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SEISMOTECTONIC MAP SHOWING FAULTS, IGNEOUS ROCKS, AND GEOPHYSICAL AND NEOTECTONIC FEATURES IN THE VICINITY OF THE LOWER WABASH VALLEY, ILLINOIS, INDIANA, AND KENTUCKY

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INTRODUCTION

This is the fourth in a folio of six seismotectonic maps of the seismically active lower Wabash Valley map area, which includes southeastern Illinois, southwestern Indiana, and most of western Kentucky (table 1). Seismotectonic maps show, superimposed on each other, much of the geologic and geophysical information needed to assess seismic hazard (Hadley and Devine, 1974; Pavoni, 1985). The first map in the folio (Rhea and Wheeler, 1996) summarizes the geologic and seismological setting of the map area, relates the folio to previous work, and describes construction of the base map used for all maps in the folio.

The map area is in the southern part of the Illinois Basin (Kolata and Hildenbrand, 1997). Most of the map area is underlain by flat-lying or gently dipping upper and middle Paleozoic platform strata of the midcontinent (Willman and others, 1967; McDowell and others, 1981; Gray and others, 1987; Noger, 1988). The Paleozoic rocks generally dip toward the central part of the map area, which is the deepest part of the Illinois Basin (Kolata, 1991). However, the gentle dips of the middle and upper Paleozoic rocks mask an underlying system of grabens and large normal faults, which developed mainly during Cambrian time.

The Cambrian normal faulting formed two large grabens and one small one (fig. 1). The seismically active Reelfoot Rift extends northeastward into the middle of the map area and includes the New Madrid seismic zone of Nuttli (1979). The sparsely seismic Rough Creek Graben extends westward into the middle of the map area, where the rift and graben merge. The much smaller Grayville Graben is mostly north of latitude 38° N in the Wabash Valley Fault System. This north-northeast-trending graben is nowhere wider than 18 km and is defined by the three longest fault zones of the Wabash Valley Fault System (Bear and others, 1997). Earthquakes are scattered across and beyond the map area north of the Rough Creek Graben. Thus, the sparsely seismic Rough Creek Graben separates the Reelfoot Rift and its seismicity from the Grayville Graben, the Wabash Valley Fault System, and the scattered northern seismicity. The nature of the structural and seismological connection, if any, between the New Madrid seismic zone of the Reelfoot Rift and the scattered seismicity in and around the northern half of the map area remains unclear (Hildenbrand and Ravat, 1997; Kolata and Hildenbrand, 1997; Wheeler, 1997; see also other papers in Seismological Research Letters, v. 68, no. 4, a special issue titled "Investigations of the Illinois Basin Earthquake Region").

EARTHQUAKE EPICENTERS

The map shows epicenters of three groups of earthquakes for comparison with locations of faults and other features. Rhea and Wheeler (1996) describe the first two groups more fully than do the following summaries.

In the first group are 168 events that a permanent seismograph network located in the map area between July 29, 1974, and December 31, 1994. Ninety percent of the 168 events had magnitudes less than m_{bLg} 3.0. Most have calculated horizontal precisions (ERH values) of 1.5 km or less. However, total locational uncertainties probably exceed the ERH values, perhaps because crustal heterogeneities may be insufficiently represented in the crustal velocity model that was used to calculate the epicentral locations. The event locations from the permanent network are shown on this map as red, undated circles that are sized by magnitude.

In the second group are 16 earthquakes that occurred within the map area and were large enough to cause damage there between 1827 and 1996 (table 2). All but two of them occurred before installation of the permanent network. Epicenters of the damaging earthquakes that occurred before 1958 were estimated from intensity reports, and Rhea and Wheeler (1996) estimated that their epicenters are accurate only to within a few tens of kilometers. The 1958 and subsequent damaging shocks have more reliable, instrumentally determined epicenters. Here we correct two oversights by Wheeler in selecting locations that Rhea and Wheeler (1996) published for the 1968 and 1974 earthquakes. For both shocks, we use the revised locations of Dewey and Gordon (1984) and Gordon (1988), which replace the result of Stauder and Nuttli (1970) and Gordon and others (1970) for the 1968 earthquake and the result of Herrmann (1979) for the 1974 earthquake. The effects are to move the 1968 and 1974 epicenters southeastward approximately 9 km and 6 km, respectively, from the locations shown by Rhea and Wheeler (1996). The 16 epicenters of historical damaging earthquakes are shown on this map as larger, thicker red circles with dates.

The small earthquakes located by the permanent network are distinct from the medium-sized earthquakes that caused damage, with two exceptions. The earthquakes of June 29, 1984, and June 10, 1987, appear in both groups. Because both shocks were large enough to cause slight local damage, each was the subject of special studies that calculated epicenter locations that differ slightly from those produced by the standard analysis procedures of the permanent network. Rhea and Wheeler (1996) showed both the network epicenters and the special-study epicenters; we show only the latter. Thus, this map shows all 16 epicenters of damaging earthquakes but only 166 of the 168 network epicenters.

In the third group are prehistoric earthquakes. Mapping and analyses of Holocene and Late Pleistocene liquefaction features demonstrated the occurrence of prehistoric earthquakes in southern Illinois and southern Indiana that were larger than any historical shocks in that region (Obermeier, 1996; Munson and others, 1997; Pond and Martin, 1997; see also previous reports cited by these authors). Four of the prehistoric earthquakes occurred inside the map area. We represent the approximate locations of all four earthquake source areas with circles of the same large size, because we interpret the descriptions of Munson and others (1997) to indicate that probably these source area locations are uncertain by a few tens of kilometers or less. Munson and others (1997) described the constraints on the individual source area locations, and chose the names that we show on the map for the four prehistoric earthquakes.

The reader is encouraged to examine the map for spatial associations between epicenters and the traces of mapped faults. However, four cautions apply. (1) Some events in Kentucky, in Hopkins County and adjacent counties, might be blasts instead of earthquakes. Hass and others (1992, p. 399) noted that in and after 1987, these events occurred mostly in the daytime, particularly on weekdays. Blasts are illegal at night and uncommon on weekends. Also, R. L. Street has recorded events in central Kentucky since 1982 and recalls only one likely earthquake there (oral commun., 1997). (2) Both epicenters and fault traces have locational uncertainties. Uncertainties in locations of epicenters were characterized earlier in this section, and are generally a kilometer or less to a few tens of kilometers. Uncertainties in locations of fault traces are usually smaller, especially of traces at ground level that were determined by geologic mapping. Fault-trace uncertainties are mainly determined by the closeness of control points. In the cases of fault traces at ground level, most control points are bedrock exposures encountered during geologic mapping. In the cases of fault traces on buried horizons like the Cambrian-Precambrian unconformity of this map, most control points are wells and faults interpreted on seismic reflection profiles. Thus, assessing fault-trace uncertainties requires examining the original geologic maps or other reports. (3) Most earthquakes in the map area have poorly constrained or unknown depths, because the earthquakes occurred either far from the nearest seismograph or before any instruments were installed. Also, few faults are perfectly planar or vertical, and the geometries of most large faults in the map area are uncertain between their traces at ground level and observed hypocentral depths of 5-25 km (Wheeler and Johnston, 1992). Finally, some faults within the Reelfoot Rift and Rough Creek and Grayville Grabens (fig. 1) are interpreted to die out either upward or downward within the Paleozoic interval (Potter and others, 1995, 1997). Thus, even if an epicenter and fault trace coincide, the hypocenter and fault might not coincide at depth. (4) Worldwide, in stable continental regions such as the map area, a typical earthquake with moment magnitude of 3.0 is likely to have a rupture zone approximately 0.2 km in diameter (Johnston, 1993). The earthquake might occur on a preexisting fault only a few times the length of the rupture zone, and such a small fault would be hard to detect at hypocentral depths. Accordingly, one or a few small earthquakes whose epicenters coincide with the trace of a mapped fault might have occurred instead on another, undetected fault. Spatial associations involving many epicenters might be more reliably interpreted.

EDGE OF MISSISSIPPI EMBAYMENT

In the southwestern corner of the map area an unconformity atop the Paleozoic rocks dips southwestward under Mesozoic and Cenozoic sediments and sedimentary rocks of the Mississippi Embayment (Dart, 1995). We show the edge of the embayment within the map area to be the contact between Paleozoic rocks on the northeast and younger strata on the southwest. At the edge of the embayment in the map area, strata of Quaternary, Tertiary, and Late Cretaceous ages are exposed successively northeastward. R. L. Dart (written commun., 1992) digitized the contact between embayment strata and Paleozoic rocks from state geologic maps (Willman and others, 1967; McDowell and others, 1981) and then generalized it. We use the generalized version, which ignores Cretaceous and Cenozoic outliers and Paleozoic inliers in southern Illinois and especially in western Kentucky.

EXPOSED AND NEAR-SURFACE FAULTS

The faults shown on the map as red lines had been digitized by others to produce three published source maps, each of which is a compilation (Noger, 1988; Frankie and others, 1994; Nelson, 1995a) (table 3). We obtained all three digitized sets of fault locations. Of the three source maps, that of Nelson (1995a) has the largest publication scale and was compiled at the still larger scale of 1:100,000. Thus, it probably has the smallest uncertainty in the fault locations. Accordingly, it was used wherever it overlaps the other two source maps. For the same reason we used the 1:1,000,000-scale map of Frankie and others (1994) only outside the areas covered by the other two larger-scale source maps. The result is that we show the faults compiled by Nelson (1995a) west of longitude 88° W and between latitudes 37° N and 38° N. Outside this rectangle, we show the faults compiled by Noger (1988) in Kentucky and those compiled by Frankie and others (1994) in Illinois and Indiana. We did not verify the three fault compilations against the mostly 1:24,000-scale original geologic maps.

Noger (1988) compiled the 1:500,000-scale geologic map of Kentucky from its 1:250,000-scale predecessor (McDowell and others, 1981), which was itself compiled from 1:24,000-scale geologic maps. We obtained the previously digitized linework for roads and faults of the Noger (1988) map. However, the lines had been digitized in inches from an arbitrary origin instead of in degrees of latitude and longitude, so the network of faults could not be fit straightforwardly to the scale and projection of our base map. Accordingly, we used a technique known as rubber sheeting. We chose several tens of recognizable points, such as road intersections and road bends, in the digital network of roads on the map of Noger (1988). At each point we distorted the road network until the point overlaid its representation on our base map. We then applied the same set of distortions to the network of lines that represent faults on the 1988 map. Finally, we adjusted individual faults from the 1988 map that approach to within 1 cm of the edge of the map area of Nelson (1995a), to insure that such faults would match at the edges of both maps.

Frankie and others (1994) simplified and digitally compiled faults, folds, domes, and impact and cryptoexplosion structures for the entire Illinois Basin from previous compilations by Treworgy (1981), Gray and others (1987), and Nelson (1991, 1995b), and from published 1:24,000-scale U.S. Geological Survey Geologic Quadrangle maps of Kentucky. We show only the faults from Frankie and others (1994), and then only in those parts of our map area not covered by the more detailed maps of Nelson (1995a) and Noger (1988).

On the map, our two intents are to show the overall fault pattern, and to show the main exposed and near-surface faults for comparison to their deeper subsurface locations that are described in the next section. Accordingly, we made little attempt to edit details of the digitized faults, beyond adding tick marks to indicate the dip directions of a few normal faults, mostly in the Wabash Valley Fault System and the Fluorspar Area Fault Complex. The three source maps use different combinations of solid, dashed, and dotted lines to code faults as to certainty of existence and location (table 3). We retained the three different sets of line codings. For details, such as exact locations, fault dips, separations, and crosscutting relations, readers should consult the original geologic maps that are cited by the source maps listed in table 3. This recommendation applies especially to intricately faulted areas such as the Rough Creek Fault System and the Fluorspar Area Fault Complex, and to transitions between parts of the fault pattern that were taken from different source maps.

DEEP SUBSURFACE STRUCTURES

The map shows two components of deep subsurface structure: structure contours and faults. Both are mapped at a horizon interpreted as the Cambrian-Precambrian unconformity. The unconformity surface was mapped primarily using seismic-reflection data and sparse well information, with much of the reflection data being proprietary. Wheeler and others (1997; table 1) show locations of some of the wells and seismic-reflection lines. Data sources for the northern and southern parts of our map area will also be described more extensively in publications that are in preparation by G. W. Bear and J. A. Drahovzal, respectively.

The nature of the Cambrian-Precambrian unconformity and the characteristics of the associated overlying and underlying rocks differ across the map area. In the northern part of the map area, the unconformity separates the overlying Late Cambrian Mt. Simon Sandstone from the underlying igneous and interpreted metamorphic Precambrian rocks (Bear and others, 1997). In contrast, in the southern part of the map area, an angular unconformity separates the interpreted base of Cambrian clastic rocks from an underlying sequence of inferred clastic and volcanic rocks of suggested Late Proterozoic age (Drahovzal, 1997). The Cambrian section within the Rough Creek Graben is considered to include rocks much older than the Mt. Simon Sandstone, perhaps as old as Early Cambrian (Goetz and others, 1992).

All or parts of the map area have been previously mapped at the same general horizon, but with less detail. Buschbach and Kolata (1990) constructed a generalized basement map for the Illinois Basin. A map constrained with additional seismic-reflection data was produced for the southern part of the basin by Goetz and others (1992). A similar map of only the Rough Creek Graben part of the area was constructed by Drahovzal (1994). Hildenbrand and Hendricks (1995) calculated the maximum depth to magnetic basement for the southern Illinois Basin and the Reelfoot Rift. Bear and others (1997) completed deep subsurface structure maps of the base of the Mt. Simon Sandstone and of a sub-Mt. Simon horizon for the central part of our map area in parts of Indiana, Illinois and Kentucky.

In constructing our map, published seismic-reflection data for the area (Hester, 1988; Bertagne and Leising, 1991; Pratt and others, 1992; Potter and others, 1995, 1997; Bear and others, 1997; Drahovzal, 1997) were used together with additional proprietary surveys. All interpreted seismic-reflection data were converted to approximate true depth in feet below sea level. The velocities used in making the conversions from two-way travel times to true depth were based on sonic information from nearby wells. The selected velocities ranged from 13,780 to 16,500 ft/s (4,200-5,029 m/s) for the sedimentary interval above the Cambrian and Ordovician carbonate strata of the Knox Group; from 20,012 to 21,400 ft/s (6,100-6,522 m/s) for the Knox Group; and from 18,000 to 18,700 ft/s (5,486-5,700 m/s) for the sedimentary interval below the Knox Group and above the Cambrian-Precambrian unconformity, including the Mt. Simon Sandstone where it is present.

The prominent east-west structure in the southern half of the map area is the western part of the Rough Creek Graben. At its deepest point, south of the graben-bounding Rough Creek Fault System in Webster County, Kentucky, the depth of the Cambrian-Precambrian unconformity in the Rough Creek Graben exceeds 30,000 ft (9,100 m) below sea level (see also Bertagne and Leising, 1991; Goetz and others, 1992; Drahovzal, 1994). At this point the throw on the Rough Creek Fault System is more than 15,000 ft (4,600 m). Near the eastern edge of the map area, another structural low in the unconformity reaches a depth of more than 27,000 ft (8,200 m) below sea level. The graben shallows to the south: the unconformity is only 11,000-18,000 ft (3,400-5,500 m) below sea level on the north side of the southernmost basement fault shown on the map. The Rough Creek Graben bends to the southwest into the Reelfoot Rift and shallows in the same direction. At this bend, the deepest part of the graben system changes from the north side of the Rough Creek Graben to the southeast side of the Reelfoot Rift (Potter and others, 1994, 1995, 1997).

North of the Rough Creek Graben and extending northward along the Wabash River is the Wabash Valley Fault System. The fault system cuts a roughly circular low area in the Cambrian-Precambrian unconformity near the confluence of the Wabash and Ohio Rivers. In the circular low area the unconformity reaches depths of more than 15,000 ft (4,600 m) below sea level. Two west-northwest-trending low areas are intersected by the Wabash Valley Fault System farther north. These latter two low areas range in depth from 13,500 to 14,100 ft (4,100-4,300 m) below sea level (Bear and others, 1997).

Four other aspects of deep structure on the map are noteworthy or require explanation. First, by showing exposed or near-surface faults and deep faults on the same map, we enable the reader to estimate the subsurface geometry of numerous faults. Second, at its deepest point in the map area, the contoured unconformity is interpreted to be more than 30,000 ft (9,100 m) below sea level, and there may be additional faulted Proterozoic sedimentary strata beneath the unconformity (Drahovzal, 1997; Potter and others, 1997). Thus, the interpretations of the seismic reflection data indicate that the Rough Creek Fault System penetrates to hypocentral depths (Wheeler and Johnston, 1992). Third, some structure contours cross individual faults of the Wabash Valley Fault System, but show horizontal offsets that are opposite to the offsets expected from the known normal slip on the faults. Bear and others (1997) attribute the apparent discrepancy to 2-4 km of strike slip on some of the faults of the Wabash Valley Fault System. Fourth, the egg-shaped structure at lat 38° 00' N., long 88° 30' W., is an uplift (Bear and others, 1997) or buried hill (Nelson, 1995a) of granitic basement. Higher in the section, the uplift or buried hill is expressed as the Dale Dome in Mississippian and Pennsylvanian rocks (Nelson, 1995a).

NEOTECTONIC FEATURES

The neotectonic features that concern us in the map area are those younger than Miocene, for reasons described in the following paragraphs. Faults, most striking northerly to easterly, cut Cretaceous and Tertiary strata of the Mississippi Embayment near the embayment edge within the map area. Mapped geologic relations at many faults allow inference of the ages of youngest slip. The younger the most recent slip is on a fault, the more pertinent the fault is likely to be to seismic hazards assessment, for three reasons.

First, in seismically active areas east of the Rocky Mountains, the recognized absence of a geologic record of large, accumulated, Quaternary deformation implies that the seismically active areas could not have been active at their present levels for geologically long times (Coppersmith, 1988; Pratt, 1994; Schweig and Ellis, 1994). The seismicity must be episodic, shift from place to place, or do both at time intervals longer than the historic record, perhaps on scales of tens or hundreds of thousands of years. Such changes might not have much effect on hazard estimates for the coming decades or few centuries. However, fault slips older than a few million years in an area of sparse present-day seismicity might represent a now-dormant seismic source.

Second, faults may heal with time, perhaps because of circulating crustal fluids that gradually recrystallize or cement fractured, sheared, or comminuted rock along the fault (Cathles, 1990; Johnston, 1994a, p. 4-10). In time a healed fault that has been inactive since healing began might no longer be a weak surface on which stresses could preferentially be released by seismic ruptures. In contrast, renewed slip on a healing fault could restore the slipped part of the fault to its weak state. This reasoning may apply more to faults in comparatively stable continental areas like North America east of the Rocky Mountains than to faults on which slip is continually imposed within plate boundaries (Blanpied and others, 1992; Sleep and Blanpied, 1992).

Third, the orientation of the greatest horizontal compressive stress S_{Hmax} may change with time. For example, Schweig and Ellis (1994) and Nelson and others (1997) reported evidence indicating that, several million years ago in and near the map area, S_{Hmax} might have had an orientation substantially different from its present east-northeast trend (Rhea and others, 1994; Rhea and Wheeler, 1996; Wheeler, 1997). Faults that slipped while S_{Hmax} had a different orientation than the present one might be unfavorably oriented to slip today.

Accordingly, we did not examine faults in the older parts of the Cretaceous and Cenozoic sequence, which is present around the edge of the embayment. Along the embayment edge in southern Illinois and western Kentucky, Miocene and younger continental deposits overlie a significant unconformity within the Tertiary sequence (Willman and others, 1967; Noger, 1988). Two palynological samples indicate that the continental deposits are mainly of Pliocene and Pleistocene age, with the lower part possibly of Miocene age (Olive, 1980, p. 3). In Kentucky, the unconformity extends down to Upper Eocene and Oligocene rocks (Olive, 1980; Noger, 1988). In Illinois, the unconformity extends lower into the Eocene (Ross, 1963; Kolata and others, 1981). Because the palynological sample that is possibly of Miocene age is more likely Pliocene (Olive, 1980, p. 3), for simplicity we refer to the continental and younger deposits as post-Miocene strata, and we restrict our attention to them. We do not show the widespread locations of clastic dikes in the Eocene Porters Creek Clay (Olive, 1963, 1966a,b, 1980; Finch, 1966; Drahovzal and Hendricks, 1997), even though Glenn (1906) argued that they formed by early Tertiary seismic shaking.

We have not searched exhaustively for evidence of post-Miocene faulting within the map area. In Kentucky, the maps of Olive (1980), McDowell and others (1981), Trace and

Amos (1984), and Noger (1988) all show faulting of post-Miocene strata. All four maps are regional compilations of 1:24,000-scale U.S. Geological Survey Geologic Quadrangle Maps that were produced as part of a cooperative mapping program between the U.S. Geological Survey and the Kentucky Geological Survey. The most recent compilation map, that of Noger (1988), shows 27 post-Miocene offsets near the embayment edge. However, the corresponding 1:24,000-scale Geologic Quadrangle Maps show no clear post-Miocene faulting at these 27 localities, so we do not show them here. For the same reason we also do not show 36 post-Miocene offsets in the Fluorspar Area Fault Complex. These offsets are shown on the most detailed compilation map, that of Trace and Amos (1984). Along the embayment edge in Illinois, Ross (1963) suggested post-Miocene faulting as interpreted from well and topographic data, but neither he nor Kolata and others (1981) found clear evidence of post-Miocene tectonic faulting. Most localities described in the rest of this section are shown on our map and are identified by the codes listed in table 4.

Nelson and others (1997) mapped several sites in southeastern Illinois in a search for evidence of young faulting. Post-Miocene faulting was found at four sites within the present map area, all in Massac County, Illinois (localities N-NC, N-MC, N-BCA, and N-M of table 4). In addition, previous mapping shows faults cutting Pliocene(?) to Pleistocene continental deposits in Livingston County, Kentucky (Amos and Wolfe, 1966; Amos, 1967, 1974). However, all but two of the faults that are shown as post-Miocene on these three maps are coded as "approximately located," "concealed," or "location indefinite." The two exceptions are in the southeastern part of the Burna quadrangle (Amos, 1974). However, these two faults may not exist at all—Drahovzal checked Amos' field notes and field maps and found no recorded field observations that show young faulting at either place.

In and north of Posey County, Indiana, morphometric analysis, geomorphic mapping, and drilling indicate that the Wabash River Valley tilted gradually westward through the late Pleistocene and Holocene (Fraser and others, 1997). In the tilted part of the valley, the Wabash River generally hugs the west side (fig. 2 of Fraser and others, 1997). We drew the boundaries of the tilted area where the south-flowing Wabash River leaves one side of its valley and migrates gradually eastward or westward toward the other side. Thus, the northern boundary of the tilted area is approximately 3 km north of the map area, and the southern boundary is at approximately 38° 13' N. (locality F-WR of table 4).

Several strands of the Rough Creek Fault System in Kentucky might offset Pliocene (?) to Holocene alluvium. Stickney (1985) and Chadwick (1989) searched for possible young faulting by using shallow geophysical methods to select promising sites for future paleoseismological investigations. Resistivity and very low frequency electromagnetic surveys were used to locate the fault strands in bedrock beneath the Pliocene (?) to Holocene alluvium. Next, lines of auger holes were drilled across the fault strands and the auger holes were logged. Stratigraphic correlations between the auger holes could be interpreted as identifying offsets of the bedrock surface at the geophysically located fault strands in five locations at the eight study sites (localities S-SA1, S-SA2, C-SS1(N), C-SS1(S), and C-SS3 of table 4). However, the correlations could also be interpreted as the results of post-Miocene burial of older fault scarps or fault-line scarps, instead of the results of young faulting (Stickney, 1985; Chadwick, 1989). Trenching is needed to determine whether the bedrock offsets resulted from Pliocene to Holocene slip on faults that cut the alluvium.

Rhoades and Mistler (1941) observed or interpreted Cretaceous or younger faults and clastic dikes at 16 localities near the Tennessee and Cumberland Rivers in western Kentucky. However, none of the faults at localities 1-13 are clearly of post-Miocene age. We do not show these faults on the map. In contrast to localities 1-13, small faults and clastic dikes cut probable Pliocene terrace gravels at localities 14-16 of Rhoades and Mistler (1941). We could not identify locality 14 from the descriptions of Rhoades and Mistler (1941) and the geologic map of Lambert and MacCary (1964). However, Fox and Olive (1966) show an abandoned gravel pit and a road cut at locations that match the descriptions of localities 15 and 16, respectively, so we show these two localities (localities RM-15 and RM-16 of table 4).

In southeastern Illinois, the Meadow Bank scarp parallels the Herald-Phillipstown Fault Zone (Heigold and Larson, 1994). Vertical electrical sounding, seismic refraction profiling, and drilling show that the scarp is erosional instead of tectonic, so we do not show the scarp on the map. Nearby, resistivity profiling found an elongated, surficial sand body at the site of fissures and possible sand blows that were reported by an eyewitness at the time of the 1811-1812 New Madrid earthquake sequence (Heigold and Larson, 1994; locality HL of table 4). We show the location of the sand body because it is within an area of widespread evidence of prehistoric liquefaction in southern Illinois and southwestern Indiana (Rhea and Wheeler, 1996; Munson and others, 1997). If the sand liquefied in 1811-1812, perhaps it also liquefied during the prehistoric shaking. If so, examination of the sand body might further constrain the timing of the prehistoric earthquakes.

ULTRAMAFIC IGNEOUS ROCKS

Dikes, sills, and other small intrusions are abundant in the west-central part of the map area. The small intrusions can be divided into three partly overlapping groups: alkaline ultramafic igneous rocks, breccias, and veins (for example, Trace and Amos, 1984; Bradbury and Baxter, 1992; and numerous maps and reports cited by these authors). All three groups of small intrusions are known in the map area from geologic mapping, petroleum drilling, and minerals exploration and mining in Illinois and Kentucky. In addition, ultramafic dikes were inferred from analyses of high-resolution aeromagnetic data in Illinois, Indiana, and Kentucky (Hildenbrand and Ravat, 1997).

As explained later, probably the ultramafic igneous rocks are the most pertinent to assessing earthquake hazards. Accordingly, our map shows only them and we explain them first. Worldwide, in stable continental regions, such as the map area, large earthquakes tend to be concentrated in areas that underwent Phanerozoic continental rifting (Johnston, 1994a). Also, alkaline igneous rocks, particularly if mafic or ultramafic, indicate the initiation of continental rifting, whether or not crustal extension proceeded far enough to produce a graben, rift, or passive continental margin (see summary in Wheeler, 1997). Therefore, locations of the alkaline ultramafic rocks of the map area may be pertinent to future efforts to understand the local seismicity.

Breccias, many of them intrusive into surrounding rocks, are best known in the map area from the vicinity of Hicks Dome in southeastern Illinois (for example, Trace and Amos, 1984; Bradbury and Baxter, 1992; Plumlee and others, 1995). Some breccias contain entrained rock fragments that can be correlated to stratigraphic units far beneath the breccias' present positions. Some of the entrained fragments are pieces of ultramafic igneous rock, and some of these ultramafic fragments are in carbonate matrix that Bradbury and Baxter (1992) suggested was formed from carbon dioxide exsolved from a rising alkaline magma. However, the entrained ultramafic fragments have been ripped out of their geologic context, so their crystallization ages and structural relations are largely unknown (see Reynolds and others, 1997, for an exception). Accordingly, probably most of the fragments cannot illuminate the rifting history of the map area as well as the in-place ultramafic rocks can. Therefore, we show no breccia locations on the map unless the breccia accompanies an ultramafic rock that is in place.

The area containing the Fluorspar Area Fault Complex has a long history of mining, chiefly of fluorine, lead, zinc, and barium orebodies that were deposited mostly as veins in faults and along ultramafic dikes, with a few bedded fluorite deposits (Trace and Amos, 1984). Fluorite is spatially associated with several continental rifts, and is thought to be derived from rifting-related alkaline magmas (Van Alstine, 1976; Plumlee and others, 1995). However, any causal link between rifting and fluorite mineralization may be less direct than that between rifting and the alkaline rocks themselves. Accordingly, the map shows fluorite and related deposits only if they accompany an ultramafic rock that is in place.

We have not searched exhaustively for information on the characteristics of all known small intrusions throughout the map area. Thus, our exclusion of breccias and veins might have also excluded a few known ultramafic rocks. Nonetheless, we assembled known and inferred locations of the ultramafic rocks from four sources, which we describe next.

The first source is the locations of igneous rocks in Illinois south of lat 38° N. that had been compiled previously by personnel of the Illinois State, Indiana, Kentucky, and Missouri Geological Surveys for the Paducah CUSMAP (Conterminous United States Mineral Assessment Program) project. (Later we discuss the compilation for western Kentucky.) We obtained digitized locations of 45 points in the Illinois part of the map area that represent short dikes, sills, igneous rocks penetrated by wells and mines, and other exposures of igneous rock (B. J. Stiff, written commun., 1996). These rocks are nearly all Early Permian lamprophyres and mica peridotites (English and Grogan, 1948; Clegg and Bradbury, 1956; Koenig, 1956; Baxter and Desborough, 1965; Amos, 1966; Baxter and others, 1967; Zartman and others, 1967; Bikerman and others, 1982; Lewis, 1982; Snee and Hayes, 1992).

We made one deletion from and two additions to the set of 45 localities. (1) We deleted the location of weathered granite fragments that Weller and Grogan (1945) reported from abandoned prospect pits in eastern Pope County, Illinois. (2) The first addition is from Nelson and Lumm (1986, 1987), in which they show the location of a drill hole that penetrates igneous rock in east-central Saline County, Illinois, approximately 1 km north of the South Fork of the Saline River, in the NW 1/4 SW 1/4 SE 1/4 Sec. 23, T.9S., R.7E. They noted that the drill penetrated 60 ft (18 m) of peridotite. W. J. Nelson (written commun., 1997) examined the electric log of the Harper and McConnell No. 1 Martin well and confirmed the interpretation of igneous rock; the driller's log reported "lime." The Paducah compilation lacks this locality, so we added it to our map by measuring latitude and longitude from the 1:24,000-scale map of Nelson and Lumm (1986). (3) The second addition is from Clegg and Bradbury (1956, plate 1). They coded many localities on their map as "drill hole penetrating igneous rock." Three of these localities are also not in the Paducah compilation. Sargent interpreted driller's logs from the three localities, with the following results. In eastern Gallatin County, Illinois, in W 1/2 SE 1/4 Sec. 25, T.9S., R.9E., approximately 3 km northwest of the Ohio River, between the new and old locations of Shawneetown (not shown on this map), a well (Gallatin County no. 1918) penetrated an igneous dike. We added this locality by transferring it from the 1:134,000-scale map on plate 1 of Clegg and Bradbury (1956) to a 1:24,000-scale topographic map and then we measured the latitude and longitude. In northwestern central Saline County, Illinois, approximately 14 km southeast of the northwestern corner of the county and 2 km southeast of the municipal border of Galatia (not shown here), on or east of the border between R.5E. and R.6E. of T.8S., the driller's log of the J. W. Roe et al. No. 1 Summers well showed no indication of igneous rock. Accordingly, we did not add this well to our map. Another 5 km farther southeast, in central Saline County, in the south-central part of T.8S., R.6E., the driller's log of a well (Saline County no. 131) listed penetrations of several "soapstones." This term is often used in the region for coal underclays, so we also omitted this well. Finally, Clegg and Bradbury (1956, plate 1) showed an extra igneous rock locality that we did not include. Within the municipal limits of Rosiclare (not shown on our map), in southern Hardin County, Illinois, approximately one kilometer from the Ohio River, Clegg and Bradbury (1956, plate 1) showed a cluster of six localities, including those of five "igneous bodies of uncertain form" and one "drill hole penetrating igneous rock." The Paducah compilation contains five sites instead of six in this same cluster. Because the Paducah compilation had originally been verified by comparing it to the unpublished maps from which plate 1 of Clegg and Bradbury (1956) was compiled, we suspect a drafting error on plate 1, so we did not add the sixth locality to our map. Thus, we show 44 points from the Paducah compilation for southeastern Illinois, plus another two points, for a total of 46.

The second source from which we compiled known locations of igneous rocks is Nelson (1995a). Under the aegis of the Paducah CUSMAP project, Nelson compiled locations of long dikes, many of them intruded along faults. We obtained digitized locations of 20 lines that represent dikes (B. J. Stiff, written commun., 1996), all of them in the map area and in southeastern Illinois. The dikes are mica peridotite, perhaps with some lamprophyre (Clegg and Bradbury, 1956), and potassium-argon dates on dike samples are Early Permian (Nelson and Lumm, 1987).

The third source is made up of locations of igneous rocks in western Kentucky that had been mapped as part of the joint U.S. Geological Survey-Kentucky Geological Survey program of 1:24,000-scale geologic mapping of the state. Subsequently, locations of the igneous rocks and mineralized veins had been digitized for the Paducah CUSMAP project. However, when we compared the digitized locations to the 1:24,000-scale U.S. Geological Survey Geologic Quadrangle maps we discovered omissions in the digital data. Instead of laboriously correcting the omissions and identifying and deleting the vein locations, we redigitized the igneous rock locations from the geologic maps (Trace, 1962, 1966, 1974, 1976; Amos, 1967, 1974; Rogers and Trace, 1976). The result was 36 lines and 10 points, all representing locations of mapped or drilled dikes or sills. The rocks are lamprophyre and mica peridotite of Early Permian age (Zartman and others, 1967; Trace and Amos, 1984). To these 46 intrusions, we added locations of five others that are shown on the map of Trace and Amos (1984) but not on the older 1:24,000-scale geologic maps.

The fourth source is Hildenbrand and Ravat (1997), who inferred the locations of near-surface dikes from analyses of high-resolution aeromagnetic data. We obtained the digitized locations of 85 lines in the west-central part of the map area, mostly in Illinois but also in adjacent parts of Indiana and Kentucky (T. G. Hildenbrand, written commun., 1996). The lines represent locations of linear magnetic highs that Hildenbrand and Ravat (1997) interpreted as dikes. Modeling indicates that the dikes are vertical, extend to within 200 m of the surface, and have the magnetic properties of mafic or ultramafic rock. Some of the interpreted dikes closely follow known faults of the Wabash Valley Fault System, and four of the interpreted dikes coincide with the four easternmost drilled or mapped, Early Permian, mica peridotite and perhaps lamprophyre dikes of Nelson (1995a). Accordingly, Hildenbrand and Ravat (1997) concluded that the interpreted dikes are also probably Early Permian ultramafic intrusions.

Thus, our map shows the locations of 202 known or likely, Early Permian, ultramafic intrusions. Some closely spaced lines or points are indistinguishable at the scale of the map.

GRAVITY AND MAGNETIC LINEAMENTS

We show three large features, inferred from potential-field data, in the upper crust of the map area. We selected the features because of their possible influences on earthquake occurrence.

The broad Paducah gravity lineament trends southeast across the southwestern corner of the map area (Hildenbrand and Hendricks, 1995). Approximately half of the lineament is west of the map area, where the lineament is a single wide band. At the western edge of the map area the lineament splits southeastward into two parallel branches. Hildenbrand and others (1996) analyzed gravity and aeromagnetic data and concluded that the lineament represents numerous upper-crustal mafic intrusions. West of the map area, the St. Genevieve Fault Zone, of Paleozoic and possibly Precambrian age, follows the northeastern edge of the lineament (Hildenbrand and others, 1996). Within and west of the map area, small earthquakes are aligned along the northeastern edge of the lineament, and their abundance decreases abruptly northeastward across the edge (Hildenbrand and Hendricks, 1995).

The Commerce geophysical lineament trends northeastward across the map area, although it is less certainly recognized in and northeast of Saline County, Illinois, than farther southwest (Langenheim and Hildenbrand, 1997). Analyses of gravity and aeromagnetic data led Hildenbrand and Ravat (1997) to attribute the part of the lineament that lies within the map area to the aligned southeastern edges of mafic intrusions. Topographic lineaments, Quaternary offsets on mapped faults, igneous intrusions, and a few historical earthquakes align with the lineament (Harrison and Schultz, 1994; Langenheim and Hildenbrand, 1997). Four large, prehistoric earthquakes occurred near a marked offset of the lineament near Vincennes, Indiana (Hildenbrand and Ravat, 1997). Finally, the lineament also forms the northwestern boundary of the Early Permian alkaline ultramafic intrusions described in the preceding section. Hildenbrand and Ravat (1997) suggested that the lineament might represent a geologic boundary in the seismogenic upper crust. The figures of Langenheim and Hildenbrand (1997) show that the width of the lineament varies along its length and according to the kind of data in which it is expressed. We show the lineament with a constant width arbitrarily chosen to maximize legibility.

The south-central magnetic lineament trends northwest across the center of the map area and extends far beyond it in both directions (Hildenbrand and Keller, 1983; Hildenbrand and others, 1983; Hildenbrand, 1985). Gravity and aeromagnetic analyses led Hildenbrand and others (1996) to interpret the lineament as a 40-km-wide zone of intrusions of high magnetic susceptibility, intermediate composition, and probable Precambrian age. The lineament includes the west-northwest-striking Cottage Grove Fault Zone of late Paleozoic age, but is crossed obliquely by the much longer, deeper, and more frequently reactivated Rough Creek Fault Zone (Nelson, 1991, 1995b). Thus, the degree to which the lineament might have controlled Phanerozoic faulting is unclear. The lineament also includes some of the Early Permian alkaline ultramafic igneous rocks described previously. Heigold and Kolata (1993) suggested from seismic reflection and other information that the lineament may represent a Proterozoic terrane boundary. Recent unpublished aeromagnetic modeling supports this interpretation of an important crustal boundary (T. G. Hildenbrand, written and oral communs., 1997). Heigold and Kolata (1993) further suggested that differences in crustal properties across the lineament might explain the different levels of seismicity in the seismically active Reelfoot Rift south of the lineament and the less active lower Wabash Valley area north of the lineament. However, fault patterns and distributions of igneous rocks in the Fluorspar Area Fault Complex of the northernmost Reelfoot Rift indicate that the most likely northeastern limit of future Reelfoot Rift seismicity does not coincide with the south-central magnetic lineament (Wheeler, 1997). Instead, the likely seismicity limit extends from south-central Gallatin County, Illinois, to north-central Trigg County, Kentucky.

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Table 1. *Maps in the seismotectonic folio of the lower Wabash Valley and vicinity*

[Digital data for the first four maps listed here were published by Rhea (1997)]

Map	Theme: features shown	Reference
I-2583-A	Seismicity: earthquake epicenters, areas most intensely shaken, focal mechanisms, seismograph and accelerograph locations, and locations of prehistoric earthquake-induced liquefaction.	Rhea and Wheeler (1996)
I-2583-B	Modified Mercalli intensities.	Rhea and others (1996)
I-2583-C	Geophysical survey and modeling lines, wells, and global positioning system monuments.	Wheeler and others (1997)
I-2583-D	Faults, basement structure, igneous rocks, and geophysical and neotectonic features.	this map
([1])	Surficial materials: thicknesses, compositions, and ages.	([1])
([1])	Infrastructure: lifelines and critical structures of transportation, communication, energy supply, water supply, emergency response, and government functions.	([1])

[1]The surficial materials and infrastructure maps are being prepared by the Illinois Basin Consortium. Plans as of November 12, 1997, are for the consortium to publish both maps as Illinois State Geological Survey open-file reports.

Table 2. *Earthquakes with epicenters in the map area and that are known or interpreted to have caused Modified Mercalli intensity of VI or higher in the map area*

[Source: Stover and Coffman (1993) unless stated otherwise in footnotes]

Date (Year shown on map)	Highest intensity	Epicenter		Magnitude[1]
		lat N. (°)	long W. (°)	
July 5, 1827	VI	38.0	87.5	Mfa 4.8
Sept. 25, 1876	VII	38.5	87.8	Mfa 4.8
Jan. 11, 1883	VI	37.0	89.0	Mfa 4.6
Feb. 6, 1887a	VI	38.7	87.5	Mfa 4.6
Aug. 2, 1887b	VI	37.2	88.5	Mfa 4.9
July 27, 1891a	VI	37.9	87.5	Mfa 4.1
Sept. 27, 1891b	VII	38.25	88.5	**M** 5.5
Apr. 30, 1899	VII	38.5	87.4	**M** 4.3
Nov. 27, 1922	VII	37.8	88.5	**M** 4.4
Apr. 27, 1925a	VI	38.2	87.8	**M** 4.9
Sept. 2, 1925b	VI	37.8	87.5	Mfa 4.6
Nov. 8, 1958	VI	38.436	88.008	Mfa 4.4
Nov. 9, 1968	VII	37.911[2]	88.373[2]	**M** 5.4
Apr. 3, 1974	VI	38.549[2]	88.072[2]	**M** 4.3[2]
June 29, 1984	VI	37.700	88.470	m_{bLg} 4.1
June 10, 1987	VI	38.71[2]	87.95[2]	**M** 5.0

[1] **M** is moment magnitude; unless stated otherwise, from Johnston (1994b) or Johnston (1996), with preference given to the latter. m_{bLg} is body-wave magnitude calculated from Lg waves with 1 s periods. Mfa is estimate of m_{bLg} calculated from the area over which an earthquake was felt before the deployment of seismographs from which m_{bLg} could be calculated. If more than one of these magnitudes is available for an earthquake, the order of their preference is as listed in this footnote.

[2] From Stauder and Nuttli (1970), Gordon and others (1970), Herrmann (1979), Dewey and Gordon (1984), Gordon (1988), Taylor and others (1989), or Johnston (1996).

Table 3. *Sources of fault locations*

Source map	Nelson (1995a)	Noger (1988)	Frankie and others (1994)
Scale of source map	1:250,000	1:500,000	1:1,000,000
Scale of original mapping	Mostly 1:24,000	1:24,000	Various, 1:24,000 in Kentucky
Subarea in which we use faults of source map	Lat 37°-38°N., long 88°-89°W.	Kentucky where not covered by Nelson (1995a)	Illinois and Indiana where not covered by Nelson (1995a)
Source map's definition of solid line	Exposed fault	Fault	Fault
Source map's definition of long-dashed line	Inferred fault	Not used	Not used
Source map's definition of short-dashed or dotted line	Concealed fault	Concealed fault	Not used

Table 4. *Post-Miocene neotectonic features shown on map*

Map Code	Site/fault names[1]	Age of youngest deformation	Map scale[2]
N-NC	New Columbia/Lusk Creek (1)	Pliocene-early Pleistocene (?)	1:38,000
N-MC	Masaac Creek/Hobbs Creek (1)	Pliocene-early Pleistocene	1:38,000
N-BCA	Barnes Creek A/Barnes Creek (1)	Pleistocene	1:243,000
N-M	Midway/Barnes Creek (1)	Pleistocene	1:243,000
F-WR	Wabash River valley/no fault identified (2)	Holocene	1:508,000
S-SA1	Study area 1/Sebree Fault in Rough Creek Fault System (3)	Pliocene (?)-Pleistocene	1:24,000
S-SA2	Study area 2, drill-line S-B/Rough Creek Fault System (3)	Pliocene (?)-Pleistocene	1:24,000
C-SS1(N)[3]	Study site 1, drill-line 2, north/ Rough Creek Fault System (4)	Quaternary (?)	1:24,000
C-SS1(S)[3]	Study site 1, drill-line 2, south/ Rough Creek Fault System (4)	Quaternary (?)	1:24,000
C-SS3	Study site 3, drill-line 5/Rough Creek Fault System (4)	late Pleistocene (?)-Holocene	1:24,000
RM-15	Locality 15/small unnamed faults, sand and clay dikes (5)	Pliocene (?) or younger	1:24,000
RM-16	Locality 16/small unnamed fault, clay dikes (5)	Pliocene (?) or younger	1:24,000
HL	Yearby Land sand body/no fault identified (6)	1811-1812	1:100,000

[1] Numbers in parentheses identify sources: (1) Nelson and others (1997), (2) Fraser and others (1997), (3) Stickney (1985), (4) Chadwick (1989), (5) Rhoades and Mistler (1941), (6) Heigold and Larson (1994).
[2] Scale of map from which location was digitized.
[3] These two localities are 42 m apart and indistinguishable on the map.

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