Revised Instrumental Hypocenters and Correlation of Earthquake Locations and Tectonics in the Central United States

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1364

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Revised Instrumental Hypocenters and Correlation of Earthquake Locations and Tectonics in the Central United States

By DAVID W. GORDON

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1364

New determinations of hypocenters and magnitudes of instrumentally recorded earthquakes, 1931–1980, in the central United States, and an investigation of the association of seismicity with geologic structure in the region

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U. S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging-in-Publication Data

Gordon, David W., 1931-
Revised instrumental hypocenters and correlation of earthquake locations and tectonics in the central United States.

(Geological Survey professional paper ; 1364)
Bibliography: p.
Includes index.
Supt. of Docs. no.: I 19.16:1364
1. Earthquakes—Middle West—Location. 2. Earthquakes—Southern States—Location. 3. Earthquakes—Great Plains—Location. 4. Geology—Middle West. 5. Geology—Southern States. 6. Geology—Great Plains.
I. Title. II. Series.
QE75.P9 no. 1364 557.3 s 86-600412
[QE535.2.U6 [551.2'2'0977]

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

CONTENTS

ILLUSTRATIONS

TABLES

REVISED INSTRUMENTAL HYPOCENTERS AND CORRELATION OF EARTHQUAKE LOCATIONS AND TECTONICS IN THE CENTRAL UNITED STATES

By DAVID W. GORDON

ABSTRACT

Approximately 270 regionally recorded seismic events in the central United States have been relocated and the revised hypocenters have been correlated spatially with deep-seated basement structures. The events considered include all regionally recorded earthquakes with $m_b(L_g) \geq 3.0$ through 1980 with sufficient associated station data to warrant hypocenter recomputation.

Earthquake relocation has been accomplished by Joint Hypocenter Determination (JHD), a least-squares procedure that computes revised hypocenters and station travel-time corrections for a group of spatially related earthquakes simultaneously. Input data included phase arrivals taken from seismological bulletins or read on Worldwide Standardized Seismograph Network (WWSSN) film chips or paper seismograms from selected regional stations. The version of JHD computation used in this study includes P, P_g, S, and L_g phase data and weights derived from observed variances.

Tests of accuracy with respect to events having known or independently determined source coordinates indicate that the confidence regions associated with the relocated events are reasonable estimates of hypocenter accuracy. About 24 percent of the previously accepted epicenters differ from the revised epicenters by 0.2° or more in latitude or longitude. These old epicenters also lie outside the 95-percent-confidence ellipses associated with the new epicenters. Reasons for the discrepancies between the old and new epicenters could often be identified. In some cases the revised hypocenter represents the first electronic computer solution ever obtained for the event considered. Many of the original epicenters in the period through the 1960's were essentially macroseismic epicenters based on felt reports. Other epicenters changed significantly when new phase data were added to the solution. The revised hypocenters are better than the previously accepted ones because they are more accurate and because they are accompanied by uniformly determined error estimates.

Within the resolution of the estimates, the focal depths determined in this study agree with independently determined focal depths. The deepest reliable focal depths computed represent the Wabash Valley of southeast Illinois, where focal depths in the 20 to 25 km range were determined. Well-determined focal depths of 10 to 15 km were computed for shocks in the New Madrid Zone.

The relocated earthquakes were assigned $m_b(L_g)$ magnitudes taken from published sources or derived from amplitudes read on WWSSN film chips. Magnitudes published in seismological bulletins before 1973 overestimate central United States earthquakes by 0.3 magnitude units on the average. Comparison with lists of all known earthquakes indicates that the catalog of relocated earthquakes contains nearly all events with magnitude 3.5 or greater that have occurred since 1971.

Estimates of the focal depths of the relocated events suggest that significant earthquakes in the region have sources well below the Phanerozoic cover. Correlation of seismicity and tectonics in this study has emphasized ancient plate-tectonic elements that penetrate deeply into the crust. Approximately 83 percent of the known historic earthquakes in the region with total felt area of 20,000 sq km or more correlate spatially with paleorifts and other elements of a simplified model of basement tectonics in the craton. Most of the seismicity in the region is associated with complex paleorifts along the southern margin of ancestral North America. The revised epicenters in the New Madrid Zone converge on areas of high seismicity delineated by recent microearthquake locations.

The results of this investigation are consistent with the hypothesis that most significant intraplate earthquakes occur within zones of persistent crustal weakness that are favorably oriented with respect to the contemporary stress field.

INTRODUCTION

The principal objectives of this investigation are to redetermine the hypocenters of all regionally recorded earthquakes in the central United States and to examine possible spatial relationships between seismicity and tectonics in the region. The region of investigation, the central United States, is outlined in figure 1. The appendix contains the revised hypocenters of approximately 270 events, representing the time interval 1931 through 1980, that were relocated in this study.

Earthquake relocation has been accomplished by the Joint Hypocenter Determination (JHD) method (Douglas, 1967) using arrival times available in seismological bulletins or interpreted on seismograms. In the JHD method hypocenter coordinates and station travel-time corrections associated with a group of earthquakes and stations are computed simultaneously by the method of least squares. The modified version of the JHD method (Dewey, 1976) used in this study involves secondary phases (P_g, S, L_g) as well as the P-wave first arrivals.

In addition to the overall improved hypocenter accuracy derived from the use of the JHD approach,

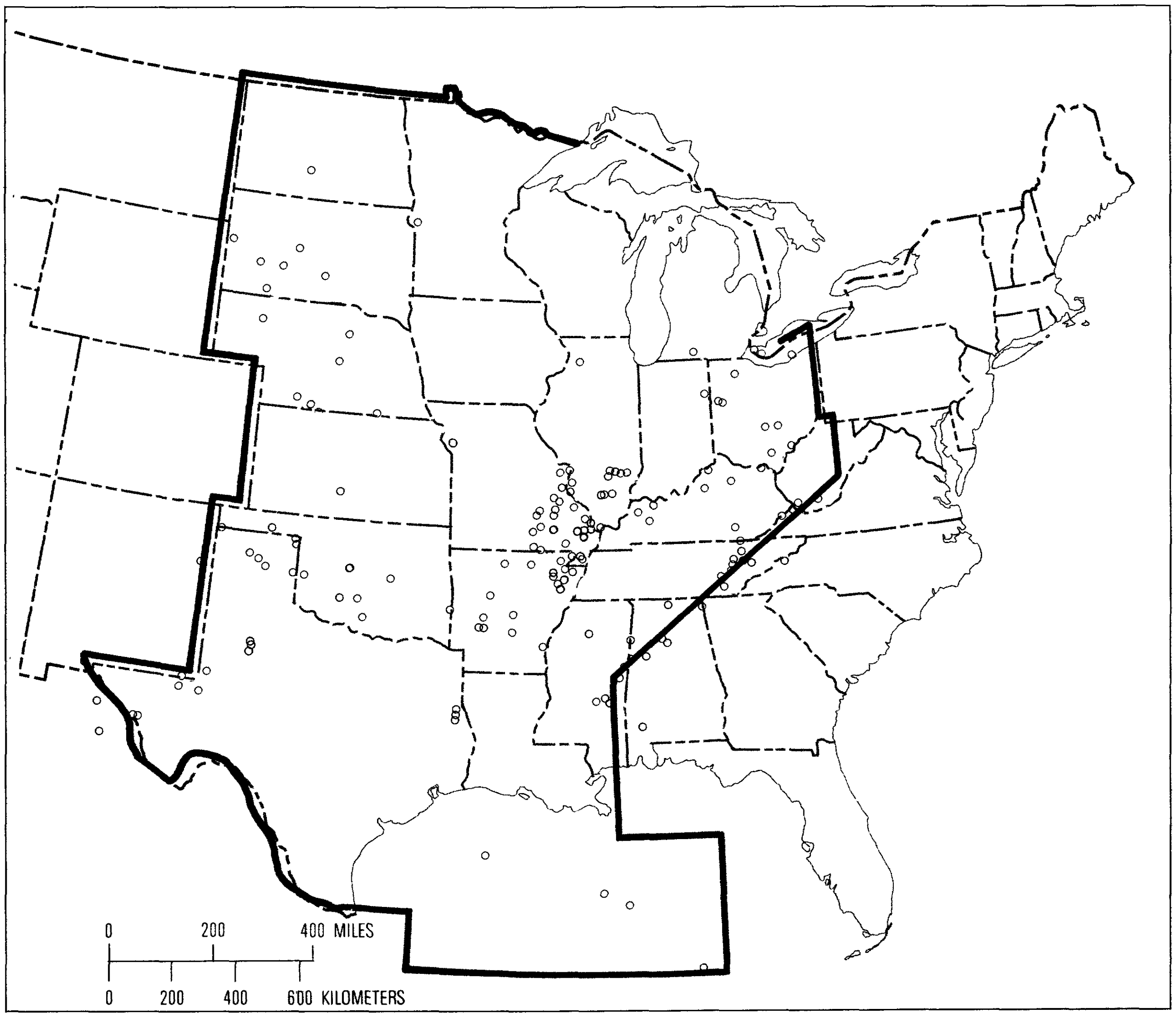


FIGURE 1.—The region of investigation and epicenters (circles) of relocated earthquakes ($m_b(L_g) \geq 3.0$) in the central United States. The heavy line denotes limit of study region.

several other factors suggest that many of the hypocenters previously listed in seismological bulletins need to be recomputed. In the era before electronic computation, instrumental epicenters in the central United States were usually determined by graphical techniques carried out with a subset of the available station data. As will be described later in this study, some of these graphical solutions apparently were adversely affected by taking felt reports into account. Some mislocations of Midcontinent earthquakes may also be attributed to the travel times used in the computations. Since the beginning of machine computation in the 1960's, most published epicenters of seismic events in the Midcontinent have been obtained using the standard travel-time curves of Jeffreys and Bullen (1940). These curves, which remain in general use today, represent worldwide averages and are not well suited to the central United States (Jordan and others, 1966; Nuttli and others, 1969; Stauder and Nuttli, 1970).

An expected spinoff of this investigation is new insight into the probable locations of historic earthquakes in the region. Although destructive earthquakes are relatively rare in the central United States, strong earthquakes have been known to occur in the region (Docekal, 1970; Coffman and von Hake, 1973; Nuttli, 1979); for example, in 1811–1812 three great earthquakes struck the then partially settled area surrounding New Madrid, Mo., in the central Mississippi Valley. Other strong shocks in the New Madrid area include the Memphis, Tenn., earthquake of 1843 and the Charleston, Mo., earthquake of 1895. Other apparent centers of historic seismicity include Anna in western Ohio, Manhattan in northeastern Kans., and El Reno in central Okla.

Although magnitudes of various types have been routinely assigned to central United States earthquakes since the 1960's, many of the previously determined magnitudes are unreliable because they were computed with the use of inappropriate attentuation functions (Nuttli, 1973). As a supplementary objective of this study, Nuttli magnitudes ($m_b(L_g)$) or equivalent magnitudes will be determined for as many as possible of the events considered.

All earthquake intensities mentioned in this paper refer to the Modified Mercalli (MM) intensity scale of 1931 (Wood and Neumann, 1931).

The results of this study, the relocated earthquakes and accompanying error estimates, will also be used to explore possible relationships between seismicity and tectonics in the region. Geologically ancient, remnant plate-tectonic features in the Precambrian basement will be emphasized in the correlation attempts.

SEISMIC SOURCE ZONES

To apply the JHD method in this study the region was divided into the 14 seismic source zones that are outlined in figure 2 and described in the appendix. Some of these zones, which have been modified from zones defined by Nuttli and Herrmann (1978), are closely related to tectonic divisions, whereas others simply refer to geographic areas. Three of the zones, the Ohio, Southern Appalachian, and Alabama Zones, which are located on the eastern side of the region, were established by J. W. Dewey and D. W. Gordon (unpub. report, 1983) to relocate eastern United States earthquakes. The calibration-station mode of the JHD method, which will be explained in a subsequent section (see *Methods*), was used to relocate the epicenters associated with the zones outlined in figure 2.

Subzones containing closely spaced epicenters within the larger source zones also are identified in figure 2. Events associated with these subzones, which were often elements of aftershock sequences or earthquake swarms, were relocated with the use of the calibration-event option of the JHD method, which also will be explained in a later section (see *Methods*). The names of the subzones refer to nearby towns or villages.

The geographic codes, which accompany the hypocenters in the catalog (see appendix), designate zones or subzones corresponding to groups of events considered in separate JHD solutions.

DATA SOURCES

The principal sources of station arrival times used in this investigation were the bulletins of the International Seismological Centre (ISC) and its predecessor, the International Seismological Summary (ISS); bulletins of the Bureau Central International Seismologique (BCIS); *Preliminary Determination of Epicenters* (PDE's), *Earthquake Data Reports* (EDR's), and other seismological data compiled by the National Earthquake Information Service and its predecessors; and seismological bulletins and data from the files of Saint Louis University. The PDE's and EDR's are distributed to seismologists and others by the National Earthquake Information Center, U.S. Geological Survey (Derr, 1977). Supplementary phase data were read on film chips from stations of the Worldwide Standardized Seismograph Network (WWSSN) and from original seismograms obtained from selected stations, including Fayetteville, Ark., Lawrence, Kans., Manhattan, Kans., and Bloomington, Ind.

Although the first seismograph stations in the central United States were installed in the late 1900's (Poppe, 1979), due to the low station density and low instrumental magnifications, only a very few earthquakes with magnitude less than 4.0 were located instrumentally until the 1960's. The deployment of the WWSSN, which eventually included 10 stations in the study region, coincided with a dramatic increase in the number of instrumentally located earthquakes in the region after 1961. The locations of conventional seismograph stations that were most useful in this study are shown in figure 3. These stations belong to an informal network of individual stations sponsored by universities, state agencies, and the Federal Government, which cooperate in earthquake investigation. Although new stations were installed and old stations were discontinued throughout the entire time interval considered, the stations plotted in the figure are most representative of the period 1960 to 1974.

Data recorded by microearthquake networks deployed in the central United States in the 1970's also made a significant contribution to this study. Summaries of the data recorded by the networks have been published in the annual *United States Earthquakes* since 1978 (see for example, Bollinger, 1980). Regionally recorded events that occurred within microearthquake networks were included in JHD solutions where it was feasible to do so. This was done because it was assumed that the increase in hypocenter accuracy associated with the close-in microearthquake stations would improve the reliability of travel-time corrections computed for more distant stations.

Figure 4 shows the locations of the microearthquake networks considered. The first network to be established, the Central Mississippi Valley Network (CMVN), was deployed in the New Madrid Zone in 1974 and was enlarged to cover the Wabash Zone in 1978

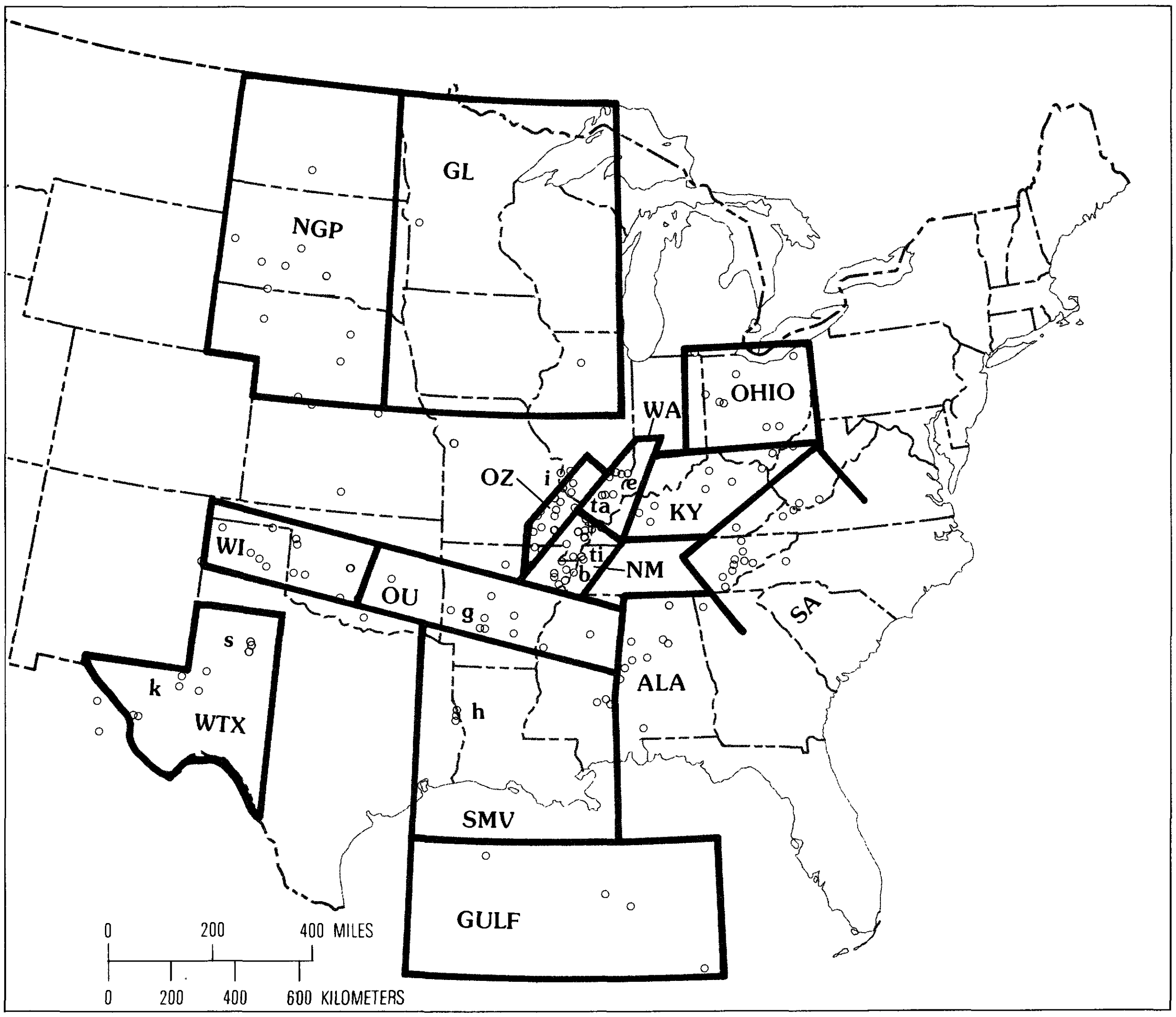


FIGURE 2.—Seismic source zones, subzones, and epicenters (circles) of relocated earthquakes ($m_b(L_g)\geq 3.0$). In alphabetical order, seismic zones (codes in upper case) and subzones (codes in lower case) are as follows: Alabama (ALA), Blytheville (b), Eldorado (e), Great Lakes (GL), Gulf (GULF), Gurdon (g), Hemphill (h), Ironton (i), Kentucky (KY), Kermit (k), New Madrid (NM), Northern Great Plains (NGP), Ohio (OHIO), Ouachita (OU), Ozark (OZ), Snyder (s), Southern Appalachian (SA), Southern Mississippi Valley (SMV), Tamms (ta), Tiptonville (ti), Wabash (WA), West Texas (WTX), Wichita (WI). Heavy lines denote zone boundaries. Subzone codes are placed close to associated epicenter groups.

(Stauder and others, 1976; Stauder, 1982). The Tennessee Earthquake Information Center operates the Memphis Area Regional Seismic Network (MARSN) and the Southern Appalachian Regional Seismic Network (SARSN) (Nava and Johnston, 1984; Johnston and others, 1985). Networks in Oklahoma (OGSN), Kansas (KGSN), and Nebraska (NGSN) monitor microearthquake activity along the Midcontinent gravity high and the Nemaha uplift (Burchett and others, 1983). The Central Minnesota Seismic Array (CMSA) and the Michigan-Wisconsin Seismic Network (MWSN) have detected minor seismicity in the vicinity of the northern part of the Midcontinent gravity high (Mooney, 1981; Frantti, 1982). Jackson and others (1982) have discussed results from the Western Ohio Seismic Array (WOSA), which was deployed near Anna, Ohio, in 1977. The Kermit Array (KA) was installed in West Texas in 1975 to investigate possible correlation between seismicity and secondary recovery of oil and gas (Keller and others, 1981).

United States Earthquakes provided most of the intensity data discussed in this study. The U.S. Coast and Geodetic began publication of this annual in 1928. The U.S. Geological Survey assumed primary responsibility for *United States Earthquakes* in 1973.

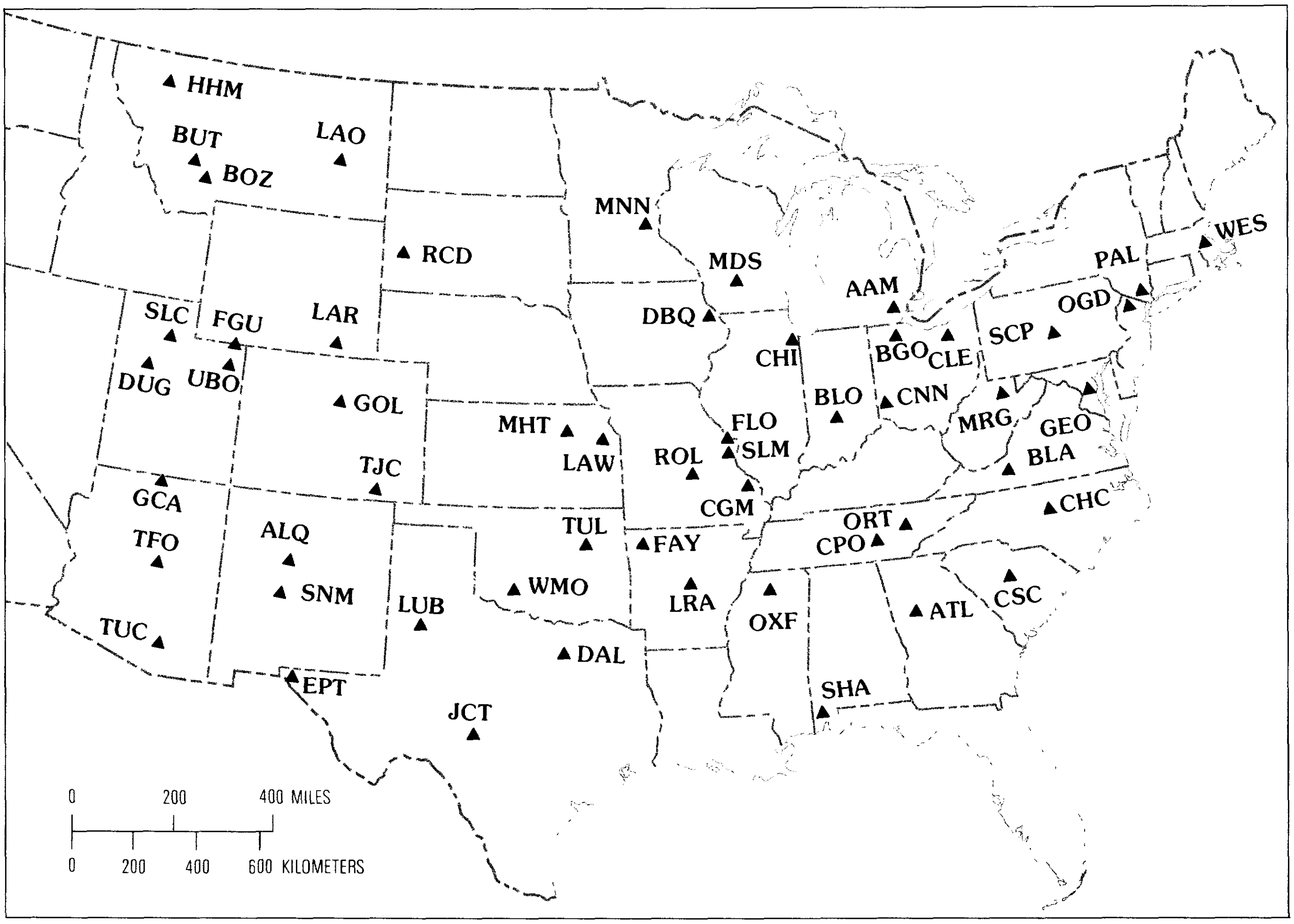


FIGURE 3.—Representative seismograph stations (triangles) used in the relocation of central United States earthquakes (1931–80). The three-letter station designations refer to the standard U.S. Geological Survey station codes (Presgrave and others, 1985).

ACKNOWLEDGMENTS

Part of the research reported in this paper was performed in the preparation of a Ph.D. dissertation submitted to Saint Louis University (Gordon, 1983). The cooperation of the many individuals within the U.S. Geological Survey and Saint Louis University, who made this joint venture possible, is gratefully acknowledged. Special thanks are extended to R. B. Herrmann, O. W. Nuttli, and Rev. William Stauder, S.J., of the university for their guidance and counsel.

Many aspects of this investigation were discussed with colleagues at the U.S. Geological Survey. J. W. Dewey introduced the author to Joint Hypocenter Determination and some of the more subtle details of hypocenter computation.

J. W. Dewey, W. H. Diment, and J. N. Taggart reviewed this original manuscript and suggested important revisions that have been made to the paper.

The author also wishes to thank the station directors, including Henry Beck (MHT), R. H. Konig (FAY), Judson Mead (BLO), E. F. Pawlowicz (BGO), and G. H. Rothe (LAW), who cooperated in this project by loaning original seismograms of selected events.

TECTONICS

Most investigators now accept the preexisting-zones-of-weakness hypothesis as a working hypothesis to explain intraplate seismicity (Sbar and Sykes, 1973; Hinze and others, 1977; Sykes, 1978; Braile, Hinze and others, 1982). This hypothesis states that earthquakes in intraplate regions, such as the central United States, represent reactivation of preexisting zones of persistent crustal weakness that are favorably oriented with respect to the present-day stress field. Basement structure initiated during ancient plate-tectonic regimes will

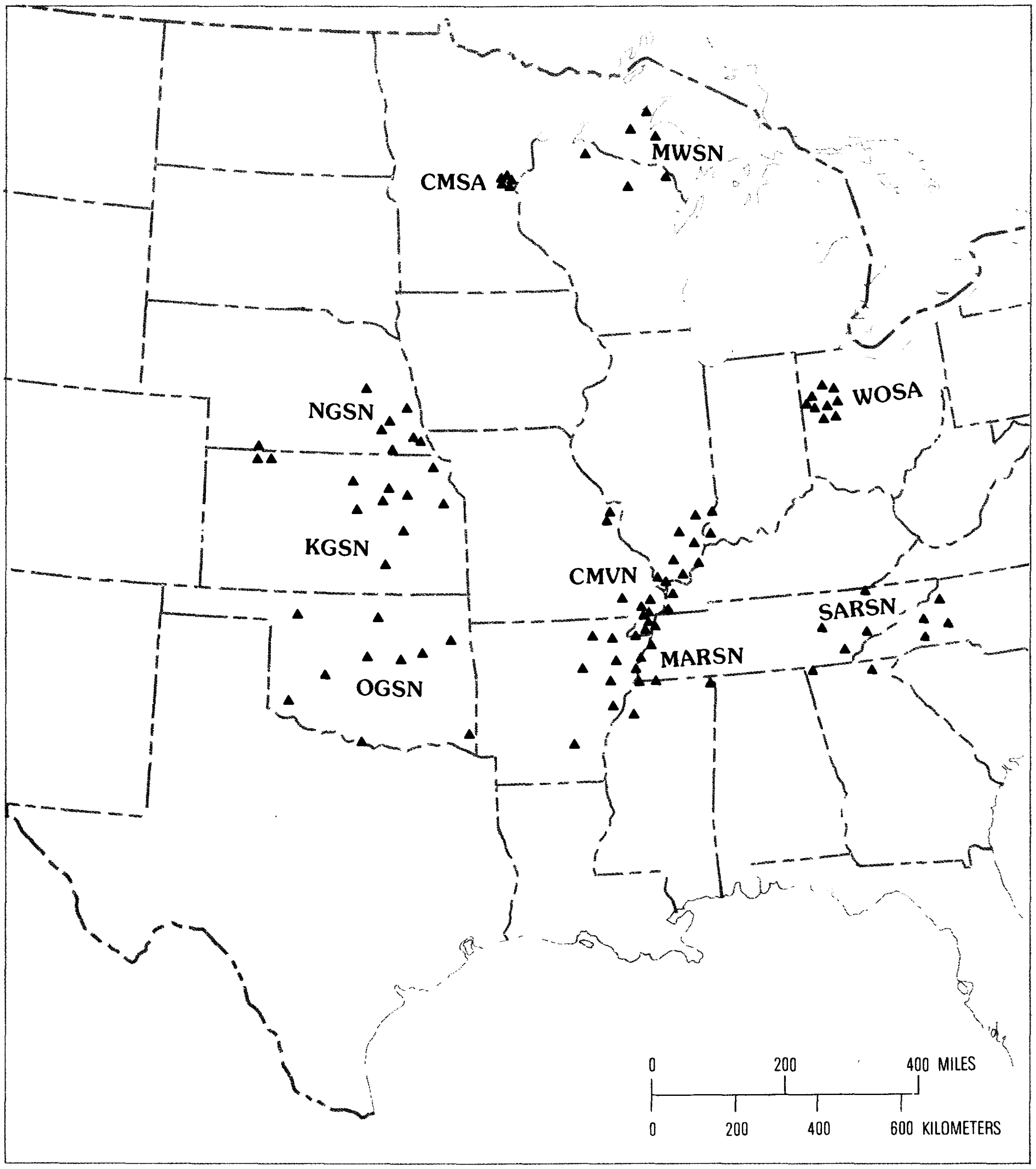


FIGURE 4.—Selected microearthquake networks in the central United States. Central Minnesota Seismic Array (CMSA). Central Mississippi Valley Network (CMVN). Kansas Geological Survey Network (KGSN). Memphis Area Regional Seismic Network (MARSN). Michigan-Wisconsin Seismic Network (MWSN). Nebraska Geological Survey Network (NGSN). Oklahoma Geological Survey Network (OGSN). Southern Appalachian Regional Seismic Network (SARSN). Western Ohio Seismic Array (WOSA). Triangles designate individual seismograph locations.

be emphasized in this section of the paper because these structures imply deep-seated inhomogeneity and possible crustal weakness (Walper, 1976; Hinze and others, 1980; Hamilton, 1981). Most of the revised epicenters are located within the Midcontinent stress province of Zoback and Zoback (1980, 1981), which they have characterized as a compressive stress domain with the greatest principal stress axis horizontal and oriented northeasterly to easterly.

Figure 5 is a sketch map of relatively shallow structures in the central United States, primarily basins and uplifts in the Phanerozoic sedimentary section, that have been revealed by conventional surface and subsurface mapping (Cohee, 1961; Bayley and Muehlberger,

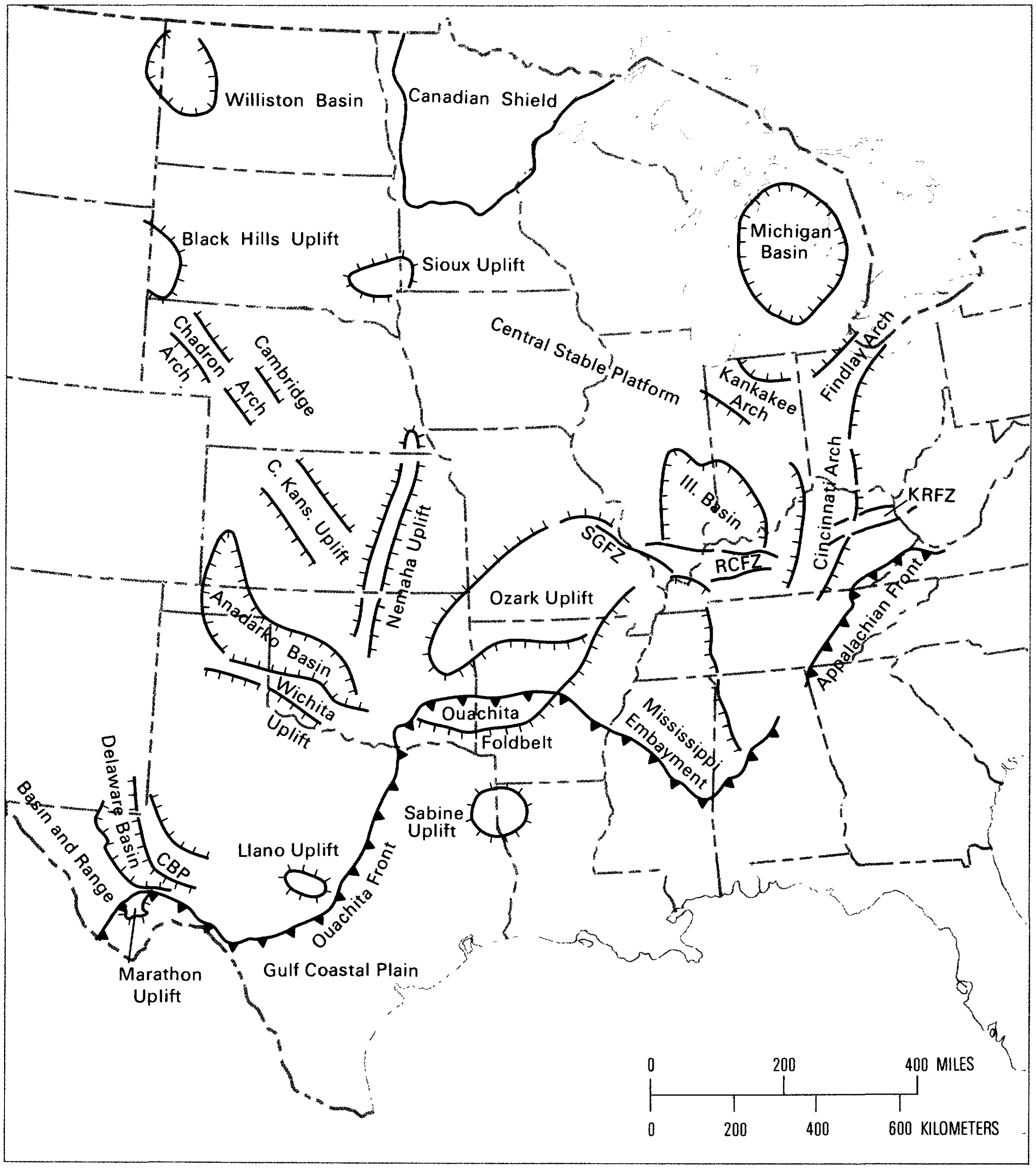


FIGURE 5.—Selected Phanerozoic basins, uplifts, and fault zones in the central United States. Hachured lines outline basins and uplifts. Lines with sawteeth delimit major Paleozoic thrust faulting and folding. Thick lines designate high-angle fault zones. Central Basin platform (CBP). Kentucky River fault zone (KRFZ). Rough Creek fault zone (RCFZ). Ste. Genevieve fault zone (SGFZ). Generalized after Cohee (1961) and Eardley (1951).

1968; King and Beikman, 1974). The Central Stable Platform or Craton, a major tectonic province, occupies the northern three-fourths of the region. This province is characterized by gently dipping Phanerozoic strata overlying the Precambrian basement. Episodes of mild deformation during Phanerozoic time have produced broad, gentle undulations in the Precambrian basement and in the overlying Phanerozoic section, which has an average thickness of about 1.0 km. Structural downwarps include the Illinois and Michigan basins and the Anadarko basin of western Oklahoma, the deepest basin in the region with a maximum depth of about 10 km. Positive structural elements include the Ozark and Sioux uplifts, where Precambrian rocks crop out. The

Nemaha uplift, a particularly sharp, relatively narrow uplift which extends north-northeasterly from central Oklahoma to southeast Nebraska, has been interpreted as a buried, granitic mountain range uplifted in late Paleozoic time (Eardley, 1951; King, 1951). A major east-west system of high-angle faults, composed of the St. Genevieve, Rough Creek, and Kentucky River fault zones (SGFZ, RCFZ, and KRFZ), crosses east-central Missouri, southern Illinois, and northern Kentucky. Although most of the faults in this system exhibit normal-type displacements, reverse and strike-slip faulting have also been recognized. King (1951) indicated that major movement on these faults took place between the late Paleozoic and late Mesozoic. The Gulf Coastal Plain in the southern part of the region is composed of Paleozoic basement rocks overlain by a wedge of upper Mesozoic and Cenozoic sediments which thicken towards the seacoast and have a maximum thickness of about 5 km. Listric normal faults with strikes sub-parallel to the coastline characterize the Coastal Plain. The Mississippi Embayment, an anomalous northern extension of the Gulf Coastal Plain, is a structural trough, which has subsided about 800 m during the last 60 million years. The Ouachita front marks the northern limit of the Ouachita foldbelt, which is concealed beneath younger, Gulf Coastal Plain sediments over most of its length. The exposed parts of the foldbelt, the Ouachita Mountains of Arkansas and Oklahoma and the Marathon uplift of west Texas, correspond to the Valley and Ridge section of the Appalachian foldbelt.

The best estimates of focal depth (Herrmann, 1979) and the general absence of historic surface faulting suggest that most significant Midcontinent earthquakes occur in the crystalline basement. Figure 6 is an interpretation of Midcontinent basement tectonics. The figure is schematic and no attempt has been made to indicate structural details or age relationships. The structures shown represent proposed paleorifts, wrench fault zones, and suture zones related to plate-tectonic processes involving the opening and closing of ancient oceans. Although the nature of the origin, geologic age, and deformational history of some of these plate-tectonic remnants is somewhat uncertain, most of these elements have distinct gravity and magnetic signatures that imply that the sources of the anomalies extend well into the crust. Many of these plate-tectonic remnants represent structures formed during the Precambrian that have been reactivated during Phanerozoic periods of tectonism. This reactivation, which is often marked by renewed volcanism and faulting, suggests that these structures coincide with zones of persistent crustal weakness.

The northeast-striking Colorado lineament (CL), possibly the oldest feature shown in figure 6, crosses the northwest quarter of the study region. This remarkably long lineament, which extends southwesterly across Colorado and into Utah and Arizona, may represent a continental-scale, middle Precambrian wrench fault or a collision boundary between two tectonic plates (Warner, 1978; Muehlberger, 1980). The Colorado lineament partly coincides with the Transcontinental arch, and it may be tectonically related to this well-known, broad upwarp which was formed in the early Paleozoic and extends from New Mexico to Minnesota. However, some authorities regard the extension of the Colorado lineament across the Great Plains as equivocal (see *Seismotectonics of the Northern Great Plains Zone*).

The Missouri gravity low (MGL) is an elongate, northwest trending, basement structure characterized by negative gravity anomalies of 15 to 30 milligals (Arvidson and others, 1982; Guinness and others, 1982). As shown in figure 6, this feature begins in southeast Nebraska and northeast Kansas, crosses Missouri from northwest to southeast, and continues into the bootheel section of Missouri where it intersects the Reelfoot rift (RR). The MGL may correspond to the failed arm of a Precambrian rift system or to an ancient transcurrent fault system which has been reactivated during various geological episodes (Arvidson and others, 1982; Guinness and others, 1982). Paleozoic reactivation is marked by the Pascola arch that coincides with the MGL in the bootheel section (Ervin and McGinnis, 1975).

The most prominent geophysical anomaly in the central United States, the Midcontinent gravity high (MCGH), extends south-southwesterly from eastern Minnesota to central Kansas, a distance of more than 1000 km. Most researchers attribute this anomaly to an aborted Keweenawan or middle Proterozoic continental rift system, analogous to the modern Red Sea rift (King and Zietz, 1971; Ocola and Meyer, 1973; Chase and Gilmer, 1973; Halls, 1978). Detailed geophysical investigations of prominent sections of the MCGH indicate that the axial zone of the anomaly coincides with a structural horst (Mooney and others, 1970). The apparent left-lateral offsets of the MCGH may have been inherited from a preexisting fracture pattern, or they may represent incipient transform faults of an aborted continental rift system, or they may reflect wrench faulting that occurred later in geologic time. Halls (1978) suggested that the MCGH is the western leg of a more extensive rift system, marked by gravity highs, that continues to the east into Michigan, Indiana, Ohio, Kentucky, and Tennessee. One of these anomalies, the Mid-Michigan geophysical anomaly (MMGA), coincides with a basement trough filled with clastic Keweenawan red beds and basic igneous rocks (Hinze and others, 1975; Brown and others, 1982). The Fort Wayne geophysical anomaly (FWGA), a similar gravity and

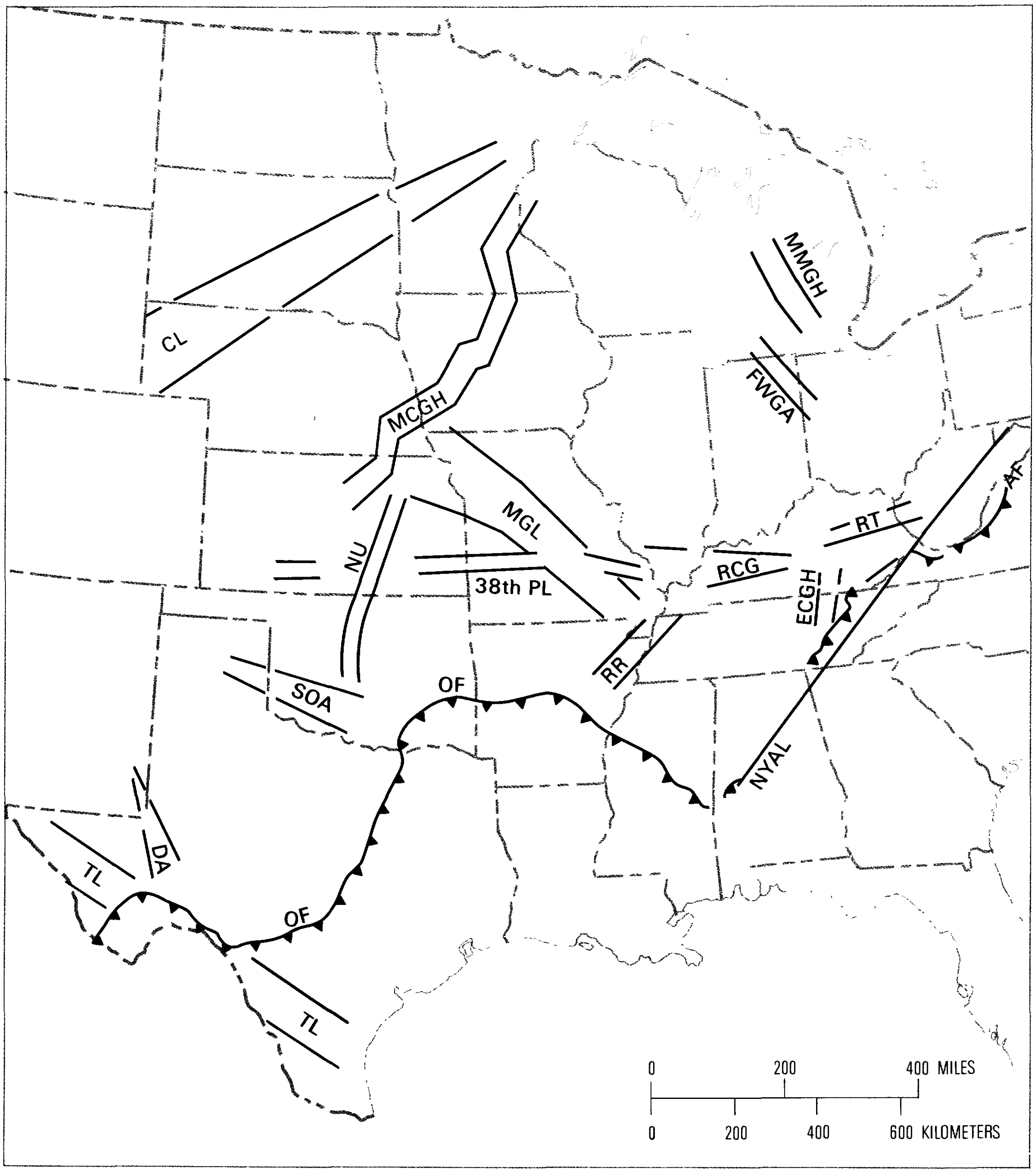


FIGURE 6.—Selected ancient plate-tectonic elements in the central United States. Thick lines indicate the outline or trend of major tectonic elements. Lines with sawteeth delimit major Paleozoic thrust faulting and folding. Appalachian front (AF). Colorado lineament (CL). Delaware aulacogen (DA). East Continent gravity high (ECGH). Midcontinent gravity high (MCGH). Missouri gravity low (MGL); Mid-Michigan gravity high (MMGH). Nemaha uplift (NU). New York—Alabama lineament (NYAL). Ouachita front (OF). Rough Creek graben (RCG). Reelfoot rift (RR). Rome trough (RT). Southern Oklahoma aulacogen (SOA). Texas lineament (TL). Thirty-eighth Parallel lineament (38thPL).

magnetic high in northeast Indiana, and the East Continent gravity high (ECGH) in Kentucky and Tennessee may also reflect Keweenawan rifting (Ammerman and Keller, 1979; Keller and others, 1982; McPhee, 1983).

King and Zietz (1978) have identified a northeast trending, magnetic lineament called the New York-Alabama lineament (NYAL) in the basement beneath the east side of the region outlined in figure 6. As originally defined, this lineament passed through Alabama, Tennessee, Kentucky, West Virginia, Pennsylvania, and

New York. However, Diment and others (1980) suggested that the lineament does not continue to the northeast beyond southern Pennsylvania.

Figure 6 also shows several deep-seated structural troughs in the basement of the Midcontinent, which have been interpreted as aulacogens or the failed arms of triple junctions (Burke and Dewey, 1973; Hoffman and others, 1974). These structures are the Delaware aulacogen (DA) of West Texas, the Wichita or Southern Oklahoma aulacogen (SOA), and the Reelfoot rift (RR) in the central Mississippi Valley (Ervin and McGinnis, 1975; Walper, 1977; Burke, 1980). The proposed aulacogens are associated with rifting that preceded the opening of the Paleozoic Atlantic Ocean along a line approximately parallel to the trend of the Ouachita foldbelt. Walper (1975) has indicated that the Delaware aulacogen coincides spatially with the Delaware basin and the Central Basin platform in West Texas. Hoffman and others (1974) and Wickham (1978) have discussed the Southern Oklahoma aulacogen from its origin in the late Precambrian through major deformation in the late Paleozoic. Ervin and McGinnis (1975) suggested that the Reelfoot rift formed initially in the late Precambrian and that major subsidence followed reactivation of the rift in the late Mesozoic. Kane and others (1981) have delineated a downdropped block in the magnetic basement, the Mississippi Valley graben, which is probably a remnant of the Reelfoot rift.

Heyl (1972) and Lidiak and Zietz (1976) have described a remarkable zone of wrench faulting in the Precambrian basement, the 38th Parallel lineament (38thPL). This feature, which is marked by magnetic anomalies, faults that penetrate basement rocks, small igneous intrusions, and changes in trends of crossing structures, can be traced across the central and eastern United States. Figure 6 shows only the western part of this lineament, the section west of the Mississippi River. The eastward continuation of the lineament coincides with the Rough Creek graben (RCG) and the Rome trough (RT), which are sediment-filled depressions in the Precambrian basement in Kentucky and West Virginia (Ammerman and Keller, 1979; Soderberg and Keller, 1979).

From the plate-tectonic viewpoint, the Ouachita front (OF) represents late Paleozoic convergence of North American with Africa-South America (Keller and Cebull, 1973; Wickham and others, 1976; Hinze and others, 1980). Deformation accompanying this continental convergence also formed mountain ranges in areas such as the Southern Oklahoma aulacogen and the Nemaha uplift.

The Texas lineament (TL) is a zone of structural discontinuity 100–150 km wide that extends northwesterly across western Texas and continues across southwest New Mexico, through Arizona, and into Nevada. Although some geologists have proposed that the Texas lineament is a geologically ancient, continental-scale, wrench-fault system, its origin is controversial (Muehlberger, 1965; King, 1969; Wiley and Muehlberger, 1971; Warner, 1978).

METHODS

The Joint Hypocenter Determination method is an extension of the Geiger (1910) or single-event method of hypocenter estimation (Douglas, 1967; Dewey, 1971; Dewey, 1972). In the JHD approach, data from a group of events and a suite of stations is inverted in one simultaneous least-squares solution to obtain the hypocenter coordinates of the events considered and the station corrections to the travel-time tables. The station corrections are estimates of the differences between real source-to-station travel times and theoretical travel times for each phase at each station. In this investigation travel-time corrections called station-phase adjustments were computed for the P, P_g, S, and L_g phases (Dewey, 1976). The application of Joint Hypocenter Determination in this study followed the JHD methods developed by Dewey (1983) to relocate regionally recorded events. Only a brief outline of these procedures, which were fully described in a previous paper by Gordon (1983), will be given here.

TRAVEL TIMES

The P-wave and S-wave travel times used in hypocenter recomputation were derived from a composite, spherical earth model specified by Dewey and Gordon (1984). The upper 246 km of this velocity model is identical to the crustal and upper mantle model by Nuttli and others (1969) representing the central United States. This model assumes a 20-km-thick upper crust with a compressional velocity of 6.15 km/s, overlying a 20-km-thick lower crust with a compressional velocity of 6.70 km/s, and a sub-Moho velocity of 8.18 km/s. The corresponding shear-wave velocities are 3.50 km/s in the upper crust, 3.67 km/s in the lower crust, and 4.68 km/s below the Moho. The remainder of the composite model, beginning at a depth of 246 km, corresponds to the average earth model QM2 by Hart and others (1977). The secondary phases P_g and L_g, which were also considered in the computations, were each assigned zero time intercepts and phase velocities of 6.2 km/s and 3.6 km/s, respectively.

WEIGHTS AND CONFIDENCE REGIONS

The weights assigned in the JHD/JED computations are the product of two factors. The first factor is a quantity inversely proportional to the square root of the assumed variance of the observation. The second factor is a function that minimizes weights associated with extreme residuals by the method of uniform reduction (Bolt, 1960; Dewey, 1971). To estimate variances the observations are placed in separate weight classes defined on the basis of phase type and epicentral distance. Although the observations that make up an individual weight class represent different stations and events, it is assumed that all of the observations in the weight class have a common variance. For the first two iterations of the JHD/JED computations, provisional variances are assigned to each weight class. After the second iteration, the weighting factors are modified by taking into account the actual sample variance associated with each weight class. These same sample variances are then used in the third and all subsequent JHD/JED iterations. The weight classes considered in this study are identified in table 1.

Two measures of hypocenter precision, the epicenter ellipse and the depth axis (Dewey and Gordon, 1984), which were both derived from the 90-percent-confidence ellipsoid on the hypocenter coordinates (Evernden, 1969; Jordan and Sverdrup, 1981), are specified in the earthquake catalog (appendix). The epicenter ellipse is defined as the elliptical projection of the 90-percent-confidence ellipsoid on the earth's surface. Dewey and Gordon (1984) have pointed out that this epicenter ellipse may cover some computed hypocenters that lie outside the 90-percent ellipsoid, and that it actually closely approximates the 95-percent-confidence ellipse on the epicenter coordinates. Therefore, this epicenter ellipse will be associated with the nominal 95-percent-confidence region in the remainder of this paper. The depth axis, the steepest axis of the 90-percent-confidence ellipsoid, is a rough measure of focal depth precision. A refined measure of focal depth precision, the confidence interval on the depth coordinate, is used in a later section (see *Hypocenter Accuracy* and table 4). This confidence interval is defined as the projection on the vertical of the semi-length of the steepest axis (the depth axis) of the 90-percent-confidence ellipsoid, multiplied by 0.78 to make the interval approximately equivalent to the 95-percent level of confidence (J. W. Dewey and D. W. Gordon, unpub. report, 1983). In this later section, confidence limits of events having independently known coordinates are used to examine the question of possible bias associated with the recomputed hypocenters.

COMPUTATIONAL PROCEDURES AND OPTIONS

A two-step computational procedure was followed to obtain the revised earthquake locations listed in the appendix. First, a variation of the Joint Hypocenter Determination method called Joint Epicenter Determination (JED), in which focal depths are restrained throughout the computations, was used to compute station-phase travel-time corrections and to estimate weight class variances for each seismic source zone. In the second step, final hypocenters were computed using a single-event program that incorporated the travel-time corrections and weights generated by the JED runs.

Joint Epicenter Determination eliminates computational difficulties that arise from poor depth resolution in JHD computations; for example, the entire JHD solution becomes unstable if the focal depth of one event goes negative. In the JED approach focal depths may be held to independently estimated values or to an assumed mean focal depth representing the seismic zone. It is also necessary to stabilize JHD/JED solutions by restraining some of the unknowns, which are not all independent (Dewey, 1978; Herrmann and others, 1981). This stabilization was accomplished in this study by the use of the calibration-station option or the calibration-event option. The calibration-station option, the principal mode of the JHD/JED computations carried out in this study, was specifically developed to relocate regional earthquakes in zones of diffuse seismicity (Dewey, 1978). To obtain stable JHD/JED solutions in the calibration-station option, station-phase corrections representing epicentral distances less than a predetermined calibration distance (Δ_0) are held to zero values. Station-phase corrections corresponding to epicentral distances greater than the calibration distance, which was usually set at 2.0° in this study, were computed. The calibration-event option, the form of JHD/JED computation initially applied to relocate closely spaced groups of teleseisms, refers to JHD/JED computations performed with the coordinates of one event held constant (Dewey, 1971; Dewey, 1972).

The revised earthquake hypocenters were determined by the sequential application of two computer programs, JHD77 and SE77, written for the Honeywell Multics computer. The first stage of the data processing was performed by the JHD77 program, which embodies the JHD/JED method. Input to the JHD77 program may include arrival-time data from as many as 15 seismic events. A maximum of 100 station-phases may be considered in each JHD77 run. Although the output from JHD77 runs includes hypocenter coordinates, the primary purpose of these runs was to

TABLE 1.—*Weight classes and provisional variances*

Weight class	Phase type	Distance range	Provisional variance (sec^2)	Typical observed variance (sec^2)
1..........	P	$0° \leq \Delta \leq \Delta_o$	1.0	0.5
2..........	P	$\Delta_o < \Delta_{ave} \leq 5°$	1.0	0.7
3..........	P	$5° < \Delta_{ave} \leq 20°$	10.0	3.0
4..........	P	$20° < \Delta_{ave}$	10.0	2.5
5..........	S	$0° \leq \Delta \leq \Delta_o$	10.0	3.0
6..........	S	$\Delta_o < \Delta_{ave} \leq 5°$	100.0	6.0
7..........	S	$5° < \Delta_{ave}$	100.0	9.0
8..........	P_g	$0° < \Delta_{ave} < 5°$	100.0	3.5
9..........	P_g	$5° < \Delta_{ave} \leq 10°$	100.0	11.5
10..........	L_g	$0° < \Delta_{ave} \leq 5°$	100.0	9.5
11..........	L_g	$5° < \Delta_{ave} \leq 10°$	100.0	8.0

Δ = Epicentral distance of an individual observation.

Δ_o = Calibration distance, usually 2°, maximum distance bound of calibration station-phases.

Δ_{ave} = Average epicenter distance associated with a given station-phase.

P = Compressional wave associated with the first arrival.

S = Transverse wave corresponding to the P first arrival.

P_g = Secondary phase with an apparent velocity of 6.2 km/s.

L_g = Secondary phase with an apparent velocity of 3.6 km/s.

estimate station-phase adjustments and variances. These estimates of travel-time corrections and variances then become input in the second stage in the data processing, computation of final hypocenters by the single-event program SE77.

Preliminary data processing using JHD77 in the calibration-station mode involved an inventory of the available station-phases, assignment of station-phases to weight classes, and the selection of the calibration distance Δ_0. The choice of Δ_0, which marks the upper distance bound of the stations associated with zero travel-time corrections, depended on the number and azimuthal distribution of the calibration station-phases. The selection criteria for $\Delta_0$which may be 2°, 3°, or 5°, require a minimum of 25 observations with epicentral distance $\Delta < \Delta_0$ representating an azimuthal spread of more than 180°. JHD77 computer solutions were carried out in the JED or fixed-depth mode with the focal depths of most events restrained to 5.0 km. Exceptions were known or suspected explosions, which were computed with zero depth, and events held to focal depths determined by the analysis of surface-wave-amplitude spectra (Herrmann, 1979). Several preliminary JED runs were necessary to edit the input data. Corrections involved such items as whole-minute errors in arrival times and revision of phase designations. The most common change-of-phase type of correction was to reinterpret, as L_g, phases that had been reported as S in the bulletins. As part of the editing process, weight classes represented by fewer than 10 readings were combined with other weight classes. Eight iterations were performed in each JHD/JED run. Epicenter coordinates seldom changed by more than 0.01° for the last few iterations.

The calibration-event method was applied to further refine the hypocenters of events in certain selected subzones characterized by closely spaced earthquakes, where at least one of the hypocenters was known or could be estimated relatively precisely. The nine selected subzones, which are designated by the names of nearby towns or cities, are shown in figure 2 and identified in the appendix. The subzones selected included subzones represented by aftershock series or earthquake swarms, and areas, such as the Mississippi Valley in the vicinity of New Madrid, covered by recently deployed microearthquake networks. For the cases considered, the results obtained by the calibration-event/single-event procedure were generally better than those originally obtained by the calibration-station/single-event sequence. For example, the calibration-event runs reduced the scatter exhibited by the epicenters of aftershock series and earthquake swarms. In the case of subzones covered by local networks, the calibration-event procedure led to more precise hypocenters.

The final hypocenters listed in the appendix were computed by the single-event mode with the use of program SE77. Input to this program consists of provisional hypocenters, associated phase data, and the travel-time corrections and estimated variances generated by the previous JHD77 runs. In addition to the subset of events used in the JED runs, all remaining events within the seismic zone or subzone considered were relocated by SE77 runs at this time. The first six iterations of the SE77 computations were carried out with depth fixed. Then eight additional iterations were carried out with depth as a free parameter. If focal depth computed by a particular free-depth iteration was negative, focal depth was held at a small positive value (0.1 km) for the next iteration. If successive iterations alternated between negative values and the fixed positive value, the solution was recomputed with focal depth held at 1.0 km. In a few cases the final single-event solutions were computed with focal depth fixed at 5.0 km. These cases corresponded to events, usually represented by only three or four *P* observations, that were characterized by very poor depth resolution.

MAGNITUDE COMPUTATIONS

Most of the magnitudes assigned to the events listed in the appendix represent $m_b(L_g)$ magnitudes based on L_g phases and defined to be approximately equivalent to m_b body-wave magnitudes determined from teleseismically recorded short-period P-waves (Nuttli, 1973). Some of the assigned magnitudes were computed during the course of this study and others were taken from published papers or seismological bulletins. The magnitudes computed during this study were of two types: instrumental $m_b(L_g)$ magnitude (Nuttli, 1973) and macroseismic $m_b(L_g)$ based on total felt area (Nuttli and Zollweg, 1974).

Approximately one-half of the assigned magnitudes were obtained by measuring L_g phase amplitudes on vertical-component, short-period WWSSN film chips. The L_g phase amplitudes were converted to magnitude using the formulas (Nuttli, 1973)

$$m_b(L_g)=3.75+0.90(\log\Delta)+\log A/T; 0.5° \leq \Delta \leq 4.0°$$

$$m_b(L_g)=3.30+1.66(\log\Delta)+\log A/T; 4.0° \leq \Delta \leq 20.0°,$$

where A is the sustained ground amplitude in microns; T is the associated period in seconds; and Δ is the epicentral distance in degrees. In the appendix, magnitudes computed in the above manner correspond to averages from at least three stations.

Magnitudes based on felt area, which were primarily assigned to pre-1963 events, account for approximately 10 percent of the values in the appendix. These magnitudes were determined using the equation (Nuttli and Zollweg, 1974)

$$m_b(L_g)=2.65+0.098f+0.054f^2$$

where f is the logarithm to base 10 of the felt area in square kilometers.

The rest of the magnitudes listed in the appendix were taken from published papers, primarily catalogs of central United States earthquakes by Nuttli (1979) and Nuttli and Brill (1981), or magnitudes reported in the EDR's of the National Earthquake Information Service or in the bulletins of the International Seismological Centre. In a very few instances, the listed magnitudes represent body-wave magnitudes (m_b) derived from teleseismically recorded P-waves or local magnitudes (M_L) based on the original magnitude scale (Richter, 1958).

RESULTS

This section contains a zone-by-zone discussion of the revised hypocenters and relationships between the earthquake locations and geologic structure. The figures accompanying the text contain the epicenters of all relocated earthquakes with $m_b(L_g) \geq 3.0$ and the associated nominal 95-percent-confidence ellipses. Individual relocated earthquakes mentioned in the text are identified by year, month, and day of occurrence and listed chronologically in the appendix. Selected epicenters in the figures are identified similarly. Previously accepted epicenters, usually those of Nuttli (1979) and Nuttli and Brill (1981), that are not covered by the corresponding epicenter ellipses, are indicated in the figures by an asterisk and a relocation vector pointing to the new location. Several earthquakes were not plotted because the semi-major axis of their epicenter ellipses exceeded a length of 50 km, the previously established exclusion criterion (Dewey and Gordon, 1984).

The Southern Appalachian, Alabama, and Ohio Zones have been described by J. W. Dewey and D. W. Gordon (unpub. report, 1983), and details of the relocations in these zones will not be reported here. Relationships between seismicity and structure in these zones are dealt with briefly in the section, *Seismicity and Plate Tectonics*.

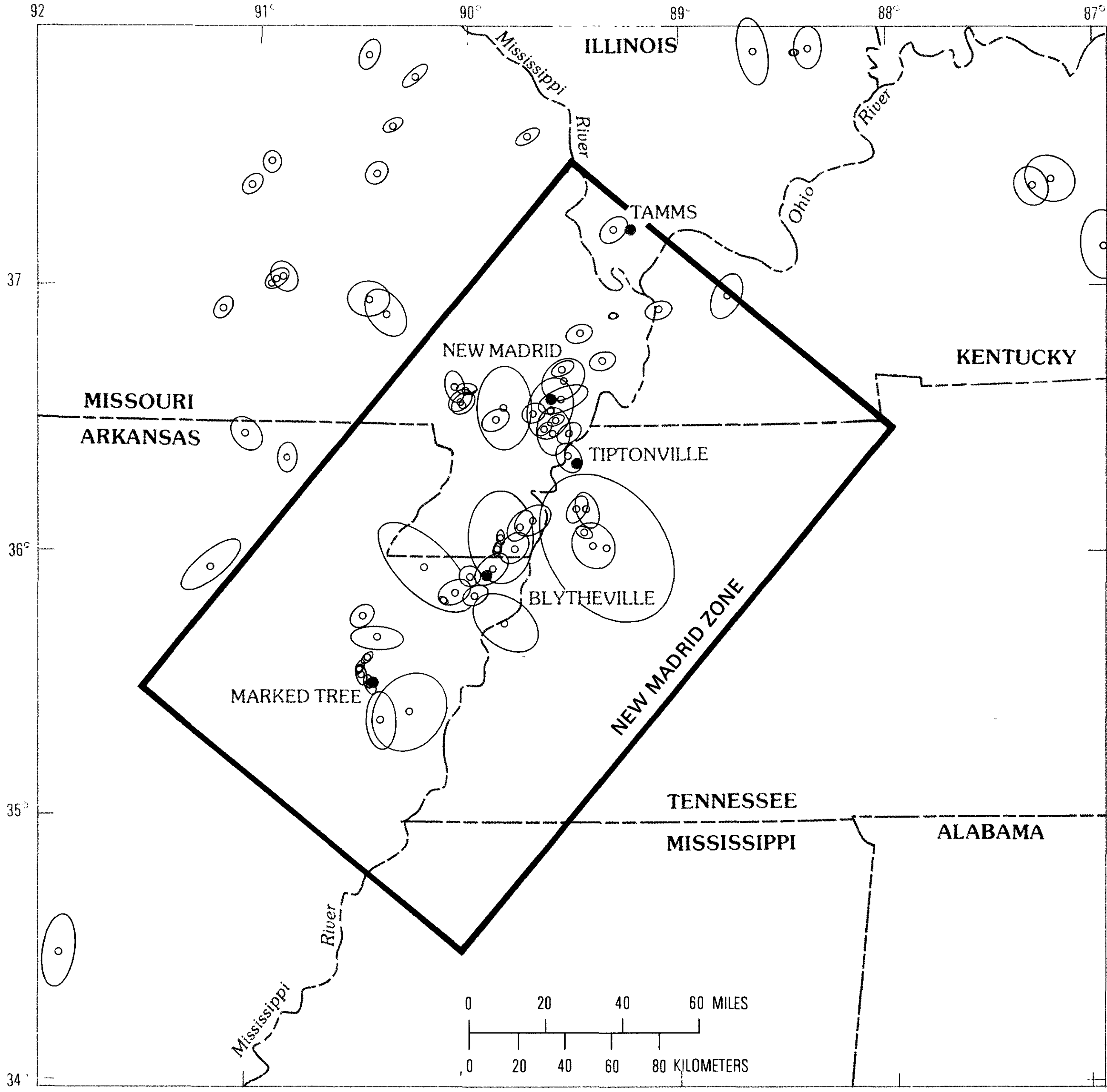


FIGURE 7.—Revised epicenters and nominal 95-percent-confidence ellipses of earthquakes ($m_b(L_g) \geq 3.0$) in the New Madrid Zone.

The Tectonic Map of the United States (Cohee, 1961) and the Basement Rock Map of the United States (Bayley and Muehlberger, 1968) are general references for the structural features shown in the figures.

REVISED HYPOCENTERS IN THE NEW MADRID ZONE

Figure 7 is an overview of the relocated epicenters in the New Madrid Zone. After completing JHD/JED calibration-station runs and single-event solutions for all shocks in this zone, most of the events in the zone were rerun using the calibration-event/single-event solution sequence. To do this the zone was divided into three subzones: the Tamms, Tiptonville, and Blytheville Subzones. The Tamms Subzone, the locale of a swarm of small earthquakes in August 1965, corresponds to the Illinois part of the New Madrid Zone, and the Tiptonville Subzone refers to the remainder of the zone north of latitude 36.3°. The Blytheville Subzone refers to the entire zone south of latitude 36.3° N.

Figures 8*A–D* show the revised epicenters and nominal 95-percent-confidence ellipses in the Tiptonville and Blytheville Subzones. To make these figures easier to interpret, each plot refers to only a portion of the time span covered by the relocated events. The figures also indicate the boundaries of the Mississippi Valley graben (MVG) and the area of highest microearthquake activity from June 1974 through June 1981. As depicted in the figures, most of the large differences between the old and new epicenters are associated with earthquakes that occurred before 1970. In addition, the relocation vectors tend to move the new epicenters toward areas of high, recently observed microearthquake activity.

Eight poorly recorded events that occurred before 1970 were not rerun in the calibration-event/single-event sequence because they had relatively large confidence regions. These events had been recorded by only a few stations, and not much change in their locations could be expected. Most of the confidence ellipses associated with shocks in this group failed to cover the previously accepted epicenters. For example, as illustrated in figure 8*A*, the revised epicenter of an earthquake (1955.01.25) originally located at 36.0° N., 89.5° W. near Finley, Tenn. (Nuttli, 1979), moved approximately 30 km west to a locality associated with high microearthquake activity in the Mississippi Valley graben (MVG). On the basis of intensity data, Nuttli (1956) originally located a magnitude-4.0 shock (1956.01.29) at 35.6° N., 89.6° W. near Henning, Tenn. (see fig. 8*A*). The revised location of this shock, which is approximately 25 km northwest of the original location, moves the event from outside to inside the Mississippi Valley graben (MVG). In a similar case, an earthquake (1962.06.01) near Memphis in the southern part of the zone has been shifted 45 km northwest from a location (35.0° N., 90.2° W.) outside the central rift to an epicenter inside this feature.

THE TIPTONVILLE SUBZONE

A magnitude-3.9 earthquake (1975.06.13) located 15 km southwest of New Madrid (see fig. 8*D*) was selected as the calibration event in the JHD/JED computations for the Tiptonville Subzone, which is composed of all of the New Madrid Zone north of 36.3° N. except a small area surrounding Tamms in southern Illinois. In these runs, the calibration event was restrained to the hypocenter (35.543° N., 89.628° W., h=8.5 km) obtained earlier by applying the calibration-station/single-event procedure to the New Madrid Zone. These coordinates agree closely with the epicenter (36.540° N., 89.680° W.) reported by Saint Louis University and the focal depth (9.0 km) determined by Herrmann (1979).

Examination of the JED runs for this subzone indicates that nearly all of the P-wave travel-time corrections associated with the local network in the Mississippi Valley fall within the range ±0.5 sec. Network stations representing the smallest epicentral distances generally exhibited the smallest corrections, adjustments that were on the order of ±0.1 or 0.2 sec. The variance of the P-wave observations associated with the microearthquake network was approximately 0.2 sec^2.

The revised hypocenters are not significantly different than microearthquake network results for the same events previously reported by Saint Louis University. On the average the new hypocenters differ from the network findings by about 0.02° in latitude and longitude and by about 2 km in focal depth. The BILLIKEN event (1963.06.28), the detonation of 20,000 lb of high explosives near Poplar Bluff, Mo., in 1963 (see fig. 8*B*), provides an estimate of the absolute accuracy of the relocated epicenters in this subzone. The known coordinates of BILLIKEN (Stauder and others, 1964) are as follows:

Origin time	= 10:00:00.1 GMT
Lat	= 36.717° N.
Long	= 90.127° W.
Depth	= 120 ft

The computed BILLIKEN epicenter listed in the appendix is approximately 5.0 km southwest of the given shot point, and the corresponding epicenter ellipse, which has semi-major and semi-minor axes of about 9.0 and 6.0 km, respectively, covers the shot point.

Although the epicenters associated with the calibration-event method do not differ significantly from those determined earlier by the calibration-station method, the areas of the epicenter ellipses associated with the calibration-event method are about 40 percent smaller than those associated with the calibration-station procedure. The calibration-event technique also led to more precise focal-depth determinations, and it was not necessary to fix focal depth to obtain stability in any of the single-event solutions associated with the calibration-event mode. In contrast, 6 of 24 solutions associated with the calibration-station mode required fixed focal depth because the solutions with free focal depth were unstable. The deepest focal depth determined in this subzone corresponds to a magnitude-3.4 earthquake (1970.12.24) located in an area of high microearthquake activity about 15 km north of New Madrid (see fig. 8*C*). This event had a computed focal depth of about 15 km and a depth axis with semi-length of approximately 5 km.

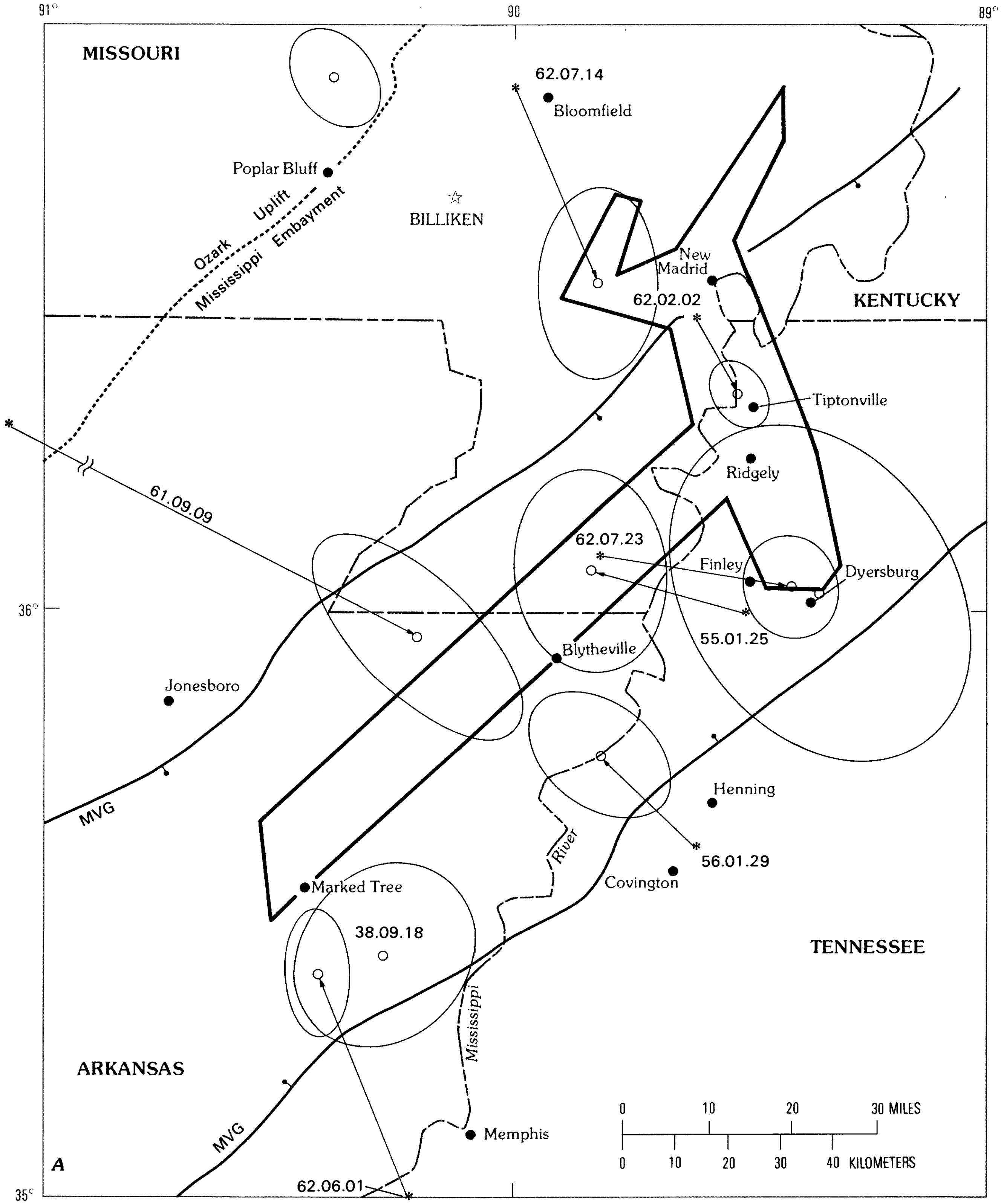


FIGURE 8.—Revised epicenters of earthquakes ($m_b(L_g) \geq 3.0$) in the New Madrid Zone. (A) From 1938 through 1962, (B) From 1963 through 1969, (C) From 1970 through May 1974, (D) From June 1974 through 1980. Asterisks indicate the positions of previously accepted epicenters that lie outside the corresponding epicenter ellipses of the revised locations. Relocation vectors connect the old epicenters to the new locations. The heavy line encloses the area of dense microearthquake locations (June 1974 through June 1981). Curved lines delimit the Mississippi Valley graben (MVG). Bar and ball on downthrown side. The star indicates the site of the BILLIKEN chemical explosion (1963.06.28).

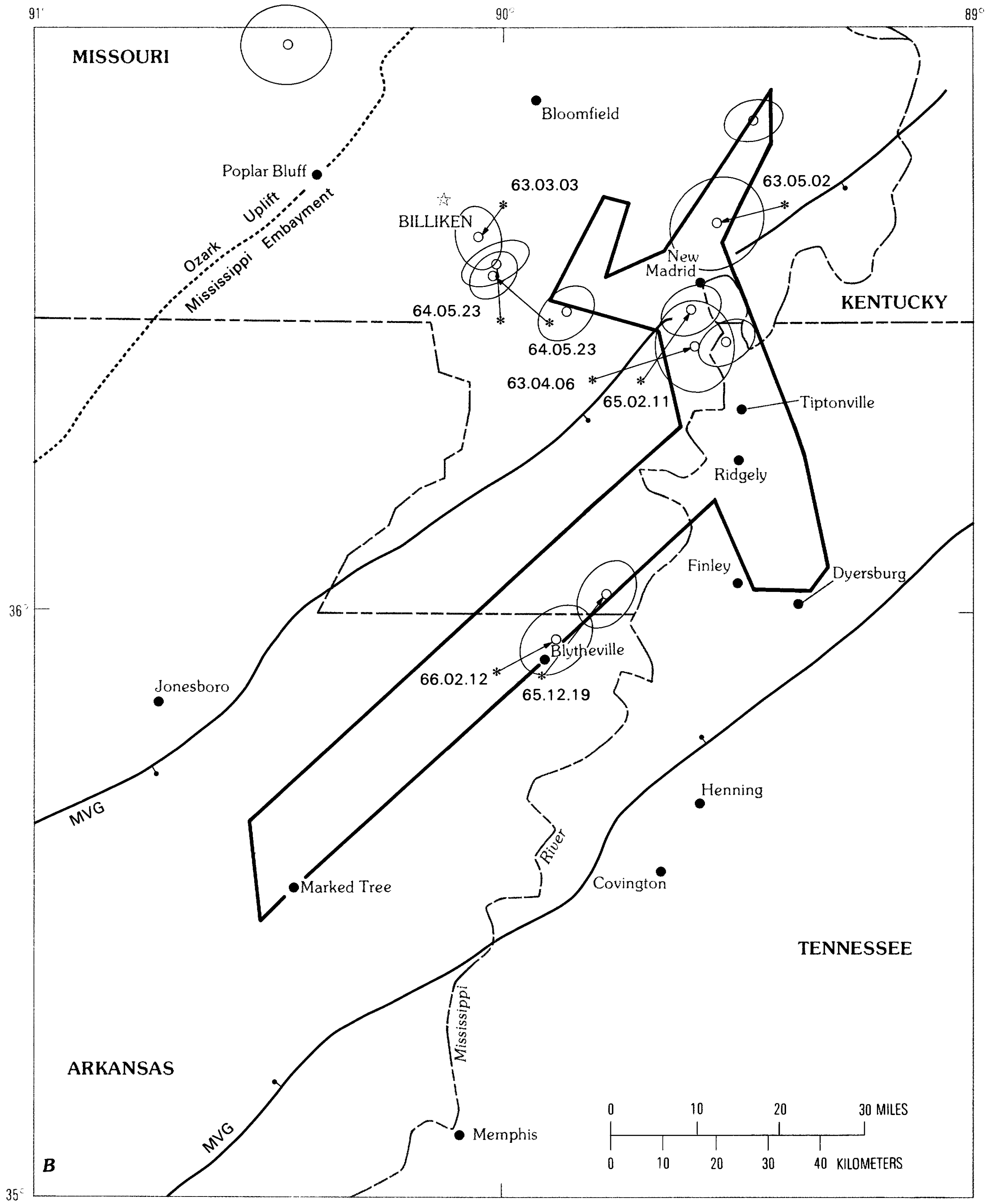


FIGURE 8.—Revised epicenters of earthquakes—Continued

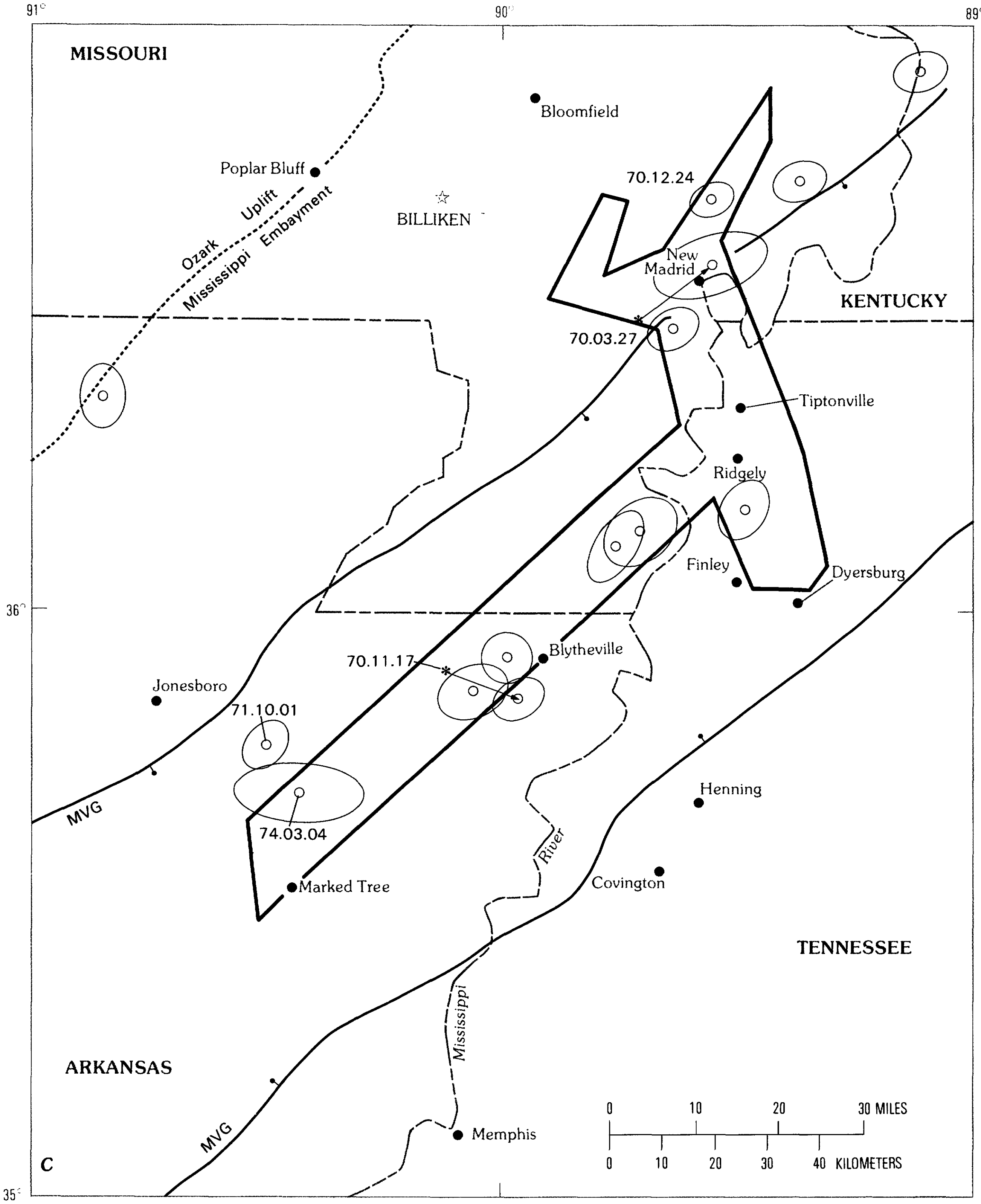


FIGURE 8.—Revised epicenters of earthquakes—Continued

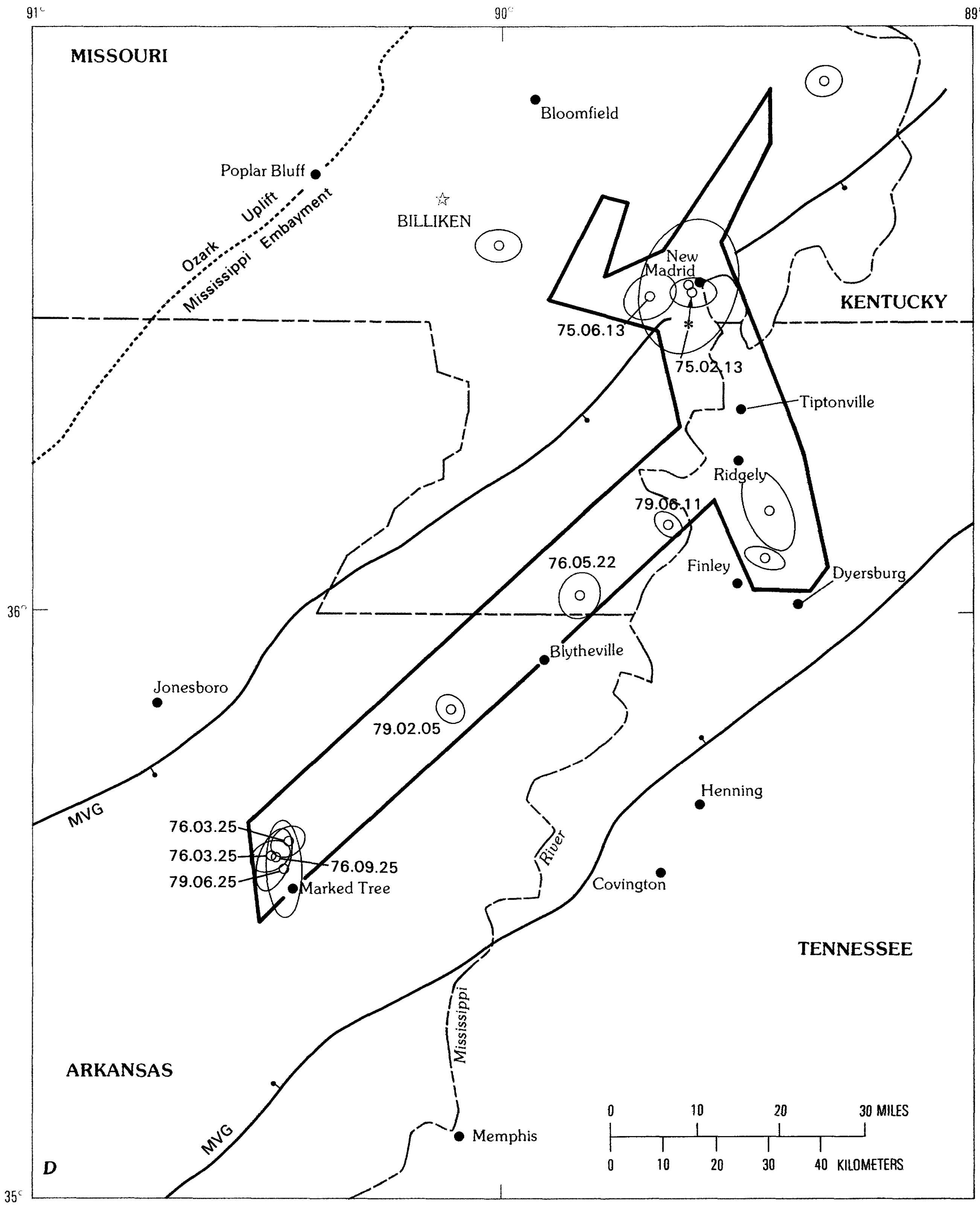


FIGURE 8.—Revised epicenters of earthquakes—Continued

THE BLYTHEVILLE SUBZONE

The Blytheville Subzone is composed of all the New Madrid Zone south of latitude 36.3° N. Nine of the 15 events used in the JHD/JED computations for this subzone occurred after the deployment of the local array in the Mississippi Embayment. The calibration event (1976.05.22), a magnitude-3.2 earthquake, was restrained to coordinates (36.031° N., 89.828° W., h=10.0 km) reported by Saint Louis University.

Station corrections representing P-waves recorded at microearthquake network stations varied from −0.5 to +0.5 sec. Observations associated with this weight class had a variance of only 0.15 sec^2. Comparison of the revised hypocenters of events after June 1974 with locations for the same shocks reported by Saint Louis University indicates that differences between corresponding hypocenters are insignificant. Six of the events in this subzone, which have epicenters distributed along the northeast-southwest seismic trend in the central part of the graben, had computed focal depths exceeding 10 km. The deepest focal depths in this group were assigned to two earthquakes (1976.03.25 [00:41:20.8], 1979.06.11) at opposite ends of the northeast-southwest seismic trend (see fig. 8*D*). Each of these events had a computed focal depth of about 15 km and a depth axis with semi-length of about 5 km.

THE TAMMS SUBZONE

Four of the five shocks considered in the Tamms Subzone (fig. 9) were part of an August 1965 swarm of earthquakes that was felt throughout a 700 sq km area of southern Illinois. Nuttli (1965) noted that the epicentral intensities of shocks in this swarm were relatively high in comparison with the sizes of the associated felt areas, and he concluded that these shocks had very shallow focal depths. The largest event in the swarm, a magnitude-3.9 earthquake (1965.08.14 [13:13:56.9]), served as the calibration event in the JHD/JED computations.

As shown in figure 9, the relocated epicenters of three events in the 1965 swarm, those shocks with $m_b(L_g)\geq3.0$, converge on the village of Tamms, Ill. The revised epicenters agree with each other to within 0.02° in latitude and longitude and their mean location is less than 4.0 km from Tamms, where the shocks were felt with maximum intensity. Although the initial locations of these shocks—obtained with the use of the calibration-station/single-event procedure—were also close to Tamms, the epicenters located by the calibration-event/single-event procedure are less scattered. Final single-event hypocenter computations carried out with unrestrained focal depths indicated either very shallow focal depths (>2.0 km) or negative focal depths for events in this group. Using spectral analysis, Herrmann (1979) obtained a focal depth of 1.5 km for the largest shock in the Tamms swarm.

SEISMOTECTONICS IN THE NEW MADRID ZONE

The New Madrid Zone has a long seismic history that includes three major earthquakes in the winter of 1811–1812 (see *Historic Earthquakes and Ancient Plate Tectonics*). A detailed discussion of the seismotectonics of the zone, which is the subject of ongoing research supported by the U.S. Geological Survey, the U.S. Nuclear Regulatory Commission, and other agencies, is beyond the scope of this study. Braile, Keller and others (1982), Johnston (1982), and McKeown (1982) have published excellent summaries of recent geological and geophysical investigations in the area.

Figure 10 is a plot of the revised epicenters and selected tectonic elements in the New Madrid Zone. Major features delineated in the figure include the area of dense, recently located microearthquakes. Most of the revised epicenters plotted in the figure are located within the Mississippi Valley graben (MVG), a 2-km-deep depression in the crystalline basement, which was probably initiated by early Paleozoic rifting (Hildenbrand and others, 1977; Kane and others, 1981).

The area outlined in figure 10, where microearthquake epicenters were concentrated in the period from June 1974 through June 1981, corresponds presumably to a zone of seismically active faulting (Stauder and others 1976; Stauder, 1982). As pointed out previously, the relocation vectors in this area tend to displace the old epicenters toward the area of high microearthquake activity. Focal mechanisms of teleseisms with locations along the axial seismic lineament, which extends to the northeast from Marked Tree, Ark., indicate right-lateral strike-slip on northeast striking faults in the presence of an east to northeast compressional stress field (Herrmann, 1979; Stauder, 1982). The situation is more complex with regard to the north-northwest trending, transverse seismic lineament between Dyersburg, Tenn., and New Madrid, Mo. Composite focal mechanisms representing this segment correspond to normal, reverse, and strike-slip faulting (Herrmann and Canas, 1978; O'Connell and others, 1982). However, most of the composite mechanisms are characteristic of oblique faulting with reverse and left-lateral strike-slip components.

Figure 10 also shows a series of magnetic lineaments (thick, long-dashed lines marked by ML) that may be manifestations of deep-seated faulting and fracturing (Hildenbrand and others, 1982). As indicated in the

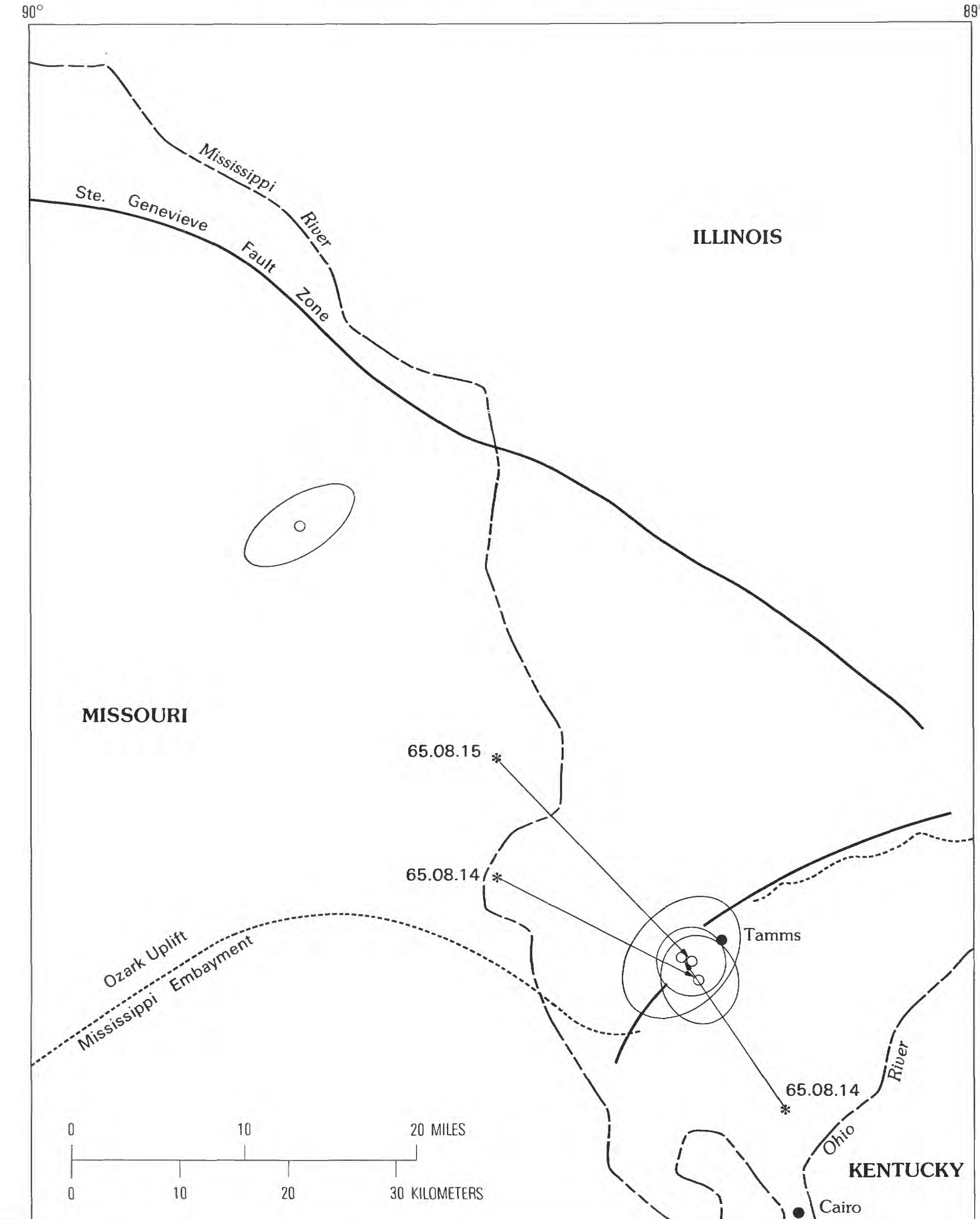


FIGURE 9.—Revised epicenters of earthquakes ($m_b(L_g) \geq 3.0$) and selected tectonic elements in the Tamms Subzone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Solid lines are high-angle faults. Northeast-striking fault near Tamms after Heyl and McKeown (1978).

figure, these lineaments tend to be either parallel or perpendicular to the trend of the Mississippi Valley graben. A group of buried igneous plutons (shaded areas) of Mesozoic age are also plotted in the figure (Hildenbrand and others, 1982; Braile, Keller and others, 1982). Most of these plutons seem to be located

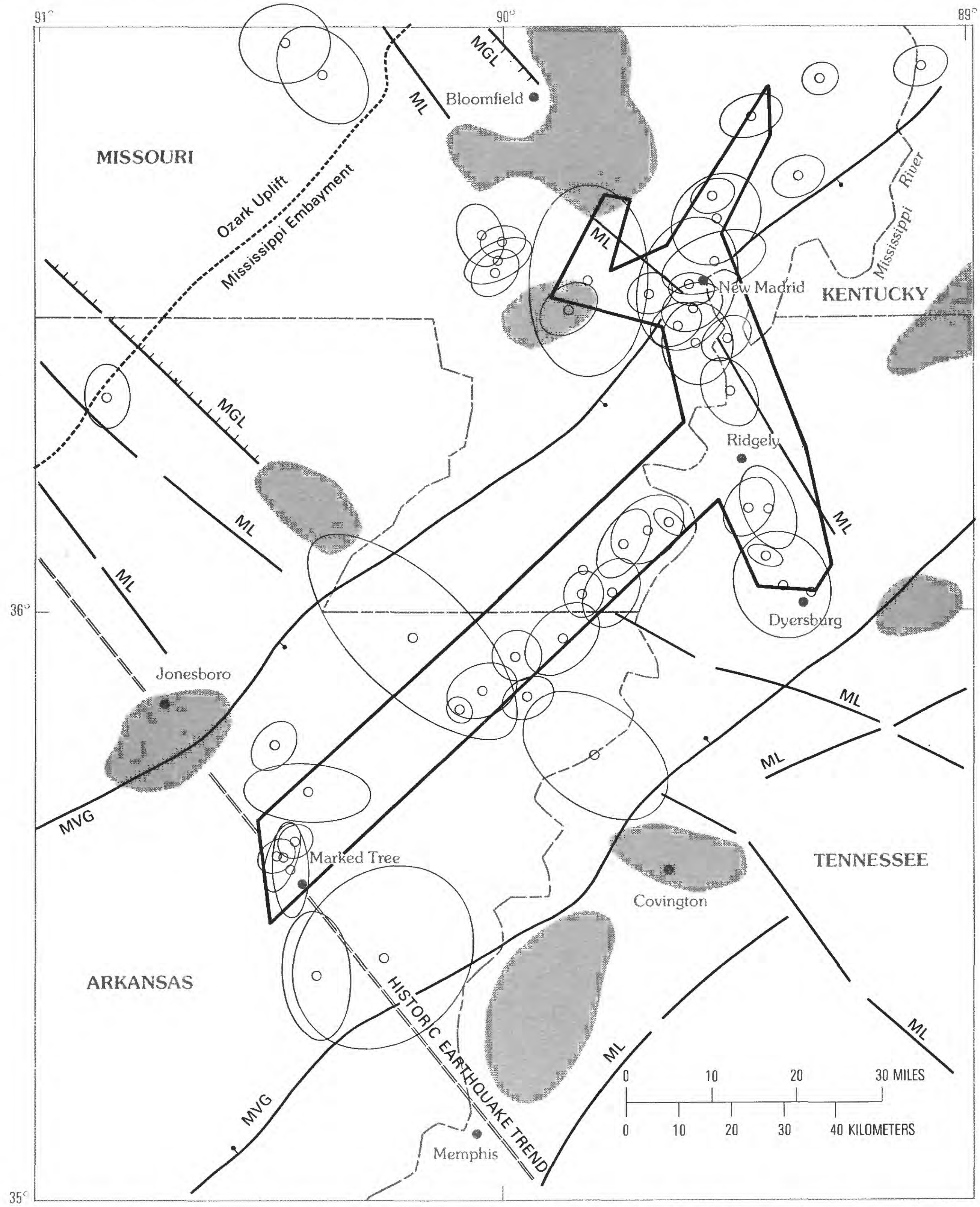


FIGURE 10.—Revised epicenters ($m_b(L_g)\geq3.0$) and selected tectonic elements in the New Madrid Zone. The heavy line encloses the area of dense microearthquakes (June 1974 through June 1981). Magnetic lineaments (thick, long-dashed lines marked by ML) and buried igneous plutons (shaded areas) after Hildenbrand and others (1982) and Braile, Keller and others (1982). Lines with hachures denote borders of the Missouri gravity low (MGL). Curved lines delimit the Mississippi Valley graben (MVG). Bar and ball on downthrown side. Double-dashed line denotes historic (pre-1930) earthquake trend.

near the intersections of northwest-trending lineaments with the northwest or southeast sides of the Mississippi Valley graben.

Several general observations concerning the seismicity and tectonics illustrated in figure 10 can be made at this point. Whereas most of the revised epicenters are located within the Mississippi Valley graben and a few are found northwest of the graben, none of the revised epicenters are located southeast of the graben. Kane and others (1981) noted a similar pattern in the historic seismicity. The northeast edge of the Missouri gravity low aligns with the Bloomfield pluton in the upper part of the figure, and the extended southwest edge of the gravity low cuts the Covington pluton in the lower right part of the figure. Arvidson and others (1982) noted that the most active part of the New Madrid Seismic Zone coincides with the intersection of the Mississippi Valley graben and the Missouri gravity low. Another interesting aspect of the seismotectonics in the figure is that the revised epicenters tend to plot outside the buried plutons.

As shown in figure 10, an apparent north-south trend of revised epicenters crosses the central graben or rift near Marked Tree, Ark. This trend may be evidence of a tectonically active transverse structure similar to the New Madrid-Dyersburg lineament. The epicenters of the four most recent shocks in this trend (1976.03.25 [00:41:20.8], 1976.03.25 [01:00:12.4], 1976.09.25, 1979.06.25) form a tight cluster near Marked Tree. The definition of the cross-graben feature depends on the revised locations of four earlier, less well-located events (1938.09.18, 1962.06.01, 1971.10.01, 1974.03.04) which occurred before the deployment of the microearthquake array. However, the associated epicenter ellipses indicate that the location differences between these four events and the Marked Tree cluster are significant. The historic earthquake data also support the existence of a transverse tectonic element near Marked Tree. Four of the most damaging earthquakes in the central United States prior to 1930, all with magnitudes greater than 5.3 (Nuttli, 1982), have epicenters on a trend passing through Jonesboro, Marked Tree, and Memphis (see doubled-dashed line in fig. 10). Plots of the epicenters of all known felt earthquakes in this area show a very sharp decrease in seismicity southwest of this trend, which marks the approximate southern limit of the New Madrid Zone (Nuttli and Brill, 1981). As shown in figure 10, the northwest trending lineament and the buried pluton near Jonesboro, and the pluton near Memphis (Braile, Keller and others, 1982) also suggest the presence of a deep-seated, northwest-trending, structural element beneath the graben in this area.

The swarm of shallow earthquakes near Tamms that occurred in August 1965, is unusual in that it seems to be spatially associated with a previously mapped fault. As shown in figure 9, the epicenter ellipses of the revised locations of the swarm overlap the trace of a fault mapped by Heyl and McKeown (1978). The focal mechanism associated with the largest shock of this series (1965.08.14 [13:13:56.9]) corresponds to strike-slip faulting (Herrmann, 1979). One of the nodal planes of the mechanism strikes north-northeast subparallel to the trace of the fault southwest of Tamms.

REVISED HYPOCENTERS IN THE OZARK ZONE

Figures 11*A* and 11*B* are plots of the relocated epicenters in the northern and southern portions of the Ozark Zone, respectively. The set of 15 events used in the JHD77 calibration station runs included five teleseismically recorded earthquakes and two regionally recorded explosions at the Pea Ridge mine near Sullivan, Mo. (fig. 11*A*). Using travel-time adjustments and variances generated by JED computer runs, 37 events were relocated by single-event computation. Subsequently, 18 of these events, shocks that were spatially associated with the St. Francois uplift, were rerun using the JHD77 calibration-event/SE77 single-event sequence (see *The Ironton Subzone*).

The relatively small confidence ellipses representing most revised epicenters in figure 11*A* and 11*B* are a consequence of the presence of nearby stations at St. Louis, Florissant, Rolla, and Cape Girardeau, all in Missouri, throughout most of the period of interest, and after June 1974, of the presence of the Central Mississippi Valley Network (see fig. 4). Most of the events considered that occurred after deployment of the microearthquake network were recorded by at least three stations with epicentral distance less than 1.5°. Incomplete station reporting and the absence of definitive felt information make the revised epicenters of several of the early shocks in this zone relatively uncertain. A magnitude-3.8 earthquake (1961.09.09) in the southern part of the zone, which was reported felt only at Pochontas, Ark., and Doniphan, Mo. (Lander and Cloud, 1963), represents the least certain case of this type (see fig. 11*B*). Only three *P* phases (first arrivals) could be identified among the phase data reported by seven stations. The revised epicenter, based on three *P* and seven secondary phases, is approximately 110 km southeast of the previously accepted epicenter (Nuttli, 1979). The available *P* and secondary phase data do not fit the original hypocenter. A widely felt, magnitude-4.4 earthquake (1956.11.26) north of Poplar Bluff apparently represents another case of this type. Five P-wave observations and 10 secondary phases fit the revised epicenter, which is approximately 30 km southeast of the former, graphically determined epicenter.

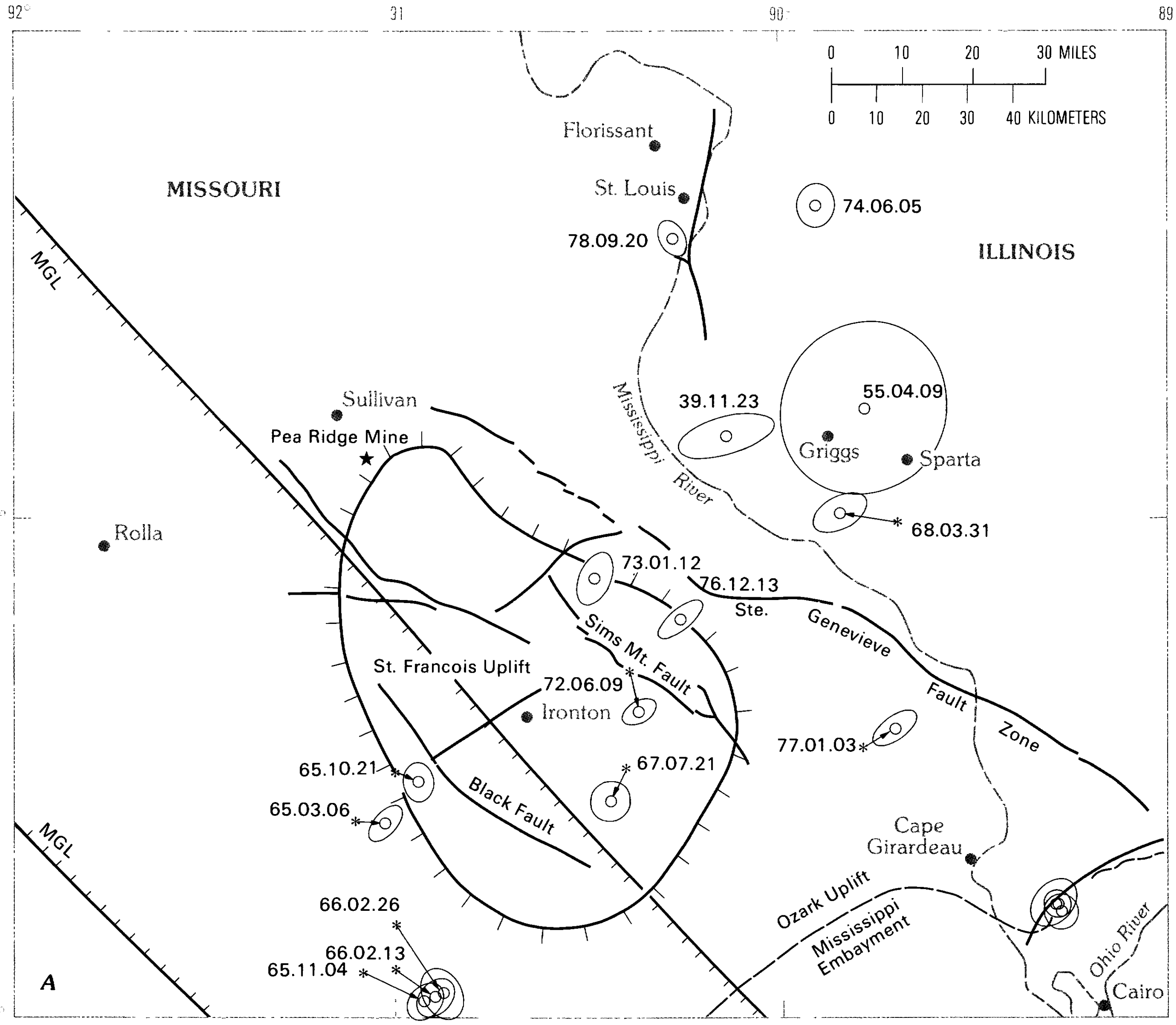
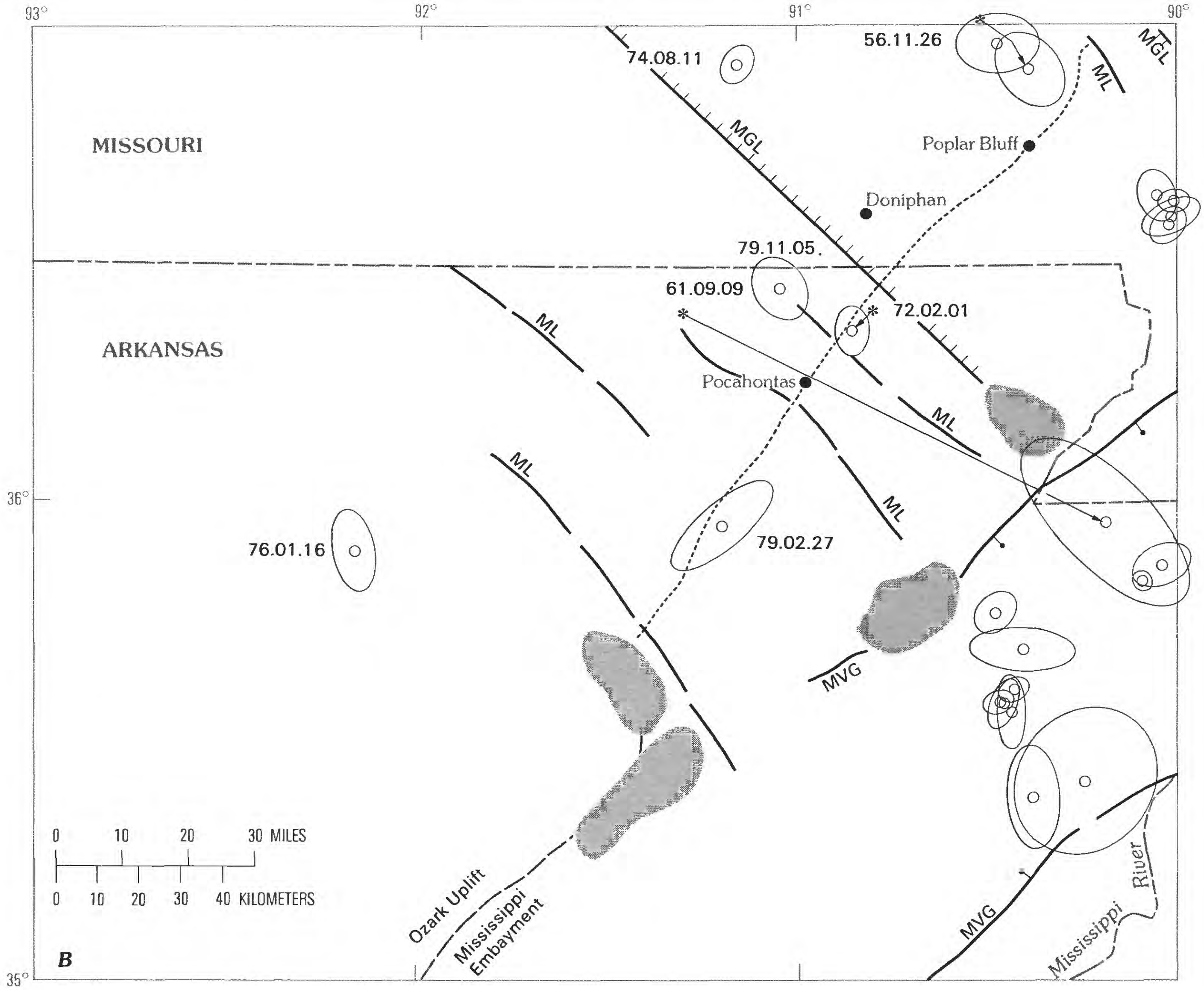


FIGURE 11 (above and facing page).—Revised epicenters ($m_b(L_g)\geq 3.0$) and selected tectonic elements in the Ozark Zone. (A) Northern section, (B) Southern section. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Straight lines with closely spaced hachures indicate approximate boundaries of the Missouri gravity low (MGL). Line with widely spaced hachures surrounds St. Francois uplift. Curved lines mark limits of the Mississippi Valley graben (MVG). Bar and ball on downthrown side. Magnetic lineaments (thick, long-dashed lines marked by ML) and buried igneous plutons (shaded areas) after Hildenbrand and others (1982). High-angle faults (solid lines) generalized from Heyl and McKeown (1978).

THE IRONTON SUBZONE

The calibration-event method was applied to relocate 18 events near Ironton in the St. Francois uplift of southeast Missouri (see fig. 11*A*). A regionally recorded explosion (1976.12.11) at the Pea Ridge mine southeast of Sullivan was designated as the calibration event. The 15 events used in the JED computation group included three teleseismically recorded earthquakes (1965.03.06, 1965.10.21, 1967.07.21) and two other explosions (1975.01.10, 1976.03.13) at the Pea Ridge mine. The computed locations of the explosions differ from each other by only a few kilometers, and each of the associated epicenter ellipses covers the known location of the mine. Figure 11*A* indicates that three earthquake epicenters (1965.11.04, 1966.02.13, 1966.02.26), which orginally exhibited scatter of several tenths of a degree in latitude and longitude, have converged to approximately the same source at about 37.05° N., 90.90° W.



SEISMOTECTONICS IN THE OZARK ZONE

The Ozark Zone, which was defined by Nuttli and Herrmann (1978), corresponds to the Ozark uplift, a Paleozoic structure in southern Missouri and northern Arkansas. Major tectonic elements of the zone depicted in figures 11*A* and 11*B* include a series of northwest trending magnetic lineaments, the previously described Missouri gravity low (MGL), and the St. Francois uplift (Hildenbrand and others, 1982; Arvidson and others, 1982). The northwest-trending lineaments, which are marked by gravity and magnetic anomalies, may represent deep-seated faults or fracture zones. Figure 11*A* also shows high-angle, basement faults in the St. Francois uplift where Precambrian rocks crop out. Although some of the epicenter ellipses overlap the faults and lineaments, the correlation between seismicity and these features is not strong. Nuttli (1979) has pointed out that the seismicity of this area seems to be concentrated on the flanks of the St. Francois uplift, which marks the structural and topographic crest of the Ozark uplift (fig. 11*A*). The focal mechanisms associated with two strong earthquakes (1965.10.21, 1967.07.21) on the periphery of the uplift correspond to normal faulting (Mitchell, 1973; Patton, 1976; Herrmann, 1979). These mechanisms indicate that the greatest principal stress axis is nearly vertical and suggest that the St. Francois area is undergoing renewed uplift (Nuttli, 1979).

REVISED HYPOCENTERS IN THE WABASH ZONE

The earthquake epicenters considered in the Wabash Zone are plotted in figure 12. After obtaining solutions for these earthquakes using the JED calibration-station option, all the events in the zone were reworked using the JED calibration-event mode. This change in computational procedure seemed reasonable in view of the relatively small area covered by the epicenters and the added control provided by the local network deployed in the Wabash Valley in 1978 (see fig. 4).

THE ELDORADO SUBZONE

The Eldorado Subzone corresponds to the same geographic area as the Wabash Zone. Formerly accepted locations (Nuttli, 1979) that lie outside the epicenter ellipses associated with the new locations are indicated in figure 12. During the JED computer runs the regionally recorded calibration event (1978.06.02) was restrained to the hypocenter given by Saint Louis University. The close-in P-wave observations associated with the microearthquake network, which were treated as a separate weight class, had a variance of about 0.05 sec^2. Travel-time corrections associated with P-waves recorded by the seven stations in the Wabash Valley had an average value of less than 0.1 sec. Although the coordinates of most epicenters did not change by more than 0.1° in going from the calibration-station method to the calibration-event approach, the areas of the confidence ellipses associated with post-local network events were 3 to 10 times smaller.

Comparison of estimated focal depths suggests that earthquake foci are deeper in this area than elsewhere in the central United States. The computed focal depths of three of the recent, post-local network events (1978.06.02, 1978.12.05, 1980.03.13) in this group were in the 20–25 km depth range. In each case, the semilength of the corresponding depth axis was approximately 3.0 km. Using the spectral amplitude of surface waves, Herrmann (1979) determined a focal depth of 22 km for the largest earthquake (1968.11.09) in this group, a teleseism in the southwest part of the area. The revised hypocenter of this event, which occurred before the deployment of the local network in 1978, indicates a focal depth of 21.1±23.9 km. Herrmann (1979) obtained a depth of 15 km for a magnitude-4.7 event (1974.04.03) in the northern part of the area. In comparison, the single-event solution obtained in this study for the same event indicated a focal depth of 13.5±12.4 km.

SEISMOTECTONICS IN THE WABASH ZONE

The relocated epicenters and the principal tectonic features of the Wabash Zone are displayed in figure 12. Approximately 3 km of Paleozoic sedimentary rocks overlie Precambrian basement in this area, which is part of the Illinois basin. The faults and folds delineated in the figure, which deform the Paleozoic section, are generalized from Bristol and Treworgy (1979) and Treworgy (1981). The northeast-striking Wabash Valley fault system is composed of high-angle, normal faults with maximum displacements on the order of 150 m (Bristol and Treworgy, 1979). The Clay City anticlinal belt belongs to a group of elongate flexures in the Illinois basin which may be related to late Paleozoic igneous intrusions along Precambrian fractures (King, 1951). The shaded areas shown in the figure correspond to correlative gravity and magnetic anomalies that probably represent dense, magnetic, igneous plutons in the Precambrian basement (Braile, Keller and others, 1982). The revised epicenters do not correlate with the area traversed by the Wabash Valley fault system. This is surprising in view of the previously accepted spatial association of historic seismicity with this section of the Wabash Valley (Nuttli, 1979). The prominent gravity-magnetic high centered at approximately 38.2° N., 88.4° W. apppears to separate the plotted epicenters into northern and southern groups. None of the revised epicenters plot within the outline of this anomaly.

Stauder and Nuttli (1970) and Herrmann (1979) have worked out focal mechanisms for two of the larger earthquakes in this area, the well-recorded teleseism on November 9, 1968, and the earthquake of April 3, 1974. The mechanism of the 1968 earthquake implies reverse faulting. The corresponding nodal planes strike northerly and dip about 45° to the east and west, respectively. The mechanism of the 1974 earthquake, which resembles the mechanisms of events along the prominent axial trend in the New Madrid area, represents strike-slip faulting with steeply dipping nodal planes striking northeast and northwest, respectively. In both focal-mechanism solutions the compressional axis is nearly horizontal and oriented east-west.

REVISED HYPOCENTERS IN THE KENTUCKY ZONE

Figure 13 contains the revised epicenters of eight earthquakes with $m_b(L_g)\geq 3.0$ in the Kentucky Zone. The unlabeled epicenters on the right side of the figure belong to the Southern Appalachian and Ohio Zones. With the exception of a magnitude-5.2 earthquake (1980.07.27) near Sharpsburg, Ky., the events considered

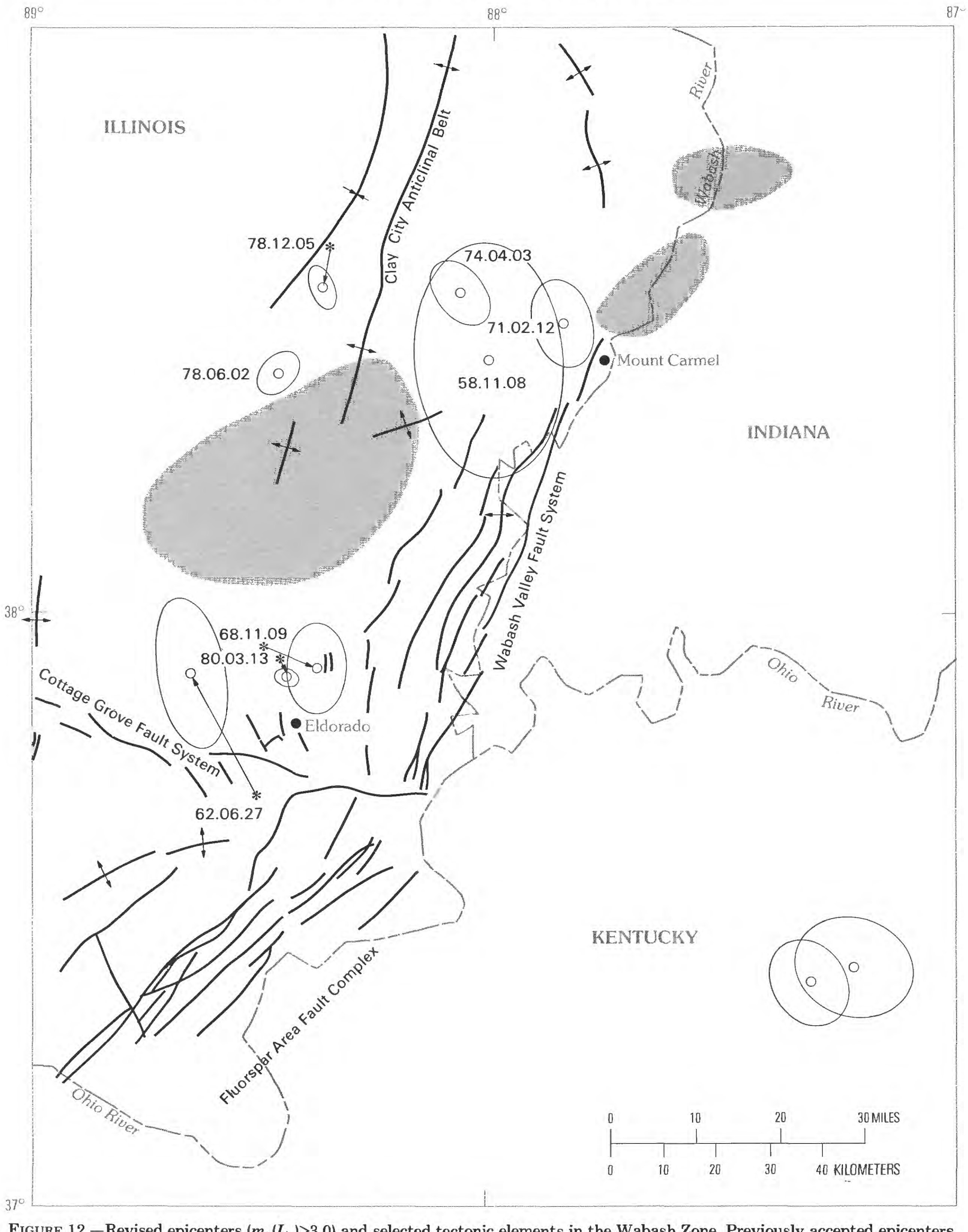


FIGURE 12.—Revised epicenters ($m_b(L_g)\geq3.0$) and selected tectonic elements in the Wabash Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Shaded areas mark probable buried igneous plutons (Braile, Keller and others, 1982). High-angle faults (light solid lines) and folds (thick lines, arrows denote anticline or syncline) after Bristol and Treworgy (1979) and Treworgy (1981).

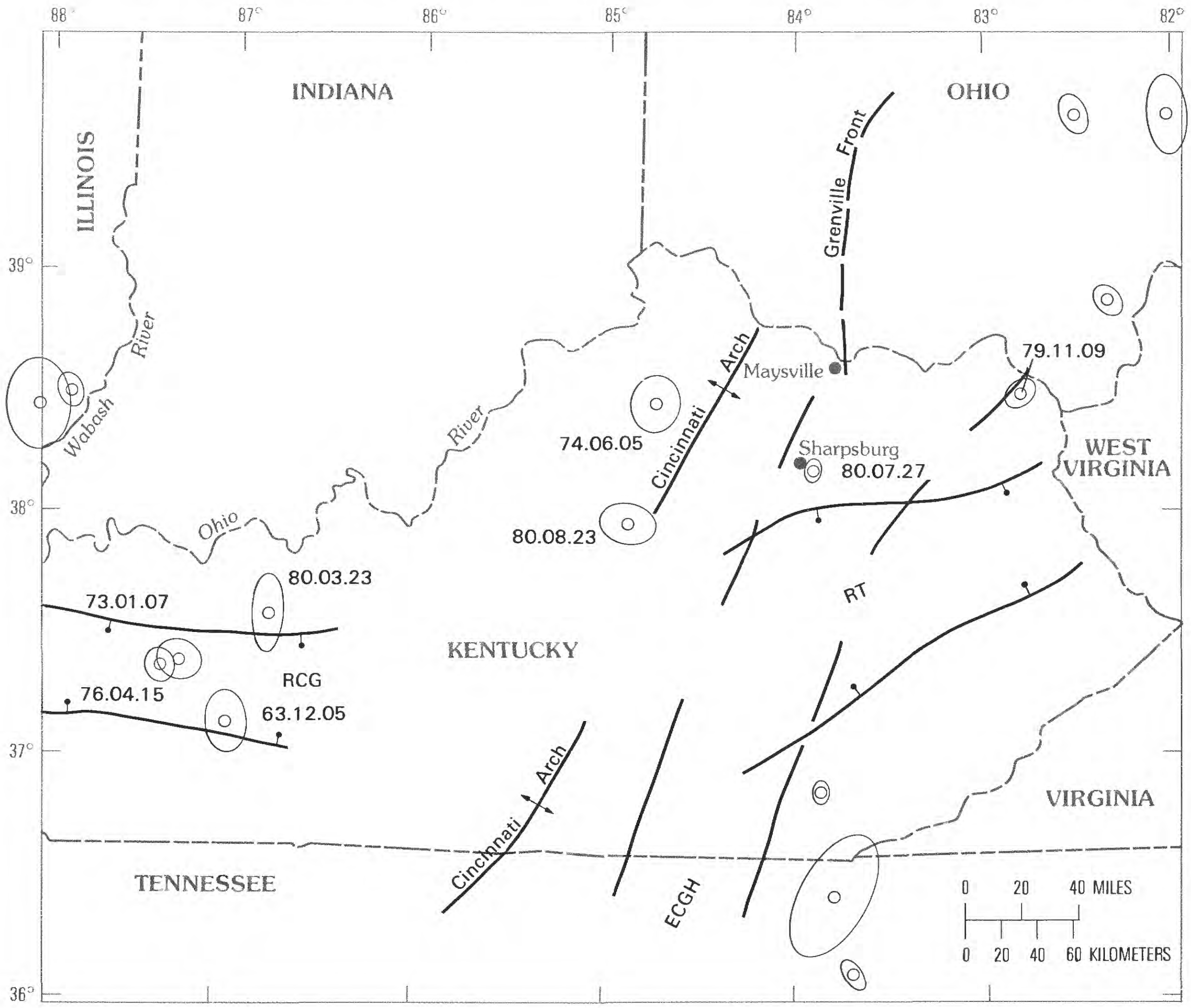


FIGURE 13.—Revised epicenters ($m_b(L_g) \geq 3.0$) and selected tectonic elements in the Kentucky Zone. Rome trough (RT) after Ammerman and Keller (1979). Rough Creek graben (RCG) and East Continent gravity high (ECGH) after Soderberg and Keller (1979) and Keller and others (1982). Structural depressions marked by lines with bar and ball on relatively downthrown side.

in this section had magnitudes of 3.6 or less. No differences larger than about 0.1° in latitude or longitude were discovered when the old and new epicenters were compared. The computed focal depths in this zone are relatively imprecise. In most cases the steepest semiaxes of the accompanying confidence ellipsoids have lengths of 20 km or more.

The northern Kentucky teleseism of July 27, 1980, which had a felt area of approximately 600,000 sq km, is the most important event in this group. The instrumental epicenters of this earthquake and its aftershocks are located near the village of Sharpsburg, Ky., approximately 50 km south of the Ohio River. However, the maximum intensity (VII) for the main shock was assigned to Maysville, Ky., the population center nearest to the epicenter (Reagor and others, 1981). Using data from close-in, temporary stations, Herrmann and others (1982) located 69 aftershocks of the July 27 earthquake whose epicenters outlined an area of about 30 sq km surrounding Sharpsburg. The hypocenters of the aftershocks, which were concentrated in the depth range 12–14 km, suggest a fault plane with northeast strike and southeast dip. The epicenter ellipses of the main shock and two of the larger aftershocks (1980.07.31, 1980.08.25), which are listed in the appendix, overlap the area outlined by the aftershock epicenters determined with the temporary-station data. None of the temporary-station observations were used in computation of the revised epicenters.

SEISMOTECTONICS IN THE KENTUCKY ZONE

Three major tectonic elements underlie the crystalline basement of northern Kentucky: the East Continent gravity high (ECGH), the Rome trough, and the Rough Creek graben (fig. 13). The ECGH refers to a narrow, northerly trending band of positive gravity anomalies and high magnetic intensity which can be traced through Tennessee and Kentucky and possibly into Ohio. Keller and others (1982) attributed this anomaly to dense, magnetic, igneous rocks formed by continental rifting during Keweenawan time. Volcanic rocks associated with the ECGH that lie east of the Grenville front appear to have been metamorphosed by the Grenville event (Keller and others, 1982). The Rome trough and Rough Creek graben are apparently remnants of a late Precambrian-early Paleozoic rift zone (Ammerman and Keller, 1979; Soderberg and Keller, 1979). These two features also lie along the trend of the 38th Parallel lineament and the Rough Creek and Kentucky River fault zones (see *Tectonics*). The Rome trough, a sediment-filled graben in the Precambrian basement, 4 to 7 km deep, intersects the ECGH in eastern Kentucky. Four of the revised epicenters in western Kentucky are spatially associated with the Rough Creek graben, which Soderberg and Keller (1979) have described as a fault-bounded depression in the Precambrian basement that contains Paleozoic sedimentary rocks. Analysis of rock cores and gravity data indicates that the Precambrian basement of the graben is composed of individual fault blocks.

From an analysis of surface-wave amplitudes and P-wave first motions from the main shock, composite focal mechanisms derived from aftershocks, and the spatial distribution of the aftershocks, Herrmann and others (1982) concluded that the Sharpsburg earthquake (1980.07.27) was associated with right-lateral strike-slip displacement on a fault plane with strike N. 30° E. and dip 50° SE. The pressure and tension axes of the inferred mechanism are oriented east-west and north-south, respectively. Gravity contours that delineate the ECGH in the epicentral area (Ammerman and Keller, 1979) are approximately parallel to the strike of the preferred fault plane.

REVISED HYPOCENTERS IN THE SOUTHERN MISSISSIPPI VALLEY ZONE

Figure 14 shows the epicenters of the relocated events in the Southern Mississippi Valley Zone. This zone was established to deal with a group of small seismic events in southern Mississippi and Alabama and with a swarm of earthquakes in 1964 near Hemphill, Tex. The SALMON event (1964.10.22), a 5-kiloton, underground nuclear explosion detonated near Hattiesburg in southern Mississippi (Jordan and others, 1966), was included in this group to constrain the station corrections generated by the JED computations. The position of SALMON was held very close to its given location by incorporating observations from close-in, temporary stations in the JED computations. The single-event epicenter for SALMON, which was computed after removing the temporary-station data from the input, had an absolute error of about 4.5 km. The corresponding epicenter ellipse covered the given shot point. The WWSSN station at Spring Hill (SHA) in southwest Alabama furnished observations at local distances in the southern quadrant for the cluster of small-magnitude shocks near the Mississippi-Alabama border. The largest discrepancy between the revised and old epicenters in this cluster is related to the relocation of the southeast Mississippi earthquake of 1976.10.23. The revised location places this event approximately 33 km southwest of the EDR epicenter, which was obtained without the benefit of a reading from Spring Hill. The computed focal depths in this zone are very imprecise. The associated depth axes have semi-lengths of 25 to 50 km.

THE HEMPHILL SUBZONE

In figure 14 the Hemphill Subzone corresponds to a group of seven small earthquakes on the Texas-Louisiana border that were relocated by the calibration-event method. This group of events is part of a swarm of 17 earthquakes detected in this area during the period from April 24 to August 16, 1964 (Nuttli and Brill, 1981). According to *United States Earthquakes* for 1964, the combined felt area, defined by localities where one or more of the earthquakes were felt, contains about 950 sq km in central Sabine County, Tex., and western Sabine County, La. (von Hake and Cloud, 1966). The principal shock (1964.04.24, 07:33:51.4) of the series, a regionally recorded earthquake with magnitude 3.6, was selected as the calibration event in the JED computations. LRSM data were obtained for this event from a special-event report by the Seismic Data Laboratory (Anonymous, 1965). The revised epicenter (31.42° N., 93.80° W.) of the calibration event compares favorably with the center (31.45° N., 93.80° W.) of the combined felt area and with the coordinates (31.33° N., 93.85° W.) of Hemphill, where the shocks were slightly damaging. In comparison, the previously accepted position (31.6° N., 93.8° W.) of the main shock locates near the northern limit of the combined felt area. The apparent north-south trend of the epicenters plotted in figure 14 is probably spurious, an effect of the associated station distribution as suggested by the north-south elongation of the confidence ellipses (Dewey, 1979). The relationship of these events to

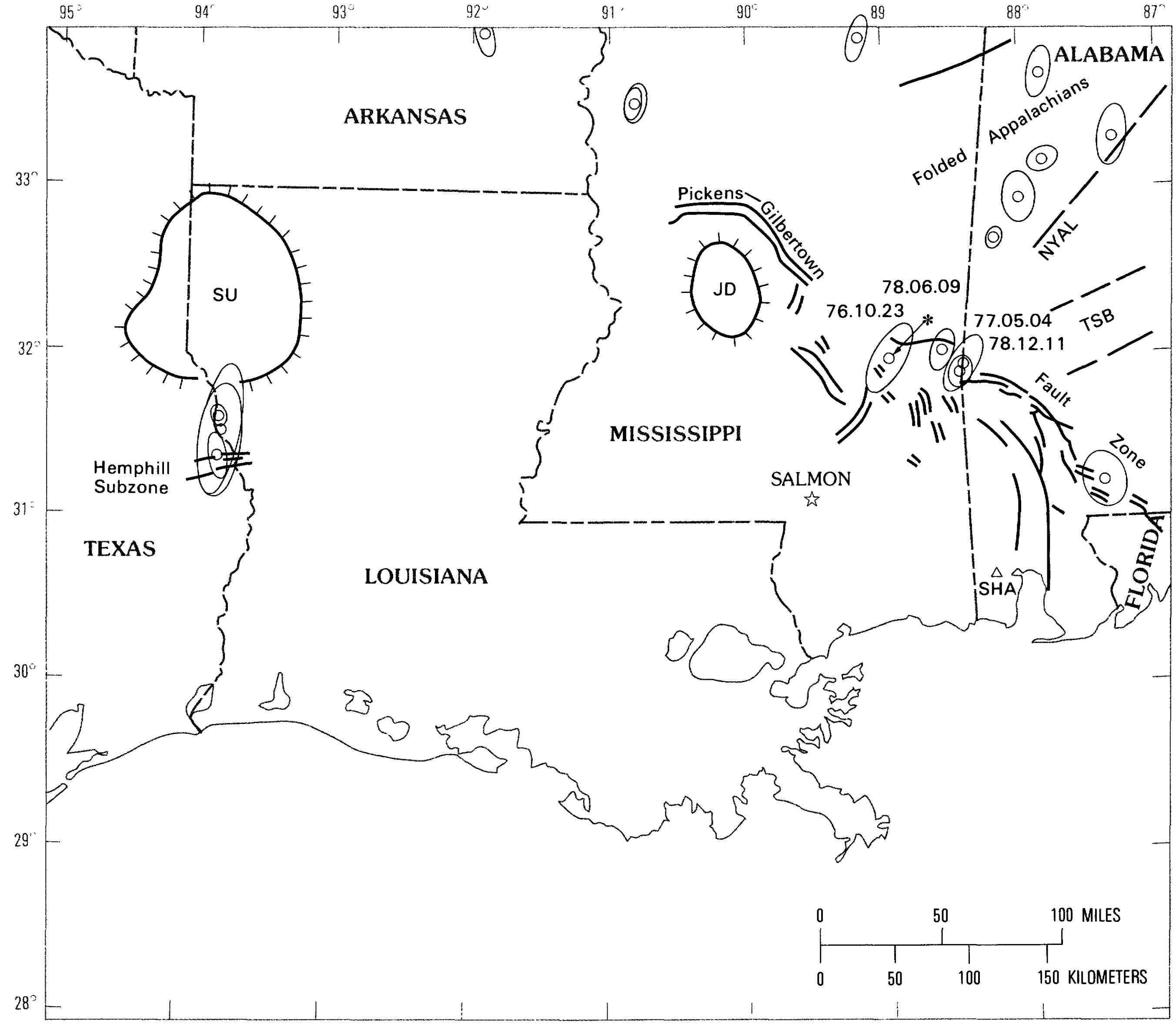


FIGURE 14.—Revised epicenters ($m_b(L_g)\geq3.0$) and selected tectonic elements in the Southern Mississippi Valley Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). The star marks the cite of the underground nuclear explosion, SALMON (1964.10.22). The open triangle denotes the Spring Hill seismograph station (SHA). Solid lines designate high-angle faults. East-northeast-striking faults on the Texas-Louisiana border after King and Beckman (1974). Pickens-Gilbertown fault zone after Cohee (1961). Jackson dome (JD). Sabine uplift (SU). Dashed lines denote the New York-Alabama lineament (NYAL) and the Talladega slate belt (TSB) in the crystalline basement (King and Zietz, 1978; Thomas, 1973).

geologic structure and the possible association of this seismicity with hydrocarbon production will be discussed in the next section.

SEISMOTECTONICS IN THE SOUTHERN MISSISSIPPI VALLEY ZONE

The four small earthquakes (1976.10.23, 1977.05.04, 1978.06.09, 1978.12.11) with epicenters near the Alabama-Mississippi border (fig. 14) have magnitudes in the 3.0–3.5 range. As shown in the figure, these epicenters correlate spatially with the Pickens-Gilbertown fault zone, a prominent graben system that displaces Tertiary sediments in the Gulf Coastal Plain region (Cohee, 1961; Walthall and Walper, 1967). As it crosses central Mississippi, this graben system nearly coincides with the continental margin of ancient North America (see *Seismicity and Plate Tectonics*). This coincidence suggests that these events are related to a zone of crustal weakness which has existed for a geologically long time. The epicentral area of these earthquakes is also associated with a sharp bend in the structural trend joining the Appalachian and Ouachita foldbelts (see fig. 5). The four epicenters also correlate with a subcrop of the Talladega slate belt (see fig. 15), a component of the structurally complex, late Paleozoic Appalachian foldbelt (Thomas, 1973).

As shown in figure 14, the epicentral area of the 1964 swarm of earthquakes on the Texas-Louisiana border correlates spatially with several closely spaced, east-northeast striking faults south of the Sabine uplift (King and Beikman, 1974). The relatively small felt area of these earthquakes and their comparatively high epicentral intensity (Nuttli and Brill, 1981) suggests that these events were shallow. These earthquakes may represent activity on the mapped faults. The absence of historic earthquakes in the area prior to 1964 (Nuttli and Brill, 1981) suggests that the Hemphill earthquakes may have been related to human activity. For example, the swarm may have been induced by secondary recovery operations in oil fields or changes in physical conditions brought about by impounding water in a large reservoir. However, neither of these possibilities seem likely. Although the adjacent county in Louisiana, also called Sabine County, is an oil-producing area (Coiqnet, 1964), there are no known oil fields in Sabine County, Tex. A large body of water, the Toledo Bend Reservoir, occupies the Sabine Valley along this section of the Texas-Louisiana border. However, the fact that this reservoir was not filled until 1967 (Anonymous, 1975) rules it out as a possible contributing factor to the 1964 swarm.

REVISED HYPOCENTERS IN THE OUACHITA ZONE

The labeled epicenters in figure 15 represent nine earthquakes in the Ouachita Zone with magnitude ≥3.0. As originally defined by Nuttli and Herrmann (1978),

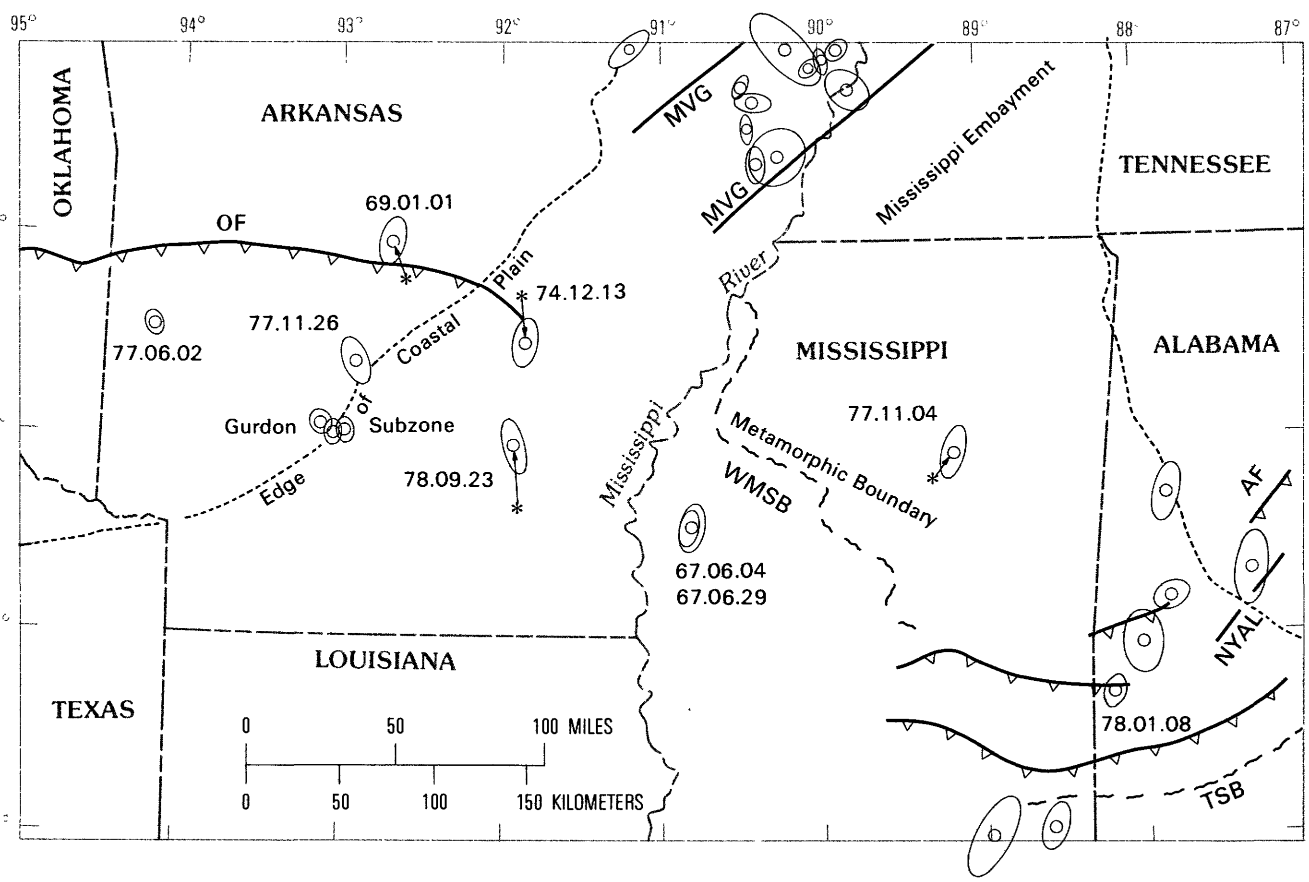


FIGURE 15.—Revised epicenters ($m_b(L_g) \geq 3.0$) and selected tectonic elements in the Ouachita Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Lines with sawteeth designate major thrust faults or limits of belts of extensive folding and thrusting. Wavy, dashed lines mark metamorphic boundaries in the basement. Basement tectonics in Mississippi generalized from Thomas (1973). Appalachian front (AF). Mississippi Valley graben (MVG). Bar and ball on downthrown side. New York-Alabama lineament (NYAL). Ouachita front (OF). Talladega slate belt (TSB). West Mississippi slate belt (WMSB).

the Ouachita Zone referred to an area of major historic seismicity associated with the Ouachita foldbelt in Oklahoma and Arkansas. In this study, as shown in figure 2, the Ouachita Zone has been extended southeastward across northern Mississippi and into northern Alabama where it abuts the Alabama Zone of J. W. Dewey and D. W. Gordon (unpub. report, 1983). Input to the JED computations carried out in the calibration-station mode consisted of data from 15 events, including 4 large earthquakes borrowed from the adjacent Alabama Zone. The close-knit cluster of events near the edge of the embayment at about 34° N., 93° W. was later relocated using the calibration-event method (see the next section, *The Gurdon Subzone*).

As indicated by the relocation vectors in figure 15, several of the confidence ellipses associated with the revised epicenters do not cover the former locations. These discrepancies seem to be due to differences in the data sets used in the solutions. For example, in the case of a teleseism (1969.01.01) near the Ouachita front (OF) in central Arkansas, 22 P-wave observations, which were poorly distributed with respect to aximuth, were used in the previous solution. In contrast, about 45 *P* readings with improved azimuthal control were available for computation of the revised epicenter. Several of the discrepancies are due to the fact that data from the Central Mississippi Valley Network (see fig. 4) exclusively were used to determine the original epicenters of events that were exterior to the network. The largest discrepancies of this type, involving probable mislocations of 20 to 30 km, correspond to two small events (1974.12.13, 1978.09.23) beneath the embayment in eastern Arkansas.

THE GURDON SUBZONE

The calibration-event method was used to redetermine the hypocenters of six small events on February 15 and 16, 1974, near Gurdon, a small town in central Arkansas. These earthquakes, which occurred during a time span of about 12 hours, probably had essentially the same source. Three of these events, those with magnitudes $\geq$3.0, are plotted in figure 15. The epicenter ellipses of the five smaller events cover the epicenter of the calibration event, a magnitude-3.8 teleseism (1974.02.15, 22:49:04.4). The computed focal depths of these shocks have a mean value of about 15 km. However, because the most nearly vertical axes of the corresponding confidence ellipsoids have semi-lengths of 20 to 40 km, these focal depths are relatively imprecise.

SEISMOTECTONICS IN THE OUACHITA ZONE

The revised epicenters and selected tectonic features of this zone are shown in figure 15. Generalized spatial relationships among the Ouachita foldbelt, the Mississippi Embayment, and the Appalachian foldbelt (AF) are outlined in figure 5. The Ouachita foldbelt (OF) is exposed in southeast Oklahoma and western Arkansas, where it consists of folded, mainly clastic Paleozoic rocks. Approximately 1000 m of post-Paleozoic sediments conceal the foldbelt in southeastern Arkansas. The Appalachian foldbelt, which is composed of folded and faulted sedimentary and crystalline rocks, plunges beneath the Mississippi Embayment in central Alabama. The Appalachian foldbelt and Ouachita foldbelt apparently meet in central Mississippi, where they are concealed by approximately 2000 m of embayment sediments. The nature of the subsurface junction between the foldbelts has been investigated by Thomas (1973) with the use of data from deep wells. His interpretation of the subsurface geology, which is outlined in figure 15, indicates that the folded and faulted component (Valley and Ridge province) of the Appalachian foldbelt does not extend beyond central Mississippi. In western Mississippi, the West Mississippi slate belt (WMSB), a subcrop of weakly metamorphosed, lower Paleozoic, clastic rocks with quartz veins, represents the orogenic belt. As shown in the figure, a sinuous metamorphic front forms the northern boundary of the slate belt in western Mississippi. Thomas (1973) attributed the peculiar shape of this boundary to northwest-striking anticlines which flatten out to the east.

From the plate-tectonics viewpoint, the exposed Ouachita foldbelt, the exposed Appalachian foldbelt, and the intervening concealed foldbelt in Mississippi, are manifestations of the late Paleozoic convergence of North America and Africa-South America. Central Mississippi may have been near a northwest-trending plate margin in late Precambrian time and also in late Paleozoic time. Various explanations for the interruption of the Ouachita-Appalachian trend in Mississippi have been offered. King (1975) and Thomas (1976) suggested that a northwest-striking transform fault cut diagonally across what is now Mississippi during the late Precambrian and early Paleozoic separation of North America and South America. Burgess (1976) proposed that, during late Paleozoic continental convergence, a large, northwest-striking, wrench fault intersected the Appalachian foldbelt at the Mississippi-Alabama border. Cebull and others (1976) have postulated that the offset of the foldbelt in Mississippi coincides with a trench-trench transform fault that existed during Paleozoic continental convergence. Walper (1980) interpreted the Mississippi segment of the concealed foldbelt as a late Paleozoic continental suture composed of the crushed and metamorphosed remnants of a subduction complex. All of these interpretations point to the possible existence of a northwest-trending zone of crustal weakness beneath central Mississippi.

Herrmann (1979) determined focal mechanisms for two earthquakes in this group that were each assigned magnitude 4.4. One of these mechanisms corresponds to a teleseism (1967.06.04) in west-central Mississippi associated spatially with the buried section of the Ouachita foldbelt. The focal mechanism for this shock implies right-lateral, strike-slip faulting on a plane with north-northeast strike or left-lateral strike-slip on a plane with west-northwest strike, subparallel to the trend of the foldbelt in the area. Herrmann (1979) estimated a focal depth of 12 km for this event, suggesting that the source of the shock was well below the post-Paleozoic sediments in the epicentral area. The other mechanism refers to a well-recorded earthquake (1969.01.01) near the Ouachita front (OF) in central Arkansas. This mechanism indicates reverse faulting in response to northwest-southeast compression.

REVISED HYPOCENTERS IN THE WICHITA ZONE

Data from earthquakes in the Texas Panhandle were combined with data from events in western Oklahoma to obtain sufficient arrival times for JED computations in this zone, which is illustrated in figure 16. The defined region coincides with the western part of the Wichita-Ouachita Zone delineated by Nuttli and Herrmann (1978).

In the JED computations for this region, stations associated with epicentral distances of 5° or less were designated as calibration stations. All events were represented by at least two calibration-station observations. Lubbock (LUB) and Tulsa (TUL), which each reported ten or more of the events, were the most frequently represented close-in stations.

The strongest earthquake considered in the region, a teleseism in central Oklahoma on April 9, 1952, had

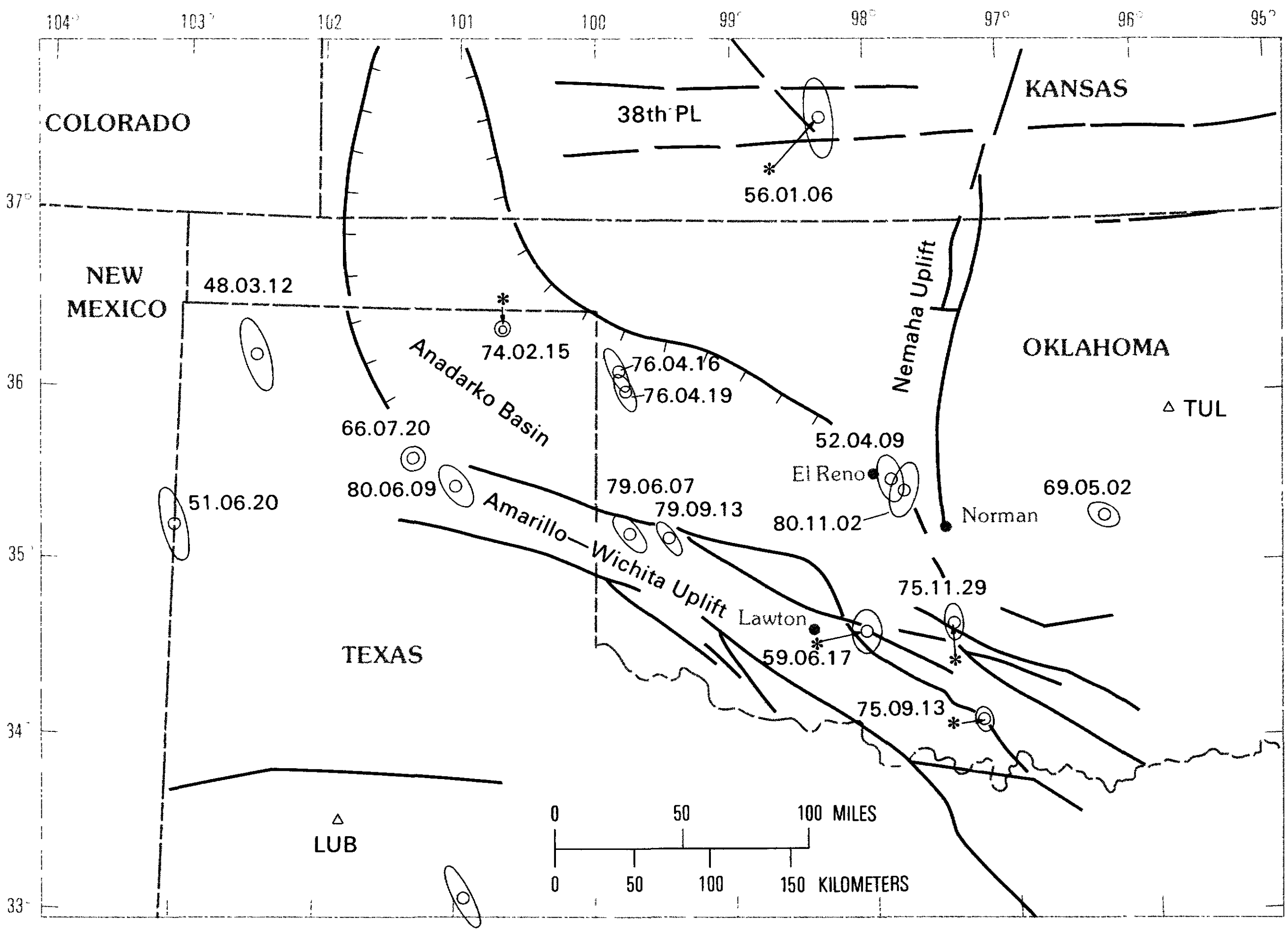


FIGURE 16.—Revised epicenters ($m_b(L_g)\geq3.0$) and selected tectonic elements in the Wichita Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Thick, solid lines designate basement faults (Bayley and Muehlberger, 1968). Line with hachures indicates approximate boundary of the Anadarko basin (Luza and Lawson, 1983). Thick, segmented lines at upper right designate major magnetic trends associated with the 38th Parallel lineament (38th PL) as interpreted by Lidiak and Zietz (1976). Open triangles denote the Tulsa (TUL) and Lubbock (LUB) seismograph stations.

a magnitude of 5.0 ($m_b(L_g)$) based on felt area, and a magnitude of 5.5 (M_s) based on surface-wave amplitudes (Nuttli and Brill, 1981). The revised epicenter of this event is located about 6 km southeast of El Reno (35.55° N., 97.95° W.), which is close to the macroseismic center of the shock. The previously accepted epicenter (35.4° N., 97.8° W.), which was determined in a special study by Miller (1956), is about 20 km southeast of El Reno. The confidence ellipse associated with the new epicenter covers the previous epicenter and El Reno. The greatest concentration of microearthquake activity in Oklahoma for the years 1977 through 1981 coincides with the epicentral area of the 1952 earthquake (Luza and Lawson, 1983).

The two largest discrepancies between the new and the previously published epicenters in this region correspond to the Barber County earthquake of January 6, 1956, in south-central Kansas, and the magnitude-4.2 earthquake (1959.06.17) in southwest Oklahoma. Both of the old epicenters of these events may have been mislocated due to the relative imprecision of epicenters derived from intensity data. The previous location of the Barber County event was determined on the basis of the distribution of intensities (Dellwig, 1956). The coordinates (34.6° N., 98.4° W.) of the old epicenter of the 1959 Oklahoma shock agree to the nearest 0.1° with those of Lawton, Okla., the largest town in the meizoseismal area. This fact suggests that this epicenter represents a combination macroseismic and instrumental epicenter. It seems likely that, in the original solution, the epicenter was fixed at Lawton and the associated station data were used to compute an appropriate origin time.

SEISMOTECTONICS IN THE WICHITA ZONE

The revised epicenters demonstrate good spatial correlation with basement tectonics in the Wichita Zone. As shown in figure 16, the Amarillo-Wichita uplift, the Anadarko basin, and the Nemaha uplift are the principal geologic structures in this zone. The borders of the Amarillo-Wichita uplift, which occupies most of southwest Oklahoma and extends into the Texas Panhandle, are formed by reverse faults with lengths of hundreds of kilometers. The Anadarko basin, which is more than 500 km long and approximately 120 km wide, includes almost all of northwest Oklahoma and extends westward across the Texas Panhandle. This structure, the deepest basin in the North American Platform, contains more than 10 km of relatively undisturbed Paleozoic rocks.

The Amarillo-Wichita uplift and the Anadarko basin are genetically related to the Southern Oklahoma or Wichita aulacogen, which has been described by Burke and Dewey (1973), Hoffman and others (1974), and Wickham (1978). Wickham (1978) recognized three stages in the development of the aulacogen during the Paleozoic: (1) a period of rifting marked by uplift, initiation of normal faulting, graben formation, and extrusive and intrusive igneous activity; (2) a subsidence stage involving rapid downwarping and accumulation of sediments; and (3) a deformation stage characterized by intense folding and wrench faulting on preexisting extensional faults. The rifting stage is related to the opening of the Proto-Atlantic Ocean in late Precambrian or early Paleozoic time and the deformation stage corresponds to the closing of the ocean in the late Paleozoic. During the subsidence stage the aulacogen, a mechanically weak zone in the lithosphere, subsided at a faster rate than the surrounding craton. In the deformation stage, separate uplifts and basins were formed. These structures, which are probably Pennsylvanian features, include the Anadarko and Ardmore basins and the Amarillo-Wichita and Arbuckle uplifts. Schematic plots usually delineate only the assumed nucleus of the Southern Oklahoma aulacogen, the Amarillo-Wichita uplift. The Nemaha uplift was probably also created during the late Paleozoic deformation stage (Kluth and Coney, 1981; Luza and Lawson, 1983; Brown and others, 1983).

The relocated epicenters in figure 16 seem to delineate a seismic trend associated with border faults marking the northeast side of the Amarillo-Wichita uplift. These epicenters include the earthquake (1959.06.17) near Lawton, Oklahoma, and several smaller shocks (1966.07.20, 1980.06.09, 1979.06.07, 1979.09.13). The epicenter of the magnitude-5.0 El Reno, Okla., earthquake (1952.04.09) is very near the northwest-southeast trending boundary of the Anadarko basin, which may be marked by basement faulting in the El Reno area (Luza and Lawson, 1983). Miller (1956) suggested that the 1952 earthquake was associated with the Anadarko basin and the Nemaha uplift. In the upper right part of figure 16, the revised epicenter of the January 6, 1956, Barber County, Kans., earthquake nearly coincides with a magnetic trend that cuts across the 38th Parallel lineament (Lidiak and Zietz, 1976). When extended to the northwest, this lineament coincides with a basement fault that marks the southwest flank of the Central Kansas uplift (Bayley and Muehlberger, 1968).

The only published focal mechanism for shocks in this zone is associated with a magnitude-4.5 earthquake (1974.02.15) in the northeast corner of the Texas Panhandle (Herrmann, 1979). This focal mechanism corresponds to strike-slip faulting associated with WNW-ESE compression (Herrmann, 1979). One nearly vertical, nodal plane strikes northeast, subparallel to contours on the Precambrian basement in the area, and the other high-angle, nodal plane strikes north-northwest.

REVISED HYPOCENTERS IN THE NORTHERN GREAT PLAINS ZONE

Figure 17 shows the revised epicenters of 15 relocated earthquakes in the Northern Great Plains Zone. Some of the differences between the old and new epicenters indicated in the figure are apparently due to regional travel-time bias combined with station distribution. For example, the former epicenters of three events (1961.12.31, 1967.11.23, 1971.10.19) in central South

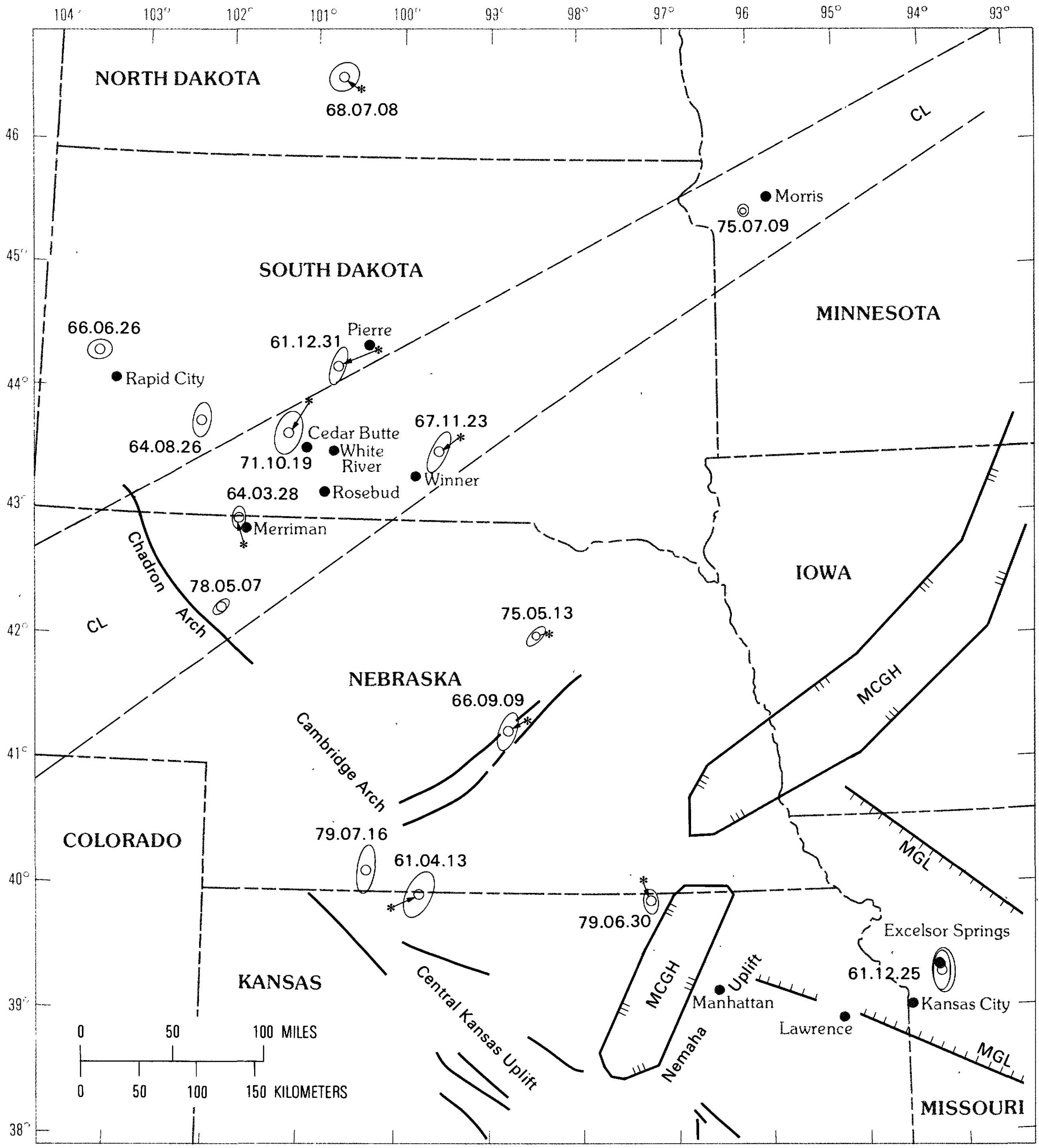


FIGURE 17.—Revised epicenters ($m_b(L_g)\geq3.0$) and selected tectonic elements in the Northern Great Plains Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). Solid lines designate high-angle basement faults. Dashed lines delimit Colorado lineament (CL). Lines with short, single hachures delineate the Missouri gravity low (MGL). Lines with triple hachures outline the Midcontinent gravity high (MCGH).

Dakota are displaced 20 to 40 km to the northeast with respect to the more accurately located, revised epicenters. The arrival-time data associated with these events have three common characteristics: (1) few or no close-in observations, (2) data associated with the southwest quadrant restricted to regional distances at stations in the Western Cordillera, and (3) meager or no teleseismic coverage. Review of the P-wave station corrections generated by the JHD/JED runs reveals that these corrections depend on epicenter-to-station azimuth and distance. These corrections imply that travel times to southwest quadrant stations in the distance range 8°–10° are delayed by about 1.5 sec and that travel times to stations in the north and east in this distance range are as much as 1.5 sec early. The largest travel-time adjustments, positive corrections of 3.0–4.0 sec, characterize epicentral distances of 10°–15° in the southwest quadrant, which corresponds to reception in the Basin and Range province. Examination of the arrival-time data associated with these three events indicates that the systematic southwest sense of the associated relocation vectors is due to relatively late readings at regional distances in the southwest quadrant and to relatively early readings at near-regional and regional distances in the other quadrants.

Two of the largest changes of location between the old and new epicenters are associated with a pair of earthquakes that occurred less than one hour apart near the Kansas-Missouri border on December 25, 1961. Time differences between corresponding phase arrivals at stations covering a wide range of azimuths imply that the two events had essentially the same source. The previously accepted epicenter (39.1° N., 94.6° W.) of both shocks agrees to 0.1° with the coordinates of Kansas City, Mo., the regional population center. The revised epicenters are near Excelsior Springs, 25–30 km northeast of Kansas City. The new locations are compatible with the isoseismal maps prepared by Dellwig and Gerhard (1962), which disclose two localities of high intensity, one at Kansas City and the other at Excelsior Springs (see fig. 18). Consideration of the available information suggests that the previously published epicenters were computed with partial arrival-time data and that they were essentially macroseismic epicenters based on incomplete felt data.

SEISMOTECTONICS IN THE NORTHERN GREAT PLAINS ZONE

Figure 17 also shows selected tectonic features in the Northern Great Plains. The apparent association of seismicity with the northeast-trending Colorado lineament (CL), which may represent a Precambrian wrench

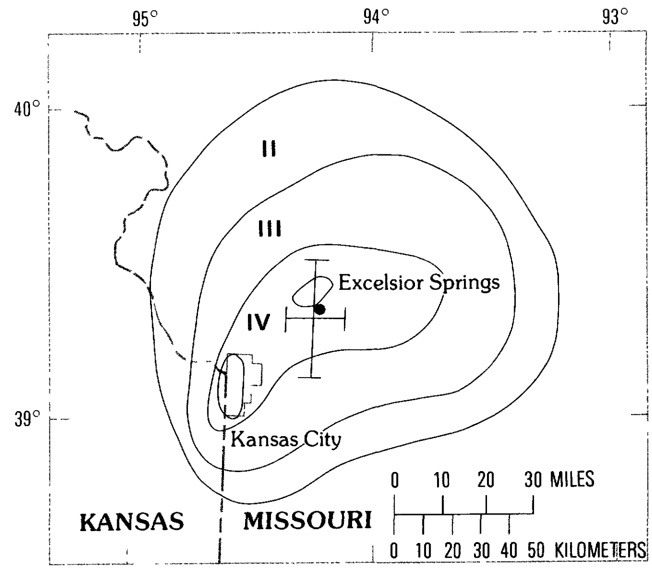


FIGURE 18.—Modified Mercalli (MM) isoseismals of the 1961.12.25 (12:58:16.8) earthquake in western Missouri (Dellwig and Gerhard, 1962). Fiducial cross marks axes of the associated confidence ellipse.

fault (Warner, 1978; Muehlberger, 1980), has been described by Brill and Nuttli (1983). Epicenters of five of the strongest earthquakes relocated in this zone correlate spatially with the Colorado lineament as it passes through the northern half of the zone. These earthquakes include the two largest events in the group, a magnitude-4.2 earthquake (1961.12.31) near Pierre, S. Dak., and a magnitude-4.5 teleseism (1964.03.28) in the vicinity of Merriman, Neb. Several strongly felt, historic earthquakes, one near the South Dakota-Nebraska border (43.0° N., 101.3° W.) on May 10, 1906, and another in northwest Nebraska (42.2° N., 103.0° W.) on July 30, 1934, also have locations within the lineament (Nuttli, 1979). No focal mechanism solutions are available to substantiate the correlation of seismicity with the lineament in Nebraska or South Dakota. However, one of the nodal planes associated with the mechanism of the Morris earthquake (1975.07.09) centered in northwest Minnesota agrees with the trend of the lineament (see *Seismotectonics in the Great Lakes Zone*).

Wheeler (1985) has demonstrated that the Colorado lineament is a zone of relatively high seismicity in the Rocky Mountains and Great Plains region. However, a note of caution should be expressed concerning the extension of the Colorado lineament across the Great Plains. Warner (1978) originally assigned the term Colorado lineament to a northeast-trending belt of Precambrian faults that can be traced from northwest Arizona to southeast Wyoming. Although the supporting evidence was meager, he also proposed that this feature continues northeasterly across the Great Plains to Lake Superior. Dutch (1983) suggested that the Colorado lineament, including the proposed Great Plains segment, marks a fossil shear zone that is very close to the northwest boundary of a northeast-trending crustal province accreted to ancestral North America beginning about 1.8 Ga. Sims and others (1980) have questioned the extension of the Colorado lineament across the plains. They have defined another major crustal discontinuity, the Great Lakes Tectonic Zone, that lies along the northeast projection of the Colorado lineament in Minnesota. This zone of tectonism is a fault-bounded belt of deformed Archean and Early Proterozoic rocks that extends from Minnesota eastward through the northern Great Lakes region to southern Ontario. Basement maps prepared by Denison and others (1984) suggest that the Great Lakes Tectonic Zone continues southwesterly into central South Dakota. Other investigators have challenged the validity of the Great Plains segment of the Colorado lineament and its overall significance as a seismic source (Wong and others, 1983). Although detailed geological and geophysical investigations are needed to establish the continuity of the lineament in Nebraska and South Dakota and to determine the nature of its intersection with the Great Lakes Tectonic Zone, the extension of the Colorado lineament across the Great Plains is adopted as a reasonable working hypothesis in this study.

The relationship between seismicity and tectonics in the southeast part of this zone is not clear. Three major structural elements; the Missouri gravity low (MGL), the Midcontinent gravity high (MCGH), and the Nemaha uplift; intersect in this area (see *Tectonics*). One (1979.06.30) of the relocated events and two widely felt, historic earthquakes (April 24, 1867 [39.5° N., 96.7° W.]; March 1, 1935 [40.3° N., 96.2° W.]) have epicenters in the general area of this intersection. This area is also characterized by a major, left-stepping offset in the Midcontinent gravity high. The epicenter ellipses of the two recomputed earthquakes (1961.12.25 [12:19:58, 12:58:16]) in the vicinity of Excelsior Springs, Mo., correlate spatially with the Missouri gravity low.

Four of the revised epicenters (1961.04.13, 1979.07.16, 1966.09.09, 1975.05.13) plotted in figure 17 locate along an apparent trend of epicenters that crosses central Nebraska from southwest to northeast. The proposed trend, which was first recognized by Steeples (1984) in the distribution of microearthquake epicenters, and a pair of northeast-striking faults in central Nebraska have nearly the same trend in this area (see fig. 17).

REVISED HYPOCENTERS IN THE GREAT LAKES ZONE

Figure 19 illustrates the Great Lakes Zone. This zone, which is not a recognized seismic zone (Nuttli and Herrmann, 1978), was established as a matter of convenience to relocate events that did not seem to fit into the other zones. Input to the JHD/JED computer runs for this zone consisted of data from only eight events. Three of these were teleseisms borrowed from adjacent zones to increase the sample size used in the estimates of the travel-time corrections and variances. The events considered also included three well-recorded chemical explosions in Lake Superior (1964.10.10 [08:30:01, 11:30:00], 1966.07.09), which provided additional high-quality data. The computed epicenters of these explosions are each within 5 km of the given locations (Bayer, 1966; Mansfield and Evernden, 1966), and in each case the corresponding epicenter ellipse covers the shot point. The two remaining events in this JED group were a magnitude-4.5 earthquake (1972.09.15) in northwest Illinois and a magnitude-4.6 earthquake near Morris in western Minnesota. The revised epicenters of these widely recorded shocks agree with the coordinates reported by Nuttli (1979) to within 0.05°.

SEISMOTECTONICS IN THE GREAT LAKES ZONE

Figure 19 also shows selected tectonic elements in the Great Lakes Zone. Prominent basement structures include the Colorado lineament (CL) proposed by Warner (1978), the Midcontinent gravity high (MCGH), which coincides with a Keweenawan rift zone (Chase and Gilmer, 1973; Ocola and Meyer, 1973), and a similar basaltic rift zone in eastern Illinois (Denison and others, 1984), which is herein called the La Salle rift zone (LSRZ). It should be emphasized that only selected structural features, those that seem pertinent to the description of seismotectonic relationships, are shown in the figure.

As depicted in the figure, the revised epicenter of the Morris, Minn., earthquake (1975.07.09) lies within the northeast extension of the Colorado lineament. As discussed in the previous section (see *Seismotectonics in the Northern Great Plains Zone*), when extended to Minnesota, the Colorado lineament coincides in part with a belt of shattered Archean rocks that Sims and others (1980) have described as the Great Lakes Tectonic Zone. Mooney (1979) and Mooney and Morey (1981) have indicated that most of the larger, historic earthquakes in Minnesota correlate with the Colorado lineament-Great Lakes Tectonic Zone. The focal mechanism of the Morris earthquake (1975.07.09)

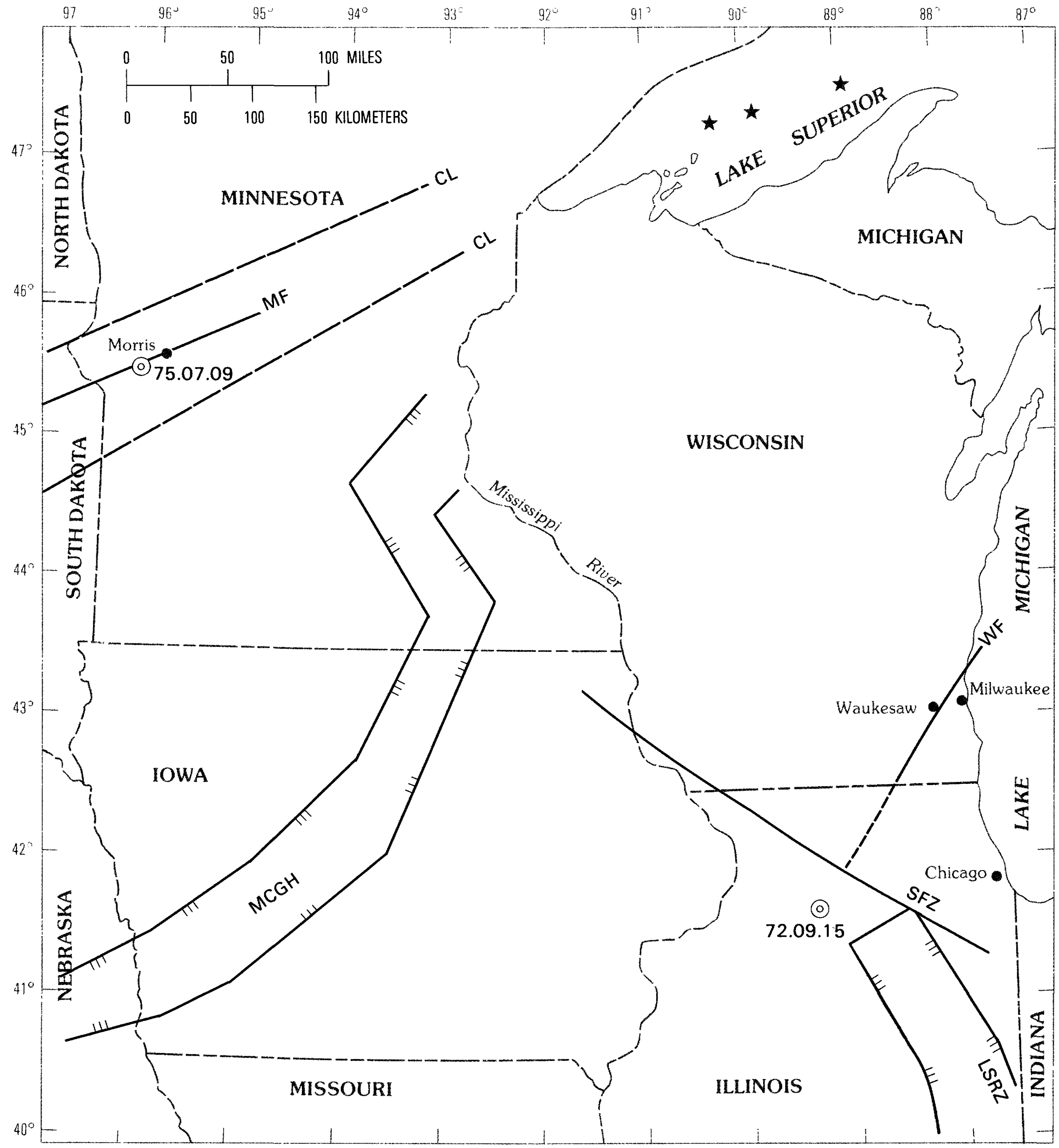


FIGURE 19.—Revised epicenters ($m_b(L_g)\geq 3.0$) and selected tectonic elements in the Great Lakes Zone. Lines with long dashes delimit the Colorado lineament (CL). Solid lines denote basement faults (short dashes where inferred). Morris fault (MF). Sandwich fault zone (SFZ). Waukesaw fault (WF). Lines with triple hachures delimit Proterozoic rift zones. Midcontinent gravity high (MCGH). La Salle rift zone (LSRZ). Stars designate chemical explosions in Lake Superior. Sources include Bayley and Muehlberger (1968), Denison and others (1984), Foley and others (1953), Mooney and Morey (1981), Sims and others (1980), and Warner (1978).

obtained by Herrmann (1979) implies strike-slip faulting. One of the associated nodal planes, which strikes N. 60° E. and dips 70° SE., is consistent with the orientation of the Morris fault (MF), a steep reverse fault that passes through Morris (Sims and others, 1980).

The relationship between the northern Illinois earthquake of 1972.09.15 and regional tectonics is enigmatic. As shown in figure 19, the Sandwich fault zone (SFZ), the La Salle rift zone (LSRZ), and an inferred extension of the Waukesaw fault (WF) of southeastern Wisconsin converge in the epicentral area of the 1972 northern Illinois earthquake.

Denison and others (1984) have mapped the Sandwich fault zone in the Precambrian basement. They show that the fault zone crosses northern Illinois and southwestern Wisconsin and continues into northeastern Iowa. The Sandwich fault zone displaces Paleozoic strata in northern Illinois, where it is composed of closely spaced, high-angle faults (Kolata and others, 1978). Maximum displacement across the fault zone in Illinois is about 240 m, down to the northeast.

The La Salle rift zone corresponds to an inferred subcrop of basaltic rocks in the Precambrian basement (Denison and others, 1984). The proposed 300-km-long rift zone begins in the Wabash Valley and ends in north-central Illinois near the epicenter of the 1972 earthquake (see fig. 25). The Paleozoic strata above this mafic igneous subcrop have been folded into a series of en echelon, north-south trending anticlines, which are collectively referred to as the La Salle anticlinal belt (McGinnis and others, 1976). A later section of this study will consider the spatial association of historic earthquakes and the proposed basaltic rift zone (see *Seismicity and Plate Tectonics*).

The Waukesha fault of southeastern Wisconsin is a high-angle fault which has a probable vertical displacement, down to the southeast, of about 30 m (Foley and others, 1953). Although some investigators (Cohee, 1961; King, 1967; King and Beikman, 1974) terminate this fault near the Wisconsin-Illinois border, Bayley and Muehlberger (1968) have mapped it as a 200-km-long basement fault that continues into north-central Illinois (Kuntz and Perry, 1976).

Herrmann's (1979) focal mechanism for the 1972 shock implies strike-slip faulting, either left-lateral slip on a nearly vertical east-west nodal plane or right-lateral slip on a steeply dipping nodal plane with strike N. 7° W. Neither of these nodal planes seems to correspond to possible fault planes associated with the structures delineated in figure 19. The nearly horizontal P-axis of Herrmann's solution trends N. 38° E., which is reasonably close to the orientation (N. 48° E.) of the maximum horizontal stress derived from hydraulic fracturing measurements in northwestern Illinois (Haimson and Doe, 1983).

REVISED HYPOCENTERS IN THE WEST TEXAS ZONE

The West Texas Zone illustrated in figure 20 corresponds to Texas south of latitude 33° N. and west of longitude 100° W. These boundaries were selected for convenience and do not refer to any recognized tectonic province or seismic zone.

GNOME, a nuclear explosion (1961.12.10) in an underground salt bed in southeast New Mexico, provided control for the computation of station-phase travel-time corrections in this zone. Arrival-time data for GNOME were furnished by Romney and others (1962). By including data from close-in, temporary stations the location of GNOME was held to within 0.03° in latitude and longitude of its known location during the JED runs. These temporary-station data were removed during the final, single-event computations. The resulting revised GNOME epicenter (32.24° N., 103.86° W.) is approximately 3 km south-southeast of the known shot point (32.26° N., 103.87° W.). The confidence ellipse of the single-event solution covers the shot point.

To improve the statistical quality of the computations, two relatively well-located earthquakes among a group of about a dozen, regionally recorded shocks in neighboring Chihuahua State, Mexico, were included in the JED input. The epicenters of the selected events (1963.09.13, 1969.10.19) in Mexico are shown in figure 20.

The Valentine earthquake (1931.08.16), a teleseism with m_b magnitude 5.8 and M_S magnitude 6.4 (Nuttli and Brill, 1981) is the largest event in this group. This earthquake, which was felt over an area of 1,400,000 sq km, caused extensive damage at Valentine. A large number of aftershocks were reported during a period of two months following the main shock (Sellards, 1932). Many of these aftershocks were felt at Valentine only. Figure 21 shows the isoseismals of the main shock, as interpreted by Sanford and Toppozada (1974), and a fiducial cross that indicates the major and minor axes of the confidence ellipse associated with the revised epicenter. The figure also contains various other, previously determined epicenters for the earthquake. These epicenters, which are relatively scattered, are as follows:

N. lat	*W. long*	*Source*
29.9°	104.2°	Neumann (1932)
30.9°	104.2°	Byerly (1934)
30.69°	104.57°	Dumas and others (1980)
30.50°	104.58°	this study

The original epicenter for the 1931 shock (Neumann, 1932), as indicated by the asterisk in figure 21, is about 80 km south of Valentine. This epicenter represents a graphical solution based on data from 20 stations. Byerly (1934) used P-wave arrivals covering the distance range from 5.8° to 16.4° to determine his epicenter, which is designated by the star symbol about 45 km northeast of Valentine in the figure. He assumed a linear travel-time curve with an apparent velocity of 8 km/sec

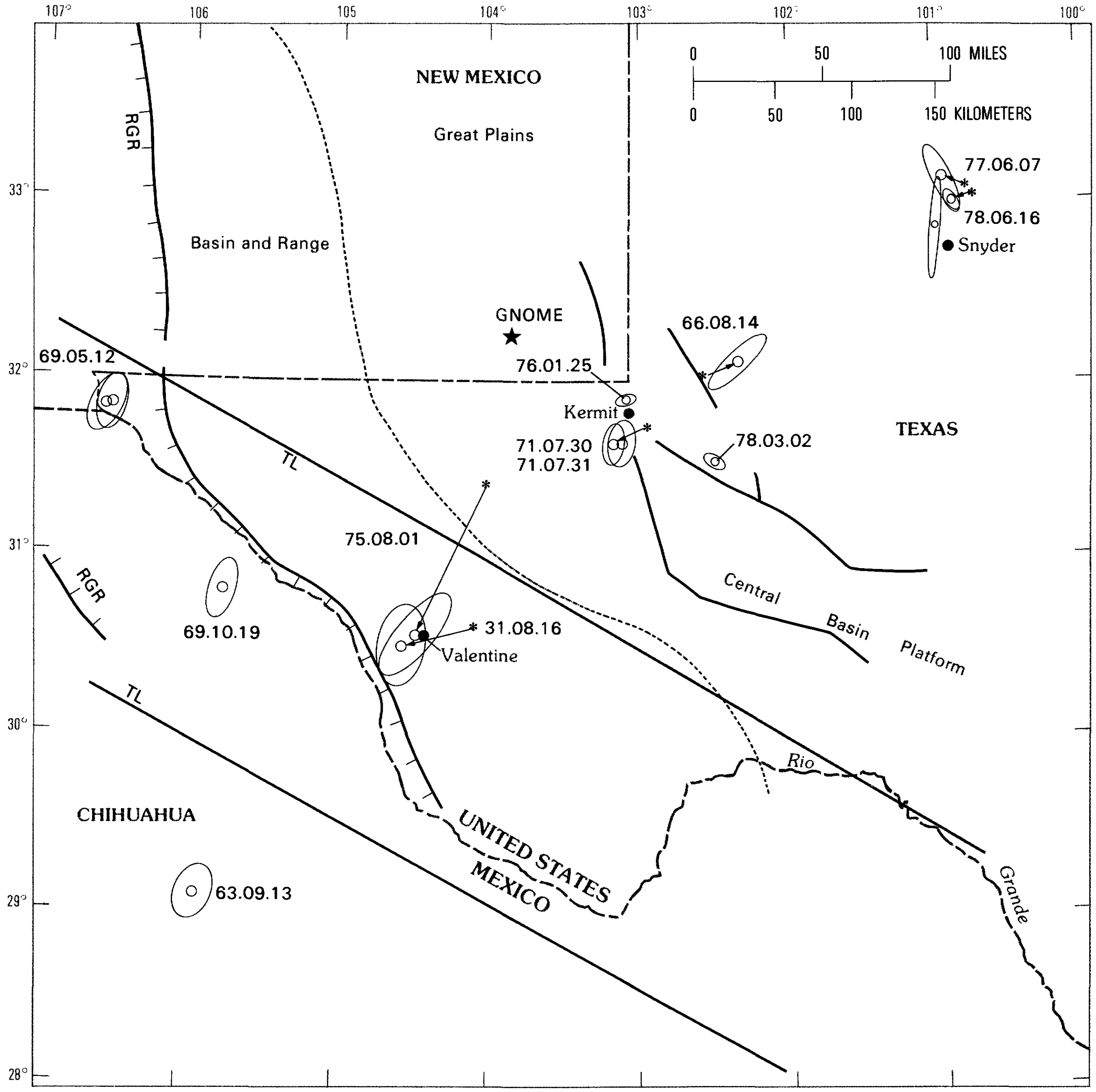


FIGURE 20.—Revised epicenters ($m_b(L_g) \geq 3.0$) and selected tectonic elements in the West Texas Zone. Previously accepted epicenters (asterisks). Relocation vectors (arrows). Revised epicenters (circles). The dotted line separates the Basin and Range province from the Great Plains province. Faults (heavy, solid lines) in the Central Basin platform after Bayley and Muehlberger (1968). Approximate boundaries (long, straight lines) of the Texas lineament (TL) after Warner (1978). The lines with hachures delimit the Rio Grande rift (RGR), as generalized from Seager and Morgan (1979). The star designates GNOME, an underground nuclear explosion (1961.12.10) in southeast New Mexico. The two epicenters (1963.09.13, 1969.10.19) in Chihuahua (Mexico) represent events added to the JED computations to enlarge the statistical sample. The seismic coverage is incomplete in Mexico for the time interval and magnitude range considered.

in his determination. The recent relocation by Dumas and others (1980), indicated by the solid triangle in the figure, moved the epicenter closer to Valentine, where the 1931 earthquake caused extensive damage. In their recomputation, an application of the master event method (Dewey, 1979), Dumas and others (1980) used travel-time residuals from GNOME as station corrections for the 1931 earthquake.

After locating all events in this zone by the calibration-station method, the calibration-event method

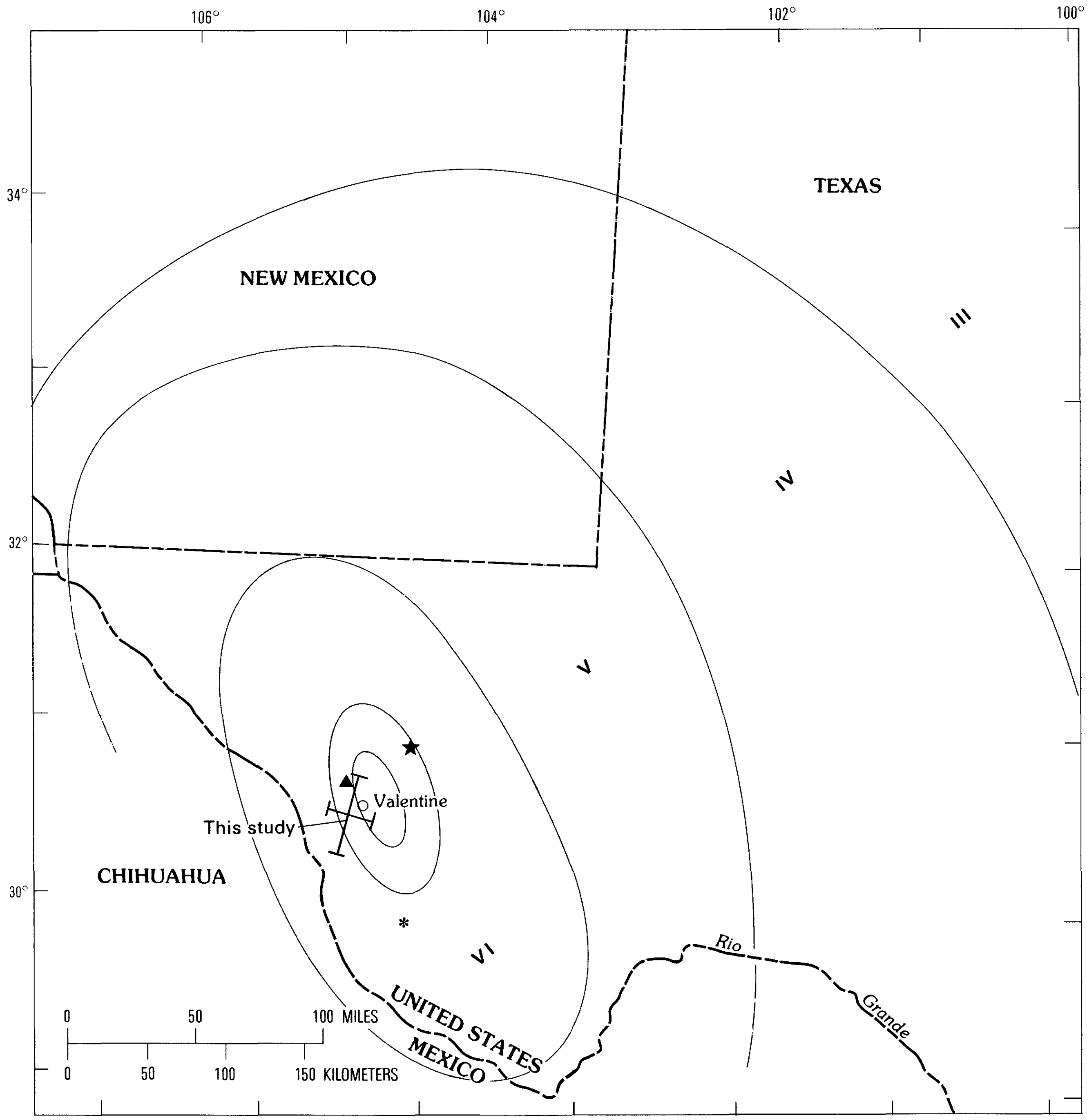


FIGURE 21.—Modified Mercalli (MM) isoseismals and previously determined epicenters of the 1931 earthquake near Valentine, Texas. The fiducial cross corresponds to the axes of the epicenter ellipse of the location obtained in this study. The other epicenters are those reported by Neumann (1932) [asterisk], Byerly (1934) [star], and Dumas and others (1980) [solid triangle]. Isoseismals after Sanford and Toppozada (1974).

was applied to relocate two clusters of earthquakes, one near Snyder and the other near Kermit (fig. 20). Dense seismograph networks have been deployed in both of these areas to study possible relationships between seismicity and secondary recovery operations in oil fields (Harding and others, 1978; Rogers and Malkiel, 1979). Rebecca Dodge (unpub. report, 1980) furnished readings at regional WWSSN stations for these two groups of earthquakes.

THE KERMIT SUBZONE

Eight relatively small earthquakes within about 70 km of Kermit were relocated by the calibration-event method.

The epicenters of five of these events (1966.08.14, 1971.07.30, 1971.07.31, 1976.01.25, 1978.03.02), those with magnitude ≥3.0, are plotted in figure 20.

Data from a local network of 12 portable seismograph systems supplemented the permanent stations data in relocating the most recent events in this group (Rogers and Malkiel, 1979; Keller and others, 1981). More than 1,300 microearthquakes were located with the use of data from this network during its period of operation, December 1975 to September 1979. The hypocenters of the four events (1976.01.19, 1976.01.25, 1977.04.26, 1978.03.02) that were located by Keller and others (1981) and that also were relocated in this study, do not differ significantly. One of these, the magnitude-3.3 earthquake on 1976.01.25, served as the calibration event in the JED computations.

As shown in figure 20, the revised epicenter of the 1966.08.14 earthquake is about 80 km northeast of Kermit. This shock was reported as damaging (VI) at Kermit, where it broke windows and knocked down street signs (von Hake and Cloud, 1968). It was reported felt at only two other localities, Wink, 12 km south of Kermit, and Loco Hills, N. Mex., approximately 135 km northwest of Kermit. If instrumental data are not considered, the felt information suggests that this shock was centered very close to Kermit. However, the instrumental data rule out an epicenter near Kermit for this event.

THE SNYDER SUBZONE

The calibration-event method was applied to relocate five earthquakes (1977.06.07, 1977.11.28, 1978.06.16 [11:46:56, 11:53:33], 1979.07.05) with epicenters about 25 km north of Snyder, Tex. These events belong to a series of small earthquakes in 1977–79 which were spatially associated with the Cogdell Canyon Reef oil field (Dumas 1979; Harding, 1981). Figure 20 contains the revised epicenters of the four events in this group with magnitude ≥3.0. The main shock of the series (1978.06.16 [11:46:55]) was selected as the calibration event in the JED calculations.

Using an array of portable seismographs, Harding (1981) located 20 microearthquakes in this area between May 1979 and March 1980. His microearthquake epicenters delineate a 4-by-6-km area (32.94° N. to 32.98° N., 100.88° W. to 100.92° W.) on the northwest flank of the Cogdell Canyon Reef oil field. Most of the computed focal depths of the microearthquakes were less than 2.0 km.

With one exception, the confidence ellipses of the revised epicenters intersect the rectangular area containing most of Harding's (1981) microearthquakes. The exception corresponds to the most poorly located event in the group, an aftershock (1978.06.16[11:53:33]) that occurred about six minutes after the main shock on June 16, 1978. The revised epicenters associated with the smallest confidence ellipses (1977.11.28, 1978.06.16 [11:46:56]) correlate spatially with the Cogdell Canyon Reef oil field.

SEISMOTECTONICS IN THE WEST TEXAS ZONE

Figure 20 also illustrates spatial relationships between the revised epicenters and regional tectonics in West Texas. The strongest shock relocated in this zone, the 1931.08.16 Valentine earthquake, occurred in the Basin and Range province, a subdivision of the great cordillera of western North America. Although discussion of the Basin and Range province is beyond the scope of this investigation, an exception will be made to briefly describe the geologic setting of this important earthquake. Consideration of the 1931 shock will first concern the regional tectonic environment of the earthquake and then turn to an examination of possible association between the earthquake source and local structure. A short account of recent earthquake occurrence in the Snyder and Kermit areas will conclude this section.

With respect to regional tectonics, the revised epicenter of the 1931 Valentine earthquake correlates spatially with the Texas lineament and also, possibly with the Rio Grande rift (see fig. 20). The continental-scale Texas lineament evidently represents an extensive Precambrian shear zone (Swan, 1975). Although the origin of the lineament remains somewhat obscure, Muehlberger (1980) believed that it resembles the Colorado lineament with regard to structural style (see *Tectonics*). The lineament apparently has been reactivated several times in the geologic past. Wood and Walper (1974) have described right-lateral slip in late Paleozoic time along the lineament. The revised 1931 epicenter also falls very close to the northeast side of the southeasterly extension of the Rio Grande rift into Mexico and West Texas proposed by Seager and Morgan (1979). The Rio Grande rift, which begins in central Colorado and extends through central New Mexico, is a Cenozoic feature characterized as a zone of geologically young faulting, volcanism, deep sedimentary basins, and high heat flow (Seager and Morgan, 1979). As shown in figure 20, the trend of the rift changes abruptly from southerly to southeasterly where it intersects the Texas lineament in southern New Mexico and West Texas. This sharp bend in the trend of the rift suggests that the lineament has influenced the location of the rift, a much younger geologic feature than the lineament.

The 1931 epicenter possibly is associated with local structure. Figure 22 shows the physical setting of the

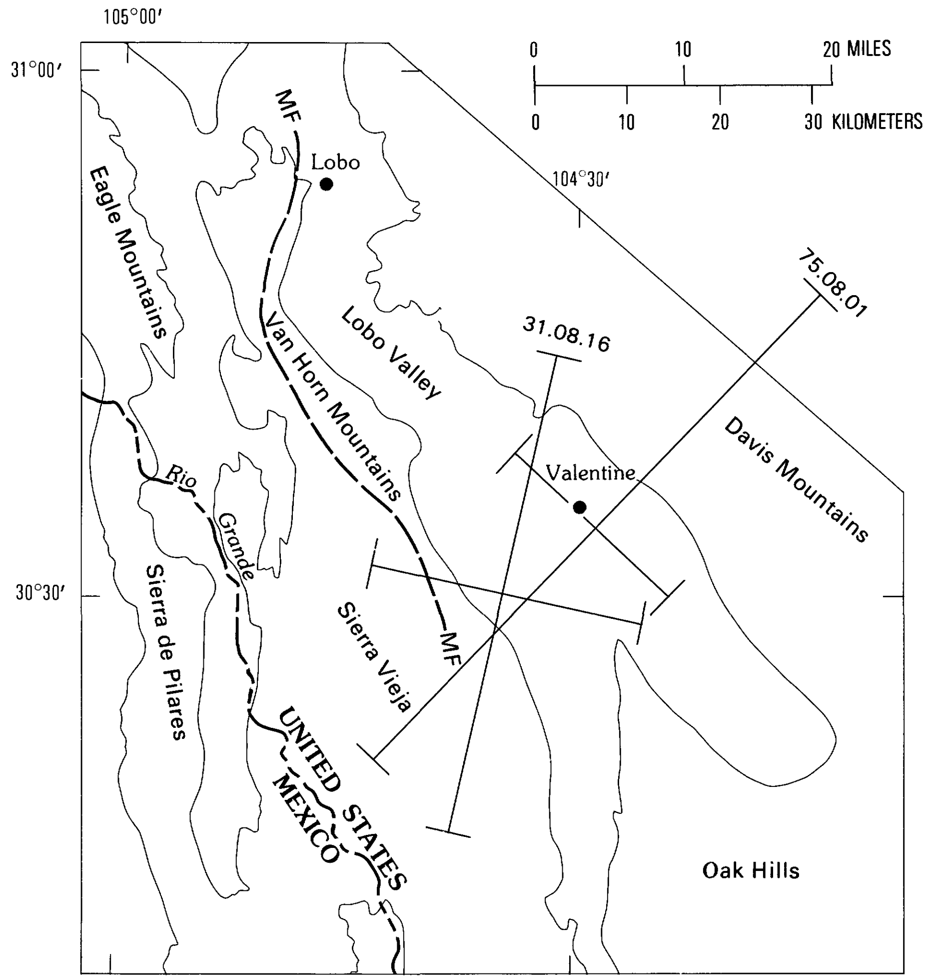


FIGURE 22.—Physical setting of the 1931 earthquake near Valentine, Texas. The large crosses indicate the major and minor axes associated with the epicenter ellipses of the 1931.08.16 and 1975.08.01 earthquakes. A continuous fault scarp, the Mayfield fault, indicated by the dashed line marked MF, coincides approximately with the southwest boundary of the Lobo Valley from Lobo to a point about 20 km southwest of Valentine (Muehlberger and others, 1978).

Valentine earthquake. As shown in the figure, the revised epicenter of the 1931 shock is located approximately 12 km southwest of Valentine within a northwest-trending alluvial basin, the Lobo Valley. The epicenter ellipse of the 1931 event intersects the trace of the Mayfield fault, a steeply dipping fault with northwest strike marked by geologically young fault scarps along the western side of the valley. Muehlberger and others (1978) have described evidence of recurrent movement on the Mayfield fault about 20 km west-southwest of Valentine. At this locality, an older surface at the base of a receding fault scarp in alluvium has been broken by two, younger, en echelon, fault scarps with displacements of 1.5 and 7.0 m.

Sanford and Toppozada (1974) obtained a focal mechanism for the Valentine earthquake based on P-wave first motions that implies normal faulting. In their solution, the preferred fault plane strikes N. 40° W. and dips 74° SW. Using essentially identical data, Dumas and others (1980) presented an alternate mechanism that indicates right-lateral, strike-slip faulting. In their solution the preferred fault plane strikes N. 59° W. and dips 70° NE., and the auxiliary plane strikes N. 36° E. and dips 70° SE. The strike (N. 59° W.) of one of these nodal planes nearly agrees with the trend (N. 60° W.) of the Texas lineament in this area. In both solutions, the axis of least principal stress is approximately horizontal and is oriented east-west.

The available data suggest that the hypocenter of the 1931 earthquake was very close to Valentine, and that small, infrequent shocks have been associated with this source since 1931. As mentioned previously, the 1931 earthquake was most damaging at Valentine and many of the aftershocks which followed were felt only at Valentine. On January 17, 1955, a small earthquake was felt with intensity IV at Valentine (Murphy and Cloud, 1957). No other locality felt the shock. As shown by their overlapping confidence ellipses in figures 20 and 22, the epicenters of the 1931 earthquake and another small, relocated shock (1975.08.01) are indistinguishable. Dumas and others (1980) located another event, which occurred on July 13, 1978, with an estimated magnitude of 2.6, at 30.50° N. and 104.55° W. This is essentially the same location as the relocated 1931 earthquake. The geologically youthful fault scarps on the west side of the Lobo Valley, the numerous aftershocks in 1931 that were felt only at Valentine, the locations of small shocks in 1955, 1975, and 1978, and the associated focal mechanism all suggest that the hypocenter of the 1931 earthquake was beneath the Lobo Valley southwest of Valentine. The 1931 earthquake may have been the result of a small displacement of the Mayfield fault or a nearby, parallel fault.

The five relocated earthquakes (1977.06.07, 1977.11.28, 1978.06.16 [11:46:56, 11:53:33], 1979.07.05) near Snyder, Tex. (see fig. 20), are spatially associated with the Cogdell Canyon Reef oil field, which has been undergoing water flooding since 1956 (Harding, 1981). Voss and Herrmann (1980) have derived a focal mechanism indicating normal faulting on a northeast-striking fault plane for the largest of these shocks, a magnitude-4.6 teleseism (1978.06.16 [11:46:56]).

Rogers and Malkiel (1979) and Keller and others (1981) have discussed the intensive microearthquake investigation in the Kermit vicinity carried out during a 3-½ year period. Their results indicate that seismicity in this area correlates spatially with oil and gas fields and pre-Permian faults that bound the Central Basin platform (fig. 20). Their findings also suggest an increase in seismicity with increased water-flood activity and increased injection pressure. They concluded that the microearthquakes, which occur at very shallow depths, are probably related to hydrocarbon production. Their composite focal mechanisms, based on the microearthquake data, indicate normal faulting. In figure 20, the five revised epicenters near Kermit appear to be associated with the east and west sides of the Central Basin platform. Gravity and magnetic data indicate that a major mafic igneous mass exists beneath the Central Basin platform (Keller and others, 1981). Walper (1977) proposed that the Central Basin platform and the adjacent Delaware basin are the principal remnants of the Delaware aulocogen, the failed rift arm of a late Precambrian triple junction.

REVISED HYPOCENTERS IN THE GULF ZONE

The Gulf Zone is included in this study because it covers an area, part of the continental shelf, that is structurally continuous with the Gulf Coastal Plain.

Only four earthquakes (1960.11.10, 1963.11.05, 1978.07.24, 1980.01.10) with sufficient associated arrival-time data to warrant relocation were found in this zone. Although an individual map was not prepared to illustrate this zone, the epicenters of the four relocated earthquakes can be seen on the seismic zone map (fig. 2).

Most of the interpretation of Gulf Zone seismicity discussed here is based on an investigation by Frohlich (1982), who relocated and determined the focal mechanism of the 1978.07.24 event, a magnitude-4.9 teleseism.

JED runs in the calibration-station mode were carried out using data from the four earthquakes and the SALMON (1964.10.22) nuclear explosion in nearby southern Mississippi. Input data from seven, close-in, temporary stations were used to restrain the SALMON hypocenter during the JED computations. In these runs the focal depths of all of the earthquakes were fixed at 15 km, the focal depth of the 1978.07.24 teleseism reported by Frohlich (1982).

Only one of the earthquake relocations, the epicenter of the event on 1978.07.24, was relatively precise. Due to poor station distribution, the semi-major axes of the epicenter ellipses of the other three earthquakes were each greater than 50 km in length. Therefore, the only meaningful result from this zone was the relocation of the July 24, 1978, teleseism using SALMON to constrain the travel-time corrections. The resulting epicenter does not differ significantly from the carefully determined location reported by Frohlich (1982).

The focal mechanism representing this teleseism (1978.07.24) indicates thrust faulting with the maximum stress axis directed approximately northwest-southeast. Frohlich (1982) suggested that this earthquake and another nearby teleseism (1960.11.10) were caused by the accumulation of sediments at the seaward edge of the Mississippi fan.

STATISTICS

This section concerns differences between the coordinates of the old and new hypocenters, the accuracy of the relocated hypocenters, comparison of the revised magnitudes with previously determined magnitudes, and the completeness of the catalog of relocated earthquakes. The section will begin with a statistical review of the differences between the revised hypocenters and previously accepted hypocenters and then will turn to estimates of the absolute errors of the relocated hypocenters. Epicenter accuracy will be estimated by comparing the coordinates of events with known or independently determined locations with the corresponding revised epicenters. Similarly, explosions and earthquakes with independently estimated focal depths will be used to test the reliability of the computed focal depths. Next, the magnitudes determined in this study will be compared with magnitudes previously determined by others for the same events. Finally, the magnitude threshold marking the lower limit of the completeness of the catalog of revised hypocenters will be estimated.

OLD AND NEW HYPOCENTERS

Differences between the revised epicenters and previously accepted epicenters will be considered first in this section and then the revised and the formerly assigned focal depths will be compared.

Table 2 summarizes the differences between the revised epicenters and the corresponding previously accepted locations. This comparison was made with respect to the approximately 200 earthquakes with $m_b(L_g) \geq 3.0$ listed in the appendix. The former locations considered were those given by Nuttli (1979) for the period through 1975 and epicenters listed in the EDR's for the period 1976 to 1980. Because most of the previous locations are stated only to the first decimal place, all epicentral coordinates were rounded to the nearest 0.1° for comparison purposes. The first column in the table indicates the maximum difference in latitude or longitude between the old and new epicenters. The next two columns show the percentages of the old epicenters that are or are not covered by the nominal 95-percent-confidence ellipses associated with the revised epicenters. The table indicates that about 24 percent of the events considered belong to the intersection of two sets: (1) the set associated with cases in which the old and new epicenters differ by 0.2° or more in latitude or longitude, and (2) the set of cases in which the associated confidence ellipse fails to cover the old epicenter.

The causes of the differences between the old and new epicenters include the following: (1) the original solution was essentially a macroseismic epicenter, (2) the previously assigned solution was based entirely on data from a local network that did not surround the epicenter (epicenter exterior to network used in solution), and (3) the original epicenter was changed by adding more station data to the solution. Miscellaneous causes of mislocations of the old epicenters included poor resolution associated with graphical solutions, typographical errors, and uncorrected regional travel-time bias. In a few cases discrepancies arose because some of the early, less well-located epicenters were originally given to the nearest whole degree of latitude and longitude.

In this study two categories of assigned focal depth are considered to be well determined. These are defined as follows: (1) focal depth associated with free-depth solutions where the most nearly vertical axis of the corresponding confidence ellipsoid has a semi-length of 10 km or less, and (2) focal depth fixed at 1.0 km where the major axis of the corresponding confidence ellipse has a semi-length of 10 km or less. This second category refers to situations where free-depth computations failed to converge on a positive valued focal depth; that is, successive iterations alternated between positive and negative valued focal depth. As mentioned previously, these solutions were rerun with focal depth restrained to 1.0 km (see *Computational Procedures and Options*).

Figure 23 shows the relative distribution of 80 revised focal depths that are considered well determined.

TABLE 2.—*Comparison of the revised and the previously accepted epicenters*

Difference*	Percent coverage**	
	Yes	No
0.0°	25	2
0.1°	27	21
0.2°	1	12
0.3°	0	4
0.4°	0	4
≥0.5°	0	4

*Maximum difference in latitude or longitude between old and new epicenters. All coordinates rounded to nearest 0.1°.

**Percentages of epicenters in which the nominal 95-percent-confidence ellipse associated with the revised epicenter does (Yes) or does not (No) cover the old location.

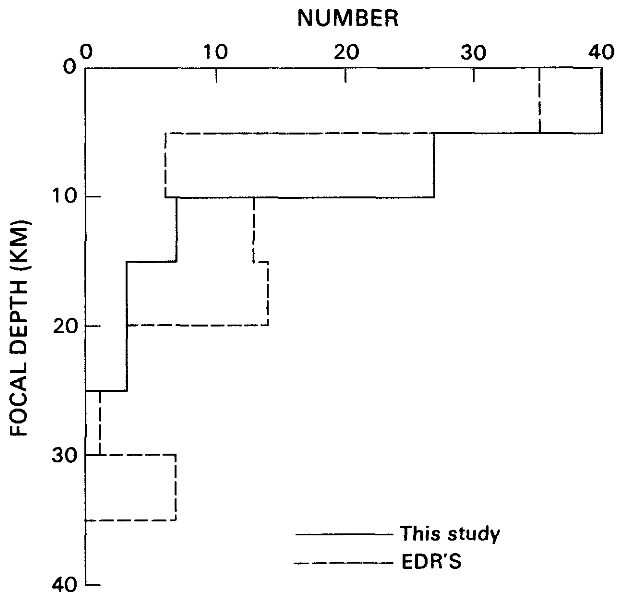


FIGURE 23.—Distribution of well-determined focal depths obtained in this study compared to the distribution of focal depths given in the EDR's for the same events. Two classes of focal depths were considered well determined: (1) free depth solutions where the steepest axis of the associated confidence ellipsoid had a semi-length of 10 km or less, and (2) cases in which depth was restrained to 1.0 km in the final solution, and the major axis of the corresponding confidence ellipse had a semi-length of 10.0 km or less.

Almost 85 percent of these events have focal depths of 10 km or less. The figure also shows the distribution of the focal depths originally assigned to this suite of earthquakes in the *Earthquake Data Reports.* In contrast to the revised hypocenters, nearly one-half of these previously published focal depths are greater than 10 km. Ten of the events that were assigned so-called "normal" focal depths (25 or 33 km) in the EDR's have revised focal depths of less than 10 km. Nearly all of the well-determined focal depths represent solutions that include close-in data recorded by recently deployed, local networks, such as the Central Mississippi Valley Network (see fig. 4).

HYPOCENTER ACCURACY

In this section events with known or independently determined source coordinates will be used to evaluate the accuracy of the revised hypocenters. The test events that will be considered include explosions, rockbursts, earthquakes located by dense temporary networks, and events assumed to have locations within areas outlined by well-located aftershocks. Epicenter accuracy will be considered first and then the reliability of the focal depths will be considered.

Table 3 lists 20 events with known or independently determined epicenters that were considered in the analysis of epicenter accuracy. The independently determined epicenters of these events are considered to be within at least several kilometers of the true epicenters. Nine of these events were explosions. The remaining events include a possible rockburst (1970.07.06) near Leadwood, Mo., and three earthquakes (1979.07.05, 1980.07.31, 1980.08.25) independently located by close-in, temporary networks. In the table, the true epicenters of two earthquakes (1978.06.16 [11:46:56, 11:53:33]) near Snyder, Tex., and the true epicenter of the Sharpsburg, Ky., earthquake (1980.07.27) were assumed to lie within areas outlined by well-located aftershocks (Harding, 1981; Herrmann and others, 1982). The village of Tamms was assumed to be the true epicenter of four small earthquakes in southern Illinois on August 14 and 15, 1965, that were felt over only a few hundred sq kilometers (Nuttli, 1965). In the table the revised epicenters are considered "consistent" if the associated epicenter ellipse covers the independently determined epicenter. Conversely, they are considered "not consistent" if the epicenter ellipse does not cover the assumed true epicenter. In the situation where the true epicenter was assumed to fall within an area outlined by aftershocks, "consistent" means that the epicenter ellipse intersects the area delineated by the aftershocks. As indicated in the table, the epicenter ellipses cover the known or independently assumed locations in 17 out of 20, or 85 percent of the cases. This ratio of agreement between the "true" and revised locations agrees reasonably well with the nominal 95-percent-confidence level associated with the epicenter ellipses (see *Weights and Confidence Regions*).

The results of the empirical accuracy tests suggest that the computational procedures performed in this study have removed most of the effects of travel-time bias from the revised epicenters. From these tests, it is reasonable to assume that the true epicenters of 85–95 percent of the relocated events are enclosed by the corresponding epicenter ellipses. However, a note of caution must be expressed concerning this general interpretation of the epicenter ellipses. A similar test of epicenter accuracy with respect to relocated earthquakes in the eastern United States revealed that the 95-percent-confidence ellipses covered the known epicenters in only 75 percent of the cases considered (J. W. Dewey and D. W. Gordon, unpub. report, 1983). Because these two studies were performed in a similar manner, there is no particular reason to expect that the central United States relocations are more accurate than the revised epicenters in the eastern United States.

TABLE 3.—*Analysis of epicenter accuracy*

Date	Time (GMT)	Zone or subzone	Type*	Consistent**	Remarks***
1961.12.10	19:00	W. Texas	X	Yes	GNOME
1963.06.28	10:00	Tiptonville	X	Yes	BILLIKEN
1964.10.10	08:30	Great Lakes	X	Yes	L. Superior
..Do......	11:30	..do.......	X	Yes	..Do..........
1964.10.22	16:00	S. Miss. Valley	X	Yes	SALMON
1965.08.14	05:04	Tamms	FA	Yes	....
..Do......	05:46	..do.......	FA	Yes	....
..Do......	13:13	New Madrid	FA	Yes	....
1965.08.15	06:07	Tamms	FA	Yes	....
1966.07.09	09:30	Great Lakes	X	Yes	L. Superior
1970.07.06	09:39	Ironton	R	No	....
1975.01.10	15:31	..do.......	X	Yes	Pea Ridge mine
1976.03.13	07:25	..do.......	X	Yes	..Do..........
1976.12.11	07:05	..do.......	X	Yes	..Do..........
1978.06.16	11:46	Snyder	AZ	Yes	....
1978.06.16	11:53	..do.......	AZ	No	....
1979.07.05	01:05	..do.......	L	No	....
1980.07.27	18:52	Kentucky	AZ	Yes	....
1980.07.31	09:27	..do.......	L	Yes	..Do..........
1980.08.25	11:41	..do.......	L	Yes	..Do..........

*Type of independent epicenter estimate: X=explosion; FA=location of maximum intensity within small felt area; R=possible rockburst; AZ=aftershock zone delineated by locally deployed, temporary staions; L=independent solution obtained by dense, local network.

**Yes or no in the consistent column means that the 95-percent-confidence ellipse does or does not cover the independently known epicenter.

***Name or geographic location of explosion.

In addition, the explosions and earthquakes used in the tests of epicenter accuracy were well-recorded events that usually received special attention and may represent "best" cases. Examination of "worst" cases, those events with large epicenter ellipses listed in the appendix, reveals that epicenter ellipses with semi-major axes more than 30 km in length are associated with meager numbers of observations. Typically, epicenter ellipses of this size are represented by three P-wave observations and about seven secondary phase readings. The small number of *P* readings and the high weight assigned to such observations in the computations make the corresponding epicenters subject to mislocation due to a gross error in one *P* reading.

As indicated in table 4, 28 events with known or independently estimated focal depths were available to test the reliability of the computed focal depths. Most of the known or independently estimated focal depths represent explosions with near-surface foci or earthquakes with focal depths independently derived from surface-wave spectra (Herrmann, 1979; Voss and Herrmann, 1980; Herrmann and others, 1982). Free-depth solutions converged to positive valued focal depths for 19 of the events listed in the table. In 17 of these cases, the differences between the known focal depths and the computed values were less than the corresponding confidence intervals (see *Weights and Confidence Regions*). Nine of the cases listed in the table involved free-depth solutions that failed to converge on positive valued focal depths. Eight of these cases were associated with explosions or other very shallow events. Although there is, in general, good agreement between the computed and known focal depths in the table, the associated confidence intervals reveal the lack of precision characteristic of many of the focal-depth estimates.

MAGNITUDES AND COMPLETENESS

The magnitudes assigned to the events listed in the appendix represent, to as great an extent as possible, $m_b(L_g)$ magnitudes (Nuttli, 1973) measured on WWSSN film chips or instrumentally determined $m_b(L_g)$ magnitudes obtained from published sources. About one-half of the listed magnitudes were obtained by measuring L_g phase amplitudes on WWSSN film chips. Magnitudes based on felt area (Nuttli and Zollweg, 1974), which make up approximately 10 percent of the

TABLE 4.—*Comparison of the computed and known focal depths*

Date	Origin time (GMT)	Zone or subzone	Type*	Known focal depth (km)	Computed focal depth** (km)	Confidence interval*** (km)
1961.12.10	19:00	W. Texas	X	0.0	(18.4)	±16.3
1962.02.02	06:43	Tiptonville	EQ	7.5	3.5	±6.1
1963.03.03	17:30	..do.......	EQ	15.0	9.2	±17.9
1963.06.28	10:00	..do.......	X	0.0	(2.9)	±4.3
1964.10.10	08:30	Great Lakes	X	0.0	(1.9)	±41.6
..Do......	11:30	..do.......	X	0.0	(-10.2)	±52.8
1965.08.14	13:13	New Madrid	EQ	1.5	(-5.3)	±8.2
1965.10.21	02:04	Ozark	EQ	5.0	7.3	±5.4
1966.07.09	09:30	Great Lakes	X	0.0	(-6.6)	±63.4
1967.06.04	16:14	Ouachita	EQ	12.0	5.9	±18.9
1967.07.21	09:14	Ironton	EQ	15.0	12.1	±9.1
1968.11.09	17:01	Eldorado	EQ	22.0	21.2	±18.4
1969.01.01	23:35	Ouachita	EQ	7.0	(27.8)	±35.5
1970.07.06	09:39	Ironton	R	0.0	(-3.8)	±5.0
1970.11.17	02:13	Blytheville	EQ	16.0	14.3	±5.5
1972.09.15	05:22	Great Lakes	EQ	13.0	10.5	±16.5
1974.02.15	13:33	Wichita	EQ	10.0	0.1	±14.5
1974.04.03	23:05	Eldorado	EQ	15.0	13.5	±9.4
1975.01.10	15:31	Ironton	X	0.0	(-5.4)	±5.1
1975.06.13	22:40	New Madrid	EQ	9.0	8.5	±5.8
1975.07.09	14:54	Great Lakes	EQ	7.5	(-1.1)	±28.1
1976.03.13	07:25	Ironton	X	0.0	(-2.9)	±4.1
1976.03.25	00:41	Blytheville	EQ	12.0	16.5	±2.9
..Do......	01:00	..do.......	EQ	16.0	13.6	±3.0
1976.12.11	07:05	Ironton	X	0.0	(-1.3)	±7.6
1978.06.16	11:46	Snyder	EQ	3.0	3.4	±11.0
1980.07.12	23:59	Kentucky	X	0.0	(-2.3)	±15.3
1980.07.27	18:52	..do.......	EQ	12.0	6.4	±15.4

*Type of event: X=explosion; R=possible rockburst; EQ=earthquake.

**Focal depths in parentheses were later recomputed with fixed focal depth.

***Confidence interval, the projection on the depth coordinate of the semi-length of the steepest axis (the depth axis) of the 90-percent-confidence ellipsoid, multiplied by 0.78 to make the interval have a nominal 95-percent level of confidence (J. W. Dewey and D. W. Gordon, unpub. report, 1983).

total, are denoted by the letter F in the catalog (appendix). The remainder of the magnitudes in the appendix were taken from published papers or seismological bulletins.

Each of the instrumental $m_b(L_g)$ magnitudes determined in this study represents the mean of individual determinations at a minimum of three WWSSN stations. Magnitudes measured at stations west of the Rocky Mountains were not considered in the calculations of mean magnitudes because, due to higher attenuation in the western region, magnitudes estimated at these stations were consistently low. A compilation of the epicentral distances involved in the magnitude estimates shows that about 35 percent of the individual magnitude measurements considered in the averages represent epicentral distances greater than 10°. Wave periods associated with the L_g phases corresponding to $m_b(L_g)$ estimates usually fell within the 0.6 to 1.0 sec range (Gordon, 1983). In actual conversion of trace amplitude and period to $m_b(L_g)$ magnitudes, a period of 0.8 sec was assumed in each case. This decision was not critical because, due to the logarithmic nature of the magnitude scale, the response characteristics of the WWSSN short-period system, and the division by the period in the magnitude conversion formula (see *Magnitude Computations*), computed magnitudes are relatively insensitive to period. For example, for a given trace amplitude, periods in the range 0.6 to 1.0 sec give rise to $m_b(L_g)$ values that differ by less than 0.05 magnitude units.

Table 5 compares the $m_b(L_g)$ magnitudes determined in this study with other published magnitudes. The largest discrepancy evident in the table involves differences between the assigned $m_b(L_g)$ values and magnitudes reported in *United States Earthquakes* from 1962 through 1973. This discrepancy, approximately 0.5 magnitude units, is shown in the first line of the table. Part of this disagreement stems from the use of inappropriate attenuation factors in the computation of magnitudes for central United States events during this period (Nuttli, 1973). Magnitude reporting practices improved after 1973 when most seismologists began to apply the $m_b(L_g)$ scale defined by Nuttli (1973) to earthquakes in the region. The last two entries in the table refer to the same set of events, a group of small earthquakes near Kermit in West Texas.

Seismologists have observed that earthquake occurrence over a given time interval with respect to a given region obeys the relationship

$$\text{Log}_{10}N = a - bM$$

where N is the cumulative frequency of earthquakes with magnitude M or greater and a and b are constants (Richter, 1958). Investigations of the completeness of earthquake catalogs focus on the determination of the magnitude threshold that marks the lower magnitude level at which $\text{Log}_{10}N$ departs from linearity.

Figure 24 is a magnitude-frequency plot covering the earthquakes listed in the catalog (appendix). Two sets of data are shown in the figure: (1) the triangles correspond to the time interval 1931 through 1980, and (2) the circles refer to 1964 through 1980. Although both sets of data in the figure exhibit approximately linear trends with slopes of about 1.0, the data are highly scattered and only crude estimates of completeness can be made. The data associated with the period 1931 through 1980 appear to depart from linearity at about the magnitude-4.2 level, whereas data corresponding to 1964–80 suggest that the threshold of completeness lies within the 3.3–3.7 magnitude range. Neither of the above estimates of completeness is very convincing. The data sample considered may be too small and heterogeneous to provide satisfactory estimates of completeness.

Table 6 is another approach to the determination of the completeness of the relocated event catalog (appendix). This table compares the catalog of relocated events to a listing by Nuttli and Brill (1981) of all known felt or instrumental earthquakes in the region with magnitude ≥3.0 covering the period through 1977. The percentages of known earthquakes in the period 1931 through 1977 that were relocated are listed in the table. The data listed for the period 1931 through 1963 indicate that only about 70 percent of the known earthquakes with magnitude ≥4.5 were relocated. The percentage of relocated events actually decreases with respect to previous estimates for most magnitude categories during the interval 1943 through 1949. The

TABLE 5.—*Comparison of $m_b(L_g)$ magnitudes estimated in this study with other reported magnitudes*

Test mag. type	Mean diff.*	Standard deviation	Number	Data source
m_b+	-0.49	0.77	31	U.S. Earthquakes (1962-1973)
$m_b(L_g)$	-0.19	0.26	32	U.S. Earthquakes (1974-1980)
$m_b(L_g)$	-0.12	0.25	30	Street and others (1975)
m_b**	-0.18	0.25	26	Nuttli and Brill (1981)
m_b***	0.00	0.10	9	Nuttli (1973)
m_b***	+0.26	0.33	10	Earthquake Data Reports
$m_b(L_g)$	-0.25	0.24	8	Rogers and Malkiel (1979)
M_L	+0.20	0.19	7	Sanford and others (1978)

+Includes a few M_S and M_L estimates.

*Magnitude from this study minus test magnitude.

**Felt area magnitude (Nuttli and Zollweg, 1974).

***Body-wave magnitude measured at teleseismic distances.

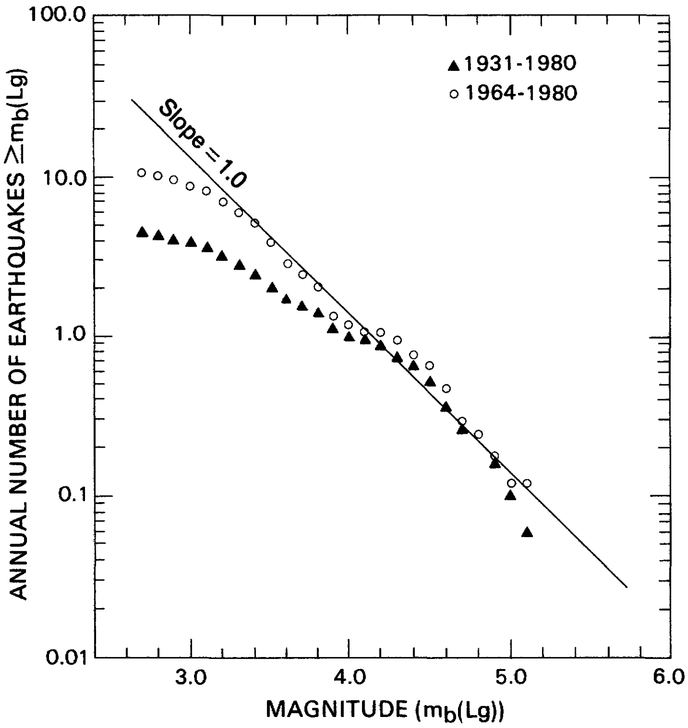


FIGURE 24.—Magnitude-frequency plot of the relocated earthquakes. Triangles refer to 1931 through 1980. Circles refer to 1964 through 1980. A straight line with slope 1.0 has been visually fitted to the data.

steady increase in the percentage of relocated events in the 1960's and 70's is the result of the establishment of the WWSSN network, the use of more efficient ways to handle seismic data, and the deployment of local and regional arrays. Although there has been significant improvement since the 1960's, the data in the table indicate that the catalog of relocated events is incomplete at the magnitude-3.5 level for 1971–77. However, it should be pointed out that the data in the table show that only one known earthquake with magnitude ≥3.5 is missing from the catalog after 1970. The missing shock was an aftershock of a relocated earthquake (1971.03.14) in Alabama.

In compiling table 6, the magnitudes of some unrelocated events listed by Nuttli and Brill (1981) were reduced. The magnitudes in question were originally determined on the basis of maximum epicentral intensity. Examination of WWNSS film chips covering these events indicated that the estimated instrumental magnitudes were generally significantly less than the values based on intensity. As a result of this examination, the magnitudes of about 15 shocks originally assigned values in the 3.5 to 4.2 range were redetermined and assigned magnitudes less than 3.5.

SEISMICITY AND PLATE TECTONICS

In this section, central United States seismicity will be related to a simplified tectonic model composed primarily of deep-seated, basement structures initially formed by extensional plate-tectonic processes. These features, which include rifted continental margins, aulacogens, and aborted continental rifts, seem to represent zones of crustal weakness that have been subjected to later, not necessarily extensional tectonism (Sykes, 1978; Hamilton, 1981). Some of the features in the model, such as the Appalachian front and the Ouachita

TABLE 6.—*Percentages of known central United States earthquakes relocated in this study*

	Magnitude ($m_b(L_g)$)							
	≥3.0		≥3.5		≥4.0		≥4.5	
Years	Number+	Percent*	Number+	Percent*	Number+	Percent*	Number+	Percent*
1931-35	67	3	39	5	11	18	4	50
1936-42	118	4	49	10	18	28	6	83
1943-49	66	5	44	7	15	20	4	75
1950-56	110	8	84	11	29	31	6	67
1957-63	74	31	44	34	19	53	3	67
1964-70	114	46	34	88	16	100	6	100
1971-77	91	86	36	97	15	100	6	100

+Number of known earthquakes (Nuttli and Brill, 1981) with magnitude equal to or greater than the specified magnitude.

*Percentage of known earthquakes with magnitude equal to or greater than the specified magnitude that were relocated in this study.

front, are related to compressional phases of Wilson cycles. In addition to the revised epicenters, the comparison of seismicity and tectonics will include the larger historic earthquakes of the region and some of the results obtained by recently deployed microearthquake networks.

THE PLATE-TECTONIC MODEL

Figure 25 is an interpretation of ancient plate-tectonic structures in the central United States based primarily on the work of Keller and others (1983) and Braile, Keller and others (1982) with contributions by Denison and others (1984) and Warner (1978). The principal elements of the model represent major rifting episodes during Keweenawan (1100 Ma), Eocambrian (600 Ma), and early Mesozoic time (175 Ma). As shown in the model, Keweenawan continental rifting forms a horseshoe-shaped arc extending from Kansas to Tennessee that joins the Midcontinent gravity high (MCGH), the Mid-Michigan gravity high (MMGH), the Fort Wayne geophysical anomaly (FWGA), and the East Continent gravity high (ECGH). Another proposed Keweenawan rift segment, herein called the La Salle rift zone (LSRZ), extends northerly from southeastern to north-central Illinois (Denison and others, 1984). Strong positive gravity anomalies characterize these Precambrian, basaltic rift zones. The width of the Keweenawan rifts shown in the figure, which varies from about 40 to 60 km, generally corresponds to the subcrop of Keweenawan igneous rocks. The total width of the Keweenawan clastic subcrop, 100 to 200 km, associated with the Midcontinent gravity high, suggests that Keweenawan extension affected a much wider section of the crust than shown schematically in the figure. Recent studies of gravity and magnetic data have suggested that subdued Keweenawan rifting continued southward from Kansas into Oklahoma, parallel to the Nemaha uplift (Yarger, 1981; Hildenbrand and others, 1982; Luza and Lawson, 1983). In this area, the late Paleozoic Nemaha uplift may coincide with the eastern flank of Keweenawan rifting. Eocambrian rifting near the northern boundary of the Gulf Coastal Plain includes three major reentrants in the craton: the Delaware aulacogen (DA), the Southern Oklahoma aulacogen (SOA), and the Reelfoot rift (RR). Eocambrian rifting subparallel to the Ouachita front in the south-central United States represents the rifted continental margin of late Precambrian North America. In the central Mississippi Valley, Braile, Keller and others (1982) recognized an Eocambrian rift complex composed of the Reelfoot rift and three branches: the Saint Louis arm (SLA), the Southern Indiana arm (SIA), and the Rough Creek graben (RCG). Mooney and others (1983) have suggested that Eocambrian rifting in this area was due to a triple junction centered in the northernmost part of the Mississippi Embayment. The Rome trough (RT) in eastern Kentucky and western West Virginia represents a possible eastward extension of Eocambrian rifting. In the figure, early Mesozoic rifting, which coincides approximately with the northern limit of the Gulf Coastal Plain, corresponds to a rifted, continental margin which formed during the break-up of Pangea. The Ouachita front (OF), which marks the northern limit of severe crustal deformation associated with late Paleozoic convergence of North America with Africa-South America, is subparallel to the Eocambrian and early Mesozoic continental margins in Texas, Oklahoma, and Arkansas. The Ouachita front (OF) and the Appalachian front (AF) delimit the North American Craton on the south and east, respectively. The Colorado lineament (CL) (Warner, 1978), which cuts across the northwest corner of the figure, is an important Precambrian feature of uncertain origin (see *Tectonics* and also *Seismotectonis in the Northern Great Plains Zone*). The dotted line in the southwest corner of the figure marks the boundary between the craton and the Basin and Range Province. Discussion of the Basin and Range province, a major tectonic division of the western United States, is beyond the scope of this study.

In the schematic presentation shown in figure 25, the Southern Oklahoma aulacogen coincides approximately with the Amarillo-Wichita uplift and smaller basins and uplifts to the southeast along the Amarillo-Wichita trend (Keller and others, 1982). During the last several years, deep seismic profiling using VIBROSEIS (a reflection technique involving continuous generation of seismic waves by a vibration machine—a Continental Oil Company trademark) has revealed the possible existence of a deep Proterozoic basin south of the SOA, suggesting that the location of the SOA may have been controlled by an earlier aulacogen (Brewer and others, 1983). North of the Amarillo-Wichita uplift, VIBROSEIS results have disclosed high-angle faulting beneath the Anadarko basin that may penetrate to depths of 10 to 15 km. Low-angle reverse faulting in the transition zone between the Amarillo-Wichita uplift and the Anadarko basin, which has thrust Precambrian crystalline rocks over Paleozoic strata, can be traced to depths of more than 20 km.

REVISED EPICENTERS AND ANCIENT PLATE TECTONICS

Figure 26 is a plot of the revised epicenters ($m_b(L_g) \geq 3.0$) and the simplified plate-tectonic model described above. Examination of the figure reveals some

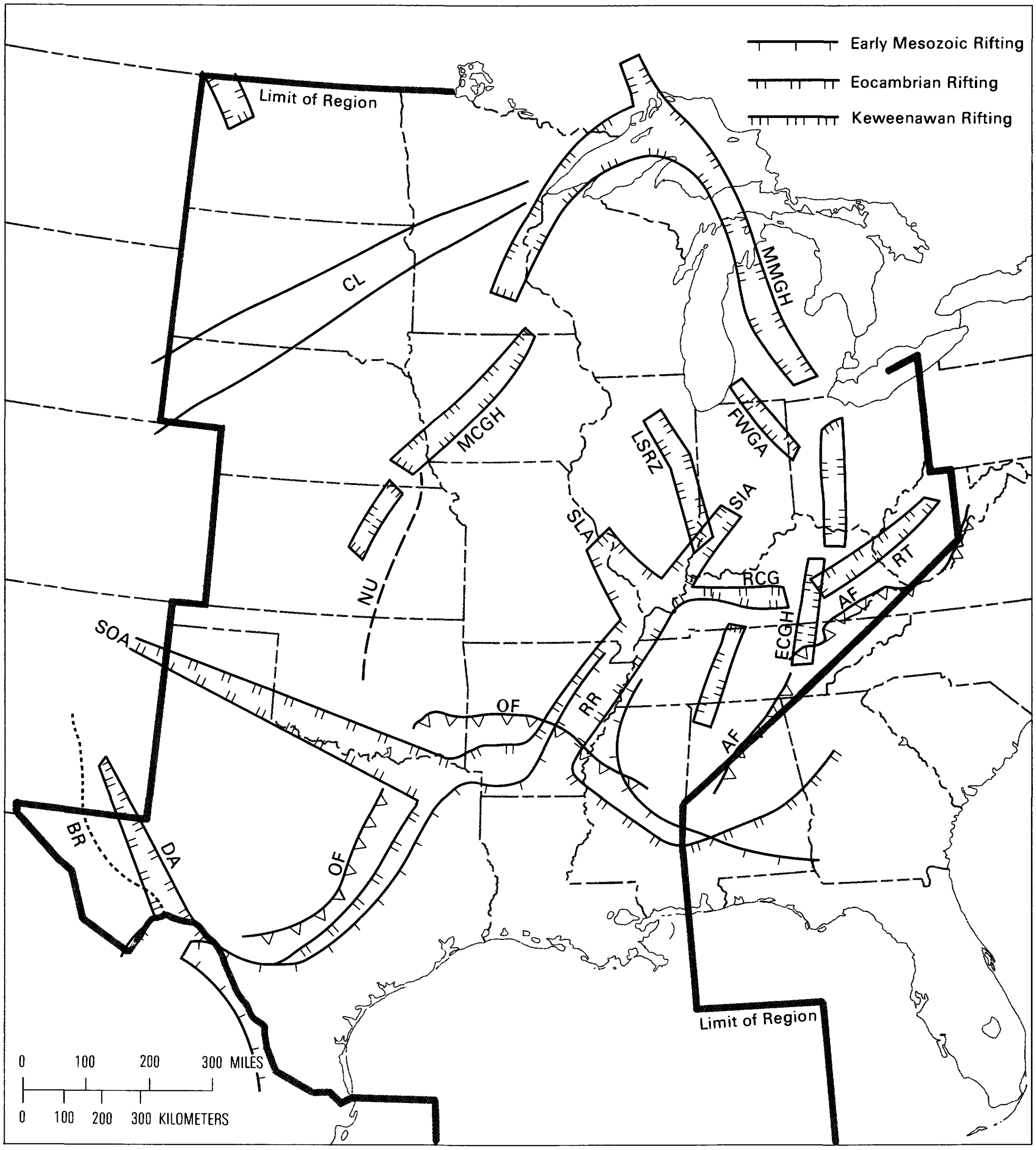


FIGURE 25.—Simplified ancient plate-tectonic model of the central United States. Appalachian front (AF). Basin and Range province (BR). Colorado lineament (CL). Delaware aulacogen (DA). East Continent gravity high (ECGH). Fort Wayne geophysical anomaly (FWGA). La Salle rift zone (LSRZ). Midcontinent gravity high (MCGH). Mid-Michigan gravity high (MMGH). Nemaha uplift (NU). Ouachita front (OF). Rough Creek graben (RCG). Reelfoot rift (RR). Rome trough (RT). Saint Louis arm (SLA). Southern Indiana arm (SIA). Southern Oklahoma aulacogen (SOA). The indicated geologic ages date the initiation of major rifting in the designated areas.

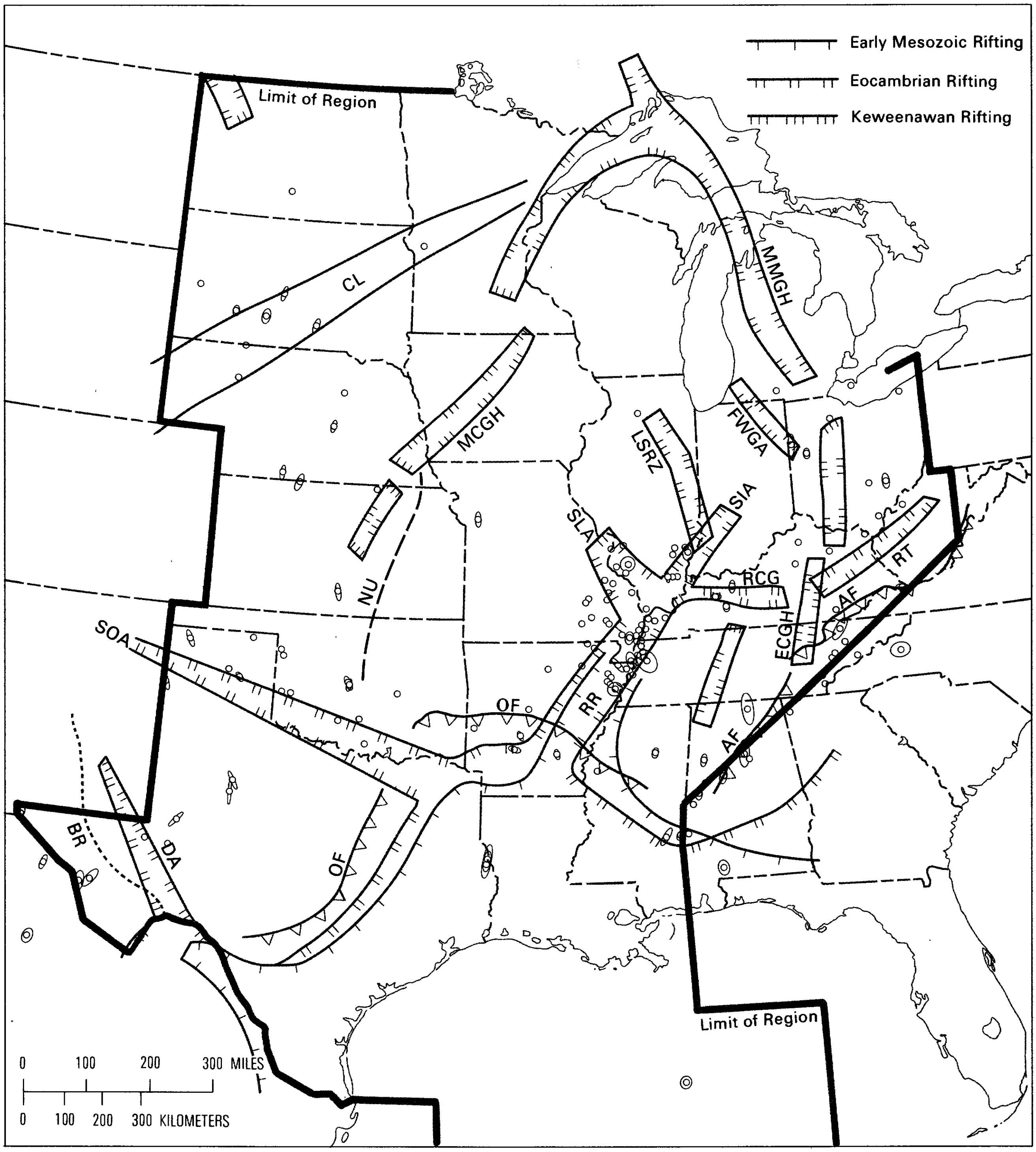


FIGURE 26.—Revised epicenters (circles) of earthquakes with $m_b(L_g)\geq 3.0$, 95-percent-confidence ellipses, and simplified ancient plate-tectonic model of the central United States. Appalachian front (AF). Basin and Range province (BR). Colorado lineament (CL). Delaware aulacogen (DA). East Continent gravity high (ECGH). Fort Wayne geophysical anomaly (FWGA). La Salle rift zone (LSRZ). Midcontinent gravity high (MCGH). Mid-Michigan gravity high (MMGH). Nemaha uplift (NU). Ouachita front (OF). Rough Creek graben (RCG). Reelfoot rift (RR). Rome trough (RT). Saint Louis arm (SLA). Southern Indiana arm (SIA). Southern Oklahoma aulacogen (SOA).

interesting aspects of regional seismicity and tectonics. Epicenters are most dense in the New Madrid area and in the surrounding rift complex in the central Mississippi Valley.

A conspicuous feature of the seismicity depicted in the figure is a northwest-southeast trend of epicenters that begins in the Texas Panhandle and extends southeasterly to Alabama. The western part of this trend is associated with the Southern Oklahoma aulacogen, and the eastern part of the trend is subparallel to the Eocambrian continental margin and the Ouachita front in Arkansas and Mississippi.

In the northwest part of the study region, epicenters representing six relatively large earthquakes in the Great Plains are associated with the Colorado lineament.

As shown in the figure, the Anna seismic source in west-central Ohio, which is marked by the revised epicenters of shocks on 1931.09.20, 1937.03.02, and 1937.03.09, lies between two Keweenawan rift segments, the Fort Wayne geophysical anomaly and a north-south oriented segment. During the period 1976–81, the Western Ohio Seismic Array (see fig. 4) recorded about a dozen microearthquakes in the Anna area (Jackson and others, 1982). The epicenters of most of these microearthquakes are located in a tight cluster about 15 km east of the revised epicenters of the events in the 1930's.

In the southeast part of the region, the revised epicenters seem to be concentrated near the Appalachian front in Alabama and Tennessee. Recent microearthquake locations in this area indicate that southern Appalachian seismicity is spatially associated with deep-seated magnetic lineaments with northerly trends (Bollinger, 1980, 1981, 1982, 1984; Reinbold and Johnston, 1983; Nava and Johnston, 1984). Focal depths and fault-plane solutions for events in eastern Tennessee suggest that contemporary faulting in this area is primarily right-lateral strike-slip on northerly striking basement faults beneath the southern Appalachian thrust sheet (Herrmann, 1979; Johnston and others, 1985).

None of the revised epicenters are associated with the Nemaha uplift in Kansas and northern Oklahoma. However, the locations of microearthquakes recorded by recently deployed local networks (see fig. 4) indicate some activity along this north-northeast trending feature (Steeples, 1980, 1981). In the vicinity of the Oklahoma-Kansas border, microearthquakes seem to correlate with the Nemaha uplift and the southward continuation of the MCGH.

Relatively few epicenters locate in the Gulf Coastal Plain south of the Eocambrian and early Mesozoic continental margins and those that do are associated with magnitudes less than 3.5. Minor seismicity in the Gulf of Mexico, which has been described by Frohlich (1982), will not be considered here.

Certain ground rules were established to quantify the spatial correlation between the epicenters and tectonic features in figure 26. For correlation purposes, only the craton or interior part of the study region was considered. In effect, areas east of the Appalachian front and south of the Ouachita front, and epicenters in the Basin and Range province were excluded. Within the craton, a positive spatial correlation was assumed if an individual epicenter ellipse plotted within or intersected the boundaries of the Colorado lineament or one of the Keweenawan or Eocambrian rifts outlined in the figure. These tectonic elements occupy approximately one-sixth of the craton considered. Within this context, approximately 66 percent of the revised epicenters ($m_b(L_g) \geq 3.0$) in the craton correlate spatially with the Colorado lineament or the paleorifts outlined in figure 26. About one-half of the revised epicenters are located in the rift complex in the central Mississippi Valley, which is composed of the Reelfoot rift, the Saint Louis arm, the Southern Indiana arm, and the Rough Creek graben. Exclusive of this Eocambrian rift complex, roughly 43 percent of the relocated earthquakes ($m_b(L_g) \geq 3.0$) considered correlate spatially with the other specified tectonic elements: the Colorado lineament, the Southern Oklahoma aulacogen, and the Keweenawan rifts. These elements occupy about one-seventh of the remaining part of the craton. In both of the cases discussed above, the percentages of correlations with the specified tectonic elements increase by 20–30 percent if the earthquake samples are restricted to larger shocks, events with $m_b(L_g) \geq 3.5$.

HISTORIC EARTHQUAKES AND ANCIENT PLATE TECTONICS

The earthquake history of the central United States has been documented by Docekal (1970), Coffman and von Hake (1973), Nuttli and Brill (1981), and Nuttli (1982). This history has an important bearing on understanding regional seismotectonics because it indicates that in the past earthquakes have occurred in areas where instrumental epicenters have not been located. Although Nuttli and Brill's (1981) catalog of central United States earthquakes contains over 1,100 entries, this section will emphasize the larger historic shocks, approximately 180 events, each with total felt area ≥20,000 sq km. These shocks correspond to events with $m_b(L_g)$ magnitude greater than about 4.0 (Nuttli and Zollweg, 1974). Hereafter, such earthquakes will be called widely felt earthquakes. Herrmann's (1979) focal-depth estimates for a sample of 16 widely felt, Midcontinent earthquakes indicate an average focal depth of about 12 km with the shallowest event at a depth of 5 km. These depths suggest that most widely felt shocks in the region represent basement sources that are well below the supracrustal rocks. Figure 27 is a plot of the proposed tectonic model and all known widely felt earthquakes in the central United States through 1980 (Nuttli and Brill, 1981; Stover and von Hake, 1980, 1981, 1982).

As made evident by the figure, earthquakes associated with Reelfoot rift in the New Madrid Zone dominate the seismicity of the Midcontinent. Three great earthquakes, each among the strongest shocks ever felt in the United States, struck the New Madrid area during the winter of 1811-12. Each of these earthquakes had a surface-wave magnitude in the 8.4-8.7 range (Nuttli and Brill, 1981). The figure also shows that many of the historic epicenters correlate spatially with two of the other branches of the proposed Eocambrian rift complex in the central Mississippi Valley, the Saint Louis arm and the Southern Indiana arm.

Figure 27 also shows clusters of epicenters and apparent seismic lineaments in places outside the central Mississippi Valley. A conspicuous seismic trend seems to coincide with the Colorado lineament, and clusters of closely spaced earthquakes are associated with paleorifts in the Texas Panhandle and in western Ohio. Although many individual epicenters do not correlate with structures depicted by the model, all of the prominent clusters of epicenters seem to be spatially associated with structural elements plotted in the model.

Since 1875, four relatively strong earthquakes have shaken the Anna (40.4° N., 84.2° W.) area in western Ohio. Each of these events was felt in an area of more than 100,000 sq km. As shown in figure 27, the closely spaced epicenters of these earthquakes lie between two Keweenawan rift segments. Well logs and other geophysical data reveal faulting in the Paleozoic section beneath the Anna area where thick glacial deposits conceal bedrock (Jackson and others, 1982; Christensen and others, 1983). The Anna-Champaign fault, the most conspicuous fault in this area, parallels the Fort Wayne geophysical anomaly, which McPhee (1983) has associated with a 60-km-wide subcrop of mafic volcanics.

A cluster of the historic shocks near Manhattan (39.2° N., 96.6° W.) in northeastern Kansas seems to correlate with the Nemaha uplift-Midcontinent gravity high. Chelikowsky (1972) has discussed strike-slip faulting in late Mesozoic time associated with the eastern flank of the MCGH near Manhattan. According to his interpretation, this faulting accompanied intrusion of a group of ultramafic igneous plugs, the kimberlites of Riley County, into the Phanerozoic section. Burchett and others (1983) have identified a possible northwest-trending microearthquake lineament that is spatially associated with the apparent left-lateral offset of the MCGH near the Kansas-Nebraska border. The relocated epicenters (1961.12.25 [12:19:58.3, 12:58:16.8]) of two widely felt shocks near Excelsior Springs, Mo., are located along this proposed trend (see figs. 17 and 27).

Explanation of the cluster of four earthquakes in the Texas Panhandle in terms of tectonic reactivation is not new. Pratt (1926) attributed the largest shock in this group, an earthquake felt over an area of about 500,000 sq km on July 30, 1925, to renewed displacement on an "old line of weakness" parallel to the buried, northwest extension of the Wichita Mountains. To the southeast along this structural trend, Donovan and others (1983) have attributed ground breakage along a 26 km segment of the Meers fault north of Lawton, Okla., to a major Holocene earthquake (see fig. 16). Surface deformation along this fault, which is part of the frontal fault zone between the Wichita uplift and the Anadarko basin, indicates a maximum vertical displacement of 3.0-5.0 m and a significant left-lateral, strike-slip component.

Two of the epicenters in figure 27 that correlate spatially with the Keweenawan rifting correspond to earthquakes on the Keweenaw Peninsula of Upper Michigan. Nuttli and Brill (1981) listed eight other smaller shocks with epicenters on the Keweenaw Peninsula during the time interval 1905-55. Because the peninsula is a notable copper-mining district, some of these events may have been induced by mining. Frantti (1982) used contemporary newspaper accounts, mining records, and interviews with local residents who experienced the earthquakes to ascertain, if possible, whether these events were natural earthquakes or were seismic events related to mining. He found that four of the events definitely could be attributed to rockfalls or rockbursts in mines. However, he believed that a natural earthquake is the most likely explanation of the largest event in the group, the Calumet earthquake of July 27, 1905, which had a felt area of 40,000 sq km. During his investigation, Frantti also found accounts of an earthquake that had not been previously listed in the historic catalogs. As deduced from eyewitness accounts by early travelers in the region, this earthquake took place in the spring of 1793 and had a felt area of over 10,000 sq km. Presumably it was centered in the Porcupine Mountains (46.8° N., 89.8° W.) near Lake Superior in westernmost Upper Michigan. Frantti also located several microearthquakes beneath Lake Superior off the northeast tip of the Keweenaw Peninsula.

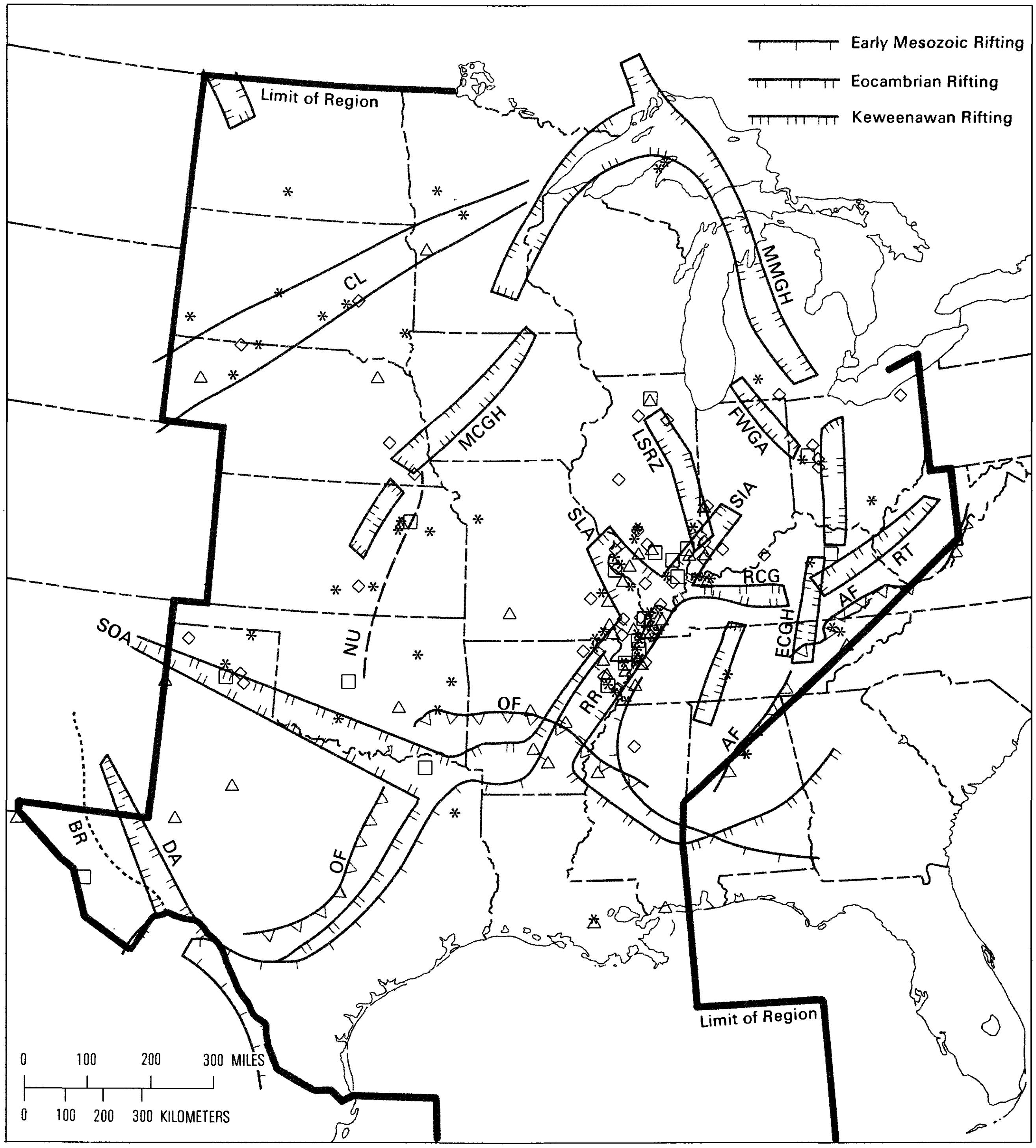


FIGURE 27.—Epicenters of widely felt, historic earthquakes and simplified ancient plate-tectonic model of the central United States. Squares represent earthquakes with total felt area (FA) of 500,000 sq km or more. Diamonds (500,000>FA≥100,000). Triangles (100,000>FA≥50,000). Asterisks (50,000>FA≥20,000). Appalachian front (AF). Basin and Range province (BR). Colorado lineament (CL). Delaware aulacogen (DA). East Continent gravity high (ECGH). Fort Wayne geophysical anomaly (FWGA). La Salle rift zone (LSRZ). Midcontinent gravity high (MCGH). Mid-Michigan gravity high (MMGH). Nemaha uplift (NU). Ouachita front (OF). Rough Creek graben (RCG). Reelfoot rift (RR). Rome trough (RT). Saint Louis arm (SLA). Southern Indiana arm (SIA). Southern Oklahoma aulacogen (SOA).

The criteria applied to decide whether or not a particular historic epicenter correlated spatially with the assumed tectonic model were similar to the ground rules established for this purpose in the case of the revised epicenters (see *Revised Epicenters and Ancient Plate Tectonics*). Again, the principal criterion was that only epicenters west of the Appalachian front and north of the Ouachita front were considered. In this case, positive spatial correlation meant that a historic epicenter was located inside or within 0.3° of the boundary of one of the tectonic features considered. Within these specifications, about 83 percent of the epicenters corresponding to widely felt earthquakes in the craton correlate spatially with the Colorado lineament or the ancient aulacogens and other paleorifts outlined in figure 27. If the Eocambrian rift complex in the central Mississippi Valley is removed from the region of consideration, about 60 percent of the historic epicenters correlate with the Colorado lineament or with the remaining paleorifts in the craton. Approximately one-third of the widely felt, historic earthquakes outside the central Mississippi Valley rift complex are spatially associated with the proposed Keweenawan rifts.

DISCUSSION

The preceding sections have demonstrated that a relatively high percentage of the earthquakes considered are spatially associated with elements of the assumed tectonic model. Exclusive of the central Mississippi Valley, about 40–60 percent of the events considered correlate with structures in the assumed model. There is also a suggestion that the percentage of earthquakes that are spatially associated with elements in the model increases with increasing magnitude.

The seismotectonic relationships that have been discussed are consistent with the preexisting-zones-of-weakness hypothesis (see *Tectonics*). According to this hypothesis, relatively strong intraplate earthquakes represent reactivation of planes-of-crustal-weakness in the contemporary stress field. Earthquakes correspond to slip on preexisting planes (deep-seated faults) that intersect the greatest principal stress axis at small (10° to 40°) angles (Raleigh and others, 1972). In the Mid continent, focal mechanisms and in-situ stress measurements have indicated a relatively uniform stress field in which the greatest and least principal stress axes are horizontal and oriented approximately east-northeast and north-northwest, respectively (Herrmann, 1979; Zoback and Zoback, 1980). Braile, Hines and others (1982) analyzed seismicity patterns, structural trends, and regional stress conditions in the Midcontinent. They reported that most seismically active zones in the region are characterized by northeast to east-trending structures, the expected condition under the zones-of-weakness hypothesis and the stress regime described above. In this interpretation, elongate trends of epicenters in the central United States, such as the Colorado lineament and the Amarillo-Wichita trend, represent preferred seismic directions, zones of wrench or strike-slip faulting, in a relatively uniform stress field.

The geologic age, mode of origin, and deformational history of some of the paleorifts outlined in figure 25 will undoubtedly be revised in the future and additional rifting may be recognized. However, the interpretation of these features, which are mostly marked by distinct gravity and magnetic anomalies, as persistent zones of crustal weakness will probably not change. The fact that some paleorift segments have little or no history of seismicity needs an explanation. The lack of historic activity may be related to the absence of extensive faulting during the rifting phase. In addition, the extent of crustal weakness associated with a particular rift segment may depend on the aggregate tectonism undergone by the rift during subsequent geologic time. For example, some of the rifts apparently owe much of their present architecture to compressional tectonism and wrench faulting during later geologic time. Some paleorift segments may be comparatively aseismic because they are not favorably oriented with respect to the regional stress field. In the case of some paleorifts, earthquakes may occur on nearby, tectonically related structures instead of on the central part of the rift. The Nemaha uplift in Oklahoma and Kansas may be an example of such a related structure.

In this study, it was expedient to use widely felt earthquakes to explore relationships between historic seismicity and basement tectonics. It was also convenient to emphasize very large tectonic elements, such as paleorifts and continental-scale shear zones, instead of individual basement faults, in attempts to correlate seismicity and tectonics. However, during the investigation, it became apparent that some seismicity is closely associated with such faults. For example, revised epicenters corresponding to comparatively small shocks seem to be associated with frontal faults on the northeast flank of the Amarillo-Wichita uplift (see fig. 16), and the 1975 western Minnesota earthquake correlates spatially with the Morris fault (see fig. 19). More detailed comparison of historic earthquake locations with tectonics, taking into account less widely felt shocks and individual basement faults, would probably disclose significant new seismotectonic relationships.

SUMMARY AND CONCLUSIONS

The principal quantitative results of this study, the revised hypocenters and magnitudes listed in the appendix, represent a marked improvement over previously accepted estimates of these parameters. The revised hypocenters should be incorporated in future earthquake catalogs because: (1) they are more accurate than previously published hypocenters, and (2) they are accompanied by uniformly determined error estimates.

About 24 percent of the old epicenters differ from the new epicenters by 0.2° or more in latitude or longitude. These same old epicenters also lie outside the corresponding 95-percent-confidence ellipses of the new epicenters. The causes of the differences between the old and new epicenters can often be identified. The factors that account for these differences include: (1) the original epicenters were graphical solutions or macroseismic epicenters, (2) more data were available for the revised epicenters, (3) the old epicenters were mislocated due to regional travel-time bias, (4) typographical errors were associated with the coordinates given for some of the old epicenters, and (5) a few of the original epicenters were based entirely on data from local networks that did not surround the epicenter.

The revised epicenters are demonstratively better than the old epicenters in the New Madrid Zone because: (1) the new epicenters are less scattered, and (2) the relocated epicenters tend to fall within seismic lineaments delineated by recent microearthquakes.

Nearly all of the well-determined focal depths, defined as those in which the steepest semi-axis of the corresponding confidence ellipsoid has a length of 10 km or less, were associated with earthquakes recorded by recently deployed microearthquake networks. Approximately 85 percent of the well-determined focal depths were 10 km or less. However, about one-half dozen well-determined focal depths in the 10–15 km range were determined for shocks in the New Madrid Zone. The deepest reliable hypocenters correspond to the Wabash Zone where several of the relocated earthquakes have focal depths in the 20 to 25 km range. Within the resolution of the measurements, the focal depths determined in this study agree with independent estimates based on the spectral amplitudes of surface waves. The findings derived from spectral measurements suggest an average focal depth of about 12 km for earthquakes with magnitudes greater than about 4.0 in the central United States.

Tests of hypocenter accuracy indicate that the confidence regions associated with the relocated hypocenters are reasonably reliable measures of accuracy. Tests of the confidence ellipses as measures of epicenter accuracy were made with explosions and other events having known or independently determined epicenters. The nominal 95-percent-confidence ellipses of the revised epicenters covered the true or assumed epicenters in 17 out of 20 cases considered. Comparisons of the computed focal depths with the corresponding known or independently determined focal depths indicate that the length of the steepest semi-axis of the accompanying confidence ellipsoid is a reliable measure of the uncertainty of the revised focal depths.

The calibration-event option of the JHD/JED method has been applied successfully in this study to relocate earthquakes in selected Midcontinent areas. Use of the calibration-event option instead of the calibration-station option led to more precise results. The choice of the calibration-event or calibration-station option depends on the relative spacing of the group of events considered, station distribution, and the presence or absence of an appropriate, well-recorded calibration event with known or accurately estimated source coordinates.

The catalog of relocated hypocenters listed in the appendix is a compilation of events that are normally recorded regionally or teleseismically and included in national and international seismological bulletins. For the entire region and time span considered, compilations of earthquakes that were reported felt are more complete than instrumental findings. Comparison with lists of known earthquakes felt in the region indicates that the catalog of relocated hypocenters is essentially complete at the magnitude-3.5 level for the period beginning in 1971.

The best estimates of earthquake focal depths in the study region suggest that most significant Midcontinent earthquakes have foci in the Precambrian basement well below the supracrustal rocks. The foci of most widely felt central United States earthquakes are apparently associated with basement structures that extend deep into the crust. Approximately 83 percent of the known earthquakes in the craton with felt areas exceeding 20,000 sq km correlate spatially with paleorifts, ancient wrench-fault zones, and other ancient plate-tectonics elements in the Midcontinent. Most of the historic seismicity, including activity in the central Mississippi Valley and in the Wichita Zone, is spatially related to aulacogens and complex rifting along the southern margin of ancestral North America.

Interpretation of intraplate seismicity in terms of the preexisting-zones-of-crustal-weakness hypothesis suggests that prominent seismic lineaments in the Midcontinent, such as the northeasterly trend in the New Madrid Zone, the Wichita trend, and the Colorado lineament, correspond to preferred seismic directions in a relatively uniform stress field.

REFERENCES CITED

Ammerman, M. L., and Keller, G. R., 1979, Delineation of the Rome trough in eastern Kentucky by gravity and deep drilling data: American Association of Petroleum Geologists Bulletin, v. 63, p. 341-353.

Anonymous, 1965, Texas-Louisiana earthquake 24 April 1964: Air Force Technical Applications Center, Seismic Data Laboratory Report no. 114, 24 p., Washington, D.C.

_____1975, Water Supply Paper 2122: U.S. Geological Survey.

Arvidson, R. E., Guinness, E. A., Strebeck, J. W., Davies, G. F., and Schulz, K. J., 1982, Image processing applied to gravity and topographic data covering the continental United States: EOS Transactions, American Geophysical Union, v. 63, p. 261-265.

Bayer, K. C., 1966, Preliminary report on the 1966 Lake Superior seismic experiment: U.S. Department of Commerce, Coast and Geodetic Survey, 19 p.

Bayley, R. W., and Muehlberger, W. R., compilers, 1968, Basement rock map of the United States: U.S. Geological Survey, scale 1:2,500,000, 2 sheets.

Bollinger, G. A., 1979, Attenuation of the L_g phase and the determination of m_b in the southeastern United States: Seismological Society of America Bulletin, v. 69, no. 1, p. 45-63.

_____1980, Southeastern United States earthquakes, 1978, *in* Stover, C. W., and von Hake, C. A., eds., United States earthquakes, 1978: U.S. Geological Survey and National Oceanic and Atmospheric Administration, p. 91.

_____1981, Southeastern United States earthquakes, 1979, *in* Stover, C. W., and von Hake, C. A., eds., United States earthquakes, 1979: U.S. Geological Survey and National Oceanic and Atmospheric Administration, p. 124-125.

_____1982, Southeastern United States earthquakes, 1980, *in* Stover, C. W., and von Hake, C. A., eds., United States earthquakes, 1980: U.S. Geological Survey and National Oceanic and Atmospheric Administration, p. 148-149.

_____1984, Southeastern United States earthquakes, 1981, *in* Stover, C. W., ed., United States earthquakes, 1981: U.S. Geological Survey Special Publication, p. 112-113.

Bolt, B. A., 1960, The revision of earthquake epicenters, focal depths and origin-times using a high-speed computer: Geophysical Journal of the Royal Astronomical Society, v. 3, p. 433-440.

Braile, L. W., Hinze, W. J., Sexton, J. L., Keller, G. R., and Lidiak, E. G., 1982, Seismicity and tectonics of the Midcontinent United States: Third International Earthquake Microzonation Conference Proceedings, v. 1, p. 25-38.

Braile, L. W., Keller, G. R., Hinze, W. J., and Lidiak, E. G., 1982, An ancient rift complex and its relation to contemporary seismicity in the New Madrid seismic zone: Tectonics, v. 1, p. 225-237.

Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., and Kaufman, Sidney, 1983, COCORP profiling across the Southern Oklahoma aulacogen—Overthrusting of the Wichita Mountains and compression within the Anadarko basin: Geology, v. 11, p. 109-114.

Brill, K. G., and Nuttli, O. W., 1983, Seismicity of the Colorado lineament: Geology, v. 11, p. 20-24.

Bristol, H. M., and Treworgy, J. D., 1979, The Wabash fault system in southeastern Illinois: Illinois State Geological Survey, Circular 509, 19 p.

Brown, L., Jensen, L., Oliver, J., Kaufman, S., and Steiner, D., 1982, Rift structure beneath the Michigan basin from COCORP profiling: Geology, v. 10, p. 645-649.

Brown, L., Serpa, L., Setzer, T., Oliver, J., Kaufman, S., Lillie, D., Steiner, D., and Steeples, D. W., 1983, Intracrustal complexity in the United States Midcontinent—Preliminary results from COCORP surveys in northeastern Kansas: Geology, v. 11, p. 25-30.

Burchett, R. R., Luza, K. V., Van Eck, O. J., and Wilson, F. W., 1983, Seismicity and tectonic relationships of the Nemaha uplift and Midcontinent geophysical anomaly: U.S. Nuclear Regulatory Commission, NUREG/CR-3117, 34 p.

Burgess, W. J., 1976, Geologic evolution of the Mid-Continent and Gulf Coast areas—A plate tectonics view: Gulf Coast Association of Geological Societies Transactions, no. 26, p. 132-143.

Burke, Kevin, 1980, Intracontinental rifts and aulacogens, *in* Continental tectonics: National Academy of Science, Washington, D.C., p. 42-49.

Burke, Kevin, and Dewey, J. F., 1973, Plume-generated triple junctions—Key indicators in applying plate tectonics to old rocks: Journal of Geology, v. 81, p. 406-433.

Byerly, Perry, 1934, The Texas earthquake of August 16, 1931: Seismological Society of America Bulletin, v. 24, p. 81-99.

Cebull, S. E., Shurbet, D. H., Keller, G. R., and Russell, L. R., 1976, Possible role of transform faults in the development of apparent offsets in the Ouachita-Southern Appalachian tectonic belt: Journal of Geology, v. 84, p. 107-114.

Chase, C. G., and Gilmer, T. H., 1973, Precambrian plate tectonics—The Midcontinent gravity high: Earth and Planetary Science Letters, v. 21, p. 70-78.

Chelikowsky, J. R., 1972, Structural geology of the Manhattan, Kansas area: Kansas State Geological Survey Bulletin 204, pt. 4, 13 p.

Christensen, D. H., Wiedenbeck, M. G., and Jackson, P. L., 1983, Geophysical investigations of the western Ohio-Indiana region: U.S. Nuclear Regulatory Commission, NUREG/CR-3145, 103 p.

Coffman, J. L., and von Hake, C. A., 1973, Earthquake history of the United States: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Publication 41-1, 208 p.

Cohee, G. V., Chairman, 1961, Tectonic map of the United States: U.S. Geological Survey and American Association of Petroleum Geologists, scale 1:2,500,000, 2 sheets.

Coignet, G. O., 1964, Oil and gas map of Louisiana: Louisiana Geological Survey, scale 1:500,000.

Dellwig, L. F., 1956, The Barber County earthquake of January 6, 1956: State Geological Survey of Kansas, Bulletin 119, p. 175-185.

Dellwig, L. F., and Gerhard, L. C., 1962, The December 25, 1961, earthquakes in northwestern Missouri and northeastern Kansas: State Geological Survey of Kansas, Bulletin 157, p. 1-12.

Denison, R. E., Lidiak, E. G., Bickford, M. E., and Kisvarsanyi, E. B., 1984, Geology and geochronology of Precambrian rocks in the central interior region of the United States: U.S. Geological Survey Professional Paper 1241-C, 20 p.

Derr, J. S., 1977, Preliminary determination of epicenters (PDE) and earthquake data report (EDR): U.S. Geological Survey, Earthquake Information Bulletin, v. 9, p. 34-35.

Dewey, J. W., 1971, Seismicity studies with the method of joint hypocenter determination: Berkeley, Calif., University of California at Berkeley, Ph.D. thesis, 164 p.

_____1972, Seismicity and tectonics of western Venezuela: Seismological Society of America Bulletin, v. 62, p. 1711-1751.

_____1976, Use of secondary P-waves, S-waves, and surface waves in joint hypocenter determination [abs.]: Earthquake Notes, v. 47, p. 11-12.

_____1978, Joint hypocenter determination using calibration stations—Application to eastern North America [abs.]: Earthquake Notes, v. 49, p. 35.

_____1979, A consumer's guide to instrumental methods for determination of hypocenters, *in* Hatheway, A. W., and McClure, C. R., eds., Geology in the siting of nuclear power plants: Geological Society of America, Reviews in Engineering Geology, v. 4, p. 109-117.

______1983, Relocation of instrumentally recorded pre-1974 earthquakes from the South Carolina region, *in* Gohn, G. S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p. Q1–Q9.

Dewey, J. W., and Gordon, D. W., 1984, Map showing the recomputed hypocenters of earthquakes in the eastern and central United States and adjacent Canada, 1925–1980: U.S. Geological Survey Miscellaneous Field Studies Map MF-1699.

Diment, W. H., Muller, O. H., and Lavin, P. M., 1980, Basement tectonics of New York and Pennsylvania as revealed by gravity and magnetic studies, *in* Wones, D. R., ed., The Caledonides in the USA: Department of Geological Sciences, Virginia Polytechnic Institute and State University, Memoir 2, p. 221–227.

Docekal, Jerry, 1970, Earthquakes of the stable interior, with emphasis on the Midcontinent: Lincoln, Neb., University of Nebraska, Ph.D. thesis, 501 p.

Donovan, R. N., Gilbert, M. C., Luza, K. V., Marchini, David, and Sanderson, David, 1983, Possible Quaternary movement on the Meers fault, southwestern Oklahoma: Oklahoma Geological Survey, Oklahoma Geology Notes, v. 43, no. 5, p. 124–133.

Douglas, A., 1967, Joint epicentre determination: Nature, v. 215, p. 47–48.

DuBois, S. M., and Wilson, F. W., 1978, A revised and augmented list of earthquake intensities for Kansas, 1867–1977: Kansas Geological Survey, Environmental Geology Series 2, 56 p.

Dumas, D. B., 1979, Active seismic focus near Snyder, Texas: Seismological Society of America Bulletin, v. 69, p. 1295–1299.

Dumas, D. B., Dorman, H. J., and Latham, G. V., 1980, A reevaluation of the August 16, 1931, Texas earthquake: Seismological Society of America Bulletin, v. 70, p. 1171–1180.

Dutch, S. I., 1983, Proterozoic structural provinces in the north-central United States: Geology, v. 11, no. 8, p. 478–481.

Eardley, A. J., 1951, Structural geology of North America: Harper Brothers, New York, N.Y., 624 p.

Engdahl, E. R., and Gunst, R. H., 1966, Use of a high speed computer for the preliminary determination of earthquake hypocenters: Seismological Society of America Bulletin, v. 56, p. 325–336.

Ervin, C. P., and McGinnis, L. D., 1975, Reelfoot rift—Reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, p. 1287–1295.

Evernden, J. F., 1969, Precision of epicenters obtained by small numbers of world-wide stations: Seismological Society of America Bulletin, v. 59, p. 1365–1398.

Flinn, E. A., 1960, Local earthquake location with an electronic computer: Seismological Society of America Bulletin, v. 50, p. 467–470.

Foley, F. C., Walton, W. C., and Drescher, W. J., 1953, Ground-water conditions in the Milwaukee-Waukesaw area, Wisconsin: U.S. Geological Survey Water-Supply Paper 1229, 96 p.

Frantti, G. E., 1982, Seismicity investigation of the southern Lake Superior Precambrian province, final report 1977–1981: Report prepared for U.S. Nuclear Regulatory Commission, Michigan Technological University, Houghton, Mich., 70 p.

Frohlich, Cliff, 1982, Seismicity of the central Gulf of Mexico: Geology, v. 10, p. 103–106.

Fuller, M. L., 1912, The New Madrid earthquake: U.S. Geological Survey, Bulletin 494, 119 p.

Geiger, L., 1910, Herdbestimmung bei Erdbeben aus den Ankunftszeiten: Nachrichten der Koniglichen Gesellschaft der Wissenschaften zu Gottingen, Mathematisch-Physikalische Klasse, p. 331–349.

Gordon, D. W., 1983, Revised hypocenters and correlation of seismicity and tectonics in the central United States: Saint Louis, Mo., Saint Louis University, Ph.D. thesis, 199 p.

Guinness, E. A., Arvidson, R. E., Strebeck, J. W., Schulz, K. J., Davies, G. F., and Leff, C. E., 1982, Identification of a Precambrian rift through Missouri by digital image processing of geophysical and geological data: Journal of Geophysical Research, v. 87, p. 8529–8545.

Haimson, B. C., and Doe, T. W., 1983, State of stress, permeability, and fractures in the Precambrian granite of northern Illinois: Journal of Geophysical Research, v. 88, p. 7355–7371.

Halls, H. C., 1978, The late Precambrian central North American rift system, *in* Ramberg, I. B., and Neumann, E. R., eds., Tectonics and geophysics of continental rifts: Reidel Publishing Company, p. 111–123.

Hamilton, R. M., 1981, Geologic origin of eastern United States seismicity, *in* Beavers, J. E., ed., Proceedings of earthquakes and earthquake engineering in the eastern United States, v. 1, p. 3–23, Knoxville, Tennessee: Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

Harding, S. T., 1981, Induced seismicity at the Cogdell Canyon Reef oil field: U.S. Geological Survey Open-File Report 81–167, p. 452–455.

Harding, S. T., Carver, D., Henrisey, R. F., Dart, R. L., and Langer, C. J., 1978, The Scurry County, Texas, earthquake series of 1977–1978—Induced seismicity? [abs.]: Earthquakes Notes, v. 49, p. 14–15.

Hart, R. S., Anderson, D. L., and Kanamori, H., 1977, The effect of attenuation on gross earth models: Journal of Geophysical Research, v. 82, p. 1647–1654.

Henry, C. D., 1979, Geologic setting and geochemistry of thermal water and geothermal assessment, Trans-Pecos, Texas: Bureau of Economic Geology, University of Texas at Austin, Report of Investigations 96, 48 p.

Herrmann, R. B., 1979, Surface wave focal mechanisms for eastern North American earthquakes with tectonic implications: Journal of Geophysical Research, v. 84, p. 3543–3552.

Herrmann, R. B., and Canas, J., 1978, Focal mechanism studies in the New Madrid seismic zone: Seismological Society of America Bulletin, v. 68, p. 1095–1102.

Herrmann, R. B., Langston, C. A., and Zollweg, J. E., 1982, The Sharpsburg, Kentucky, earthquake of 27 July 1980: Seismological Society of America Bulletin, v. 72, no. 4, p. 1219–1239.

Herrmann, R. B., Park, S., and Wang, C., 1981, The Denver earthquakes of 1967–1968: Seismological Society of America Bulletin, v. 71, p. 731–745.

Heyl, A. V., 1972, The 38th parallel lineament and its relationship to ore deposits: Economic Geology, v. 67, p. 879–894.

Heyl, A. V., and McKeown, F. A., 1978, Preliminary seismotectonic map of the central Mississippi Valley and environs: U.S. Geological Survey Miscellaneous Field Studies Map MF–1011, scale 1:500,000, 2 sheets.

Hildenbrand, T. G., Kane, M. F., and Hendricks, J. D., 1982, Magnetic basement in the upper Mississippi Embayment region—A preliminary report, *in* McKeown, F. A., and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236–E, p. 39–53.

Hildenbrand, T. G., Kane, M. F., and Stauder, W., 1977, Magnetic and gravity anomalies in the northern Mississippi Embayment and their spatial relation to seismicity: U.S. Geological Survey Miscellaneous Field Studies Map MF–914, scale 1:1,000,000, 2 sheets.

Hildenbrand, T. G., Simpson, R. W., Godson, R. H., and Kane, M. F., 1982, Digital colored residual and regional Bouguer gravity maps of the conterminous United States with cut-off wavelengths of 250 km and 1000 km: U.S. Geological Survey Geophysical Investigations Map GP–953–A, scale 1:7,500,000, 2 sheets.

Hinze, W. J., Braile, L. W., and Keller, G. R. 1977, A tectonic overview of the central Midcontinent: U.S. Nuclear Regulatory Commission NUREG/0382, 63 p.

Hinze, W. J., Braile, L. W., Keller, G. R., and Lidiak, E. G., 1980, Models for Midcontinent tectonism, *in* Continental tectonics: National Academy Sciences, Washington, D.C., p. 73-83.

Hinze, W. J., Kellogg, R. L., and O'Hara, N. W., 1975, Geophysical studies of basement geology of southern peninsula of Michigan: American Association of Petroleum Geologists Bulletin, v. 59, no. 9, p. 1562-1584.

Hoffman, Paul, Dewey, J. F., and Burke, Kevin, 1974, Aulacogens and their genetic relation to geosynclines, with a Proterozoic example from Great Slave Lake, Canada, *in* Dott, R. H., and Shaver, R. H., eds., Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 19, p. 38-55.

Jackson, P. L., Christensen, D. H., and Mauk, F. H., 1982, Geophysical investigations of the western Ohio-Indiana region, final report, November 1975-September 1981: U.S. Nuclear Regulatory Commission, NUREG/CR-2484, 167 p.

Jeffreys, Harold, and Bullen, K. E., 1940, Seismological tables: British Association for the Advancement of Science, Gray Milne Trust, Office of the British Association, Burlington House, London, 50 p.

Johnston, A. C., 1982, A major earthquake zone on the Mississippi: Scientific American, v. 246, No. 4, p. 60-68.

Johnston, A. C., Reinbold, D. J., and Brewer, S. I., 1985, Seismotectonics of the southern Appalachians: Seismological Society of America Bulletin, v. 75, p. 291-312.

Jordan, J. N., Mickey, W. V., and Helterbran, Wayne, 1966, Travel times and amplitudes from the SALMON explosion: Journal of Geophysical Research, v. 71, p. 3469-3482.

Jordan, T. H., and Sverdrup, K. A., 1981, Teleseismic location techniques and their application to earthquake clusters in the south-central Pacific: Seismological Society of America Bulletin, v. 71, p. 1105-1130.

Kane, M. F., Hildenbrand, T. G., and Hendricks, J. D., 1981, Model for the tectonic evolution of the Mississippi Embayment and its contemporary seismicity: Geology, v. 9, p. 563-568.

Keller, G. R., Bland, A. E., and Greenberg, J. K., 1982, Evidence for a major late Precambrian event in the eastern Midcontinent region, United States: Tectonics, v. 1, p. 213-223.

Keller, G. R., and Cebull, S. E., 1973, Plate tectonics and the Ouachita system in Texas, Oklahoma, and Arkansas: Geological Society of America Bulletin, v. 83, p. 1659-1666.

Keller, G. R., Lidiak, E. G., Hinze, W. J., and Braile, L. W., 1983, The role of rifting in the tectonic developement of the Midcontinent, U.S.A.: Tectonophysics, v. 94, p. 391-412.

Keller, G. R., Rogers, A. M., Lund, R. J., and Orr, C. D., 1981, A seismicity and seismotectonic study of the Kermit seismic zone, Texas: U.S. Geological Survey Open-File Report 81-37, 383 p.

King, E. R., and Zietz, Isidore, 1971, Aeromagnetic study of the Midcontinent gravity high of the central United States: Geological Society of America Bulletin, v. 82, p. 2187-2208.

______1978, The New York-Alabama lineament: Geophysical evidence for a major crustal break in the basement beneath the Appalachian basin: Geology, v. 6, p. 312-318.

King, P. B., 1951, The tectonics of Middle North America: Princeton University Press, Princeton, New Jersey, 203 p.

______1969, The tectonics of North America: U.S. Geological Survey Professional Paper 628, 95 p.

______1975, Ancient southern margin of North America: Geology, v. 3, p. 732-734.

King, P. B., and Beikman, H. M., compilers, 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000, 3 sheets.

Kluth, C. F., and Coney, P. J., 1981, Plate tectonics of the ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Kolata, D. R., Buschbach, T. C., and Treworgy, J. D., 1978, The Sandwich fault zone of northern Illinois: Illinois State Geological Survey Circular 505, 26 p.

Kuntz, C. S., and Perry, A. O., 1976, History of reports on selected faults in southern and eastern Wisconsin: Geology, v. 4, p. 241-246.

Lander, J. F., and Cloud, W. K., 1963, United States earthquakes, 1961: U.S. Department of Commerce, Coast and Geodetic Survey, 106 p.

Lidiak, E. G., and Zietz, Isidore, 1976, Interpretation of aeromagnetic anomalies between latitudes 37° N. and 38° N. in the eastern and central United States: Geological Society of America, Special Paper 167, 37 p.

Luza, K. V., and Lawson, J. E., 1983, Seismicity and tectonic relationships of the Nemaha uplift in Oklahoma: U.S. Nuclear Regulatory Commission, NUREG/CR-3109, 115 p.

Mansfield, R. H., and Evernden, J. F., 1966, Long-range seismic data from the Lake Superior seismic experiment, 1963-1964, *in* Steinhart, J. S., and Smith, T. V., eds., The earth beneath the continents: American Geophysical Union, Geophysical Monograph 10, p. 249-269.

McGinnis, L. D., and Heigold, P. C., 1961, Regional maps of vertical magnetic intensity in Illinois: Illinois State Geological Survey Circular 324, 12 p.

McGinnis, L. D., Heigold, P. C., Ervin, C. P., and Heidari, M., 1976, The gravity field and tectonics of Illinois: Illinois State Geological Survey Circular 494, 28 p.

McKeown, F. A., 1982, Overview and discussion, *in* McKeown, F. A., and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-A, p. 1-14.

McPhee, J. P., 1983, Regional gravity analysis of the Anna, Ohio, seismogenic region: West Lafayette, Ind., Purdue University, M.S. thesis, 99 p.

Miller, H. J., 1956, The Oklahoma earthquake of April 9, 1952: Seismological Society of America Bulletin, v. 46, p. 269-279.

Mitchell, B. J., 1973, Radiation and attenuation of Rayleigh waves from the southeastern Missouri earthquake of October 21, 1965: Journal of Geophysical Research, v. 78, p. 886-889.

Mooney, H. M., 1979, Earthquake history of Minnesota: Minnesota Geological Survey Report of Investigations 23, 20 p.

______1981, Minnesota earthquakes, 1979, *in* Stover, C. W., and von Hake, C. A., eds., United States earthquakes, 1979: U.S. Geological Survey and National Oceanic and Atmospheric Administration, p. 115-118.

Mooney, H. M., Craddock, Campbell, Farnham, P. R., Johnson, S. H., and Volz, Gary, 1970, Refraction seismic investigations of the northern Midcontinent gravity high: Journal of Geophysical Research, v. 75, p. 5056-5086.

Mooney, H. M., and Morey, G. B., 1981, Seismic history of Minnesota and its geological significance: Seismological Society of America Bulletin, v. 71, p. 199-210.

Mooney, W. D., Andrews, M. C., Ginzburg, A., Peters, D. A., and Hamilton, R. M., 1983, Crustal structure of the northern Mississippi Embayment and a comparison with other continental rift zones: Tectonophysics, v. 94, p. 327-348.

Muehlberger, W. R., 1965, Late Paleozoic movement along the Texas lineament: New York Academy of Science Transactions, Series II, v. 27, p. 385-392.

______1980, The shape of North America during the Precambrian, *in* Continental tectonics: National Academy of Sciences, Washington, D.C., p. 175-183.

Muehlberger, W. R., Belcher, R. C., and Goetz, L. K., 1978, Quaternary faulting in Trans-Pecos, Texas: Geology, v. 6, p. 337-340.

Murphy, L. M., and Cloud, W. K., 1957, United States earthquakes, 1955: U.S. Department of Commerce, Coast and Geodetic Survey, 83 p.

Nava, Sue, and Johnston, Arch, 1984, Southern Mississippi Valley and southern Appalachian earthquakes, 1981, *in* Stover, C. W., United States earthquakes, 1981: U.S. Geological Survey Special Publication, p. 102-106.

Neumann, Frank, 1932, United States earthquakes, 1931: U.S. Department of Commerce, Coast and Geodetic Survey, 26 p.

Nuttli, O. W., 1956, Tentative velocities of seismic crustal waves in the central United States: Earthquake Notes, v. 27, p. 41-44.

______1965, The southern Illinois earthquakes of August 14 and 15, 1965 [abs.]: Earthquake Notes, v. 36, p. 26.

______1973, Seismic wave attenuation and magnitude relations for eastern North America: Journal of Geophysical Research, v. 78, p. 876-885.

______1979, Seismicity of the central United States, *in* Hatheway, A. W., and McClure, C. R., eds., Geology in the siting of nuclear power plants: Geological Society of America, Reviews in Engineering Geology, v. 4, p. 67-93.

______1982, Damaging earthquakes of the central Mississippi Valley, *in* McKeown, F. A., and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-B, p. 15-20.

Nuttli, O. W., and Brill, K. G., 1981, Earthquake source zones in the central United States determined from historical seismicity, *in* Barstow, N. L., Brill, K. G., Nuttli, O. W., and Pomeroy, P. W., eds., An approach to seismic zonation for siting nuclear electric power generating facilities in the eastern United States: U.S. Nuclear Regulatory Commission, NUREG/CR-1577, p. 97-143.

Nuttli, O. W., and Herrmann, R. B., 1978, Credible earthquakes for the central United States: U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper S-73-1, 101 p.

Nuttli, O. W., Stauder, William, and Kisslinger, Carl, 1969, Travel-time tables for earthquakes in the central United States: Earthquake Notes, v. 40, p. 19-28.

Nuttli, O. W., and Zollweg, J. E., 1974, The relation between felt area and magnitude for central United States earthquakes: Seismological Society of America Bulletin, v. 64, p. 73-85.

Ocola, L. C., and Meyer, R. P., 1973, Central North American rift system, I. Structure of the axial zone from seismic and gravimetric data: Journal of Geophysical Research, v. 78, p. 5173-5194.

O'Connell, D. R., Bufe, C. G., and Zoback, M. D., 1982, Microearthquakes and faulting in the area of New Madrid, Missouri-Reelfoot Lake, Tennessee, *in* McKeown, F. A., and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-D, p. 31-38.

Patton, Howard, 1976, A note on the source mechanism of the southeastern Missouri earthquake of October 21, 1965: Journal of Geophysical Research, v. 81, p. 1483-1486.

Poppe, B. B., 1979, Historical survey of U.S. seismograph stations: U.S. Geological Survey Professional Paper 1096, 389 p.

Pratt, W. E., 1926, An earthquake in the panhandle of Texas: Seismological Society of America Bulletin, v. 16, no. 2, p. 146-149.

Presgrave, B. W., Needham, R. E., and Minsch, J. H., 1985, Seismograph station codes and coordinates, 1985 edition: U.S. Geological Survey Open-File Report 85-714, 385 p.

Raleigh, C. B., Healy, J. H., and Bredehoeft, J. D., 1972, Faulting and crustal stress at Rangely, Colorado: American Geophysical Union Monograph 16, p. 275-284.

Reagor, B. G., Stover, C. W., and Hopper, M. G., 1981, Preliminary report of the distribution of intensities for the Kentucky earthquake of July 27, 1980: U.S. Geological Survey Open-File Report 81-198, 71 p.

Reinbold, D. J., and Johnston, A. C., 1983, A seismogenic zone in the Tennessee valley and ridge province [abs.]: Programs and Abstracts of the Eastern Section of the Seismological Society of America, 55th Annual Meeting, Sept. 19-21, 1983.

Richter, C. F., 1958, Elementary seismology: Freeman and Company, 768 p.

Rogers, A. M., and Malkiel, A., 1979, A study of earthquakes in the Permian basin of Texas-New Mexico: Seismological Society of America Bulletin, v. 69, p. 843-865.

Romney, Carl, Brooks, B. G., Mansfield, R. H., Carder, D. S., Jordan, J. N., and Gordon, D. W., 1962, Travel times and amplitudes of principal body phases recorded from GNOME: Seismological Society of America Bulletin, v. 52, p. 1057-1074.

Russ, D. P., 1979, Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee: Geological Society of America Bulletin, v. 90, p. 1013-1018.

Sanford, A. R., Sandford, S., Caravella, F., Merritt, L., Sheldon, J., and Ward, R., 1978, Seismic studies of the Los Medanos area in southeastern New Mexico: New Mexico Institute of Mining and Technology, Geophysical Open-File Report 20, 39 p.

Sanford, A. R., and Toppozada, T. R., 1974, Seismicity of proposed radioactive waste disposal site in southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 143, 15 p.

Sbar, M. L., and Sykes, L. R., 1973, Contemporary compressive stress and seismicity in eastern North America—An example of intraplate tectonics: Geological Society of America Bulletin, v. 84, p. 1861-1882.

Seager, W. R., and Morgan, Paul, 1979, Rio Grande rift in southern New Mexico, West Texas, and northern Chihuahua, *in* Riecker, R. E., ed., Rio Grande rift—Tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 87-106.

Sellards, E. H., 1932, The Valentine, Texas, earthquake: University of Texas Bulletin, no. 3201, p. 113-138.

Sims, P. K., Card, K. D., Morey, G. B., and Peterman, Z. E., 1980, The Great Lakes tectonic zone—A major crustal structure in central North America: Geological Society of America Bulletin, v. 91, p. 690-698.

Soderberg, R. K., and Keller, G. R., 1979, A gravity and tectonic study of the Rough Creek fault zone and related features: U.S. Nuclear Regulatory Commission NUREG/CR-1014, p. 135-164.

Stauder, William, 1982, Present-day seismicity and identification of active faults of the New Madrid seismic zone, *in* McKeown, F. A., and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-C, p. 21-30.

Stauder, William, Dowling, John, and Jackson, W. H., 1964, The BILLIKEN calibration shot in southeast Missouri: Air Force Cambridge Research Laboratories, Bedford, Mass., Scientific Report AFCRL-64-659, 26 p.

Stauder, William, Kramer, M., Fischer, G., Schaefer, S., and Morrissey, S. T., 1976, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array: Seismological Society of America Bulletin, v. 66, p. 1953-1964.

Stauder, William, and Nuttli, O. W., 1970, Seismic studies: South central Illinois earthquake of November 9, 1968: Seismological Society of America Bulletin, v. 60, p. 973-981.

Steeples, D. W., 1980, Operation and maintenance of and data analyses from a microearthquake seismograph network near reservoirs in Kansas—Final report for fiscal year 1979: Report submitted to the U.S. Army Corps of Engineers by the Kansas Geological Survey, 25 p.

______1981, Kansas earthquakes, 1979, *in* Stover, C. W., and von Hake, C. A., eds., United States earthquakes, 1979: U.S. Geological Survey and National Oceanic and Atmospheric Administration, p. 114-117.

———1984, Kansas and Nebraska earthquakes, 1981, *in* Stover, C. W., ed., United States earthquakes, 1981: U.S. Geological Survey Special Publication, p. 101-103.

Stover, C. W., and von Hake, C. A., eds., 1980, United States earthquakes, 1978: U.S. Geological Survey and National Oceanic and Atmospheric Administration, 112 p.

———1981, United States earthquakes, 1979: U.S. Geological Survey and National Oceanic and Atmospheric Administration, 170 p.

———1982, United States earthquakes, 1980: U.S. Geological Survey and National Oceanic and Atmospheric Administration, 182 p.

Street, R. L., Herrmann, R. B., and Nuttli, O. W., 1975, Spectral characteristics of the L_g wave generated by central United States earthquakes: Geophysical Journal of the Royal Astronomical Society, v. 41, p. 51-63.

Swan, M. M., 1975, The Texas lineament-Tectonic expression of a Precambrian orogeny [abs.]: Geological Society of America Abstracts with Programs, v. 7, no. 7, p. 1288-1289.

Sykes, L. R., 1978, Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621-688.

Thomas, W. A., 1973, Southwestern Appalachian structural system beneath the Gulf Coast Plain: American Journal of Science, v. 273-A, p. 372-390.

———1976, Evolution of Ouachita-Appalachian continental margin: Journal of Geology, v. 84, p. 323-342.

Treworgy, J. D., 1981, Structural features in Illinois—A compendium: Illinois State Geological Survey, Circular 519, 22 p.

von Hake, C. A., and Cloud, W. K., 1966, United States earthquakes, 1964: U.S. Department of Commerce, Coast and Geodetic Survey, 91 p.

———1968, United States earthquakes, 1966: U.S. Department of Commerce, Coast and Geodetic Survey, 110 p.

Voss, J. A., and Herrmann, R. B., 1980, A surface wave study of the June 16, 1978 Texas, earthquake: Earthquake Notes, v. 51, p. 3-14.

Walper, J. L., 1975, The evolution of the Delaware aulacogen in West Texas [abs.]: South-Central Section, Geological Society of America Abstracts with Programs, v. 7, p. 243.

———1976, Plate tectonics and earthquake assessment: U.S. Army Engineer Waterways Experiment Station, Miscellaneous Paper S-73-1, 104 p.

———1977, Paleozoic tectonics of the southern margin of North America: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 230-241.

———1980, Tectonic evolution of the Gulf of Mexico, *in* Pilger, R. H., ed., The origin of the Gulf of Mexico and the early opening of the central North Atlantic Ocean: Proceedings of a symposium at Louisiana State University, Baton Rouge, La., March 3-5, 1980, p. 87-98.

Walthall, B. H., and Walper, J. L., 1967, Peripheral Gulf rifting in northeast Texas: American Association of Petroleum Geologists Bulletin, v. 51, p. 102-110.

Warner, L. A., 1978, The Colorado lineament: A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, p. 161-171.

Wheeler, R. L., 1985, Evaluating point concentrations on a map—Earthquakes in the Colorado lineament: Geology, v. 13, p. 701-704.

Wickham, John, 1978, The Southern Oklahoma aulacogen, *in* Wickham, John, and Denison, Roger, eds., Structural style of the Arbuckle region: Geological Society of America, South-Central Section Field Trip no. 3, p. 8-41.

Wickham, John, Roeder, D., and Briggs, G., 1976, Plate tectonics models for the Ouachita foldbelt: Geology, v. 4, p. 173-176.

Wiley, M. A., and Muehlberger, W. R., 1971, The Texas lineament, *in* Seewald, K., and Sundeen, D., eds., The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society, p. 15-23.

Wong, I. G., Becker, D. J., Zeltinger, J. M., Brill, K. G., and Nuttli, O. W., 1983, Comments and reply on "Seismicity of the Colorado lineament": Geology, v. 11, no. 9, p. 558-561.

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

Wood, M. L., and Walper, J. L., 1974, The evolution of the interior Mezozoic basin and the Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 24, p. 31-41.

Yarger, H. L., 1981, Aeromagnetic survey of Kansas: Transactions American Geophysical Union, v. 62, no. 17, p. 173-178.

Zoback, M. D., 1979, Recurrent faulting in the vicinity of Reelfoot Lake, northwestern Tennessee: Geological Society of America Bulletin, v. 90, p. 1019-1024.

Zoback, M. D., Hamilton, R. M., Crone, A. J., Russ, D. P., McKeown, F. A., and Brockman, S. R., 1980, Recurrent intraplate tectonism in the New Madrid seismic zone: Science, v. 209, p. 971-976.

Zoback, M. D., and Zoback, M. L., 1981, State of stress and intraplate earthquakes in the United States: Science, v. 213, p. 96-104.

Zoback, M. L., and Zoback, M. D., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113-6156.

APPENDIX

Catalog of revised instrumental hypocenters in the central United States, 1931-1980

Explanation: Each event in the file is represented by two data lines.

1. The first data line gives the event date, origin time (GMT), coordinates (LAT,LONG), focal depth (FD) in kilometers, magnitude (MAG), and code of the zone or subzone associated with the hypocenter. Focal depths accompanied by an asterisk designate events computed with fixed focal depth. Explosions are designated by "X" between the date and origin time. "R" in this position designates a probable rockburst. Magnitudes not followed by letter codes are $m_b(L_g)$ magnitudes (Nuttli, 1973) computed in this study. Magnitudes identified by letter codes were obtained from other sources. Unless indicated otherwise, all magnitudes listed are $m_b(L_g)$ magnitudes. Sources of the magnitudes are as follows:
   - B—Bollinger (1979)
   - DG—Dewey and Gordon (1984)
   - F—felt area magnitude (Nuttli and Zollweg, 1974) computed in this study
   - GS—$m_b(L_g)$ reported in EDR's
   - m_b—P-wave magnitude (Richter, 1958) reported in EDR's
   - M_L—local magnitude (Richter, 1959) reported in EDR's
   - N—Nuttli (1979) or Nuttli and Brill (1981)
   - TIC—Tennessee Earthquake Information Center
   - AAM, BLA, OTT, PAL, SLM, TUL—three-letter codes of seismograph stations that reported the magnitude

   The codes refer to the zones or subzones (see fig. 2) associated with the listed hypocenter. Upper-case codes denote zones which correspond to geographic areas. Lower-case codes denote subzones which are identified by nearby towns or villages. Zones, codes, and related subzones are as follows:

Zone	*Code*	*Subzone*	*Code*
Alabama	ALA	---	---
Great Lakes	GL	---	---
Gulf	GULF	---	---
Kentucky	KY	---	---
New Madrid	NM	Blytheville, Ark.	b
		Tamms, Ill.	ta
		Tiptonville, Tenn.	ti
Northern Great Plains	NGP	---	---
Ohio	OHIO	---	---
Ouachita	OU	Gurdon, Ark.	g
Ozark	OZ	Ironton, Mo.	i
Southern Appalachian	SA	---	---
Southern Mississippi Valley	SMV	Hemphill, Tex.	h
Wabash	WA	Eldorado, Ill.	e
West Texas	WTX	Kermit, Tex.	k
		Snyder, Tex.	s
Wichita	WI	---	---

2. The first part of the second data line refers to the epicenter ellipse. The "ellps ang" is the bearing (degrees) of the major axis measured clockwise from north (negative bearings are measured counter-clockwise); "smj" is the length (km) of the semi-major axis; "smn" is the length (km) of the semi-minor axis. The second part of the second data line gives a measure of the reliability of the computed focal depth. This line lists the plunge (pl) in degrees and the length (sl) in kilometers of the steepest semi-axis of the hypocenter ellipsoid. These parameters are not given for fixed-depth solutions.

DATE O-TIME LAT LONG FD MAG CODE
YR MO DY H M S (N) (W) (KM)

1931.08.16 11 40 22.3 30.502 104.575 1.0* 5.8 N WTX
(ellps ang-167.0 smj 26.6 smn 14.8)
1931.09.20 23 05 03.4 40.429 84.270 5.0* 4.5 F OHIO
(ellps ang-178.9 smj 17.0 smn 9.9)
1933.06.15 01 14 36.8 37.568 81.973 5.0* SA
(ellps ang 177.9 smj 44.3 smn 12.1)
1936.06.20 03 24 03.5 35.310 100.773 5.0* 4.5 F WI
(ellps ang 156.7 smj 70.6 smn 14.5)
1937.03.02 14 47 33.3 40.488 84.273 2.3 4.7 F OHIO
(ellps ang 161.7 smj 9.6 smn 6.2 dpth axs pl 61.8 sl 13.8)
1937.03.09 05 44 35.5 40.470 84.280 2.9 4.9 F OHIO
(ellps ang 157.3 smj 10.4 smn 5.8 dpth axs pl 61.0 sl 15.8)
1938.09.18 03 34 28.3 35.413 90.254 0.5 4.8 F NM
(ellps ang -140.4 smj 18.7 smn 15.6 dpth axs pl 60.2 sl 25.9)
1939.11.23 15 14 52.0 38.180 90.137 0.2 4.9 F OZ
(ellps ang 73.9 smj 11.1 smn 4.2 dpth axs pl 44.5 sl 12.3)
1943.03.09 03 25 24.9 41.628 81.309 6.5 4.5 F OHIO
(ellps ang 176.0 smj 14.0 smn 9.6 dpth axs pl 68.2 sl 20.8)
1947.08.10 02 46 41.3 41.928 85.004 2.1 4.6 F OHIO
(ellps ang 144.4 smj 11.9 smn 7.9 dpth axs pl 80.0 sl 16.8)
1948.03.12 04 29 06.3 36.221 102.478 5.0* 4.8 F WI
(ellps ang 162.4 smj 24.4 smn 8.3)
1951.06.20 18 37 11.1 35.218 103.035 1.0* 4.4 F WI
(ellps ang 166.4 smj 24.6 smn 7.9)
1952.04.09 16 29 28.4 35.525 97.850 9.6 5.0 F WI
(ellps ang 162.4 smj 17.8 smn 9.4 dpth axs pl 76.6 sl 36.1)
1952.06.20 09 38 08.6 39.640 82.023 9.2 4.1 F OHIO
(ellps ang 172.5 smj 19.0 smn 8.6 dpth axs pl 55.1 sl 25.9)
1955.01.25 07 24 39.1 36.073 89.827 8.1 4.5 F NM
(ellps ang 173.5 smj 19.7 smn 14.4 dpth axs pl 48.5 sl 23.3)
1955.04.09 13 01 23.3 38.232 89.785 10.7 4.3 F OZ
(ellps ang -159.3 smj 20.1 smn 18.5 dpth axs pl 67.9 sl 24.8)
1956.01.06 11 58 07.4 37.583 98.346 28.9 4.4 F WI
(ellps ang 172.4 smj 25.6 smn 9.7 dpth axs pl 47.9 sl 27.9)
1956.01.29 04 44 15.5 35.756 89.803 16.2 4.0 F NM
(ellps ang 126.4 smj 15.7 smn 9.9 dpth axs pl 78.2 sl 26.2)
1956.09.07 13 35 50.8 36.445 83.787 5.0* 4.1 F SA
(ellps ang-151.3 smj 31.2 smn 15.1)
1956.11.26 04 12 43.3 36.914 90.387 1.0* 4.4 F OZ
(ellps ang 141.4 smj 11.0 smn 7.3)
1957.04.23 09 23 39.0 33.770 86.723 5.0* 4.2 F ALA
(ellps ang-179.5 smj 34.7 smn 15.1)
1957.05.13 14 24 51.1 35.799 82.142 5.0* 4.1 F SA
(ellps ang 77.9 smj 25.5 smn 19.0)
1957.06.23 06 34 16.0 35.946 84.095 5.0* SA
(ellps ang 165.0 smj 48.0 smn 16.2)
1958.10.23 02 29 44.3 37.205 81.905 5.0* 3.0 N SA
(ellps ang 97.2 smj 18.2 smn 9.2)
1958.11.08 02 41 12.6 38.436 88.008 4.9 4.4 F e
(ellps ang 175.4 smj 22.3 smn 14.1 dpth axs pl 59.6 sl 35.5)
1959.06.17 10 27 10.6 34.639 98.055 4.8 4.2 F WI
(ellps ang 178.7 smj 14.1 smn 10.2 dpth axs pl 76.8 sl 40.2)
1959.08.12 18 06 01.4 34.789 86.562 5.0* 3.8 F ALA
(ellps ang 171.3 smj 43.5 smn 17.1)
1959.12.21 16 23 39.6 36.033 89.338 4.8 3.4 F NM
(ellps ang 145.7 smj 35.4 smn 24.5 dpth axs pl 33.1 sl 28.9)
1960.11.10 01 33 46.0 26.060 87.925 15.0* GULF
(ellps ang-166.5 smj 50.0 smn 25.1)
1961.04.13 21 14 55.2 39.984 99.766 1.0* 3.7 F NGP
(ellps ang-154.1 smj 21.9 smn 11.1)
1961.09.09 22 42 55.0 35.959 90.193 5.0* 3.8 N OZ
(ellps ang 134.4 smj 25.9 smn 10.8)
1961.12.10 X 19 00 00.6 32.239 103.856 0.0* WTX
(ellps ang 179.6 smj 21.3 smn 7.5)
1961.12.25 12 19 58.3 39.300 94.214 11.4 3.9 N NGP
(ellps ang 179.0 smj 20.9 smn 10.0 dpth axs pl 58.0 sl 26.1)
1961.12.25 12 58 16.8 39.320 94.244 8.9 4.1 N NGP
(ellps ang -178.1 smj 21.0 smn 10.1 dpth axs pl 59.9 sl 25.3)
1961.12.31 16 36 05.8 44.250 100.724 23.1 4.2 F NGP
(ellps ang -161.3 smj 18.7 smn 7.0 dpth axs pl 76.0 sl 27.2)

DATE O-TIME LAT LONG FD MAG CODE
YR MO DY H M S (N) (W) (KM)

1962.02.02 06 43 30.0 36.374 89.511 3.5 4.3 N ti
(ellps ang 143.8 smj 7.1 smn 4.8 dpth axs pl 60.0 sl 9.1)
1962.06.01 11 23 38.6 35.382 90.391 1.0* 3.2 N NM
(ellps ang 174.8 smj 12.2 smn 6.6)
1962.06.27 01 28 59.3 37.900 88.638 6.8 3.9 e
(ellps ang 169.9 smj 14.6 smn 6.1 dpth axs pl 49.3 sl 18.2)
1962.07.14 02 23 44.0 36.564 89.816 1.0* 3.2 N NM
(ellps ang-178.5 smj 18.5 smn 11.4)
1962.07.23 06 05 15.7 36.044 89.399 8.0 3.6 N NM
(ellps ang 154.2 smj 10.1 smn 9.0 dpth axs pl 82.6 sl 19.6)
1963.03.03 17 30 10.6 36.642 90.050 9.2 4.8 ti
(ellps ang 164.5 smj 6.0 smn 4.4 dpth axs pl 85.2 sl 23.0)
1963.04.06 07 51 01.2 36.433 89.511 10.7 ti
(ellps ang -155.2 smj 17.0 smn 7.6 dpth axs pl 70.5 sl 23.1)
1963.04.06 08 12 22.7 36.457 89.582 5.6 3.1 N ti
(ellps ang 174.2 smj 8.6 smn 7.0 dpth axs pl 62.1 sl 14.2)
1963.05.02 01 09 21.4 36.668 89.538 10.1 3.1 N ti
(ellps ang -138.5 smj 9.5 smn 7.8 dpth axs pl 49.5 sl 12.8)
1963.06.28 X 09 59 59.8 36.680 90.163 0.0* ti
(ellps ang-172.7 smj 9.5 smn 6.2)
1963.07.08 23 51 42.1 36.969 90.469 0.1 3.1 N i
(ellps ang 90.1 smj 9.5 smn 7.5 dpth axs pl 79.1 sl 16.4)
1963.08.03 00 37 49.1 36.982 88.770 6.7 3.8 ti
(ellps ang -156.0 smj 10.1 smn 5.9 dpth axs pl 76.0 sl 18.0)
1963.09.13 10 51 57.9 29.105 105.903 16.3 4.6 mb WTX
(ellps ang -152.8 smj 17.2 smn 11.0 dpth axs pl 76.0 sl 36.6)
1963.11.05 22 45 03.4 27.487 92.582 15.0* 4.8 mb GULF
(ellps ang 165.3 smj 88.2 smn 33.4)
1963.12.05 06 51 00.5 37.149 86.970 1.0* 3.2 N KY
(ellps ang 174.9 smj 15.1 smn 9.4)
1964.01.16 05 09 57.6 36.843 89.461 5.9 3.3 ti
(ellps ang 71.8 smj 6.3 smn 3.9 dpth axs pl 73.4 sl 9.2)
1964.02.02 08 22 43.8 35.306 99.606 1.0* 2.9 WI
(ellps ang-176.0 smj 13.4 smn 6.5)
1964.02.18 09 31 10.4 34.665 85.392 1.0* 4.0 B ALA
(ellps ang 179.4 smj 8.2 smn 7.4)
1964.03.28 10 08 46.5 42.997 101.798 29.5 4.5 NGP
(ellps ang -171.3 smj 10.3 smn 6.5 dpth axs pl 77.5 sl 24.5)
1964.04.24 01 20 54.2 31.381 93.807 1.0* 3.3 h
(ellps ang 157.9 smj 7.3 smn 5.1)
1964.04.24 07 33 51.9 31.422 93.812 5.0* 3.6 SMV
(ellps ang 174.3 smj 8.0 smn 4.4)
1964.04.24 07 47 17.1 31.384 93.804 5.3 3.3 N h
(ellps ang 170.1 smj 16.7 smn 6.9 dpth axs pl 59.1 sl 25.6)
1964.04.24 12 07 08.2 31.478 93.787 9.2 3.2 N h
(ellps ang -172.9 smj 39.3 smn 14.2 dpth axs pl 66.0 sl 62.7)
1964.04.26 03 24 50.2 31.546 93.784 4.6 3.3 N h
(ellps ang -169.2 smj 45.7 smn 13.1 dpth axs pl 38.8 sl 53.0)
1964.04.28 00 30 45.7 31.401 93.818 5.7 3.3 h
(ellps ang 165.9 smj 6.9 smn 4.3 dpth axs pl 79.7 sl 13.7)
1964.04.28 21 18 41.0 31.628 93.801 13.6 3.4 h
(ellps ang 156.2 smj 7.2 smn 5.2 dpth axs pl 87.1 sl 21.8)
1964.05.23 11 25 34.5 36.579 90.018 2.5 3.4 ti
(ellps ang 48.6 smj 5.6 smn 4.0 dpth axs pl 75.1 sl 9.2)
1964.05.23 15 00 34.9 36.598 90.011 8.1 3.1 ti
(ellps ang 63.3 smj 7.2 smn 4.1 dpth axs pl 79.0 sl 8.8)
1964.06.03 02 27 27.5 31.278 93.834 22.7 2.5 h
(el!ps ang -179.3 smj 13.4 smn 6.0 dpth axs pl 87.6 sl 27.5)
1964.08.26 16 58 55.1 43.774 102.248 19.7 3.0 NGP
(ellps ang -169.1 smj 15.5 smn 8.6 dpth axs pl 54.3 sl 20.8)
1964.10.10 X 08 30 01.1 47.396 89.923 0.0* GL
(ellps ang-147.4 smj 8.3 smn 6.1)
1964.10.10 X 11 30 00.9 47.350 90.276 0.0* GL
(ellps ang-152.1 smj 9.1 smn 6.4)
1964.10.22 X 16 00 01.3 31.179 89.589 0.0* SMV
(ellps ang-175.6 smj 8.8 smn 5.2)
1964.11.25 R 02 50 06.4 37.394 81.698 5.5 3.6 B SA
(ellps ang 144.3 smj 7.7 smn 5.2 dpth axs pl 72.3 sl 11.8)
1965.02.11 03 40 24.8 36.519 89.591 3.2 3.3 ti
(ellps ang 63.8 smj 6.1 smn 4.7 dpth axs pl 86.1 sl 17.2)

DATE O-TIME LAT LONG FD MAG CODE
YR MO DY H M S (N) (W) (KM)

1965.03.06 21 08 50.3 37.396 91.032 7.3 4.0 i
(ellps ang 45.3 smj 5.2 smn 3.1 dpth axs pl 63.3 sl 8.3)
1965.03.25 12 59 27.7 36.464 89.516 3.4 3.9 ti
(ellps ang 55.1 smj 5.8 smn 4.0 dpth axs pl 79.8 sl 9.2)
1965.04.26 15 26 19.7 37.325 81.602 5.0 3.5 B SA
(ellps ang 132.4 smj 7.9 smn 5.0 dpth axs pl 68.4 sl 11.1)
1965.08.14 05 04 31.3 37.209 89.292 0.9 2.5 ta
(ellps ang 135.3 smj 4.7 smn 4.1 dpth axs pl 74.5 sl 7.6)
1965.08.14 05 46 18.4 37.207 89.289 1.0* 3.0 ta
(ellps ang 166.5 smj 4.1 smn 3.7)
1965.08.14 13 13 56.9 37.226 89.307 1.0* 3.8 NM
(ellps ang-138.1 smj 6.2 smn 4.8)
1965.08.15 06 07 29.0 37.222 89.297 1.9 3.1 ta
(ellps ang 124.1 smj 3.3 smn 3.1 dpth axs pl 66.8 sl 5.8)
1965.08.30 05 17 36.4 32.084 102.419 5.0* 2.6 k
(ellps ang-136.1 smj 17.1 smn 9.6)
1965.10.21 02 04 39.1 37.479 90.944 7.3 4.8 i
(ellps ang 179.4 smj 4.6 smn 3.6 dpth axs pl 65.4 sl 7.6)
1965.10.21 04 06 49.2 37.451 90.940 1.0* 2.7 i
(ellps ang-156.0 smj 7.1 smn 5.6)
1965.11.04 07 43 37.9 37.032 90.925 3.6 3.4 i
(ellps ang -140.7 smj 4.8 smn 3.4 dpth axs pl 69.7 sl 6.5)
1965.12.19 22 19 12.0 36.034 89.765 1.3 3.8 b
(ellps ang -147.6 smj 7.4 smn 4.8 dpth axs pl 82.8 sl 11.1)
1966.02.12 04 32 12.8 35.955 89.873 1.0* 3.6 b
(ellps ang 48.5 smj 8.3 smn 5.3)
1966.02.13 23 19 37.8 37.041 90.896 6.4 3.4 i
(ellps ang -138.2 smj 5.3 smn 3.5 dpth axs pl 67.9 sl 7.1)
1966.02.14 00 08 56.4 37.081 90.893 1.3 2.9 i
(ellps ang 52.8 smj 6.0 smn 3.6 dpth axs pl 77.2 sl 8.0)
1966.02.26 08 10 17.7 37.047 90.880 1.3 3.4 i
(ellps ang 153.6 smj 6.7 smn 5.1 dpth axs pl 69.6 sl 14.6)
1966.06.26 11 59 43.1 44.296 103.428 2.1 3.1 N NGP
(ellps ang 72.8 smj 10.9 smn 9.0 dpth axs pl 70.7 sl 20.0)
1966.07.09 X 09 30 01.0 47.519 88.951 0.0* GL
(ellps ang-142.7 smj 18.8 smn 10.8)
1966.07.20 09 04 58.8 35.644 101.328 2.9 3.7 WI
(ellps ang 123.2 smj 8.1 smn 7.8 dpth axs pl 87.3 sl 19.4)
1966.08.14 15 25 53.7 32.115 102.339 2.7 3.2 k
(ellps ang 45.8 smj 25.0 smn 7.3 dpth axs pl 38.6 sl 30.2)
1966.09.09 09 50 34.2 41.298 98.814 27.1 3.1 NGP
(ellps ang -159.8 smj 18.4 smn 8.9 dpth axs pl 87.7 sl 31.9)
1967.04.08 05 40 30.5 39.647 82.527 5.0* 3.5 OHIO
(ellps ang 158.2 smj 9.9 smn 6.5)
1967.06.04 16 14 12.6 33.552 90.836 5.9 4.4 OU
(ellps ang -168.6 smj 11.7 smn 6.9 dpth axs pl 75.6 sl 25.0)
1967.06.29 13 57 06.5 33.554 90.811 2.0 3.8 OU
(ellps ang -167.4 smj 13.6 smn 7.7 dpth axs pl 67.0 sl 23.0)
1967.07.21 09 14 48.8 37.440 90.443 12.2 4.3 i
(ellps ang 59.4 smj 4.8 smn 4.5 dpth axs pl 83.7 sl 11.7)
1967.11.23 06 23 42.1 43.560 99.598 1.0* 3.5 NGP
(ellps ang-155.1 smj 19.9 smn 7.8)
1967.12.16 12 23 33.4 37.360 81.604 2.4 3.5 BLA SA
(ellps ang 135.0 smj 10.0 smn 5.0 dpth axs pl 62.6 sl 15.9)
1968.02.10 01 34 30.6 36.516 89.857 7.1 3.8 ti
(ellps ang 53.7 smj 5.9 smn 4.4 dpth axs pl 82.2 sl 14.6)
1968.03.31 17 58 09.6 38.020 89.851 1.0* 3.0 OZ
(ellps ang 61.6 smj 6.7 smn 3.7)
1968.07.08 16 50 14.7 46.588 100.742 27.3 3.7 NGP
(ellps ang 49.6 smj 14.3 smn 11.3 dpth axs pl 87.6 sl 85.5)
1968.11.09 17 01 40.5 37.911 88.373 21.2 5.5 N e
(ellps ang -178.1 smj 8.8 smn 5.4 dpth axs pl 81.7 sl 23.9)
1969.01.01 23 35 38.7 34.991 92.688 7.0* 4.4 OU
(ellps ang-163.0 smj 13.1 smn 6.8)
1969.05.02 11 33 21.7 35.289 96.313 8.4 3.3 NGP
(ellps ang 118.1 smj 11.2 smn 8.0 dpth axs pl 78.6 sl 18.1)
1969.05.12 08 26 19.6 31.853 106.516 13.3 3.4 ML WTX
(ellps ang -159.3 smj 17.4 smn 9.6 dpth axs pl 34.3 sl 20.6)
1969.05.12 08 49 17.2 31.845 106.557 14.1 3.2 ML WTX
(ellps ang -152.8 smj 18.4 smn 10.2 dpth axs pl 29.5 sl 20.8)

DATE O-TIME LAT LONG FD MAG CODE
YR MO DY H M S (N) (W) (KM)

1969.07.13 21 51 09.8 36.119 83.688 1.0* 4.2 B SA
(ellps ang 147.6 smj 7.9 smn 4.4)
1969.10.19 11 51 34.3 30.808 105.759 1.0* 3.8 mb WTX
(ellps ang-161.3 smj 18.9 smn 8.1)
1969.11.20 01 00 09.3 37.449 80.932 2.5 4.6 B SA
(ellps ang 132.7 smj 6.2 smn 4.4 dpth axs pl 54.8 sl 9.1)
1970.03.27 03 44 29.2 36.596 89.542 5.0 3.0 ti
(ellps ang 69.8 smj 11.3 smn 5.3 dpth axs pl 45.1 sl 13.3)
1970.07.06 R 09 39 13.0 37.810 90.490 0.0* 2.6 SLM i
(ellps ang 79.6 smj 3.9 smn 2.4)
1970.07.30 R 08 48 53.0 36.999 82.163 7.3 3.3 DG SA
(ellps ang 150.9 smj 9.4 smn 5.4 dpth axs pl 81.1 sl 14.4)
1970.07.30 R 15 15 16.9 36.990 82.206 11.6 3.7 DG SA
(ellps ang 145.0 smj 10.2 smn 5.7 dpth axs pl 79.5 sl 18.7)
1970.08.11 06 14 25.5 38.234 82.053 9.8 2.8 OHIO
(ellps ang 148.8 smj 16.7 smn 9.2 dpth axs pl 71.1 sl 29.2)
1970.11.17 02 13 54.1 35.856 89.947 14.3 4.3 b
(ellps ang 60.5 smj 5.4 smn 3.9 dpth axs pl 57.7 sl 8.3)
1970.12.24 10 17 56.8 36.708 89.545 15.0 3.4 ti
(ellps ang 65.7 smj 4.7 smn 3.0 dpth axs pl 47.7 sl 4.6)
1971.02.12 12 44 27.5 38.497 87.847 15.0 3.1 e
(ellps ang 165.0 smj 8.6 smn 5.5 dpth axs pl 78.7 sl 16.7)
1971.03.14 17 27 54.6 33.179 87.836 11.5 3.6 B ALA
(ellps ang 59.0 smj 11.9 smn 8.6 dpth axs pl 71.8 sl 16.5)
1971.04.13 14 00 49.4 35.775 90.218 1.0* 2.4 b
(ellps ang 62.0 smj 7.7 smn 5.5)
1971.07.30 01 45 51.4 31.644 103.173 4.6 3.6 k
(ellps ang -167.8 smj 13.2 smn 7.8 dpth axs pl 73.2 sl 17.0)
1971.07.31 14 53 49.4 31.652 103.119 1.8 3.2 k
(ellps ang -171.2 smj 15.2 smn 8.6 dpth axs pl 73.3 sl 20.0)
1971.10.01 18 49 38.5 35.773 90.486 9.1 4.2 b
(ellps ang -138.1 smj 5.7 smn 4.1 dpth axs pl 60.9 sl 9.0)
1971.10.09 16 43 32.7 35.795 83.371 8.3 3.7 B SA
(ellps ang 135.2 smj 9.5 smn 6.2 dpth axs pl 76.8 sl 13.9)
1971.10.19 21 07 37.4 43.694 101.260 17.2 3.7 NGP
(ellps ang -163.3 smj 20.0 smn 11.9 dpth axs pl 83.7 sl 36.4)
1972.01.09 R 23 24 30.1 37.385 81.660 3.2 3.0 N SA
(ellps ang 139.1 smj 9.3 smn 5.9 dpth axs pl 79.5 sl 14.8)
1972.02.01 05 42 09.5 36.366 90.850 2.9 3.7 OZ
(ellps ang 178.8 smj 5.9 smn 4.1 dpth axs pl 70.1 sl 10.0)
1972.03.29 20 38 31.7 36.116 89.741 7.1 3.7 N b
(ellps ang -148.2 smj 7.4 smn 4.1 dpth axs pl 59.4 sl 10.3)
1972.05.07 02 12 08.7 35.926 89.973 1.1 3.4 N b
(ellps ang 45.8 smj 5.0 smn 4.9 dpth axs pl 74.0 sl 10.6)
1972.05.20 R 19 39 06.9 37.055 82.294 1.0* 3.0 N SA
(ellps ang 145.6 smj 14.7 smn 8.5)
1972.06.09 19 15 18.9 37.621 90.366 11.5 3.1 N i
(ellps ang 61.7 smj 4.3 smn 2.5 dpth axs pl 81.7 sl 7.4)
1972.06.19 05 46 15.1 36.926 89.097 6.0 3.3 SLM ta
(ellps ang 73.5 smj 5.3 smn 3.9 dpth axs pl 60.9 sl 8.2)
1972.09.15 05 22 15.9 41.645 89.369 10.5 4.5 GL
(ellps ang 121.1 smj 6.0 smn 5.3 dpth axs pl 86.7 sl 21.2)
1972.10.16 05 47 32.5 42.443 99.559 25.4 2.9 NGP
(ellps ang 47.6 smj 23.3 smn 11.2 dpth axs pl 67.2 sl 30.0)
1973.01.07 22 56 06.2 37.402 87.220 13.7 3.2 SLM KY
(ellps ang 112.8 smj 11.2 smn 9.3 dpth axs pl 84.9 sl 19.4)
1973.01.08 09 11 37.9 33.796 90.515 5.0* 2.8 OU
(ellps ang 178.8 smj 15.8 smn 7.5)
1973.01.12 11 56 56.2 37.890 90.483 16.5 3.2 SLM i
(ellps ang -154.1 smj 6.5 smn 3.8 dpth axs pl 74.3 sl 14.1)
1973.04.18 12 21 53.1 38.514 90.240 20.6 2.5 SLM OZ
(ellps ang 60.8 smj 10.8 smn 7.0 dpth axs pl 34.2 sl 12.4)
1973.05.25 14 40 15.8 33.936 90.625 5.0* 2.9 OU
(ellps ang-178.5 smj 20.4 smn 7.4)
1973.10.03 03 50 19.8 35.868 90.045 5.6 3.4 SLM b
(ellps ang 66.3 smj 7.4 smn 4.9 dpth axs pl 80.9 sl 11.0)
1973.10.09 20 15 26.5 36.488 89.624 3.3 3.8 ti
(ellps ang 55.9 smj 5.1 smn 4.0 dpth axs pl 71.1 sl 7.6)
1973.10.30 22 58 39.0 35.759 84.117 0.7 3.5 DG SA
(ellps ang 158.3 smj 15.6 smn 7.5 dpth axs pl 60.8 sl 24.2)

DATE O-TIME LAT LONG FD MAG CODE
YR MO DY H M S (N) (W) (KM)

1973.11.30 07 48 40.5 35.889 83.993 12.2 4.6 B SA
(ellps ang 162.2 smj 6.4 smn 4.3 dpth axs pl 81.6 sl 13.2)
1973.12.20 10 45 00.9 36.141 89.689 10.2 3.1 b
(ellps ang 46.2 smj 8.0 smn 5.7 dpth axs pl 76.9 sl 13.8)
1974.01.08 01 12 38.1 36.178 89.471 7.4 3.9 b
(ellps ang −149.5 smj 6.1 smn 4.3 dpth axs pl 68.6 sl 8.5)
1974.02.15 13 33 49.2 36.399 100.688 0.1 4.5 WI
(ellps ang −165.0 smj 6.0 smn 5.0 dpth axs pl 85.1 sl 18.7)
1974.02.15 22 32 38.2 34.038 92.976 17.3 3.5 g
(ellps ang 169.3 smj 7.5 smn 5.4 dpth axs pl 85.6 sl 10.8)
1974.02.15 22 35 46.6 34.069 93.117 14.0 3.4 g
(ellps ang 141.5 smj 9.9 smn 6.7 dpth axs pl 82.1 sl 14.3)
1974.02.15 22 49 04.4 34.028 93.044 16.9 3.8 OU
(ellps ang 172.7 smj 7.9 smn 6.7 dpth axs pl 82.6 sl 17.6)
1974.02.15 22 53 05.1 33.998 92.981 19.8 2.8 SLM g
(ellps ang 159.7 smj 15.2 smn 9.3 dpth axs pl 75.0 sl 20.1)
1974.02.16 09 43 12.7 33.739 93.057 5.1 1.6 SLM g
(ellps ang −163.0 smj 33.3 smn 11.8 dpth axs pl 81.4 sl 18.2)
1974.02.16 09 44 37.2 33.992 93.069 19.1 2.3 SLM g
(ellps ang 178.6 smj 17.2 smn 10.0 dpth axs pl 42.1 sl 19.5)
1974.02.24 07 53 45.2 35.791 90.477 5.1 2.7 b
(ellps ang 69.9 smj 12.1 smn 5.3 dpth axs pl 58.7 sl 17.3)
1974.03.04 14 24 28.1 35.693 90.414 5.0* 3.0 SLM NM
(ellps ang 93.6 smj 12.4 smn 5.5)
1974.03.10 04 34 19.8 36.199 89.549 1.0* 2.5 SLM NM
(ellps ang 89.6 smj 14.3 smn 5.8)
1974.03.12 12 30 29.2 35.636 89.800 4.7 2.3 b
(ellps ang 62.4 smj 19.9 smn 6.9 dpth axs pl 75.4 sl 59.3)
1974.03.27 16 10 57.0 38.515 90.163 1.0* 2.4 SLM OZ
(ellps ang 61.6 smj 7.2 smn 4.0)
1974.04.03 23 05 02.8 38.549 88.072 13.5 4.7 e
(ellps ang 141.0 smj 7.1 smn 4.4 dpth axs pl 75.3 sl 12.4)
1974.04.05 19 41 14.2 38.628 90.758 1.0* 2.6 SLM OZ
(ellps ang 135.1 smj 21.2 smn 7.8)
1974.05.13 06 52 18.7 36.739 89.357 3.6 3.8 F ti
(ellps ang 68.0 smj 5.6 smn 4.1 dpth axs pl 72.4 sl 7.1)
1974.06.05 00 16 40.2 38.477 84.747 9.6 3.2 SLM KY
(ellps ang −179.6 smj 12.3 smn 11.0 dpth axs pl 81.8 sl 22.7)
1974.06.05 08 06 10.7 38.648 89.907 11.9 3.2 OZ
(ellps ang −171.7 smj 5.5 smn 4.2 dpth axs pl 59.8 sl 6.0)
1974.08.11 14 29 45.4 36.928 91.160 6.1 3.2 OZ
(ellps ang −149.9 smj 5.3 smn 3.4 dpth axs pl 66.6 sl 7.7)
1974.08.22 22 33 59.4 38.231 89.729 0.7 2.9 OZ
(ellps ang 53.9 smj 9.8 smn 4.3 dpth axs pl 80.4 sl 13.5)
1974.09.29 02 26 19.1 41.206 83.486 1.0* 3.0 SLM OHIO
(ellps ang 73.1 smj 10.4 smn 7.5)
1974.10.20 15 13 55.6 39.060 81.609 4.4 3.8 F OHIO
(ellps ang −173.5 smj 12.9 smn 7.0 dpth axs pl 66.0 sl 18.4)
1974.12.10 06 01 35.0 31.229 87.457 18.0 3.2 SMV
(ellps ang 163.6 smj 20.1 smn 14.9 dpth axs pl 59.7 sl 35.5)
1974.12.13 05 03 55.5 34.494 91.857 2.5 3.1 OU
(ellps ang −171.8 smj 15.2 smn 6.8 dpth axs pl 38.6 sl 17.0)
1974.12.13 10 13 22.5 36.738 91.612 2.5 2.8 SLM OZ
(ellps ang 48.0 smj 12.9 smn 5.0 dpth axs pl 60.5 sl 7.4)
1974.12.16 02 30 21.7 35.337 97.289 23.3 2.6 TUL WI
(ellps ang 155.0 smj 35.6 smn 8.0 dpth axs pl 72.8 sl 25.7)
1974.12.25 13 21 37.2 35.863 90.008 13.8 2.4 b
(ellps ang 58.6 smj 8.7 smn 5.4 dpth axs pl 66.1 sl 12.6)
1975.01.02 09 18 57.3 34.866 91.068 8.1 2.9 SLM OU
(ellps ang −154.4 smj 10.4 smn 6.8 dpth axs pl 67.5 sl 13.5)
1975.01.10 X 15 31 01.5 38.110 91.029 0.0* i
(ellps ang 113.1 smj 5.1 smn 3.8)
1975.02.13 19 43 58.0 36.549 89.593 3.0 3.4 ti
(ellps ang 89.9 smj 4.6 smn 3.0 dpth axs pl 71.7 sl 7.4)
1975.02.16 23 21 34.4 38.875 82.353 4.1 3.0 OHIO
(ellps ang 136.7 smj 8.4 smn 6.0 dpth axs pl 72.5 sl 19.2)
1975.03.01 11 49 51.9 32.952 88.019 1.0* 4.1 DG ALA
(ellps ang 177.0 smj 18.1 smn 11.6)
1975.05.02 16 22 58.5 35.961 84.471 12.4 2.6 SLM SA
(ellps ang −158.7 smj 10.1 smn 8.3 dpth axs pl 45.5 sl 10.3)
1975.05.13 07 53 40.0 42.070 98.503 1.1 3.3 NGP
(ellps ang −136.1 smj 12.3 smn 5.6 dpth axs pl 88.2 sl 31.2)
1975.05.14 23 03 05.2 35.981 85.301 1.0* 2.7 SLM SA
(ellps ang−157.2 smj 11.2 smn 6.8)
1975.05.16 05 57 06.0 43.283 103.894 17.8 2.8 NGP
(ellps ang 72.0 smj 16.0 smn 7.9 dpth axs pl 83.8 sl 38.9)
1975.06.13 22 40 27.5 36.543 89.682 8.5 3.9 NM
(ellps ang 56.3 smj 5.0 smn 4.0 dpth axs pl 72.1 sl 7.9)
1975.06.24 11 11 36.6 33.703 87.844 3.7 3.7 DG ALA
(ellps ang −167.6 smj 17.6 smn 7.4 dpth axs pl 77.2 sl 14.5)
1975.07.06 08 48 14.0 36.174 89.470 1.9 2.9 SLM b
(ellps ang 110.4 smj 4.4 smn 2.3 dpth axs pl 74.7 sl 6.7)
1975.07.09 14 54 21.3 45.498 96.100 7.5* 4.6 GL
(ellps ang 169.9 smj 6.6 smn 5.9)
1975.08.01 07 27 43.8 30.567 104.489 1.0* 3.2 WTX
(ellps ang−136.8 smj 33.1 smn 11.0)
1975.08.20 09 14 16.6 36.524 89.788 0.3 2.9 SLM b
(ellps ang 156.4 smj 6.5 smn 3.3 dpth axs pl 88.3 sl 13.9)
1975.08.25 00 44 14.4 37.231 90.912 5.2 2.2 i
(ellps ang 94.6 smj 3.3 smn 2.1 dpth axs pl 86.1 sl 8.6)
1975.08.25 03 01 28.5 37.226 90.908 5.5 2.5 i
(ellps ang 86.2 smj 2.8 smn 2.0 dpth axs pl 85.2 sl 7.6)
1975.08.25 07 11 08.1 36.029 89.835 8.8 2.8 b
(ellps ang 164.6 smj 3.1 smn 2.5 dpth axs pl 85.3 sl 9.6)
1975.08.25 10 00 34.7 42.574 101.548 28.8 2.9 NGP
(ellps ang −161.5 smj 26.2 smn 12.3 dpth axs pl 76.9 sl 37.0)
1975.08.29 04 22 52.1 33.659 86.588 4.2 4.4 DG ALA
(ellps ang 166.3 smj 9.4 smn 7.0 dpth axs pl 74.2 sl 16.8)
1975.09.09 11 52 46.2 30.473 89.153 6.0 2.9 TUL ALA
(ellps ang 149.4 smj 30.5 smn 10.0 dpth axs pl 53.1 sl 44.5)
1975.09.13 01 25 05.6 34.131 97.221 4.8 3.2 WI
(ellps ang 138.7 smj 8.1 smn 7.3 dpth axs pl 73.4 sl 15.0)
1975.10.12 02 58 14.1 35.115 97.521 23.7 2.7 WI
(ellps ang 150.3 smj 11.7 smn 5.8 dpth axs pl 69.6 sl 8.7)
1975.11.07 23 39 31.7 33.311 87.325 3.6 3.5 SLM ALA
(ellps ang −171.7 smj 21.2 smn 9.2 dpth axs pl 81.0 sl 23.7)
1975.11.29 14 29 44.9 34.681 97.421 14.4 3.5 SLM WI
(ellps ang 169.7 smj 13.4 smn 7.0 dpth axs pl 45.2 sl 15.8)
1975.12.03 03 00 33.7 36.556 89.603 7.8 2.8 SLM ti
(ellps ang 88.5 smj 3.1 smn 2.6 dpth axs pl 77.2 sl 5.4)
1976.01.16 19 42 56.9 35.903 92.163 7.3 3.4 OZ
(ellps ang 170.2 smj 9.8 smn 4.4 dpth axs pl 51.0 sl 10.9)
1976.01.19 04 03 31.4 31.898 103.089 3.3 2.6 k
(ellps ang 57.5 smj 3.8 smn 2.1 dpth axs pl 46.8 sl 4.0)
1976.01.19 06 20 39.6 36.866 83.861 1.0* 3.8 SLM SA
(ellps ang 178.3 smj 6.3 smn 4.7)
1976.01.25 04 48 28.5 31.900 103.087 4.0 3.3 WTX
(ellps ang 78.4 smj 5.9 smn 4.1 dpth axs pl 45.7 sl 6.9)
1976.02.02 21 14 02.3 41.882 82.731 5.0* 3.4 OTT OHIO
(ellps ang 116.4 smj 13.2 smn 10.0)
1976.03.13 X 07 25 01.1 38.113 91.044 0.0* 2.4 i
(ellps ang 112.6 smj 5.5 smn 3.1)
1976.03.25 00 41 20.8 35.585 90.478 16.5 4.9 b
(ellps ang 62.0 smj 4.0 smn 3.0 dpth axs pl 51.4 sl 4.7)
1976.03.25 01 00 12.4 35.609 90.440 13.6 4.3 b
(ellps ang 53.5 smj 3.6 smn 3.0 dpth axs pl 60.1 sl 4.4)
1976.03.30 09 27 03.3 36.642 102.233 1.0* 2.7 TUL WI
(ellps ang 168.7 smj 11.9 smn 9.9)
1976.04.15 07 03 34.4 37.376 87.311 3.9 3.3 BLA KY
(ellps ang 149.8 smj 8.7 smn 6.8 dpth axs pl 84.8 sl 15.4)
1976.04.16 18 59 48.7 36.159 99.844 14.0 3.4 TUL WI
(ellps ang 154.2 smj 16.8 smn 5.7 dpth axs pl 85.0 sl 19.6)
1976.04.19 04 42 46.9 36.041 99.790 8.2 3.5 TUL WI
(ellps ang 153.6 smj 13.1 smn 5.5 dpth axs pl 73.4 sl 20.5)
1976.05.22 07 40 46.1 36.031 89.828 8.8 3.2 SLM NM
(ellps ang −163.1 smj 4.4 smn 3.9 dpth axs pl 85.2 sl 6.8)
1976.06.19 05 54 13.4 37.344 81.602 0.9 3.3 BLA SA
(ellps ang 145.4 smj 11.8 smn 6.4 dpth axs pl 70.7 sl 17.2)
1976.07.03 20 53 45.8 37.321 81.127 1.0* 2.7 SA
(ellps ang 141.3 smj 13.7 smn 6.5)

```
 DATE         O-TIME     LAT     LONG     FD   MAG      CODE
 YR  MO DY    H  M  S    (N)     (W)    (KM)

1976.09.25   14 06 55.8 35.582  90.468  8.3  3.5       b
 (ellps ang -162.0 smj  6.8 smn  3.0 dpth axs pl 65.9   sl  5.7)
1976.10.23   00 40 59.2 31.999  88.979 10.3  3.1      SMV
 (ellps ang -149.9 smj 25.5 smn 10.4 dpth axs pl 85.8   sl 54.5)
1976.12.11 X 07 05 01.1 38.102  91.038  0.0*           i
 (ellps ang 124.6 smj  4.6 smn  3.1)
1976.12.13   08 35 55.1 37.807  90.257  9.0  3.5 SLM i
 (ellps ang   51.8 smj  6.2 smn  2.5 dpth axs pl 52.4   sl  8.9)
1977.01.03   22 56 48.5 37.583  89.714  5.2  3.6      OZ
 (ellps ang   56.3 smj  5.9 smn  2.5 dpth axs pl 51.5   sl  7.9)
1977.03.28   11 17 14.6 36.491  89.546  8.7  2.9 SLM ti
 (ellps ang  128.5 smj  4.0 smn  3.1 dpth axs pl 80.6   sl  4.7)
1977.04.26   09 03 07.6 31.900 103.079  4.5  2.7       k
 (ellps ang -142.7 smj  6.7 smn  5.2 dpth axs pl 55.8   sl  9.0)
1977.05.04   02 00 24.3 31.959  88.444  0.2  3.3      SMV
 (ellps ang -148.3 smj 20.9 smn  9.2 dpth axs pl 64.8   sl 45.6)
1977.06.02   23 29 10.6 34.560  94.172  9.8  3.6      OU
 (ellps ang  158.2 smj  7.3 smn  6.0 dpth axs pl 77.2   sl 14.2)
1977.06.07   23 01 25.0 33.133 100.938 11.7  3.4       s
 (ellps ang  153.2 smj 22.7 smn  6.3 dpth axs pl 54.7   sl 39.0)
1977.06.17   15 39 46.9 40.705  84.707  1.0* 3.2 AAM OHIO
 (ellps ang 179.5 smj 26.8 smn  8.3)
1977.07.27   22 03 20.8 35.416  84.411  4.6  3.5 BLA SA
 (ellps ang -156.2 smj  7.3 smn  5.3 dpth axs pl 76.3   sl 16.1)
1977.11.04   11 21 10.2 33.928  89.173 16.1  3.4 SLM OU
 (ellps ang -165.3 smj 15.6 smn  6.5 dpth axs pl 86.0   sl 24.1)
1977.11.26   04 18 18.1 34.393  92.912  9.7  3.1 SLM OU
 (ellps ang  159.0 smj 14.8 smn  6.6 dpth axs pl 65.5   sl 16.9)
1977.11.28   01 40 52.0 32.960 100.880  1.0* 3.0       s
 (ellps ang  82.8 smj  6.2 smn  3.4)
1978.01.08   11 34 23.4 32.704  88.205  0.8  3.1      OU
 (ellps ang -156.7 smj  9.2 smn  6.2 dpth axs pl 81.9   sl 18.1)
1978.01.18   23 46 26.4 36.245  89.414  1.0* 2.6 SLM b
 (ellps ang 140.4 smj  6.6 smn  3.5)
1978.03.01   04 08 26.5 34.516  86.643  1.0* 2.5 GS  OU
 (ellps ang-157.2 smj 21.0 smn  6.6)
1978.03.02   10 04 53.0 31.554 102.501  1.0* 3.5 ML  k
 (ellps ang 119.6 smj  7.5 smn  3.8)
1978.04.03   12 24 21.5 36.630  90.003  8.9  3.1 SLM ti
 (ellps ang   87.8 smj  4.4 smn  3.2 dpth axs pl 77.4   sl  9.9)
1978.05.07   16 06 23.0 42.264 101.949 37.9  3.6      NGP
 (ellps ang -136.0 smj  9.3 smn  4.4 dpth axs pl 89.0   sl 30.6)
1978.06.02   02 07 28.9 38.412  88.464 20.4  3.2       e
 (ellps ang   49.5 smj  4.7 smn  3.4 dpth axs pl 59.0   sl  2.4)
1978.06.09   23 15 19.6 32.042  88.595  2.3  3.3      SMV
 (ellps ang -159.4 smj 13.9 smn  6.9 dpth axs pl 66.3   sl 31.0)
1978.06.16   11 46 56.0 32.990 100.875  3.4  4.6 SLM WTX
 (ellps ang  146.2 smj  8.5 smn  4.7 dpth axs pl 70.6   sl 14.9)
1978.06.16   11 53 33.1 32.865 100.986  5.0* 3.4 TUL s
 (ellps ang-176.1 smj 32.8 smn  3.1)
1978.07.24   08 06 16.9 26.380  88.718 15.0* 4.9 mb  GULF
 (ellps ang-164.8 smj 15.3 smn 12.5)
1978.08.29   07 05 50.6 38.500  88.208 17.4  2.4 SLM e
 (ellps ang  145.0 smj  3.2 smn  2.2 dpth axs pl 26.3   sl  3.4)
1978.08.31   00 31 00.6 36.094  89.436  0.8  3.5 SLM b
 (ellps ang  110.8 smj  4.0 smn  1.9 dpth axs pl 72.7   sl  5.0)
1978.09.20   12 24 08.9 38.583  90.276  1.0* 3.1 SLM OZ
 (ellps ang 150.0 smj  4.5 smn  3.2)
1978.09.23   07 34 03.7 33.965  91.920 32.6  3.1 SLM OU
 (ellps ang  166.1 smj 16.1 smn  5.9 dpth axs pl 82.1   sl 28.6)
1978.09.23   21 56 26.2 36.315  91.164  9.2  2.8 GS  OZ
 (ellps ang  154.3 smj  5.6 smn  3.9 dpth axs pl 53.8   sl  8.1)
```

```
 DATE         O-TIME     LAT     LONG     FD   MAG      CODE
 YR  MO DY    H  M  S    (N)     (W)    (KM)

1978.12.05   01 48 01.6 38.557  88.373 23.4  3.5 SLM e
 (ellps ang  156.7 smj  4.2 smn  2.1 dpth axs pl 49.8   sl  2.9)
1978.12.11   02 06 50.1 31.909  88.471  2.5  3.5 GS  SMV
 (ellps ang -156.6 smj 11.3 smn  8.6 dpth axs pl 68.3   sl 25.6)
1979.02.05   05 31 09.4 35.837  90.096 10.0  3.2 TUL b
 (ellps ang  133.7 smj  3.1 smn  2.4 dpth axs pl 65.7   sl  4.9)
1979.02.27   22 54 54.8 35.959  91.198  9.9  3.4 TUL OZ
 (ellps ang   49.7 smj 15.3 smn  5.2 dpth axs pl 56.6   sl  6.3)
1979.04.08   22 46 07.6 41.460  98.761 34.6  2.8 GS  NGP
 (ellps ang  179.5 smj 26.1 smn  8.1 dpth axs pl 48.9   sl 35.1)
1979.06.07   07 39 36.3 35.216  99.759  2.4  3.0 TUL WI
 (ellps ang  140.5 smj 15.4 smn  7.1 dpth axs pl 68.8   sl 27.1)
1979.06.11   04 12 17.1 36.153  89.643 15.2  3.8 SLM b
 (ellps ang  128.6 smj  3.3 smn  2.1 dpth axs pl 68.6   sl  5.2)
1979.06.25   17 11 13.8 35.562  90.449  6.7  3.0 TUL b
 (ellps ang  178.1 smj  9.2 smn  3.4 dpth axs pl 64.3   sl  4.6)
1979.06.30   20 46 42.3 39.922  97.287  7.3  3.0 GS  NGP
 (ellps ang  174.7 smj 11.6 smn  7.5 dpth axs pl 43.3   sl 13.2)
1979.07.05   01 05 02.9 32.997 100.924  1.0* 2.7 TUL s
 (ellps ang  81.0 smj 16.0 smn  2.8)
1979.07.08   12 35 15.5 36.907  89.310  2.4  3.1 SLM ti
 (ellps ang   76.2 smj  3.5 smn  2.9 dpth axs pl 84.4   sl  7.9)
1979.07.13   07 29 39.2 36.065  89.777  8.8  2.7 TUL b
 (ellps ang  127.9 smj  2.8 smn  2.2 dpth axs pl 83.5   sl  5.4)
1979.07.16   00 03 48.4 40.178 100.322  4.4  3.2 TUL NGP
 (ellps ang -168.9 smj 21.7 smn  7.5 dpth axs pl 88.7   sl 31.4)
1979.08.13   05 18 56.8 35.212  84.357  9.7  3.7 BLA SA
 (ellps ang  178.0 smj  6.9 smn  4.7 dpth axs pl 85.6   sl 13.6)
1979.09.13   00 49 21.5 35.193  99.473  1.0* 3.4 TUL WI
 (ellps ang 143.8 smj 12.9 smn  4.9)
1979.11.05   16 35 25.9 36.457  91.044  6.0  3.2 SLM OZ
 (ellps ang  146.3 smj  8.1 smn  6.1 dpth axs pl 65.7   sl 15.4)
1979.11.09   21 29 59.8 38.494  82.809  1.0* 3.6 BLA KY
 (ellps ang-140.1 smj  8.5 smn  5.5)
1980.01.10   19 16 23.5 24.134  85.712 15.0* 3.9 mb  GULF
 (ellps ang 155.5 smj128.7 smn 22.5)
1980.02.21   20 42 03.5 35.189 101.013  1.0* 2.9 TUL WI
 (ellps ang 173.5 smj 17.6 smn 13.6)
1980.03.13   02 23 13.4 37.895  88.436 20.3  3.0 SLM e
 (ellps ang  107.6 smj  2.3 smn  1.8 dpth axs pl 56.2   sl  3.2)
1980.03.23   21 38 16.2 37.603  86.757  8.5  3.3 SLM KY
 (ellps ang -176.9 smj 18.4 smn  6.6 dpth axs pl 56.7   sl 26.0)
1980.06.09   22 37 12.3 35.484 101.010  1.0* 3.4 TUL WI
 (ellps ang 146.1 smj 15.5 smn  8.2)
1980.06.25   18 02 01.6 35.732  84.025  1.0* 3.3 BLA SA
 (ellps ang-159.8 smj  7.9 smn  6.1)
1980.07.05   08 54 40.1 36.560  89.600  3.6  3.5 SLM ti
 (ellps ang -163.2 smj 13.3 smn  9.3 dpth axs pl 50.7   sl 18.1)
1980.07.12 X 23 59 56.3 37.285  86.985  0.0* 3.1 GS  KY
 (ellps ang 168.8 smj 11.2 smn  6.9)
1980.07.27   18 52 21.4 38.193  83.891  6.4  5.2 TUL KY
 (ellps ang  179.1 smj  6.2 smn  5.1 dpth axs pl 85.3   sl 19.8)
1980.07.31   09 27 02.3 38.186  83.927 18.9  2.5 GS  KY
 (ellps ang   47.4 smj 15.5 smn 10.7 dpth axs pl 80.0   sl 42.0)
1980.08.23   03 49 03.7 37.977  84.874  1.0* 3.1 SLM KY
 (ellps ang 106.7 smj 13.3 smn 10.3)
1980.08.25   11 41 38.3 38.194  83.791 13.0* 2.5 TIC KY
 (ellps ang  93.7 smj 21.0 smn 11.2)
1980.11.02   10 00 48.9 35.458  97.763  0.9  3.0 TUL WI
 (ellps ang -165.0 smj 18.7 smn  9.1 dpth axs pl 64.8   sl 18.2)
1980.12.02   08 59 29.7 36.175  89.429  4.5  3.8 TIC b
 (ellps ang  157.3 smj  8.4 smn  4.7 dpth axs pl 30.1   sl  9.2)
```

★ U.S. GPO: 1989 673-047/86040

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.