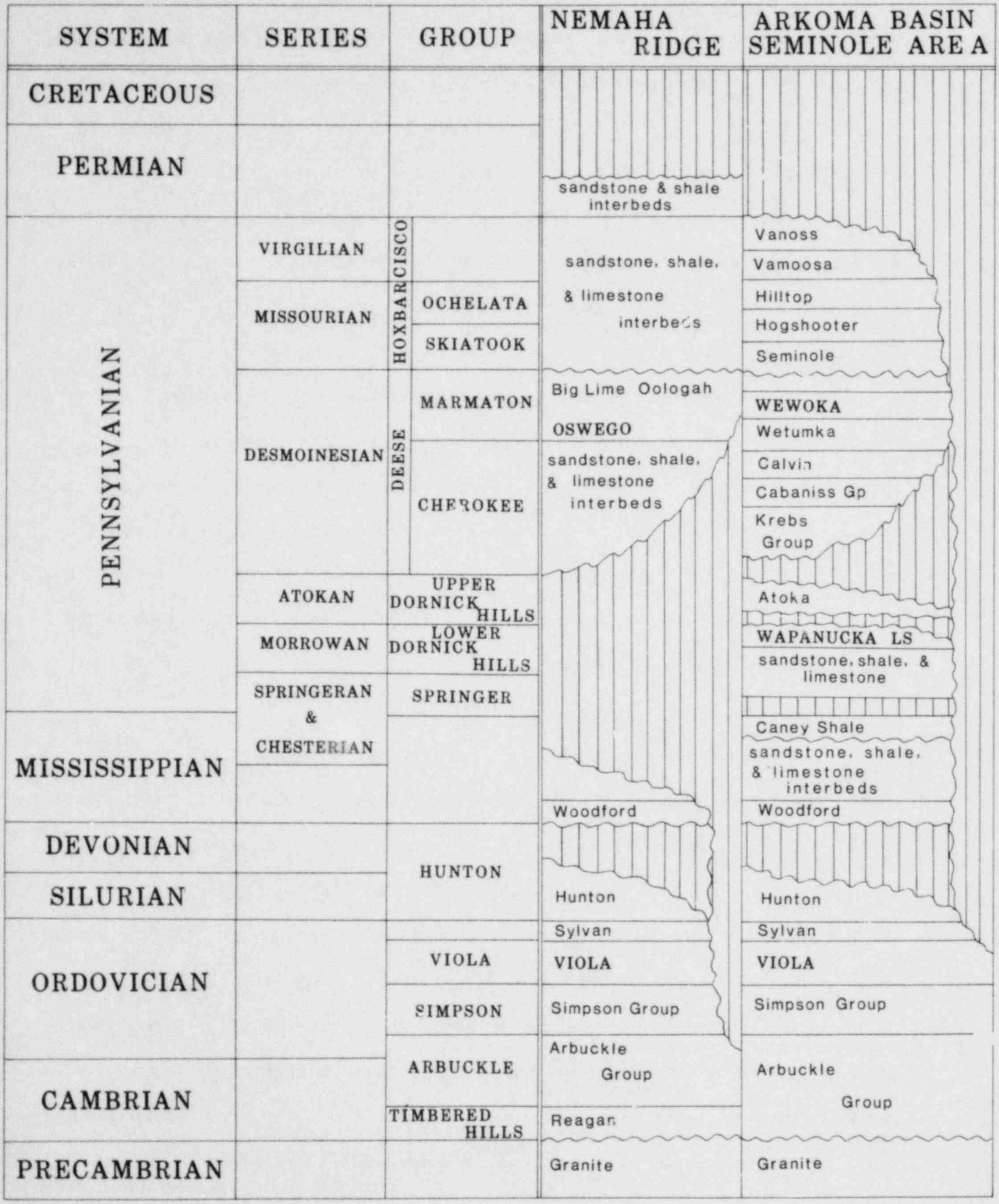


Fig. 2. Generalized correlation chart for central Oklahoma.

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. 3).

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 (60 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. 4). Most of the Upper Mississippian strata were eroded prior to the 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. Although the pre-Pennsylvanian unconformity surface is relatively flat, it 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

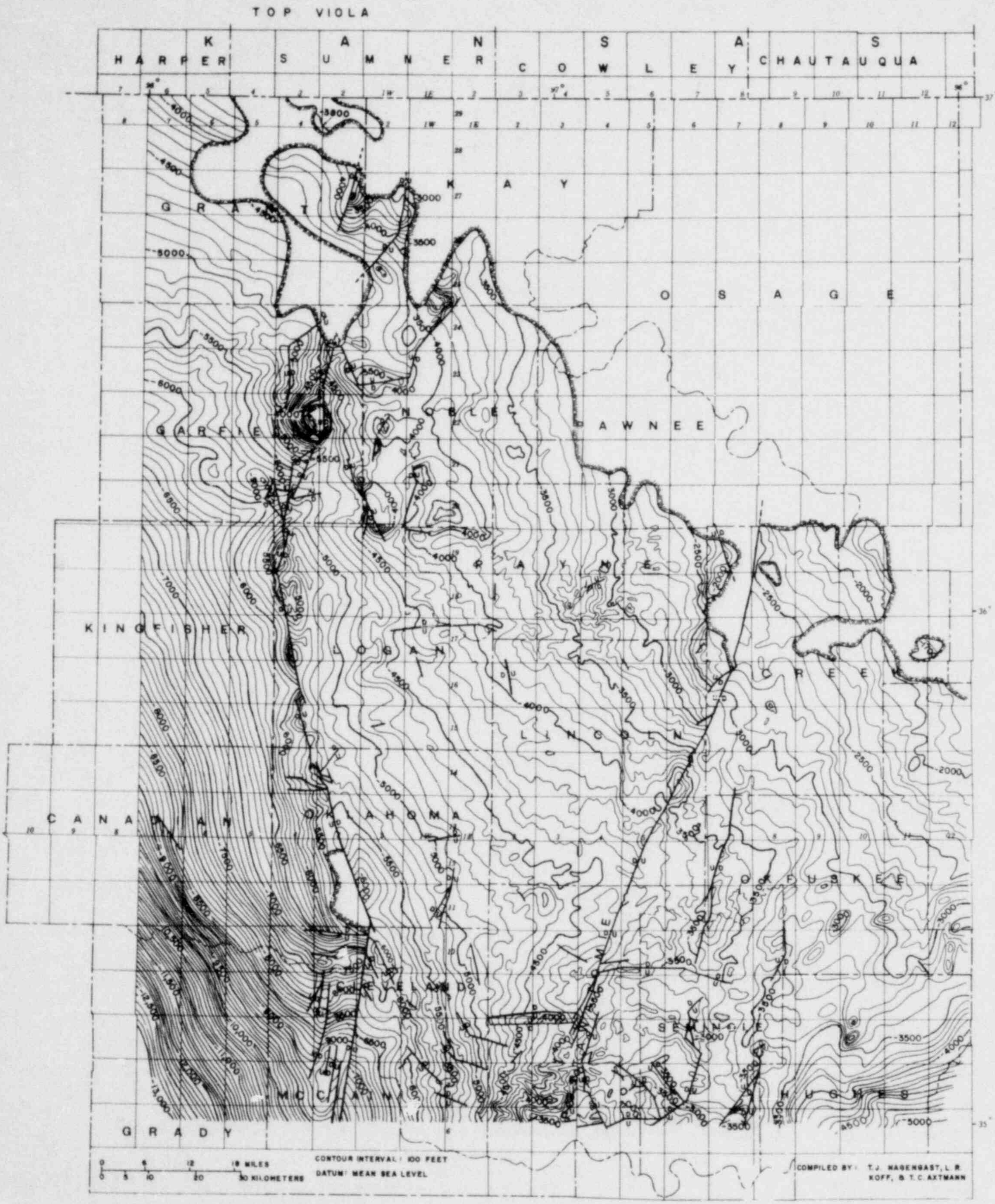
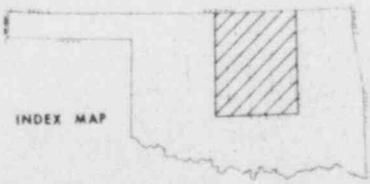
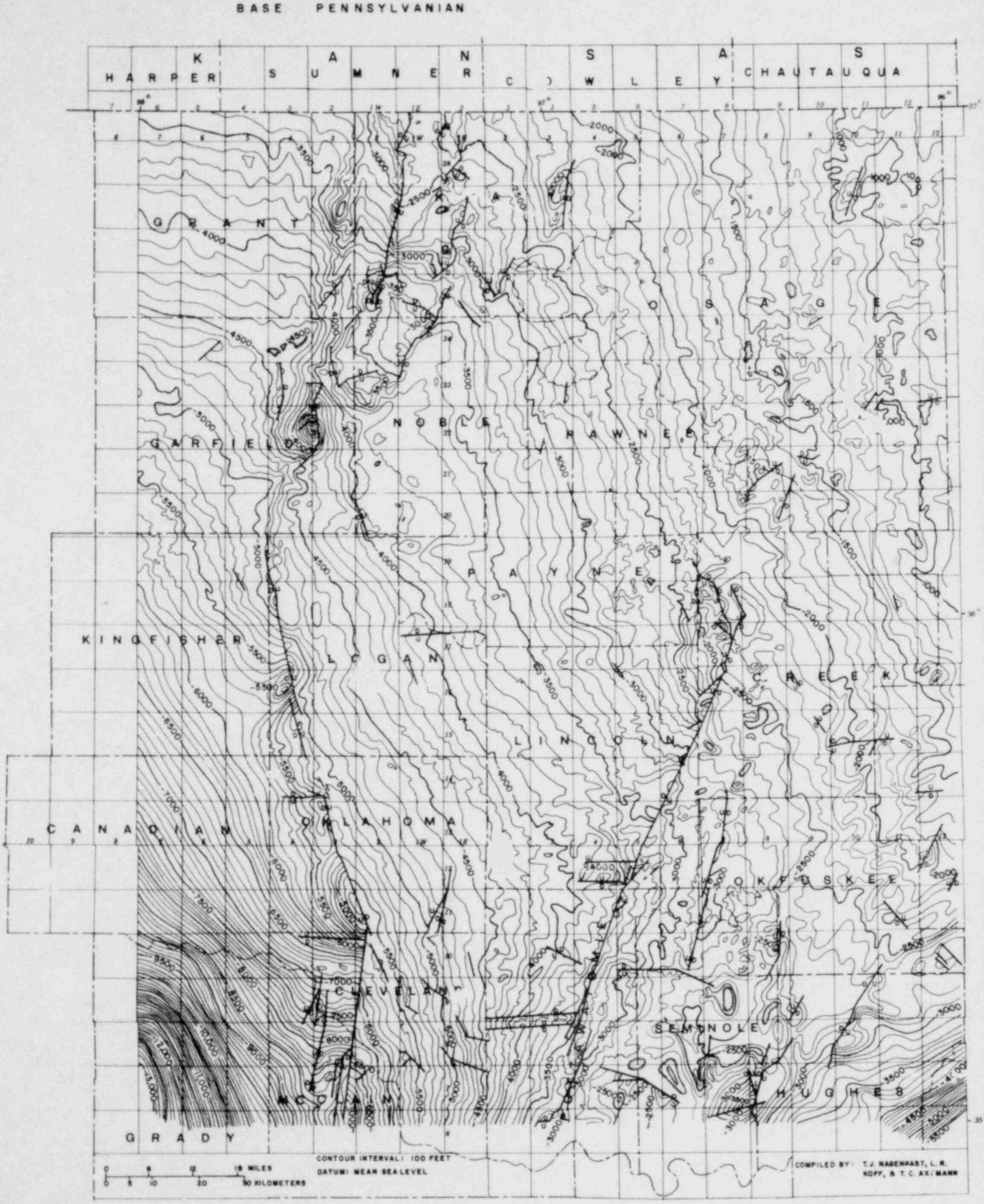


Fig. 3. Structure-contour map of top of Viola Formation.





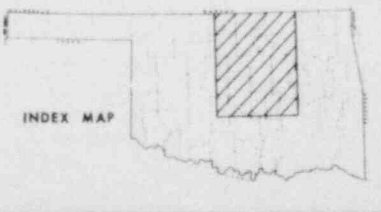


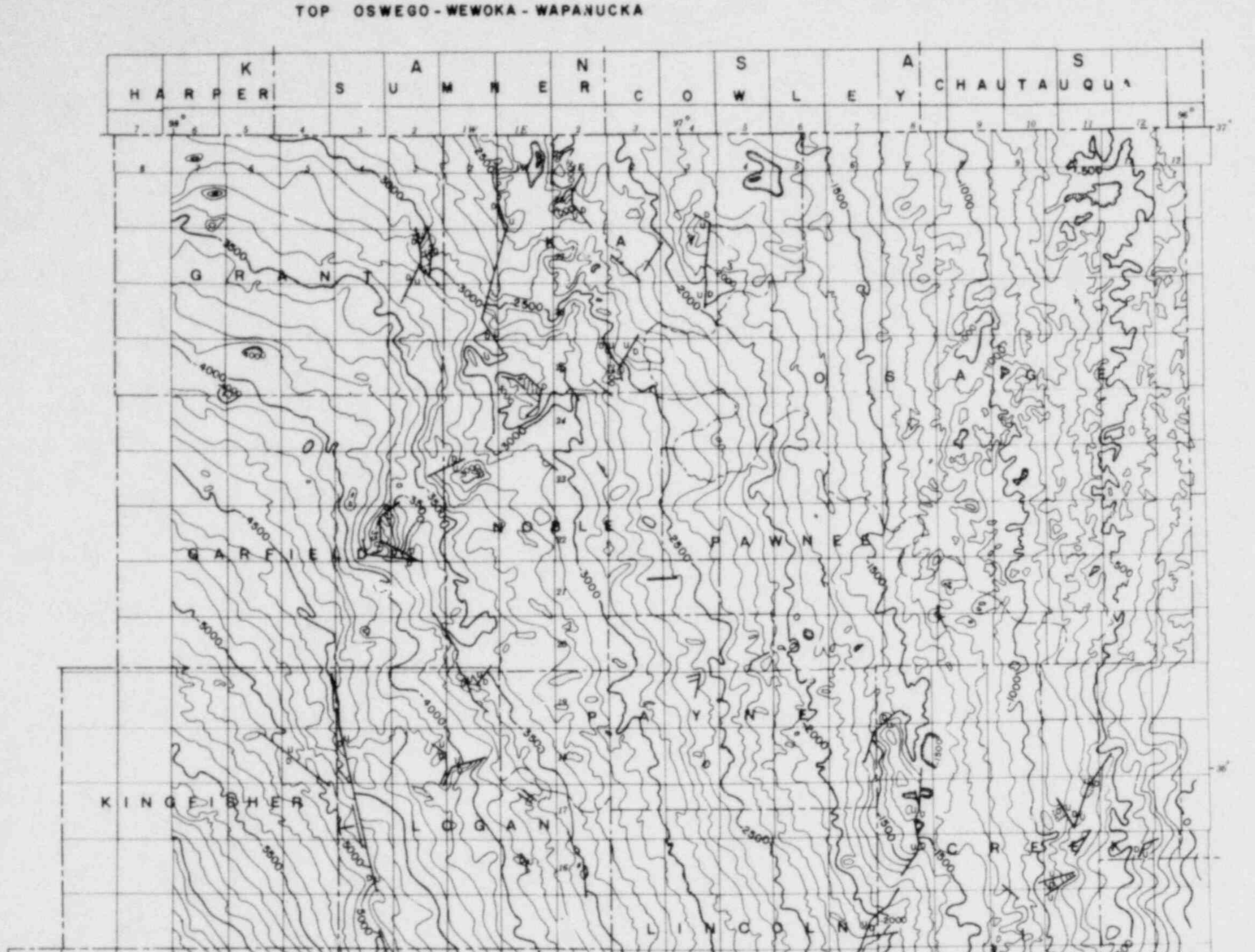
Fig. 4. Structure-contour map of base of Pennsylvanian strata.

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. 5).

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 central Oklahoma.

Data from more than 20,000 wells were used to construct the three structure-contour maps. Information from Oklahoma completion cards (scout tickets) were used to supplement data from unpublished and published reports (figs. 6-8). 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.



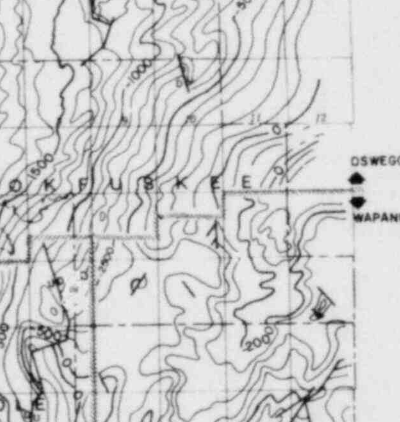
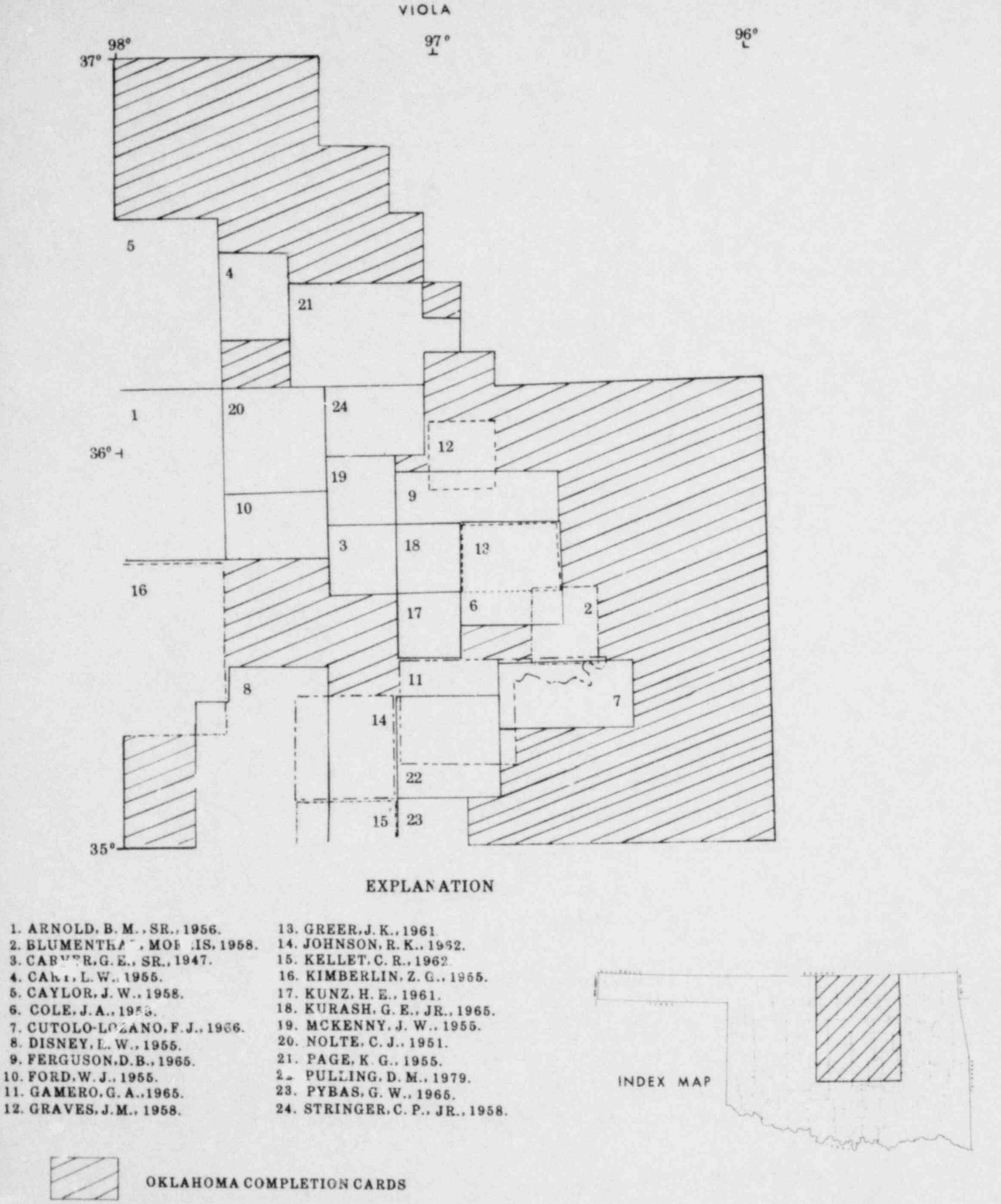


Fig. 5. Structure-contour map of top of Oswego-Wewoka-Wapanucka Formations.

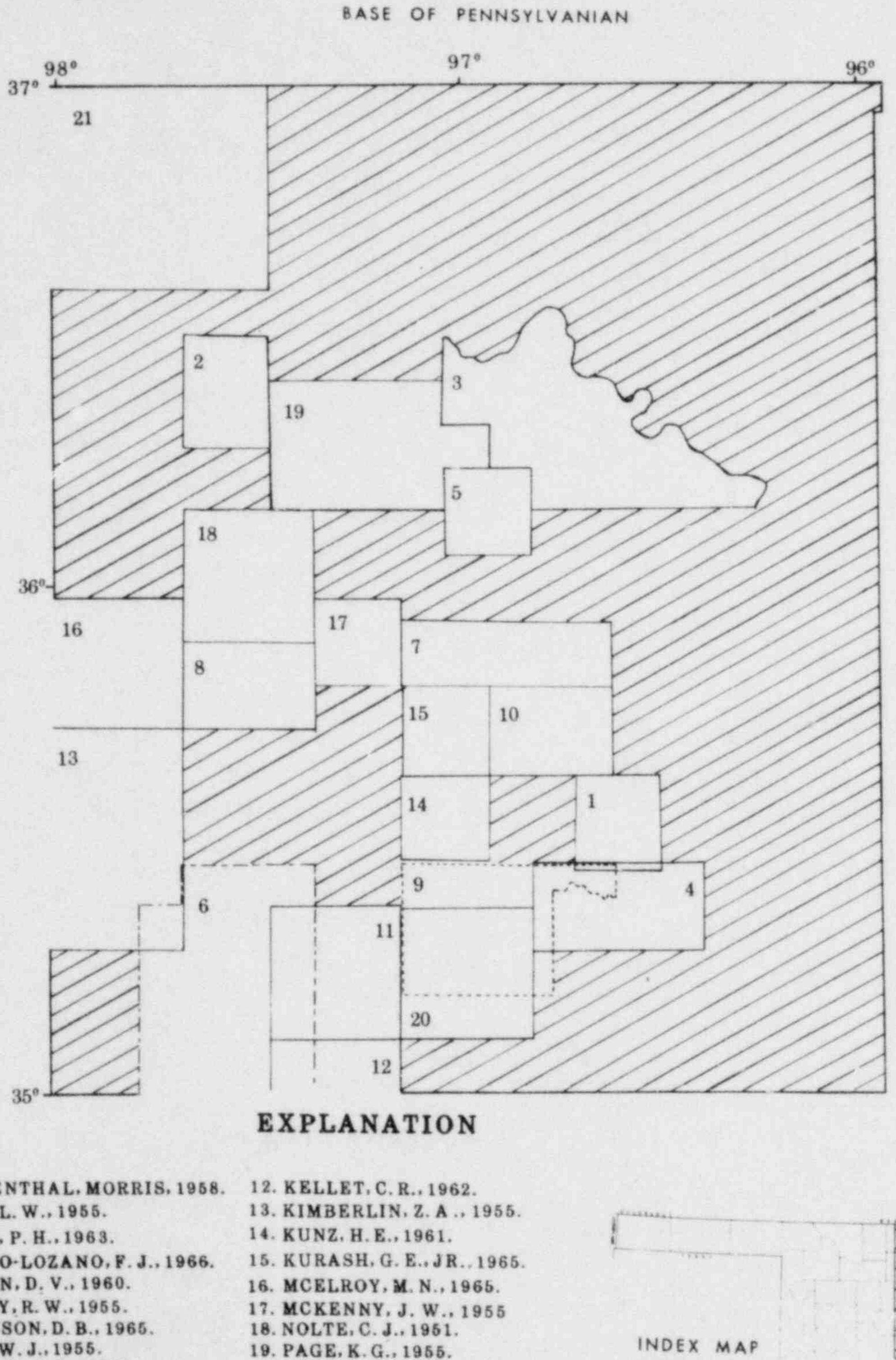


EXPLANATION

1. ARNOLD, B. M., SR., 1956.
2. BLUMENTHAL, MORRIS, 1958.
3. CARVER, G. E., SR., 1947.
4. CARY, L. W., 1955.
5. CAYLOR, J. W., 1958.
6. COLE, J. A., 1958.
7. CUTOLO-LOZANO, F. J., 1966.
8. DISNEY, L. W., 1955.
9. FERGUSON, D. B., 1965.
10. FORD, W. J., 1955.
11. GAMERO, G. A., 1965.
12. GRAVES, J. M., 1958.
13. GREER, J. K., 1961
14. JOHNSON, R. K., 1962.
15. KELLET, C. R., 1962
16. KIMBERLIN, Z. G., 1955.
17. KUNZ, H. E., 1961.
18. KURASH, G. E., JR., 1965.
19. MCKENNY, J. W., 1955.
20. NOLTE, C. J., 1951.
21. PAGE, K. G., 1955.
22. PULLING, D. M., 1979.
23. PYBAS, G. W., 1965.
24. STRINGER, C. P., JR., 1958.

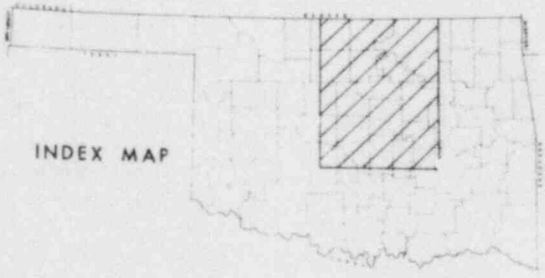
▨ OKLAHOMA COMPLETION CARDS

Fig. 6. Information sources used in preparation of structure-contour map of top of Viola.



EXPLANATION

1. BLUMENTHAL, MORRIS, 1958.
2. CARY, L. W., 1955.
3. CLARE, P. H., 1963.
4. CUTOLO-LOZANO, F. J., 1966.
5. DALTON, D. V., 1960.
6. DISNEY, R. W., 1955.
7. FERGUSON, D. B., 1965.
8. FORD, W. J., 1955.
9. GAMERO, G. A., 1965.
10. GREER, J. K., 1961.
11. JOHNSON, R. K., 1962.
12. KELLET, C. R., 1962.
13. KIMBERLIN, Z. A., 1955.
14. KUNZ, H. E., 1961.
15. KURASH, G. E., JR., 1965.
16. MCELROY, M. N., 1965.
17. MCKENNY, J. W., 1955
18. NOLTE, C. J., 1951.
19. PAGE, K. G., 1955.
20. PULLING, D. M., 1979.
21. STANBRO, G. E., 1960.



▨ OKLAHOMA COMPLETION CARDS

Fig. 7. Information sources used in preparation of structure-contour map of base of Pennsylvanian.

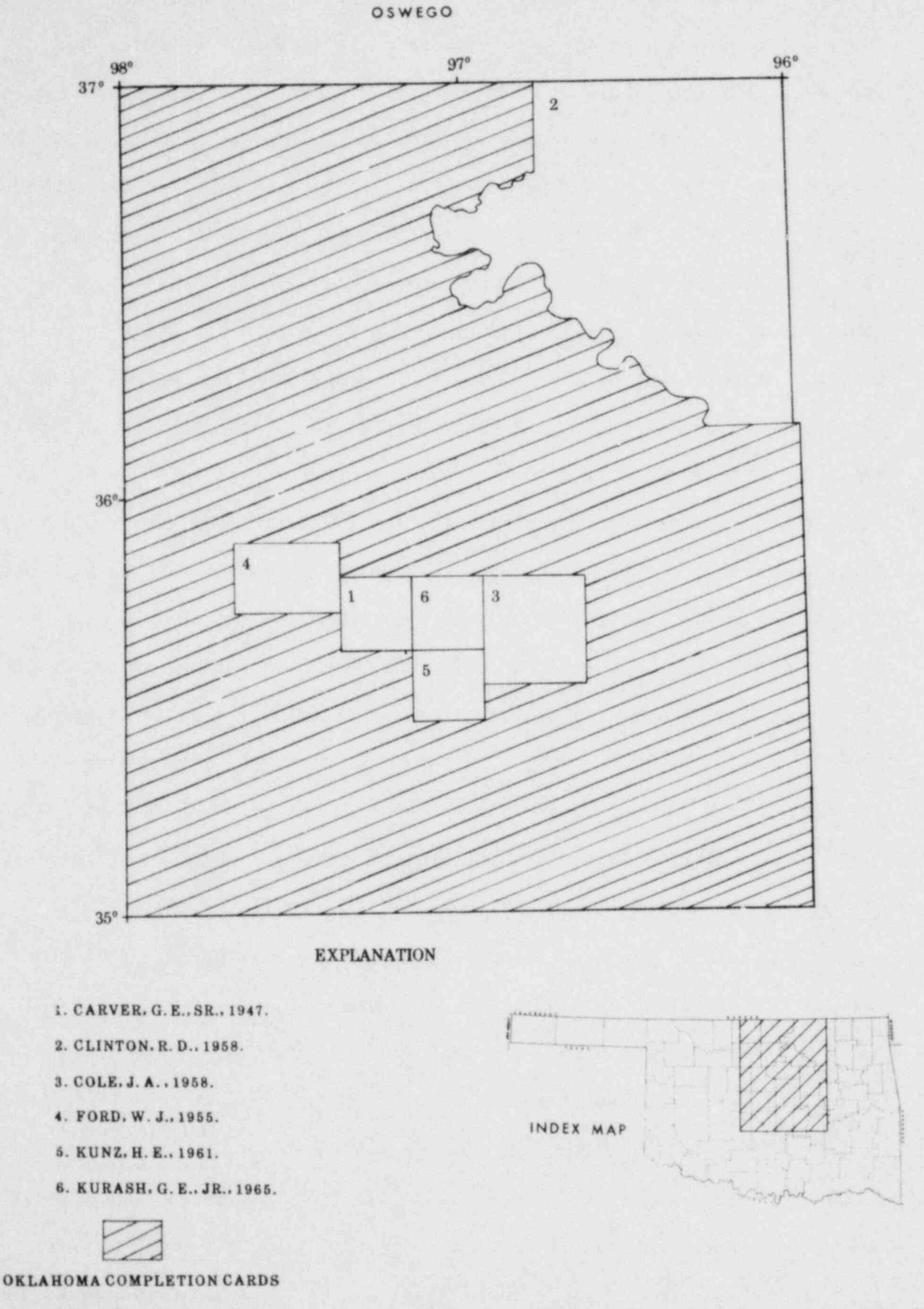


Fig. 8. Information sources used in preparation of structure-contour map of top of Oswego-Wewoka-Wapanucka.

The structure-contour maps (figs. 3-5) 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 faults on the east side that are downthrown to the east. These features form a fault zone that extends from Oklahoma City in a northwestern 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.

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. 9). Category 1, which includes the Oklahoma City and McClain County Fault zones (faults A and B, fig. 9), contains faults of constantly increasing displacement from early to late Paleozoic time.

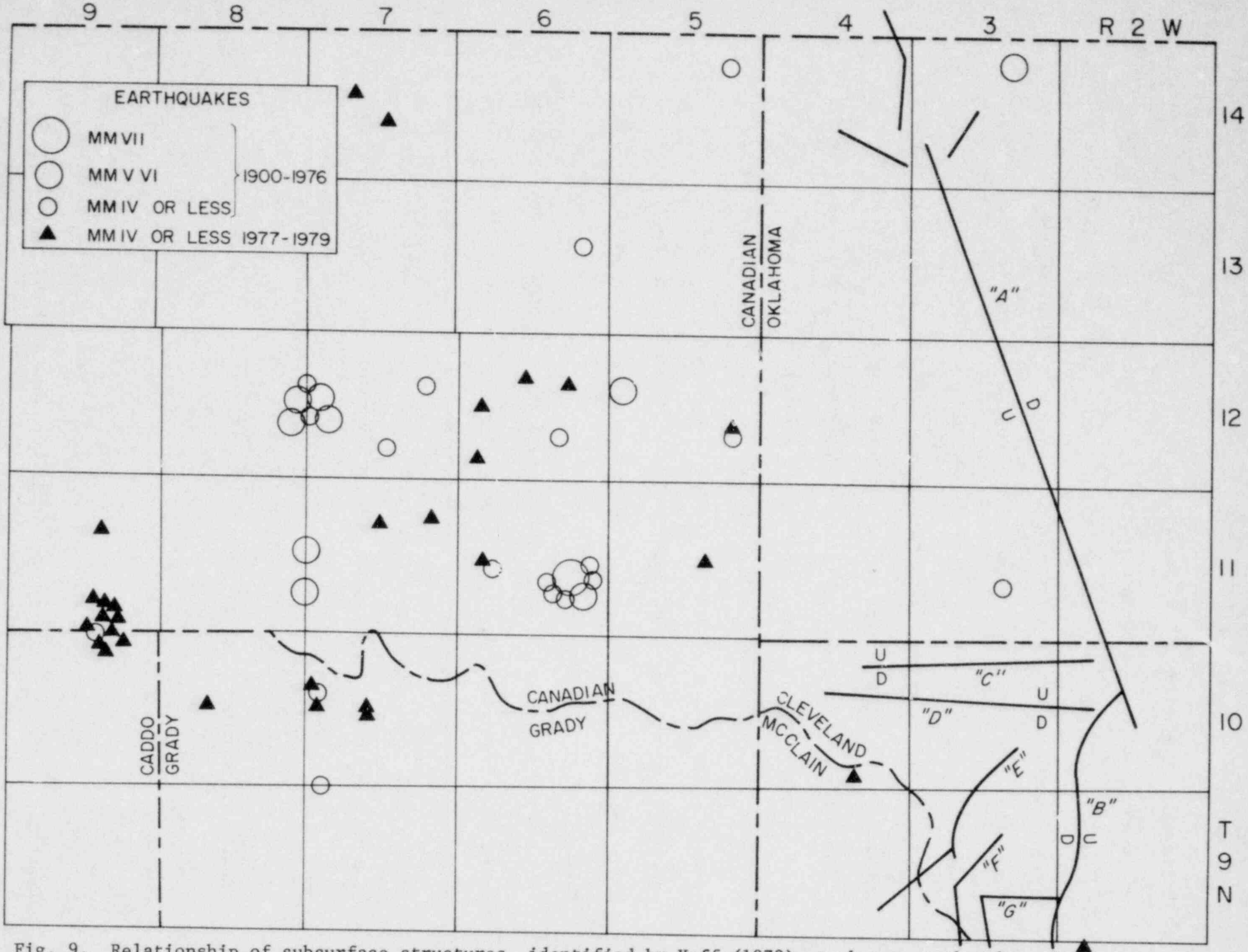


Fig. 9. Relationship of subsurface structures, identified by Koff (1978), to known earthquake epicenters.

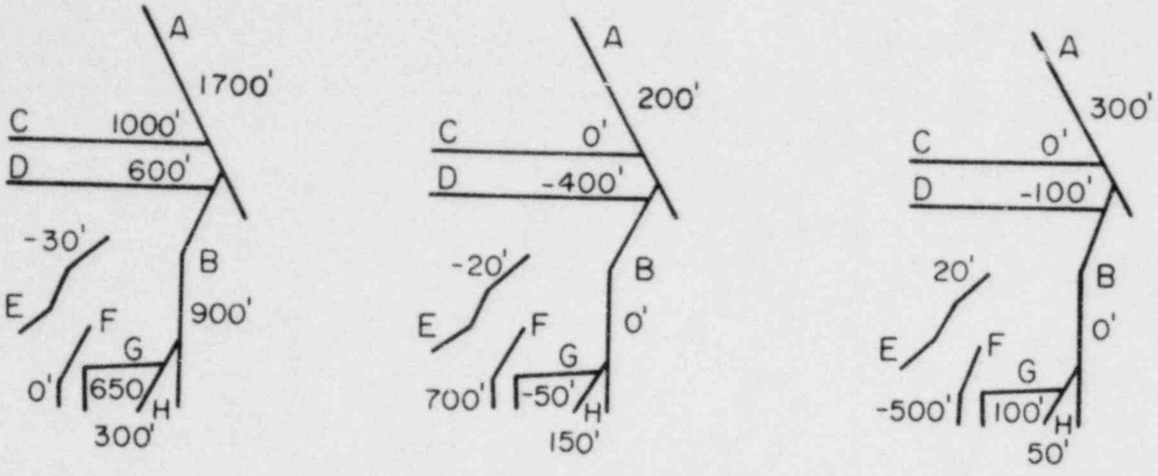
For example, the Oklahoma City Fault displacement was 1,700 feet (536 m) by the end of Oswego deposition and has now reached 2,300 feet (726 m) (figs. 10 and 11). Category 2 faults, of which there are six, exhibit both increasing and decreasing displacements from early to late Paleozoic (figs. 10 and 11). Except for faults F and H, more than 65 percent of the maximum total offset archieved on the faults occurred by the end of Oswego time (fig. 11).

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).

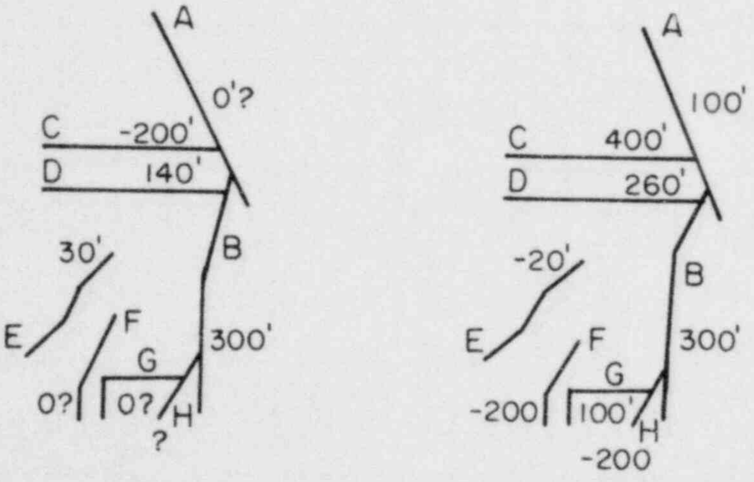
The Seminole-Cushing Ridge may have originated in Middle Devonian time, when a major epeirogeny occurred. The general uplift from the northeast may have given rise to southeastward dip in the Hunton and older rocks. Major folding took place during the Wichita Orogeny in post-Mississippian, pre-Desmoinesian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

Discussion

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)



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



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

Fig. 10. Net differences of fault displacements for selected time-depositional intervals in the Oklahoma City area.

SYSTEM	TIME	DEPOSITIONAL SEQUENCE	A	B	C	D	E	F	G	H
PRESENT			2300	1900	1300	700	100	100	800	500
	225									
PERMIAN	270	FORAKER	?	1600	900	540	150	?	?	?
	280	OREAD	2200	1300	1100	400	120	300	700	700
PENNSYLVANIAN	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		
		VICLA								
		SIMPSON GROUP			150		150			
CAMBRIAN U M	500	ARBUCKLE GROUP								

Fig. 11. Chart showing net maximum displacement of faults.

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. 4). 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 and the end of Hunton time.

The correlation of historical and recent earthquake activity with the Nemaha Uplift structures remains unclear. Some fault features that cut pre-Pennsylvanian rocks, which are compiled from Jordan (1962), Wheeler (1960), and unpublished reports, are shown in figure 12. The pre-1977 earthquake data (circles) and the 1977-1979 earthquake data (triangles) are also shown. There appears to be a zone of earthquakes, 25 miles (40 km) wide and 87 miles (140 km) long, that begins near El Reno (Canadian County) and extends northeastward to 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. Prior to the installation of the 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, mb 5.5, no earthquakes were reported for this region until 1978.

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. 9). Unfortunately, the lack of subsurface control in Canadian County did not permit the construction of the detailed

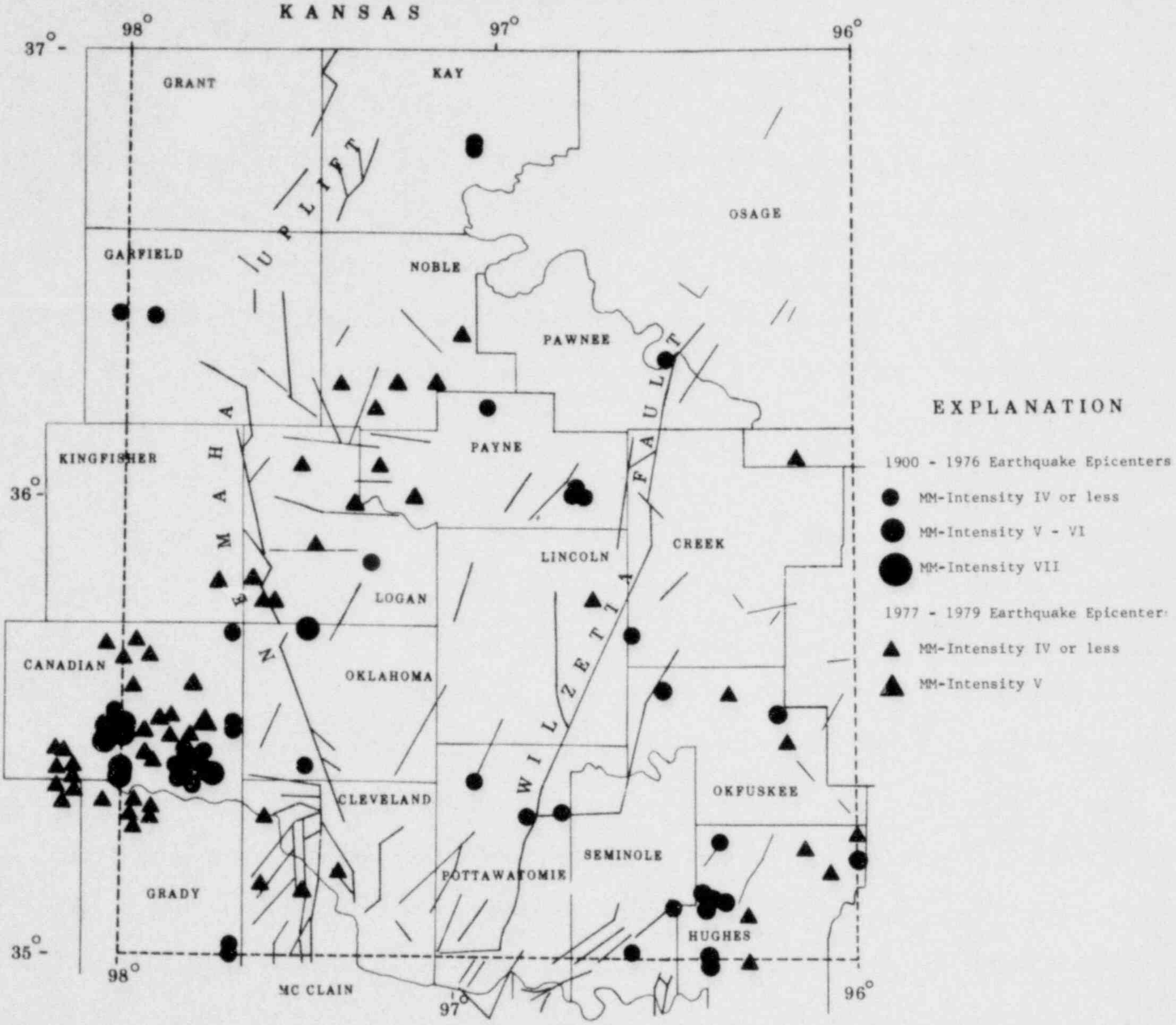


Fig. 12. Distribution of faults that cut pre-Pennsylvanian strata and earthquake epicenters for north-central Oklahoma (Wheeler, 1960; Jordan, 1962; unpublished reports).

structure and isopach maps that are needed to make correlation studies.

Uncertainty still exists in what this possible earthquake zone represents. The southern end of the zone appears to be more active than the middle and northern parts of this trend. The recent as well as the historical earthquake data seem to support this observation. A six- to seven-seismograph-station array is planned for the El Reno area during the next fiscal year. It is hoped that additional earthquake data, such as focal-depth determinations, will give us a better understanding of this feature.

GRAVITY AND MAGNETIC STUDIES

Detailed gravity and magnetic surveys were completed in the vicinity of the Medford and Kingfisher maxima in north-central Oklahoma (fig. 13). C.M. Barrett and D.J. Santiago (University of Oklahoma M.S. candidates) established 400 gravity and magnetic stations in parts of Kingfisher, Blaine, Major, Garfield, and Grant Counties. Two modeling techniques, the Talwani-Ewing modeling algorithm for magnetic data and a vertical-prism-styled modeling algorithm for gravity data, were used for data interpretation. Their preliminary conclusions derived from these modeling studies indicate that the gravity and magnetic anomalies in this area may be related to the Greenleaf anomaly of Kansas and to the Midcontinent gravity high. These anomalies may represent intra-basement intrusions of several bodies of more dense, very likely mafic-rich material. Possibly the causative bodies of the Medford and Kingfisher anomalies represent an initial or pre-rift stage of the rift development in which no actual emplacement of an axial-dike system or development of a definite spreading axis took place. The results of Barrett and Santiago's work are still in the preparation stage, and it is hoped that their final reports will be completed by the end of the summer of 1980.

The adjoining area to the south and east--Canadian, Oklahoma, and Logan Counties--is planned for detailed gravity and magnetic surveys this summer. This area includes most of the earthquake activity in north-central Oklahoma as well as the Edmond maximum (P8) and part of the granite-ridge minimum (N9) (fig. 13).

A total-field magnetic map for the Enid and Oklahoma City 1° x 2° Quadrangles was prepared from the National Uranium Resource Evaluation (NURE) data by Noel F. Rasmussen, Borehole Exploration, in Tulsa. These data are part of the aerial radiometric survey conducted for the Enid Quadrangle by Texas Instruments, Inc.

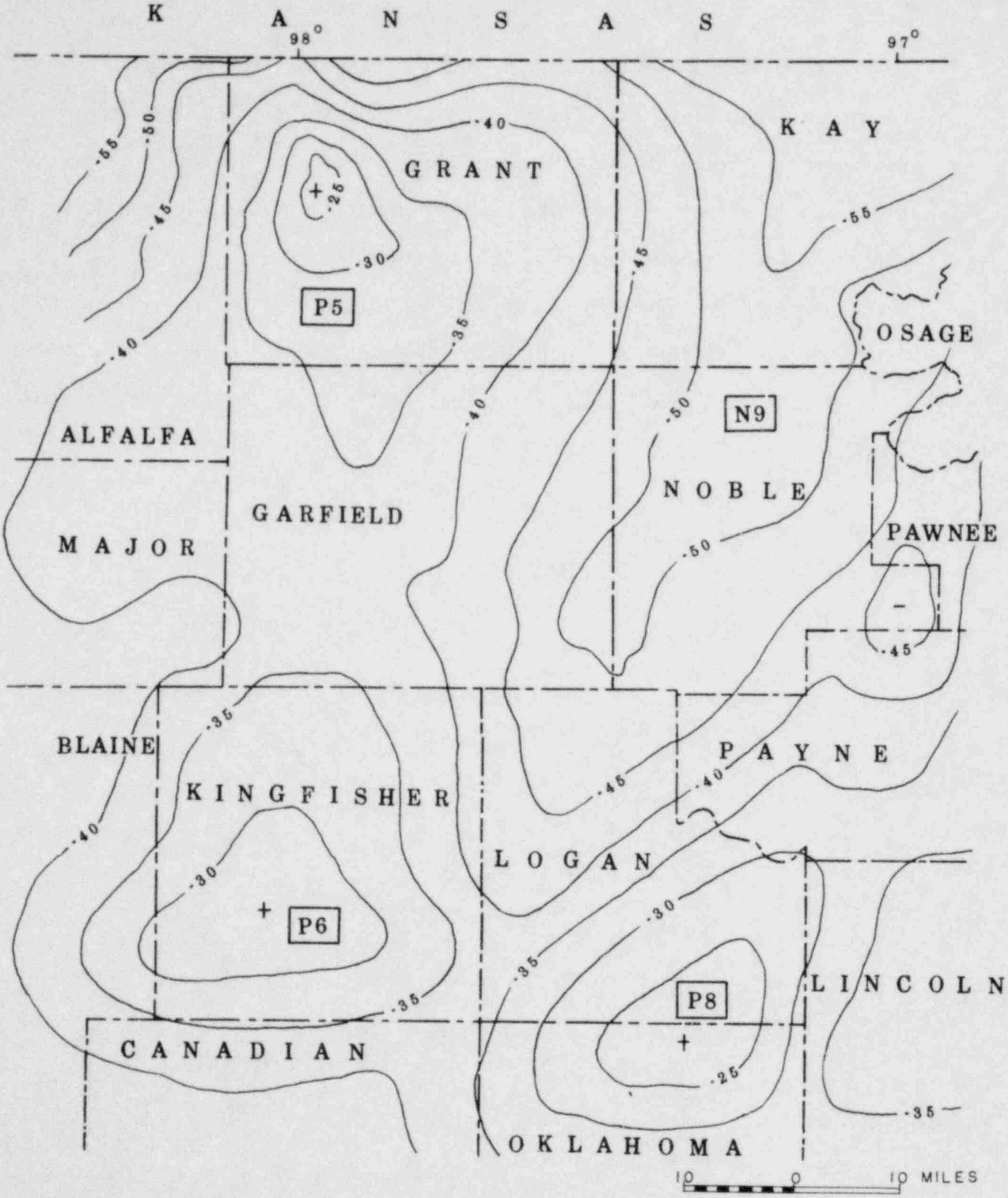


Fig. 13. Gravity anomalies: Medford maximum (P5), Kingfisher maximum (P6), Edmond maximum (P8), and granite ridge mimimum (N9), identified by Lyons (1964); contour interval, 5 milligals.

(Open-File Report GJBX-100(78)), and for the Oklahoma City Quadrangle by Geodata International, Inc. (Open-File Report GJBX-34(76)). The map was constructed in order to assist in the interpretation of basement-rock lithologies and structure. These data supplement earlier work by Jones and Lyons (1964) and Lyons (1964).

A separate map for each AMS quadrangle (1:250,000) was prepared with a 10-gamma contour interval. The data are being recompiled on a 1:500,000 base map with a 50-gamma contour interval, which should be available by the end of this year.

SEISMOLOGICAL STUDIES

Regional Net

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

New Station, GBO Fort Gibson, Oklahoma.--Because of loss of one transmitter to lightning-induced transients and one to water damage, installation of this station was deferred until a new transmitter was obtained from Oklahoma Geological Survey funds.

The two radiotelemetry stations operating were in excellent locations almost 180° apart in azimuth (to the northeast and southwest) with respect to the receiving antenna at TUL. Ideally the third station should be north or northwest or south or southeast of TUL, with south or southeast preferred because of the pattern of Oklahoma seismicity. Computer programs described in the 1977 report (Luza and others, 1978) were used to map out all locations offering line-of-sight transmission to TUL (actually the transmission path is calculated for a sphere with a radius of 87 percent of the Earth's radius, so the transmission is somewhat less than line-of-sight). All accessible sites to the north and northwest were near and (or) in the Tulsa Metropolitan area, or near four-lane freeways, railways, and an industrial corridor following the Arkansas River west of Tulsa. Most sites to the south and southeast have the line-of-sight blocked by a ridge only 5 km south of TUL. The few available sites to the southeast were very near a new freeway and a busy railway. Using the latest aeronautical charts, we searched for a high tower to the south in order to obtain tower space for a transmitting antenna. All charted towers that were high enough for line-of-sight transmission were very near cities or major highways, where the ground noise would be unacceptable. We were left with a choice of (1) not installing the third radiolink, (2) obtaining a new license and installing repeater equipment, or (3) installing the station in a less than ideal location.

The less than ideal location option was selected. The site is on privately owned property about 40 km south-southwest of the RLO radio-telemetry station. This site, northeast of Fort Gibson, Cherokee County, has a 55 km line-of-sight path to TUL. The station was named GBO (Fort Gibson). It has an 11-element Yagi-Uda transmitting antenna on top of a 30-foot telescoping portable tower.

Previously the only seismograms immediately available (without waiting for seismograms mailed from the volunteer stations) were from SIO, TUL, and RLO. Because these three stations were nearly in a straight line, preliminary locations with them were difficult and very inaccurate. GBO provided a large enough offset perpendicular to this line to greatly improve preliminary locations.

Present Station Configuration.--On September 30, 1979, 30 seismograph stations were operating in Oklahoma, Kansas, and Nebraska. The map in figure 14 shows operating stations on January 1, 1980. The map reflects two changes made after September 30. GAN, Gretna, Nebraska, was closed on October 30, 1979, for a move to a quieter location 5.48 km away. The new location, SGN, Springfield, Nebraska, began operating November 6, 1979. The other change is the opening of the first Iowa Geological Survey telephone-telemetered station, CAI, Carbon, Iowa, on December 23, 1979.

Locations, coordinates, and subjective ratings of Oklahoma stations are given in table 1. Compared to the table in the last report, the ground noise of ACO, PCO, and MRO has been upgraded one subjective category. This was not due to actual changes in ambient ground noise, however. The changes were made because accumulating experience indicated that these stations have a very high signal-to-noise ratio for small local and regional earthquakes.

Earthquake Distribution

Introduction.--Magnitudes for Oklahoma earthquakes were calculated, wherever possible, on Nuttli's m3Hz and mbLg scale. The m3Hz magnitude can be calculated for most individual stations (within an epicentral distance range of 11 to 222 km) because 3-Hz vertical-component Sg waves are usually clear. Generally, the 1-Hz vertical component waves required for mbLg are measurable only on the TUL SPNBZ (narrow passband centered on 1 Hz) seismogram. Because of considerable instability of seismic preamplifier gain, we have not felt that the radio-telemetry-station seismograms could be used to calculate ground amplitudes, but they are used to measure durations along with all stations showing a clear enough signal. We have found that Evernden's mbeus is reliable only when Pn-vertical-component waves with frequencies near 1 Hz are measured. Most frequently, we see Pn of 3 to 4 Hz

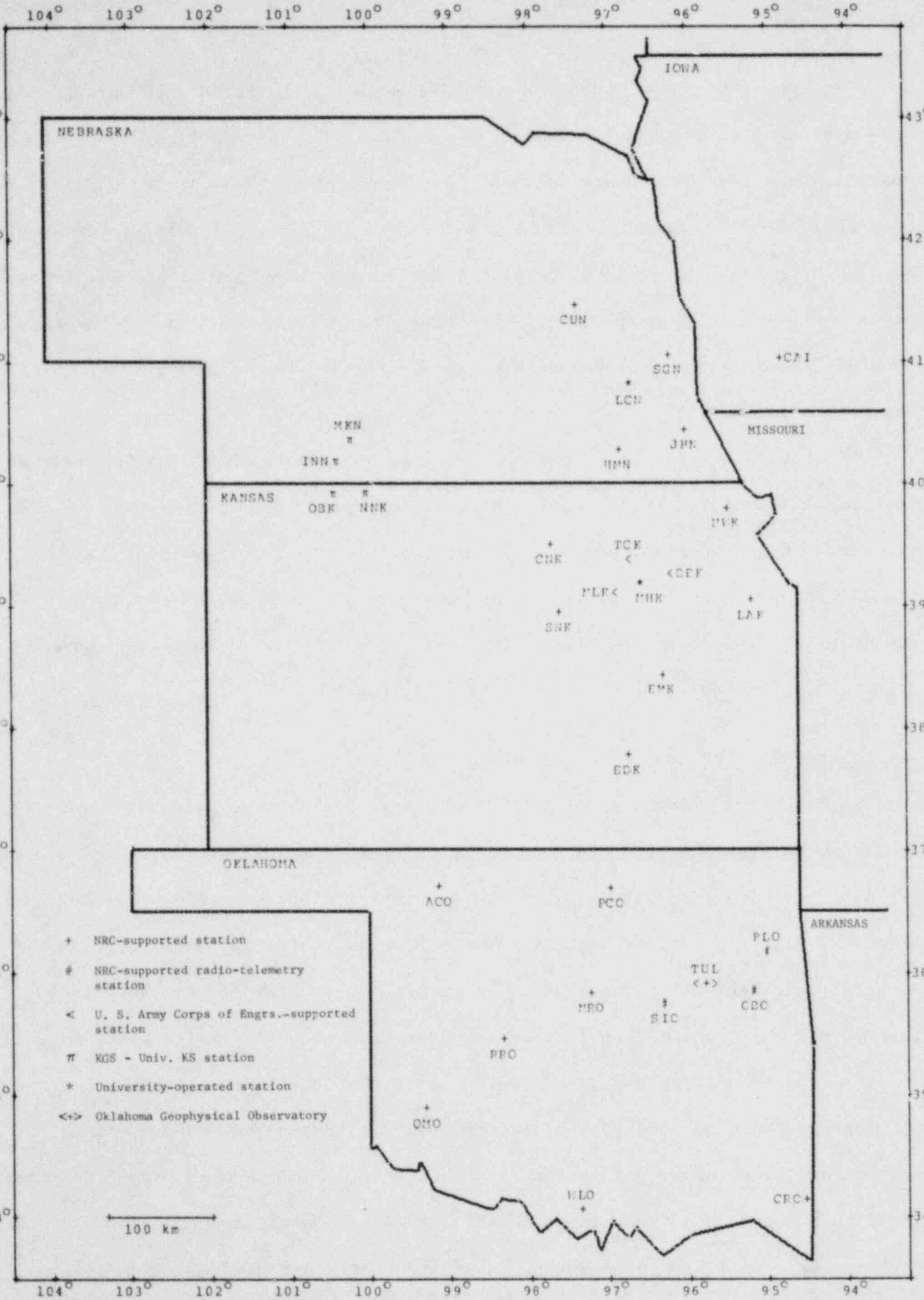


Fig. 14. Seismograph stations operating in Oklahoma, Kansas, Nebraska, and western Iowa, January 1, 1980.

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

Abb	Geographic Name and County	Latitude (Deg. N.)	Longitude (Deg. W)	Elev. (meters)	Volunteer operator or Telemetry RF and AF operating date(s)	Geographic importance to network		Quality and continuity operation	Ground noise
						At time of installation	In final network configuration		
TUL	Okla. Geophys. Obs. Tulsa County	35.900000	95.792500	255	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	B	A
WLO	SE of Wilson Love County	34.064778	97.369722	284	James L. Steel 770425	A	A	B	B
CRO	Carnasaw Mtn Lookout Tower McCurtain Co.	34.149917	94.555611	302	Wanda Webb 770517	A	A	A	A
ACO	Alabaster Cavern State Park Woodward Co.	36.698556	99.146083	521	L. H. Shepherd 770622	A	A	A	A
PCO	Ponca City Kay County	36.691222	96.978222	325	H. Walther 770705	A	A	A	B
RLO	Rose Lookout Twr. Mayes County	36.167000	95.[illegible]5194	363	218.0 MHz 1360 Hz 770722	A	A	A	A
QMO	Quartz Mtn. St. Park Greer County	34.892917	99.307056	479	J. Briley 770729	A	A	B	A
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	A
RRO	Red Rock Canyon State Park Caddo County	35.456917	98.358444	482	Bud Turner 780809	A	A	A	B

* A. Excellent; very strong reason for every necessary effort to continue operation of station
B. Good; no reason to move station.
C. Less satisfactory than desired; may consider moving station, though the move will have low priority if only one "C" is noted.
D. Although station is producing useful data, it should be moved or should be temporarily closed whenever part of the equipment is required by a higher rated station.

for local earthquakes. Three- to 4-Hz Pn waves give us mbeus often 1 unit of magnitude away from m3Hz and mbLg.

Because m3Hz and mbLg gave very close results, it was decided to develop a duration magnitude scale to approximate Nuttli's scales (see Luza and Lawson, 1979, for detailed explanation). The formula developed was

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

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.

Earthquake Distribution.--From October 1, 1978, to December 31, 1979, approximately 149 earthquakes in Oklahoma, Kansas, Nebraska, and nearby areas were located (table 2; fig. 15). By State, they were distributed as follows:

Oklahoma	101
Kansas	24
Nebraska	18
W. Arkansas	3
W. Missouri	2
N. Texas	1

Station coverage was relatively uniform over this time period. Approximately 29 seismograph stations were operational for the entire reporting period (see fig. 14). Two additional stations, CAI in southwestern Iowa and GBO in eastern Oklahoma, became operational late in calendar year 1979.

All earthquakes located in Oklahoma, Kansas, Nebraska, Iowa, and nearby states for a 3-year period, from January 1, 1977, to December 31, 1979, are shown in figure 16.

Because there have been a significant number of Oklahoma earthquakes east of 98.5° west longitude since January 1, 1977, a more detailed map for this region was prepared (fig. 17). The historical earthquake data (pre-1977), when combined with the earthquakes located by the network stations, define three general areas

Table 2. Oklahoma Geophysical Observatory regional earthquake catalog, October 1, 1978-December 31, 1979.

DATE (UTC)	ORIGIN TIME UTC	STATE-COUNTY	INT MM	MAGNITUDES 3HZ	bLg	DUR	LAT deg N	LON deg W	DEPTH km	E S
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
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

Table 2. (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	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
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

Table 2. (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 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	98.6[illegible]	[illegible].0R	O
1979 OCT19	211228.05	KS BARBER				1.8	37.090	98.5[illegible]	[illegible]	K
1979 OCT19	211228.33	KS BARBER		1.9		1.9	37.113	98.5[illegible]	[illegible]	[illegible]
1979 OCT21	072907.55	OK COAL		2.3	2.2	2.4	34.502	96.4[illegible]	[illegible].0R	O
1979 NOV 7	055409.84	OK CANADIAN		2.1		1.9	35.510	97.888	[illegible].0R	O
1979 NOV11	102657.33	OK CANADIAN		2.2	1.9	2.1	35.695	98.050	5.0R	O
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

Table 2. (continued)

	ORIGIN		INT	MAGNITUDES			LAT	LON	DEPTH	E
DATE (UTC)	TIME UTC	STATE-COUNTY	MM	3HZ	bLg	DUR	deg N	deg W	km	S
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

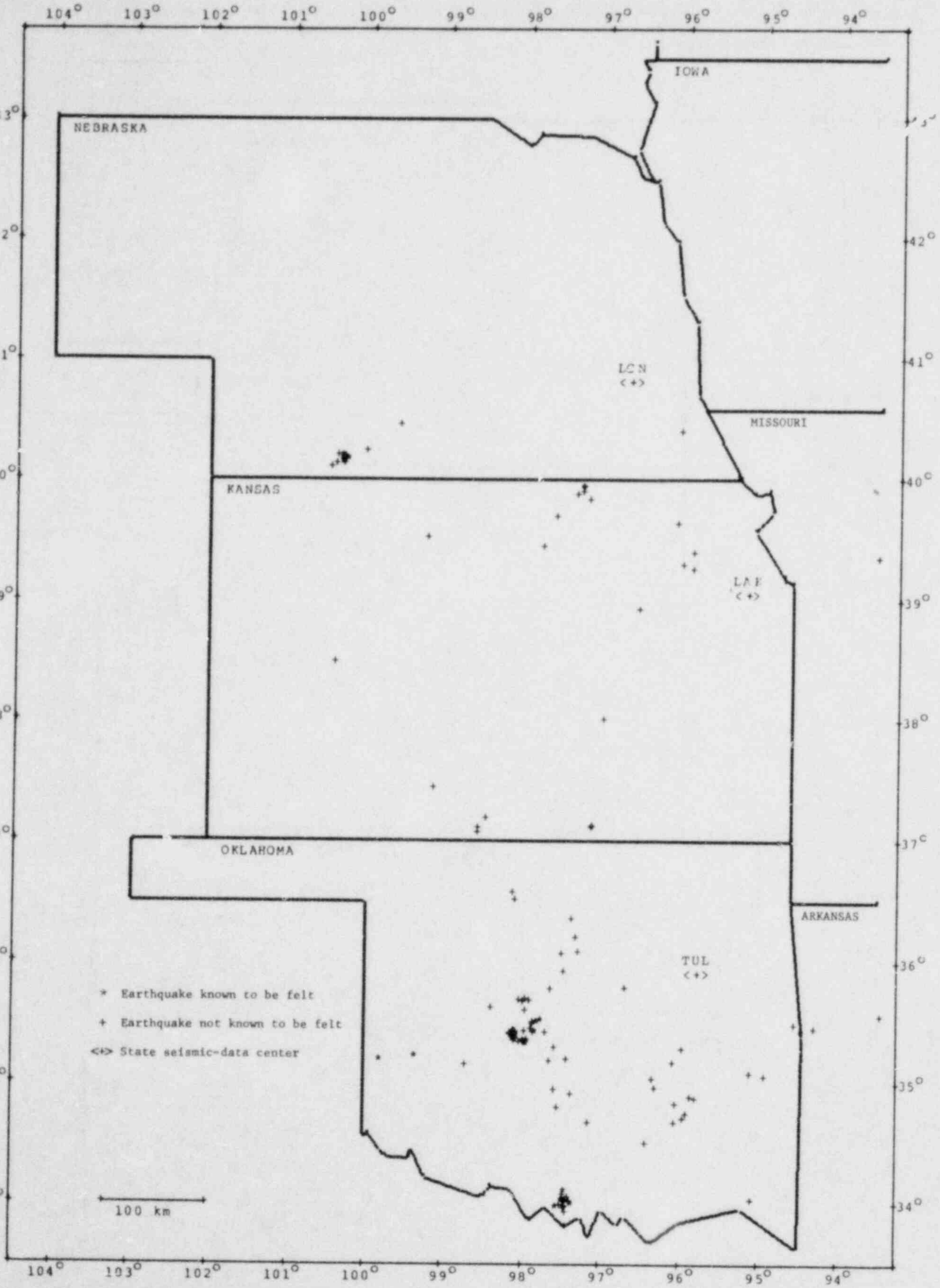


Fig. 15. Earthquake distribution for Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, October 1, 1978 to December 31, 1979.

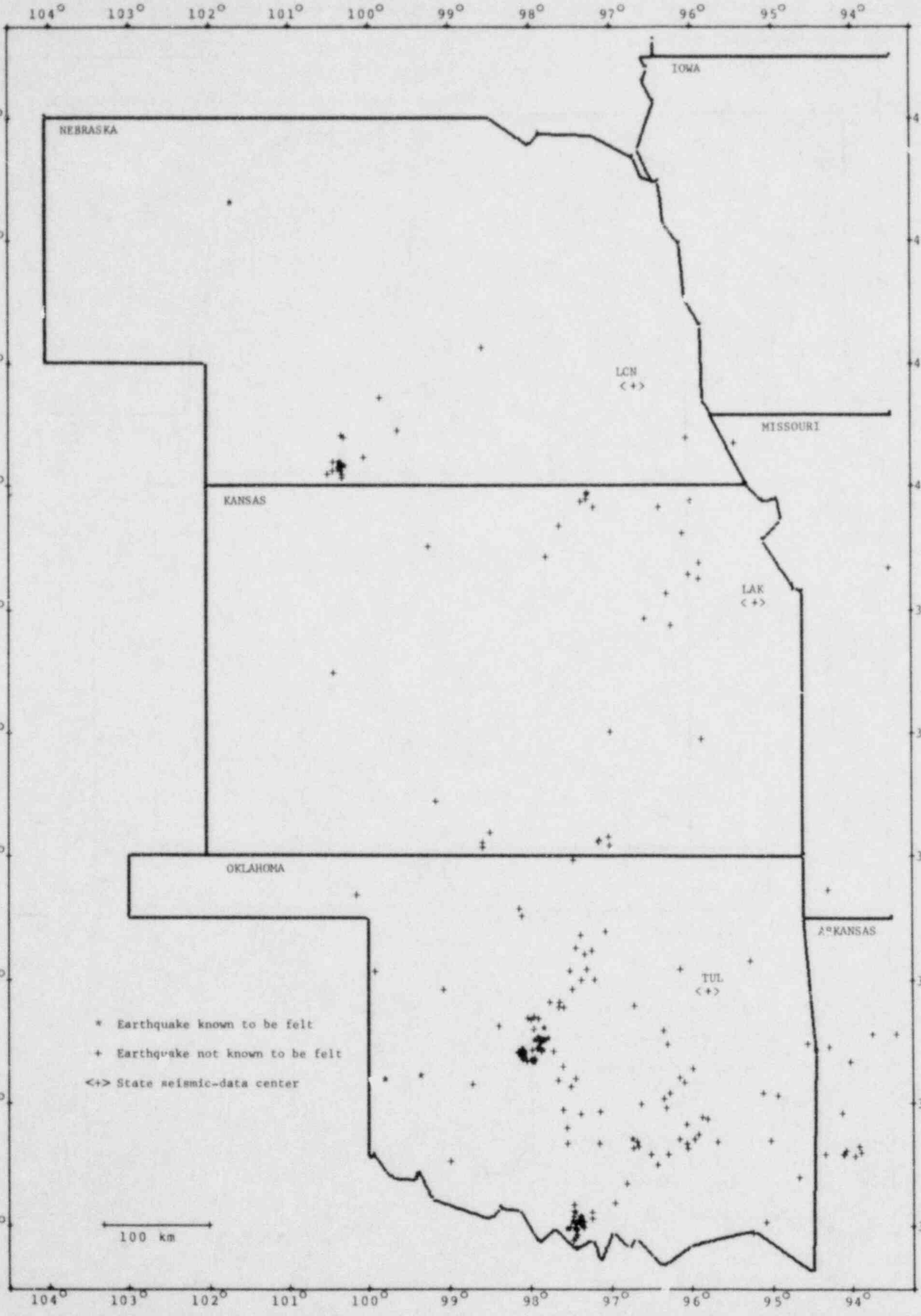


Fig. 16. Earthquake distribution for western Iowa, Nebraska, Kansas, Oklahoma, and surrounding areas, January 1, 1977, to December 31, 1979.

Fig. 17. Earthquake distribution for eastern and central Oklahoma and adjacent areas, January 1, 1977, to December 31, 1979.

of earthquake activity in Oklahoma. The first area, which is most relative to the Nemaha Uplift, is defined by a number of earthquake epicenters that form a 40-km-wide by 140-km-long zone extending northeast from the El Reno area (Canadian County) to near Perry, Oklahoma (Noble County). Over one-half (54) of the Oklahoma earthquakes reported in 1979 occurred within this zone. The southern terminus appears to be more active than the central and northern parts of this zone. On March 13-18, 1979, a swarm of 26 earthquakes occurred northeast of Cogar, Oklahoma. A second swarm of nine earthquakes, September 15-17, 1979, occurred near Minco, Oklahoma. A second area of both recent and historical earthquake activity is concentrated in Love-Carter Counties, in southern Oklahoma. During the 15-month period of October 1, 1978, to December 31, 1979, 13 additional earthquakes were located in this region. The third area is represented by apparently diffuse seismic activity along and north of the Ouachita front (Arkoma Basin) in southeastern Oklahoma. The several earthquakes that occurred west of 98.5° west longitude do not appear to form a pattern. However, the largest Oklahoma earthquakes for this time period, magnitude mbLg 3.4 in Beckham County and mbLg 3.3 in Blaine County, occurred in western Oklahoma.

Microearthquake Studies

Frequency-Magnitude Determinations.--Numerous earthquakes have been recorded in Love and Carter Counties since the operation of station WLO. The large number of earthquakes in the Wilson area enabled Dr. James E. Lawson to study the relationship between earthquake frequency and earthquake magnitude for earthquakes within a 20-km radius of station WLO. Magnitudes for nearly 400 earthquakes, recorded at WLO during 610 record days, were determined by the formula

$$\mathrm{MDUR} = 1.86 \log (\mathrm{DUR}) - 1.49, \quad (1)$$

where DUR is the difference in time between the Pg arrival and the point at which the coda decreases to half the amplitude of the background noise (Luza and Lawson, 1979). The cumulative frequencies were normalized to 1 year and plotted against magnitude (fig. 18). The mbLg magnitudes for felt earthquakes prior to the installation of WLO were determined from TUL seismograms. These data were assumed to be complete for a 4-year period. Their frequencies were also normalized to 1 year and plotted, along with the MDUR data, on the same graph (fig. 18). The data plots define a line:

$$\log N = 2.04 - 0.845\ M. \qquad (2)$$

The indicated frequencies are very high, considering that all earthquakes occurred in an area of less than 1,260 km^2.

On June 23, 1978, a swarm of about 70 earthquakes was recorded at WLO during a 6.19-hour period. The frequency data were normalized to 1 year and plotted against magnitude (fig. 19). The slope of a line fitting these points is represented by

$$\log N = 4.39 - 0.870\ M. \qquad (3)$$

Although the slopes defined by equations (2) and (3) are similar, the earthquake-swarm data indicate a seismicity level 224 times greater than the regional, long-term earthquake data. Perhaps other, non-natural, mechanisms might be contributing to the earthquake activity in the Wilson area. A reliable report from the volunteer operators of station WLO indicated that the time of the earthquake swarm coincided with the hydraulic fracturing of a formation near the bottom of a 10,000-foot oil and gas test 12 km northwest of WLO. Although it was not possible to obtain information from the operator for verification, a subsequent hydrofracturing test several months later showed a very good correlation to increased seismic activity. Therefore, we feel that some of the earthquake activity in the Wilson area may be related to oil and gas activity, particularly when hydraulic-fracturing methods are used to stimulate oil and gas production.

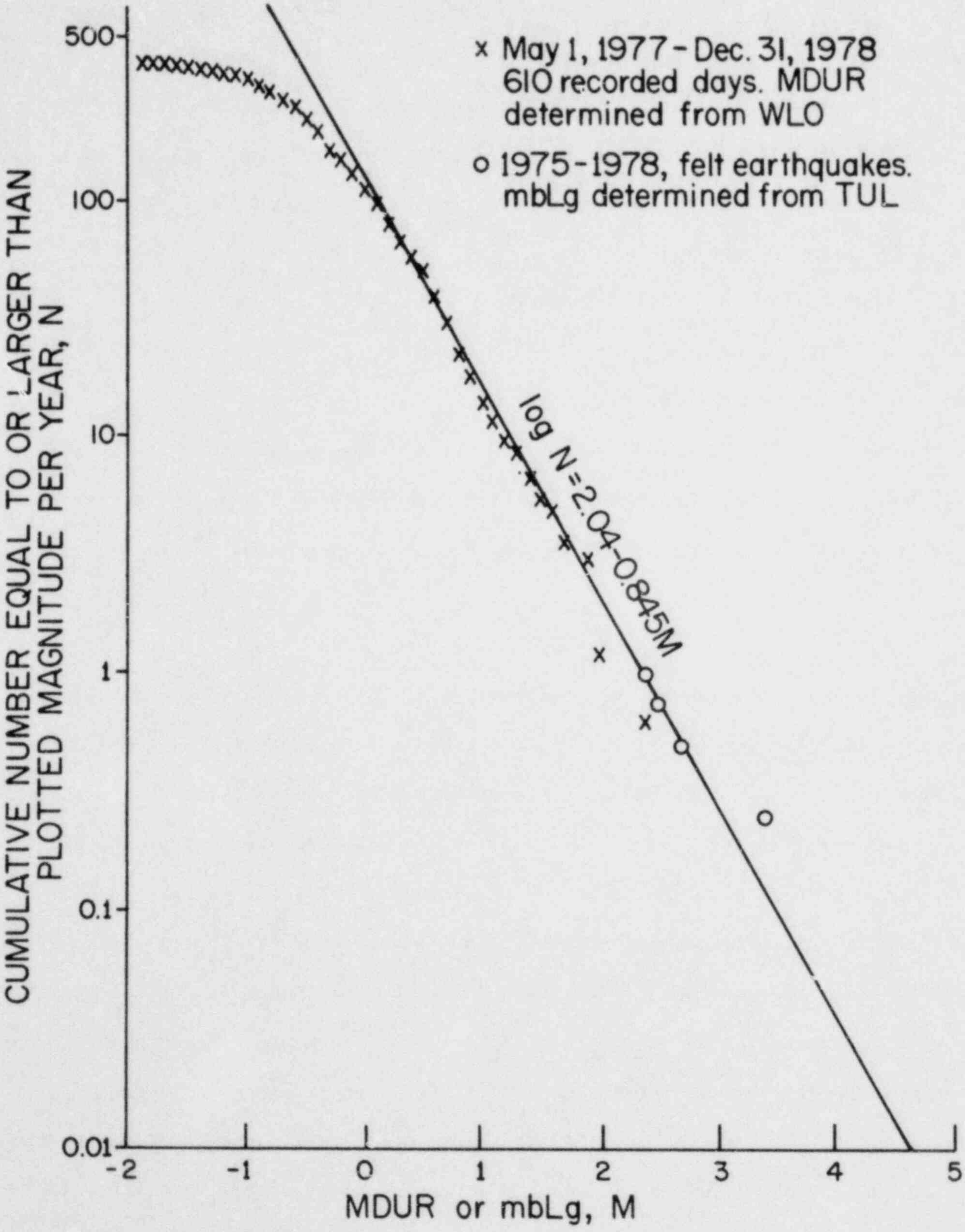


Fig. 18. Frequency vs. magnitude plots for 400 earthquakes within 20 km of WLO, Love and Carter Counties, Oklahoma.

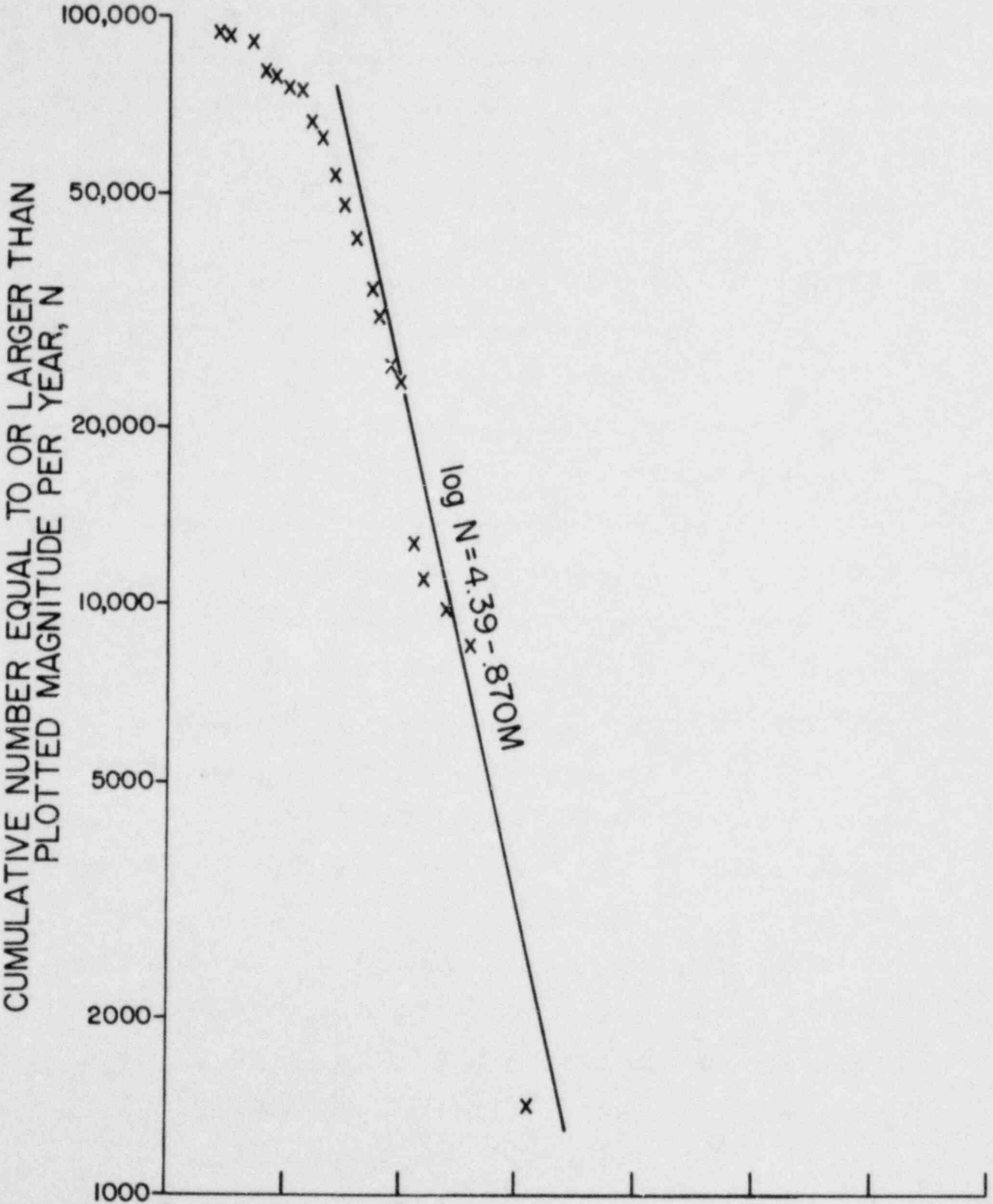


Fig. 19. Frequency vs. magnitude plots for earthquake swarm near WLO, June 23, 1978.

Equipment and Modifications.--Four portable microearthquake systems, DR-100, were purchased from Sprengnether for detailed microearthquake studies. The four Sprengnether DR-100 triggered-digital seismic recorders were modified so extensively that we have renumbered them as model DR-100-OK.

The modifications are discussed below in approximate order of importance.

1. Addition of WWVB time-signal receivers.

The internal-temperature-compensated-crystal-oscillator clock in the DR-100 is only specified as stable to 5×10^{-8}. There are 8.64×10^{7} milliseconds (msec) per day. Even a DR-100 that met the specification could drift by $(5 \times 10^{-8}) \times (8.64 \times 10^{7}) = 4.32$ msec per day. Two units could differ by an unacceptable 8.6 msec per day. Thomas Morrissey (personal communication) indicated that the DR-100 clocks do drift by on an unacceptable amount and that the drift cannot be corrected by assuming that it is linear. Also, the DR-100 does not have any method, other than comparing two blinking LED lamps, to compare the clock with a time standard. In our experience, comparison of blinking LED's is only accurate to 50 msec to 100 msec. The DR-100's do have a trigger circuit to start the clock. We measured the trigger delay and found it to be an acceptable 200 microseconds.

Before the DR-100 units were ordered, it was decided that WWVB time code should be received and recorded on one digital channel. Kinemetrics (True Time Division) 60-TLC receivers were selected for receiving WWVB pulse code on 60 KHz. The receivers' output code transitions were from a DC voltage that slowly varied from about + 1 to + 2 volts as a function of average signal level, to plus supply. To obtain sharper and more uniform transitions, we modified the receivers to transition from minus supply to plus supply by removing diode D3. The change was made in consultation with Mr. Van Gross of True Time.

To judge the reliability of the very low-frequency WWVB signal, a 60-TLC receiver was operated continuously at the Oklahoma Geophysical Observatory, which is 977 km from the WWVB transmitter. The code transitions were recorded at 90 mm/minute on a helicorder. The resultant recording allowed a quick scan for detection of dropouts or spurious transitions. The recording was continued for 40 days, of which nine (September 3 to September 11, 1978) were analyzed in detail. Of the 172,800 transitions (one per second low to high on the second, one high to low at various coded intervals after the second), the number of transitions missed, plus the number of spurious transitions, varied from 0 to 294 per 24 hours, with an average of 68. Eighty-five percent of the missed and spurious transitions occurred between 1143 and 1148 UTC, probably due to a diurnal-transmission-path effect.

The modified 60-TLC WWVB receiver was placed in the DR-100-1A lid in a position normally occupied by seismic amplifiers for channels 2 and 3. The plus and minus power supply was taken from the DC-DC inverter that supplies two-sided DC to the channel-1 AS-110 seismic amplifier. The RF input from a True Time A-60FS ferrite-core antenna and preamplifier was connected through the input connector for seismic-channel 2. The code output was divided by 2 (6 dB) so that the plus-10-volt offset of the DR-100 internal clock could be seen riding on top of the (approximately) plus-7-volt time-code offset. Without attenuation, the WWVB time code would transition from plus to minus 14 volts, which would exceed the ±10-volt digitizing range and hence blank the clock pulses when the WWVB code was high. The receiver connections are shown in figure 20.

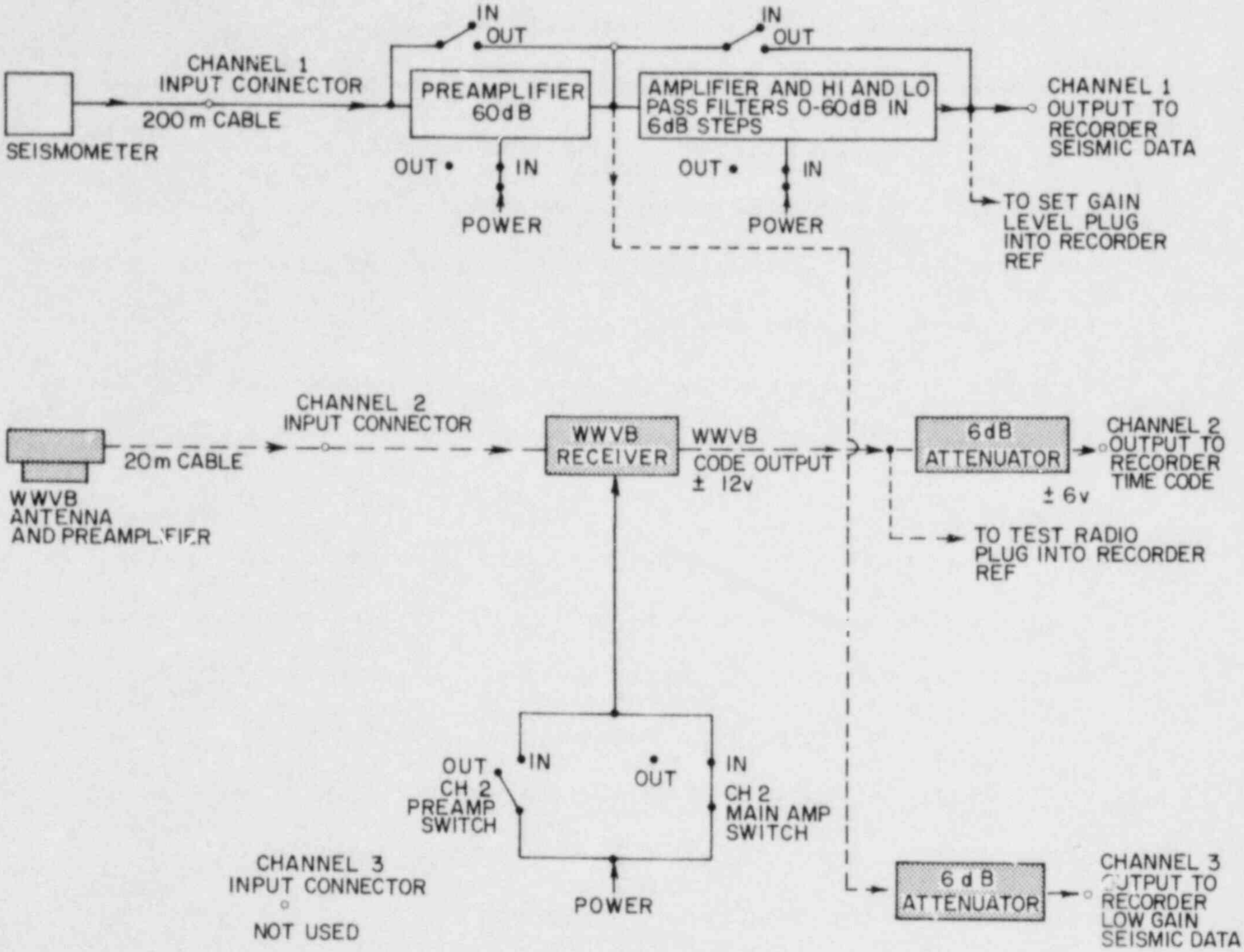


Fig. 20. DR-100 channel-connector flow chart.

The 60-TLC receiver specifications call for an 18 ± 5 msec delay between the 10-dB drop in the WWVB carrier (which occurs at the beginning of each second) and the transition to receiver output high. The 18-msec delay is caused by the low-pass spike-supressor filter. Three msec of the ±5 msec is a variation owing to the average level of coding of the signal. As this will be the same for all receivers at any one time, it will not cause a deviation between them. For a small array, the RF carrier propagation time will not vary more than a hundred microseconds (3.3 microseconds per kilometer pacing in the direction of propagation). There is only ±2 msec of uncertainty left, which is related to RF noise. As this RF noise may vary across the array, there is a possible 4-msec difference between different units.

2. Long-term average (LTA) shutdown modification of the analog seismic trigger circuit.

The DR-100 trigger circuit forms two selectable-length exponential sums of the channel-1 seismic signal, denoted long-term average (LTA), and short-term average (STA). These are not true averages but rather are exponential sums formed through RC (resistance-capacitance) integrators. The LTA average is tracked by an 8-bit digital register that maintains the voltage constant while the LTA is latched. The LTA and STA switch setting set the time constant of the RC integrators.

When the STA exceeds the LTA by a switch-selected trigger ratio, the trigger goes high, initiating recording, and the LTA latches. The triggering behavior of the DR-100 was studied by operating a DR-100 continuously at the Oklahoma Geophysical Observatory for about 50 days. The digits, in addition to being recorded on the DR-100 internal cassette, were converted by a Sprengnether DP-100 playback unit to an analog voltage. The analog voltage was recorded on a helicorder.

The trigger normally goes low when the STA/LTA ratio falls below the selected trigger value. However, we found that if the background noise increased monotonically (e.g., from rising windspeed) during the trigger period, the STA would increase above the latched LTA and hold the trigger on for hours. This could be prevented by increasing the trigger ratio to such a degree that many significant events (quarry blasts and teleseisms in the test runs) would be missed.

Intuitively we reasoned that the trigger would not be held on by rising noise levels if the LTA was not latched but was free to increase. In consultation with Lee Royer of Sprengnether, we unlatched the LTA of one DR-100 and found that it could be operated by a very low trigger ratio without ever "sticking." Having determined that this modification more than doubled the number of events we could record, we modified our other DR-100s and circulated a letter to seismic-network operators in the central United States recommending the LTA shutdown modification

3. Setting amplifier gain without external test equipment.

The background noise level is usually set for portable digital seismic equipment by observing the amplifier output on an oscilloscope.

The internal-time-reference lamp in the DR-100 is set for a threshold of 1.0 volts. We made a cable to connect the amplifier to the time-reference lamp. The amplifier gain is advanced until the lamp is blinking several times a second. This should indicate more than 1000 mV center-to-peak on the signal peaks. One bit on the DR-100 represents 5 mV. Nine bits are required to represent 1280 mV. With the LED lamp blinking, the background noise is using about 9 bits of the total 12-bit dynamic range of the recorder. In our application, in order to record signals just above the noise level, we wanted to use four bits to represent the noise background. Therefore, we decreased the gain setting by five bits, which is simply five 6-dB steps on the amplifier-gain switch. Examination of seismic-noise signals and sine waves from a function generator simultaneously on the DR-100 LED and on an oscilloscope indicated that the simplified method of setting amplifier gain was as good as using an external oscilloscope.

4. Checking the operation of the built-in WWVB receiver with the DR-100 Ref LED lamp and starting the clock with the WWVB signal.

The same cable that connects the seismic-amplifier output to the DR-100 Ref LED is used to connect the WWVB code to the LED. The regular pattern of blinking immediately confirms proper operation of the receiver.

The clock and Ref LEDs can be compared to set the clock approximately to WWVB. The varing length of the WWVB pulses makes this somewhat inaccurate. The REF lights up at the beginning of each second but remains lit for different intervals (200 msec, 500 msec, or 800 msec).

The WWVB signal cannot be used to start the clock on the minute. The code output is low for only 200 msec before becoming high at the beginning of the minute, and it has proved practically impossible to manually flip the clock switch to arm during the 200 msec. After the 58th tick there is an 800-msec interval to throw the arm switch. The 58th second is identified by listening to WWV announcement and ticks with a Radio Shack Timekube receiver. Arming the clock after the 58th second starts it 1 second before the minute. To correct for this second, the advance-retard switch is retarded for 49 ticks of the DR-100 clock. On retard, the clock slows by 20 msec per second, and, since the retarded ticks are 1.02

sec apart, 49 of them equal 50 seconds for a total change of 50 x 20 = 1000 msec. Refer to Appendix A for field instructions giving two methods for setting the clock.

5. Strong seismic motion recorded on channel 3.

The output from the 60-dB gain preamplifier section of the AS-110 seismic amplifier is attenuated 6 dB and recorded on channel 3 of the DR-100. This makes the separation between channel 1 and channel 3 equal to the gain setting on the amplifier minus 54 decibels. For example, if the amplifier is set at 90 dB gain (i.e., 60 dB preamplifier plus 30 dB in the main amplifier), the separation is 36 dB.

The gain of 54 dB for the strong-motion channel was selected to record motion that would cause mechanical clipping by the Geo Space HS-1 4.5-Hertz geophone with 1250-ohm coil (damped 50 percent critical), which was used with these systems.

Figure 20 shows the connections for the strong-motion channel 3. In addition to reduced gain, this channel is not frequency filtered, because it bypasses the active filters in the main amplifier.

6. Extending the shift-register memory.

The digitized seismic-signal channel 1, WWVB-code channel 2, and strong-motion seismic-signal channel 3 are digitized, multiplexed, and channeled into a 21,504-bit digital shift register. When the real-time-analog trigger goes high, recording commences from the end of the shift register holding the oldest data. This allows time for the tape deck to start and still record data beginning before the trigger.

Because the shift register uses considerable power, Sprengnether designed the shift register to automatically power down to 14,336 or 7,168 bits for low sample rates. We felt that the pre-trigger time recorded was short enough that a P-wave arrival might be missed if the unit were triggered by an S-wave arrival. Sprengnether modified all our units so that the entire shift register was active at all times. When two channels are recorded at 100 sps (samples per second), the memory length in the unmodified DR-100 is 5.52 sec, allowing only about 3.5 seconds of pre-trigger recording after the 2-second start time of the tape deck. When the entire shift register is used, the memory length increases to 8.28 seconds. When three channels are recorded at 100 sps, the entire shift register is active in the unmodified unit, so no increase is possible.

Wilson Microearthquake Study. -- During October and November 1979, four triggered-digital units were established in a diamond-shaped array with station WLO situated near the center of the diamond in Love-Carter Counties, Oklahoma. The stations, with their approximate locations with respect to WLO, were:

OCWI 22.5 km north
JTWI 20.9 km south (later moved to JTW2, 18.9 km south)
ORWI 10.5 km west
CHWI 9.7 km east

The area was selected because of the numerous microearthquakes (over 400) that have occurred in this area since 1978. We felt this area would offer an excellent opportunity to field test the equipment as well as to provide the necessary data to locate the microearthquake activity more precisely. Numerous earthquakes were recorded, most at CHWI and ORWI, during our test period. However, they were too small and our array too large, for any one earthquake to be recorded on more than one DR-100, although some earthquakes visible on the WLO volunteer-station analog records were also recorded on one or the other two stations closest to WLO.

Many logistical lessons were learned from this operation, which are numbered below.

1. Field-station set-up procedures were developed and printed (Appendix B).

2. The triggering sensitivity should be set so that 30 to 60 percent of a tape cassette is recorded in 24 hours. This must be checked by recording for at least one 24-hour period after the parameters are changed. A half-hour or 1-hour count of the trigger seldom if ever extrapolates to 24 hours.

3. The long-term average should be 200 seconds in absence of traffic but can be shorted to as little as 5 seconds to minimize triggering from motor traffic.

4. The short-term average for microearthquake work is optimum at 0.5 second.

5. The 4.5-hertz geophones were selected to act as electromechanical filters (rolling off at 18 dB per octave for frequencies less than 4.5-hertz) to prevent triggering on teleseisms and quarry blasts (both have 0.5- to 3-hertz waves). These geophones performed this function excellently.

6. When sensitivities are compared, the differing long-term averages must be considered as well as the trigger ratio, since the LTA is really a sum. We did this by considering the effect of a step (Heaviside) function on the STA and LTA. A step raises the ratio immediately to:

   $$\underset{\text{(in dB)}}{\text{Ratio}} = 20 \log \left(\frac{\text{length of LTA}}{\text{length of STA}} \right) .$$

   Because no wave from can cause a rise more rapid than a step, we calculated a modified sensitivity, the number of dB below the rise caused by a step, which will trigger the unit. This sensitivity is:

   $$\underset{\text{(dB below step)}}{\text{Sensitivity}} = \underset{\text{(in dB)}}{\text{Trigger ratio}} - 20 \log \left(\frac{\text{LTA}}{\text{STA}} \right) .$$

   If this sensitivity is positive, triggering cannot occur. If it is, say, -2 dB, a seismic signal will have to be nearly as sharp as a true step (zero rise time) to trigger. By contrast, -40 dB below step is the most sensitive ratio we could use at any site.

7. The DR-100-OK triggered-digital seismograph is suitable for volunteer operation. The volunteers need only to change the tape cartridge daily. The digitized WWVB trace frees them from having to set the clock.

Recordings of a typical microearthquake are reproduced in figures 21 and 22. In each case the upper trace is the seismic signal. The rectangular wave on the lower trace is WWVB time code. The small pips "riding" on top of the rectangluar wave are the second marks (every odd second only) from the DR-100-OK internal clock. Figures 21 and 22 represent the playback of the same earthquake at the following

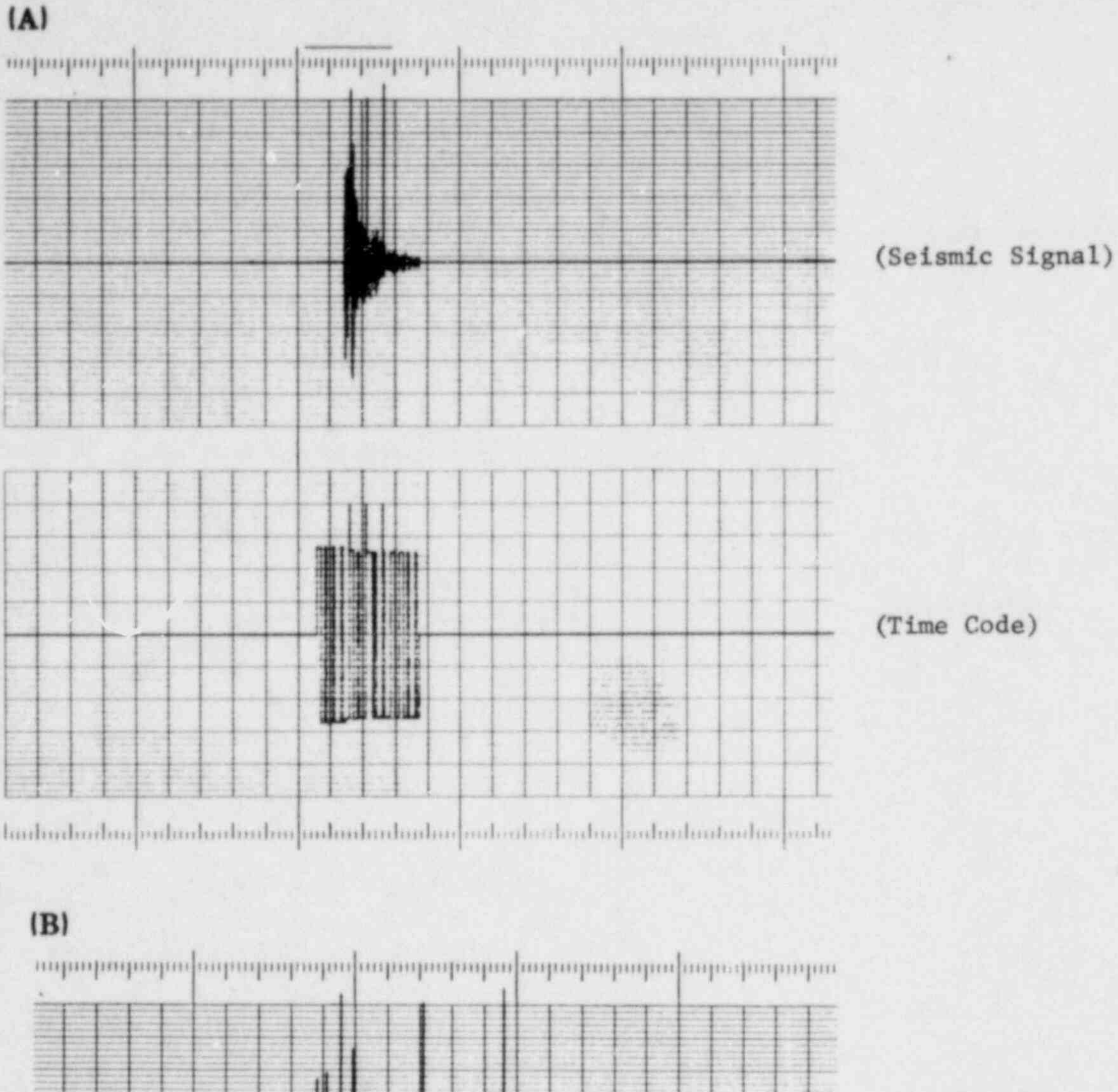


Fig. 21. Typical microearthquake recorded on DR-100-triggered digital seismograph. (A) Record generated when strip-chart recorder playback speed is 1.2 mm/sec. (B) Playback speed is 6 mm/sec.

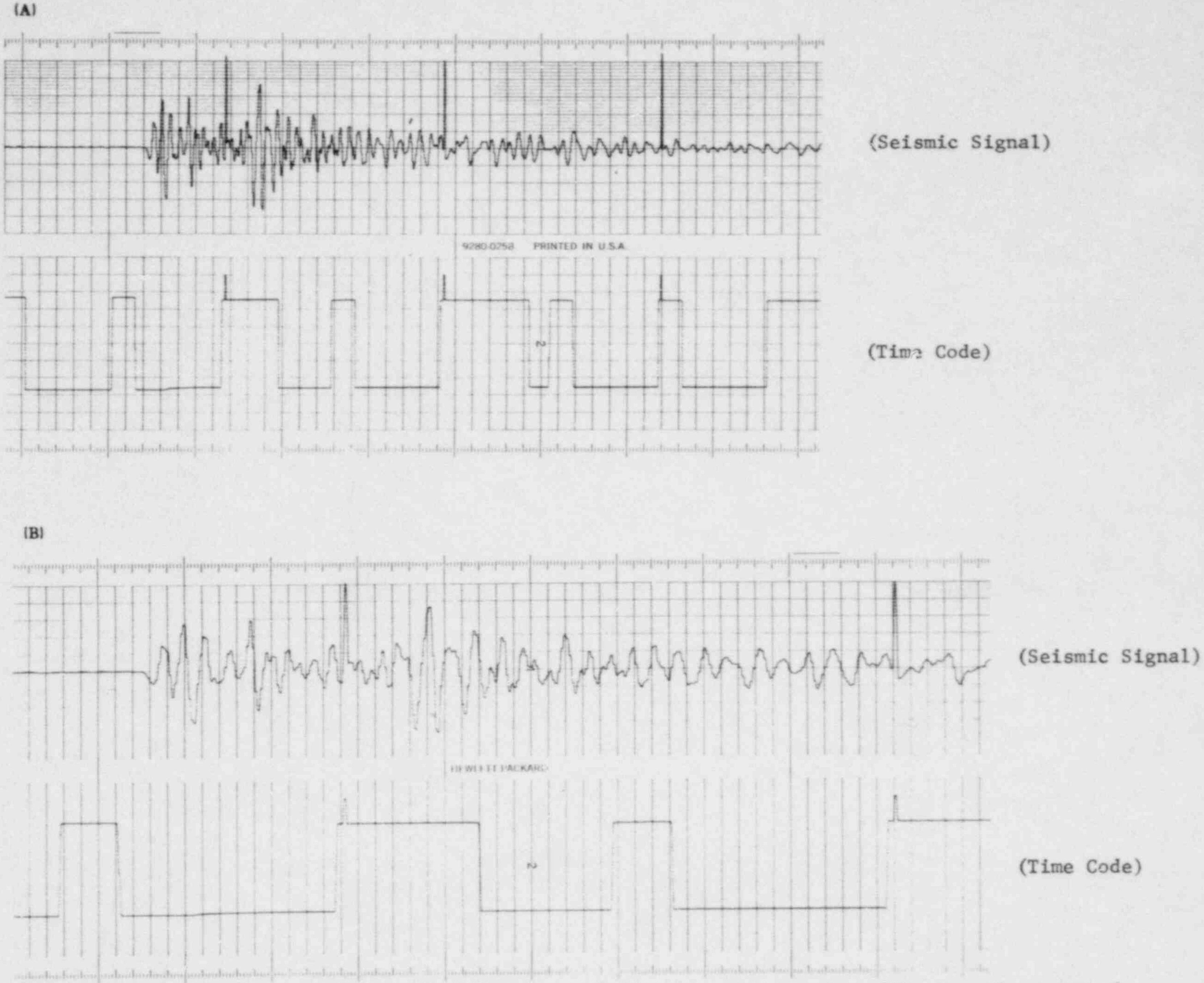


Fig. 22. Typical microearthquake recorded on DR-100-triggered digital seismograph. (A) Record generated when strip-chart recorder playback speed is 30 mm/sec. (B) Playback speed is 150 mm/sec.

chart paper speeds: 1.2 mm per second, 6 mm per second, 30 mm per second, and 150 mm per second (figs. 21, 22). The first two speeds are adequate for initial playback to separate earthquakes from other events. The 6 mm/sec speed is adequate for most phase timing. At this speed the discrete nature of the samples (100 samples per second in this case) is apparent. The individual samples are very obvious at 30 and 150 mm/sec. Notice that the internal clock is lagging the WWVB code by three samples, or 30 msec.

Historical-Earthquake-Magnitude Determinations

An attempt was made to determine magnitudes for some Oklahoma historical earthqakes from felt-area reports. Previous work included the development of an empirical relationship between felt area and magnitude by Eysteinn Tryggvason (1964). He modified and combined some of Charles Richter's equations, which relate magnitude, intensity, acceleration, and radius of perceptibility for Southern California earthquakes, to produce the following equation for Oklahoma:

$$M = 2.9 \log (r) - 1.8, \qquad (1)$$

where M is magnitude and r is radius of perceptibility in km. By comparing attenuation of Lg waves in easterly and westerly directions from a source in New Mexico, Tryggvason determined a correction factor to allow for a 25-fold smaller attenuation to the east, assuming that Lg waves came from Southern California earthquake sources. This correction factor is incorporated in equation (1).

Examination of Tryggvason's tabulated results from equation (1) indicates that he actually used felt areas in km^2 and calculated the radius of perceptibility by assuming that the areas were circles centered on the epicenters. This is a questionable procedure, since Tryggvason's own diagrams do not show even approximately circular felt areas. Substituting the formula for the area of a circle in equation (1), we have:

$$M = 2.9 \log \sqrt{\frac{A}{\pi}} - 1.8 , \qquad (2)$$

which reduces to

$$M = 1.45 \log (A) - 2.52, \quad (3)$$

where A is the felt area in km^2. Equation (3) is the equation that Tryggvason in fact used. Tryggvason apparently placed some limits of applicability on equation (1), and hence on equation (3), but an apparent typographical error makes the limit read:

for $A - 2.5$,

which cannot be deciphered.

Otto Nuttli and Jim Zollweg (1974) developed an empirical relation between felt area and magnitude:

$$mb = 2.6 + 0.098 \log(A) + 0.054 (\log (A))^2, \quad (4)$$

where A is the felt area in km^2 Most of their data either used Nuttli's (1973) mbLg or used other magnitudes assumed to be nearly equivalent. We will treat equation (4) as applying to mbLg.

Six Oklahoma earthquakes and one Nebraska earthquake have exact felt areas. The Oklahoma felt areas were determined by house-to-house canvass (Lawson and DuBois, 1976). The Nebraska felt area was determined by a map made by R.R. Burchett (personal communication, 1978) from a detailed telephone survey. The same map, in somewhat less detail, was since published by Burchett (1979). Values of mbLg calculated from seismograms recorded at the Oklahoma Geophysical Observatory (seismograph station TUL) are available for the seven earthquakes with calculated felt areas. The data, approximate location, mbLg, and felt areas are given in table 3.

Table 3. Magnitudes and felt areas of earthquakes studied.

NUMBER	DATE	LOCATION	mbLg (records)	FELT AREA (km^2)	mbLg (equation 4)
1	Dec. 16, 1974	Moore, OK	2.6*	20.7	2.9
2	Sep. 13, 1975	Wilson, OK	3.4	193	3.2
3	Nov. 24, 1975	Foster, OK	3.6	353	3.3
4	Mar. 16, 1976	Stidham-Eufaula, OK	2.3	153	3.1
5	Mar. 30, 1976	Boise City-Griggs, OK	2.1	181	3.2
6	Mar. 30, 1976	Keyes-Boise City, OK	2.7	622	3.4
7	May 7, 1978	Cherry Co., NB	3.9	15,570-18,220	4.0-4.1

*This was actually an m3Hz assumed to be equivalent to mbLg.

Figure 23 graphs Tryggvason's equation (3) and Nuttli and Zollweg's equation (4), and also shows numbered points for the seven earthquakes listed in table 3. The Cherry County, Nebraska, earthquake has two circles connected by a vertical bar to allow for a 2,650-km^2 area which lacked either felt or not-felt reports to delineate the boundary along the eastern edge of the felt area. Although there is some scatter for the smaller events, they are represented fairly well ($\simeq$ 0.5 m_bLg units) by Nuttli and Zollweg's equation, and they tend to converge at higher magnitudes. Tryggvason's equation seems much less representative. Its only merit seems to be that it fits the only data point available to Tryggvason, the Arpil 9, 1952, El Reno, Oklahoma, earthquake, m_b 5.5 (PAS, Pasadena, California), felt area 350,000 km^2, apparently from the USCGS report United States Earthquakes 1952.

The Nuttli-Zollweg equation (4) appears to be a reasonable equation for relating m_bLg to felt areas in Oklahoma. Accordingly, 25 felt areas were extracted from Docekal's (1970) dissertation, and one from Tryggvason (1964). The felt areas were used to calculate m_bLg magnitudes, which will be placed in the computerized earthquake catalog. Calculation of m_bLg equation (4) will be limited to 1961 and earlier years so that the values calculated from felt areas will not be mixed with values calculated from Lg amplitudes. One exception to this rule will be the May 2, 1969, earthquake for whch the m_bLg of 4.08, appearing in the catalog, was calculated

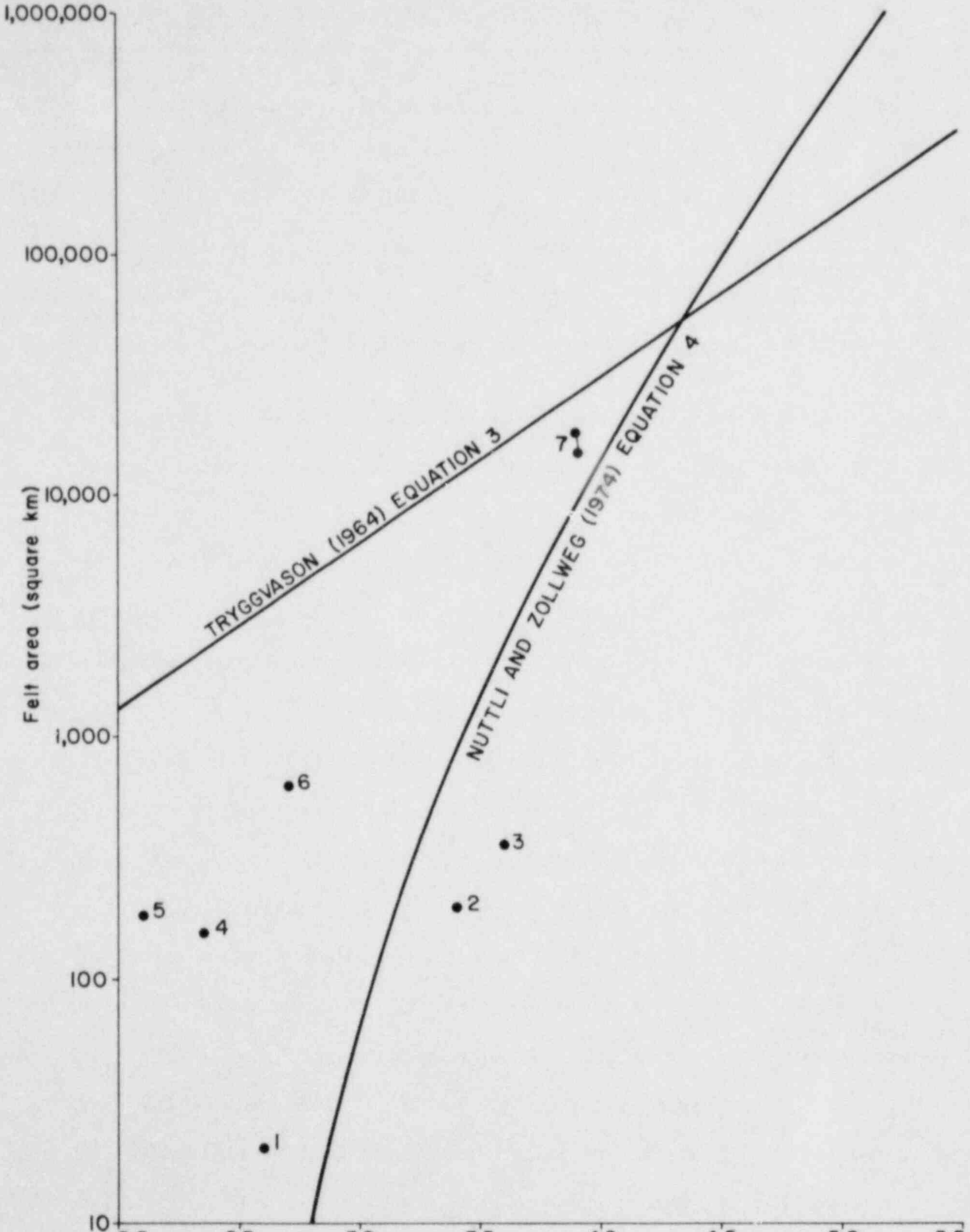


Fig. 23. Felt areas and mbLg for seven earthquakes and as related by equations (3) and (4).

by formula (4), using a 20,537 km^2 felt area scaled from the isoseismal map in United States Earthquakes 1969. This earthquake had an mbeus of 3.6 and an mb (P wave) of 4.6. Calculation of mbLg may be possible if copies of seismograms from stations more distant than TUL (where the Lg was off scale) can be obtained.

The calculated values are given in table 4. The most interesting result is the classification of the April 9, 1952, Oklahoma MM Intensity VII earthquake as m_bLg 5.0. Previously only the P-wave m_b of 5.5 from Pasadena, California was available for this earthquake.

Table 4. mbLg calculated from felt area by equation (4).

DATE	UTC (hour)	COUNTY (Oklahoma)	MM-INT.	FELT AREA (km^2)	mbLg
1915 NOV 08	00	ROGERS	F	8,000*	3.86
1918 SEP 10	16	CANADIAN	V	1,036	3.44
1918 SEP 11	06	CANADIAN	VI	1,036	3.44
1926 JUN 20	14	SEQUOYAH	V	46,620	4.28
1929 DEC 28	00	CANADIAN	VI	17,353	4.04
1933 AUG 19	19	CANADIAN	V	518	3.31
1934 APR 11	17	CHOCTAW	V	7,770	3.85
1936 MAR 14	17	MCCURTAIN	V	2,072	3.57
1936 JUL 12	00	CIMARRON	F	518	3.31
1937 JUN 08	14	POTTAWATOMIE	IV	2,590	3.61
1939 JUN 01	07	HUGHES	IV	64,750	4.37
1941 OCT 18	07	WASHITA	V	259	3.20
1942 JUN 12	05	GARFIELD	III	3,885	3.70
1952 APR 09	16	CANADIAN	VII	639,727	5.04
1952 APR 11	20	CANADIAN	IV	7,770	3.85
1952 APR 16	05	CANADIAN	F	7,770	3.85
1952 APR 16	06	CANADIAN	V	7,770	3.85
1953 MAR 17	14	CANADIAN	VI	6,993	3.82
1956 FEB 16	23	OKLAHOMA	VI	12,950	3.97
1956 APR 02	16	PUSHMATAHA	V	5,180	3.76
1956 OCT 30	10	ROGERS	VII	24,605	4.12
1959 JUN 15	12	PONTOTOC	V	12,950	3.97
1959 JUN 17	10	COMANCHE	VI	36,907	4.22
1961 JAN 11	01	LATIMER	V	6,475	3.81
1961 APR 26	07	PUSHMATAHA	II	6,475	3.81
1961 APR 27	07	LATIMER	V	20,720	4.08

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*Felt area for 1915 earthquake from Tryggvason (1964). All other felt areas from Docekal (1970).

DIRECTIONS OF STUDY FOR FY 1980

The following goals have been established for the 1980 fiscal year:

1. Complete an aeromagnetic map for the Enid and Oklahoma City 1° x 2° Quadrangles.
2. Begin preparation of plates, at a scale of 1:500,000, for inclusion in the final report to be submitted at the end of fiscal year 1981. A separate plate or plates will be prepared with the following information: (a) bedrock geologic map, (b) three structure-contour maps, (c) aeromagnetic map, (d) contour map of top of the Precambrian basement, (e) earthquake map, (f) detailed gravity map, and perhaps (g) a lineament map.
3. Prepare a 1:1,000,000-scale base map for the four-state (Iowa, Nebraska, Kansas, and Oklahoma) study area. This base map will be used to plot information to be submitted at the end of FY 1981.
4. Detailed gravity and magnetic studies will continue in north-central Oklahoma. Canadian, Oklahoma, and part of Logan Counties will be the areas of detailed study this summer.
5. The El Reno area, in western Canadian County, will be the site of detailed microearthquake studies this spring and summer. A seven-station array, using the DR-100 protable trigger-digital systems, will be installed for a 6- to 12-month period. We hope this program will provide data to make focal-depth determinations for this area.

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* Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, and the National Technical Information Service, Springfield, Va. 22161

APPENDIXES

A. DR-100--Setting the Clock

B. DR-100--Field Set-up and Operation

APPENDIX A

DR-100-OK Portable Digital Seismic Station--Setting The Clock

1. The slim gray external power cable from the lid should be connected to the PWR plug on the front of the recorder. The black cable from the WWVB antenna should be connected to Channel 2 input on back of the lid. Turn WWVB on. Connect the recorder REF IN to WWV test by inserting pin of red plug to WWV test IN and pin of black plug to WWW test OUT. REF lamp should be flashing WWVB Code, one pulse per second with pulses of unequal length.

2. Switch START-ARM-STOP signal to STOP. If clock lamp is lit, push switch up to arm or start, then return to stop. Repeat until clock is stopped with clock lamp unlit.

3. Determine day number. For example, for September 25 of a non-leap year, find in the table taped in the lid.

   SEP ADD 243

   The day number is 243 + 25 = 268. Do not set day number yet.

4. Extend antenna on Realistic Timekube. Punch WWV10 or WWV15 (whichever gives the best signal - sometimes at night WWV5 will give a better signal).

5. Select minute about 2 or 3 minutes ahead of last announcement, e.g., 23 hrs 45 min. Press set button and hold down. Press the right min button and hold down until minute digit is 5. If you run past 5, continue holding button until 5 is displayed again. Press left min button until minute digit reads 4.

6. While continuing to press set, press HR button until correct hour is displayed.

7. Press right day button until day digit is correct, center day button until tens digit is correct, and left day button until 100 digit is correct.

8. Release set button. Note that digits must be set in order from right to left.

9. Move START-ARM-STOP switch to ARM during the second-long high-pitched tone at the beginning of the minute set in the display. The clock should now be ticking a fraction of a second after the ref. Move adv-ret switch to adv until the clock and ref lamps appear to begin each flash simultaneously. This is not easy, because the ref (WWVB) flashes are longer than the clock flashes, and the ref flashes vary in length. Remember, it is the beginning of the flashes that must match up. The adv switch must be held in adv for 50 seconds to advance the clock 1 second.

10. Fine set. Turn Timekube off by pressing TIMEKUBE so that the audible

signal will not confuse you. Put one eye 1 or 2 centimeters above the clock and ref lamps so that they appear out of focus as two blurs. The flash may appear to be moving from one lamp to the other. Remember, only the beginning of the flash is important. Push the adv-ret switch opposite the direction in which the beginning of the flash appears to move. For greatest accuracy, hold adv-ret switch until the flashes appear to move in one direction, then reverse switch until direction reverses, and finally settle on no movement between the two directions.

11. Switch Timekube to WWV10 (or WWV15 or WWV5) for best signal, and check your minute and second. If clock display is off in any digit, simply press set and one of the other buttons to correct display while clock continues to tick.

Setting The Clock - Alternative Method

The clock will be automatically started by the WWVB pulse whenever the STOP-ARM-START switch is moved from STOP to ARM. However, at the beginning of the minute there is only a 0.2-sec gap between pulses, and it is almost impossible to throw the switch during the 0.2-second gap. Between the 58th and 59th second there is an 0.8-sec gap between WWVB pulses. It is possible to arm the clock in this 0.8 sec-gap, in which case the display starts counting up from zero on the 59th second, meaning that the clock is exactly 1 second fast. If the adv-ret switch is held on ret for 49 ticks of the clock, the clock will be retarded by exactly 1 second and hence will be on time (50 seconds retarding is required to lose 1 second, but when the adv-ret switch is on ret the clock takes 1.02 seconds to make one tick, or 50 seconds for 49 ticks.

1-8. The first eight steps are the same as in the first method.

9. Move start-arm-switch to stop. Listenting WWV, count 58 ticks (the click on the 29th tick is omitted from WWV). Immediately after the 58th tick, move the switch to arm. The clock should now be running 1 second fast. Before going to step 10, be sure that the clock and ref lamps are flashing simultaneously. If they are not, repeat step 9.

10. Next time the display shows 00 seconds, push adv-ret switch to ret, hold, and release when display reads 49.

11. Check the display with WWV. If it is incorrect, reset it without stopping the clock. Be sure clock and ref lamps are flashing simultaneously. Disconnect pins from WWVB test.

NOTE: WWV and WWVB are two entirely separate time stations operated by the U.S. National Bureau of Standards. Both broadcast from Fort Collins in north-central Colorado. The 60-kilohertz low-frequency WWVB, which is recorded directly on the seismograph tapes with each event, and which flashes the REF lamps, transmits only pulses. The high-frequency WWV (5, 10, and 15 megahertz), which you hear on the Timekube, transmits voice-time announcements and ticks along with some other tones and announcements.

APPENDIX B

DR-100-OK Portable Digital Seismic Station--Field Set-up And Operation

Serial numbers--The serial number of each unit is extremely important, because it is recorded on the tape with the header and trailer of each event. If it is clearly understood which recorder was at which site, all tape identification could be lost without affecting data analysis. As an additional aid in identification, the DR-100-OK with the lowest serial number should be placed at the most northerly site, and the other units should be placed with serial numbers increasing in a clockwise direction from the most northerly site. The clockwise direction is with respect to the approximate geometric center of the array.

Site selection--The sites can be preselected or selected in the field. Select sites by defining target areas and by approaching owners of isolated houses or farms in each target area. The ideal site will have an indoor location with commercial power for the DR-100-OK with relatively quiet seismometer locations within 50 meters of the indoor location.

Installation--The units will ordinarily be sent out with triggering parameters correctly set, and with the clock set and running (but with the display off to conserve battery power). The power cable and signal cable that connect the lid with the recorder should be attached to the lid only. If the power cable is connected, the lid will draw power even if all lid components are switched off. There should be no tape cartridge in the recorder. The record head will have been demagnetized.

1. Set up recorder and lid in desired (preferably indoor) location. Lid should be propped behind by a wall; otherwise its weight may bend the hinges.
2. Plug in commercial power. If available plug has only two prongs, use converter plug that is attached to basket by wire or tape.
3. Switch display to on and to time.
4. Check day on display using table in lid. For example, for October 15 in a non-leap year, find in the table:

OCT ADD 273

The day is 273 + 15 or day 288. This is not the Julian date, although it is sometimes stated to be. It should be called simply the day number.

6. Turn on the Timekube receiver for best WWV signal (usually 10 MHz; occasionally 15 MHz is better in the early morning or 5 MHz better at night). Verify hour, minute, and second.
7. If day number, hour, minute, and second are correct, the clock needs no further attention. If they are incorrect or the clock has stopped proceed to step 16 and then refer to separate sheet titled Setting the clock.

8. Take WWVB antenna plug from basket (it is attached to the black cable). Feed it inside and connect it to channel 2 on the back of the lid. Find location for the WWVB antenna (white cylinder). It can lie on the ground, but it is preferable to have it 2 or 3 meters above ground. Drag antenna to its site. Simply pull cable out of the basket; it is not necessary to carefully uncoil it. Set up antenna with its axis perpendicular to the direction to Fort Collins, Colorado.

9. Find quiet seismometer location. Take the seismometer plug and disconnect it from the female shorting plug which is wired and/or taped to the gray cable near its end. The shorting plug must always be connected when moving the seismometer by vehicle, to damp the seismometer and prevent mechanical damage to it. Feed seismometer plug inside and connect it to channel 1 on the back of the lid.

10. Drag gray seismometer cable with silver seismometer to its site, dig out one one two shovels of dirt, plant seismometer spike firmly in the bottom of the hole with seismometer vertical, and cover with dirt, being careful not to tip seismometer. If the seismometer is to be set on rock, replace the spike with the three-pointed ring (wired to the basket), set upright on rock, and cover with dirt.

Note: It may be convenient to put the WWVB antenna (which has a 20-meter cable) somewhere along the 60-meter seismometer cable so the two will have a common run. Try to place cables where they will not be driven over or cut by machinery. Mark the seismometer plant with a small rock pile, red flag, etc. and ask the landowner to avoid walking near it more than necessary. You may wish to inform the landowner that the black cable carries only 1½ volts, the same as one flashlight battery, and the gray cable carries zero voltage. Both are harmless to children and animals, even if the latter chew through the cable. You could also explain that the entire station runs from a 12-volt battery. The power cord is only for a charger to keep the battery charged. Except for the power cord and charger, there is no 110-volt AC power anywhere in the system.

11. Connect external power cable (slim gray cable) from lid to pwr plug on recorder.

12. Connect output cable (thick gray cable) from lid to cH1 on recorder.

13. Switch WWVB on (in), ch.1 preamplifier in ch.1 main amplifier in. At this point, ignore noises of the empty tape drive starting and stopping, and ignore the display flashing rows of 0's, 1's, 2's, or 3's.

14. Open tape deck and brush or blow out dust. Using cotton-tipped swab (package in basket) dipped in isopropyl alcohol (bottle in basket), clean recording head. Then, with same swab, clean two tape guides, capstan shaft, and pinch roller. Do not dip swab in the bottle more than once.

15. Test WWVB. Connect cable from recorder REF by inserting the two pins on its end in WWVB TEST IN OUT with pin on red wire to IN. REF lamp should blink 1 pulse per second (the pulses will not be the same length, as they are displaying the WWVB time code). If

blinking is erratic, allow an additional two minutes for the receiver integrators to stabilize. If blinking is still erratic, raise and/or move antenna. If REF does not blink, be sure WWVB is on, check external-power cable for connection to lid and recorder, and check antenna cable for connection to lid (channel 2) and antenna. The BNC connection at the antenna is particularly vulnerable; it may be tightened with pliers.

16. Now that the WWVB receiver is operating, set the clock if it is incorrect or stopped, according to instructions given in Setting the clock.

17. Using 7½-minute USGS topographic sheet, locate building, fence corner, etc. nearest the seismometer. Using Brunton compass and tape measure from the located point to the seismometer, mark seismometer location directly on sheet, and also mark distance to reference on sheet (e.g., 253' N of NW corner of barn). Write serial number and date next to seismometer location, and write in preassigned station abbreviation. If station abbreviation is not preassigned, pick two letters for the nearest hamlet or village or other mapped feature, one letter for the survey area, followed by the number 1. E.g.: station near Jimtown, Wilson area survey, is JTW1. If, in the future, the exact seismometer location is reoccupied, it would again be JTW1. If a different site near Jimtown was occupied it would be JTW2.

18. Set seismic-background-noise level. Check to see that map is set as follows: LOW Hz - OUT, HIGH Hz - 30 GAIN - 60. Plug line from recorder REF IN into GAIN TEST by inserting the two pins into the two holes at the bottom of the amplifier, with the pin attached to the red wire in the green hole. Ignore switching off and on of tape deck and flashing rows of digits in display while setting gain. Increase gain by one 6 dB step and pause. Continue to do so until REF lamp first flashes; it will probably continue to flash every few seconds. Increase gain by one more 6 dB step. REF lamp should be flashing more than once per second. This indicates that the seismic noise is using nine bits of the 12-bit data word. Now decrease gain by five 6 dB steps. The noise is now peaking in about the fourth bit. Remove pins from GAIN TEST.

19. Hold rewound cassette with exposed tape (the open side where recording occurs) toward you, with tape wound on reel to your left. Put strip of masking tape across top of cassette and write on it the station, serial number, the word ON, day number, year, dB gain, dB. For example:

    JTW1/#230/ON288/1979/84 dB

20. Switch display to data; push reset switch up and release. Display now reads serial number, followed by event number (00 to start with), followed by a two-digit code for some recording parameters.

21. Insert tape cartridge with tape wound to left. It is not necessary to advance tape beyond clear leader, because the test event will do this.

22. Push trigger switch to test position and release. The tape deck should cycle through one event. During parts of the cycle the display will be all two's.

23. The display will now read 01 - ready for the first event (event 00 will always be regarded as a test event). Switch display to TIME, as the time may be of more interest to the homeowner than the serial number.

24. Close the tape-deck lid. Give the homeowner a copy of General Information about OGO Digital Seismographs. Station is now operating. At whatever time the homeowner may be asked to change the tapes, give him a copy of OGO Digital Seismographs - Changing Tapes.

25. Enter in the station log

STATION - SERIAL NO.
LOCATION - OWNER
TRIGGERING PARAMETERS - read from masking tape label on recorder.
Amplifier Parameters (high Hz, low Hz gain)
Time operating.

E.g.: JIMTOWN OK JTW1 #230
near Jimtown, Love Co. - Jane Doe's farm
.5"/200 - 18dB for 10 sec.
3 ch 100 SPS
high 30 low OUT gain 84 dB
Commence operation 267-1979

The log remains with the station. Each time any parameter is changed or repair made, it should be entered in the log. If in doubt about whether or not to enter any list of information in the log, decide by entering it.

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BIBLIOGRAPHIC DATA SHEET

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16. ABSTRACT *(200 words or less)*

Structure-contour maps of the top of the Viola Formation (Ordovician), base of the Pennsylvanian, and top of the Oswego Formation (Middle Pennsylvanian) were completed for the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles.

From October 1, 1978, to December 31, 1979, approximately 149 earthquakes in Oklahoma, Kansas, Nebraska, and nearby areas were located. Approximately 29 seismograph stations (19 NRC supported) were operational for the entire reporting period. Two additional stations, CAI in southwestern Iowa and GBO in eastern Oklahoma, became operational late in calendar year 1979.

Detailed gravity and magnetic studies were completed for the Kingfisher and Medford maxima, north-central Oklahoma. An aeromagnetic map was prepared for the Enid and Oklahoma City $1^{\circ} \times 2^{\circ}$ Quadrangles from NURE data. Seismological studies included (1) a microearthquake study near Wilson, Oklahoma, (2) frequency-magnitude evaluation of the Wilson microearthquake data, and (3) magnitude determinations from earthquake felt-area reports for 25 historical Oklahoma earthquakes.

17. KEY WORDS AND DOCUMENT ANALYSIS

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17b. IDENTIFIERS/OPEN-ENDED TERMS

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