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Reelfoot scarp and New Madrid seismic zone (Class A) No. 1023

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Synopsis	In the winter of 1811-1812, at least three major earthquakes occurred in the New Madrid seismic zone, and the area remains the most seismically active area in central and eastern North America. The 1811-1812 earthquakes were among the largest historical earthquakes to occur in North America and were perhaps the largest historical intraplate earthquakes in the world. The earthquakes produced widespread liquefaction throughout the seismic zone and prominent to subtle surface deformation in several areas, but they did not produce any known surface faulting. Other than the pervasive sand blows throughout the seismic zone, the Reelfoot scarp is the most prominent geomorphic feature that has been produced by the modern tectonism. Recent studies of the scarp have provided valuable information on the recurrence of deformation on the scarp, calculated uplift rates, and the history of faulting. The evidence of

	Quaternary faulting in the New Madrid region is based on the occurrence of the major earthquakes in 1811-1812, the abundant ongoing seismicity, and the surface deformation associated with Reelfoot scarp. Other than the fault associated with Reelfoot scarp, individual seismogenic faults in the New Madrid seismic zone are not expressed at the surface, and their general locations are inferred to be associated with areas of abundant microseismicity. Because individual Quaternary faults remain unidentified throughout much of the seismic zone, it is not possible to define and measure specific attributes (azimuth, length, dip, etc.) for the faults.
Name comments	These features are located in the central part of the Mississippi River Valley. At present, structural and tectonic information about specific seismogenic faults is limited, in part because the seismogenic faults are not expressed or are poorly expressed at the surface. Furthermore, the entire river valley is covered by latest Quaternary sediments, so only the geologically youngest deformation is expressed at the surface. The Reelfoot scarp is a topographic escarpment that extends south-southeastward from near the town of New Madrid, Missouri, along the western margin of Reelfoot Lake, to a point south of the lake. It is the most prominent geomorphic feature in the entire seismic zone that is clearly known to have a tectonic origin.
County(s) and State(s)	CRAIGHEAD COUNTY, ARKANSAS CRITTENDEN COUNTY, ARKANSAS MISSISSIPPI COUNTY, ARKANSAS POINSETT COUNTY, ARKANSAS DUNKLIN COUNTY, MISSOURI MISSISSIPPI COUNTY, MISSOURI NEW MADRID COUNTY, MISSOURI PEMISCOT COUNTY, MISSOURI DYER COUNTY, TENNESSEE LAKE COUNTY, TENNESSEE
Physiographic province(s)	COASTAL PLAIN
Reliability of location	Good Compiled at 1:250,000 scale. *Comments:* Many features shown on maps of the New Madrid seismic zone are not discrete faults; the most notable exception is the Reelfoot scarp, which is located along the western shore of

	Reelfoot Lake in extreme northwestern Tennessee. The three most commonly noted features associated with the contemporary deformation are: (1) the Lake County uplift and Reelfoot scarp, (2) areas of suspected coseismic subsidence, and (3) areas of abundant liquefaction during the 1811-1812 earthquakes. The locations of these features are derived from the digital data used to generate the suite of seismotectonic maps of the New Madrid, Missouri area (Wheeler and Rhea, 1994 #754; Rhea and others, 1994 #3814).
Geologic setting	The modern seismicity in the New Madrid seismic zone is intimately associated with the Reelfoot rift (Ervin and McGinnis, 1975 #735), a northeasterly-trending, 70-km-wide graben that has as much as 2 km of structural relief on magnetic basement (Hildenbrand and others, 1982 #721; Hildenbrand, 1985 #736). The rift is best defined by magnetic data, which also reveal the presence of major positive magnetic anomalies along the flanks and axis of the rift that are inferred to be mafic plutons (Hildenbrand and others, 1982 #721; Hildenbrand, 1985 #736). The follow sequence of events summarizes the geologic history of the Reelfoot rift and the current tectonic setting of the New Madrid seismic zone. Crustal extension that resulted in development of the Reelfoot rift began in latest Precambrian or Early Paleozoic time. It is likely that the Reelfoot rift is generally contemporaneous with other large-scale late Precambrian-Early Paleozoic, extensional features along the rifted margin of southeastern North America, including the Southern Oklahoma aulacogen, the Rough Creek-Rome graben system, and the Marathon rift (Thomas, 1991 #678). Active rifting ceased by Late Cambrian time, and the Reelfoot rift was filled with a 1- to 4-km-thick sequence of marine clastic and carbonate sedimentary rocks. During the Late Paleozoic and much of the Mesozoic, the region was uplifted, and several kilometers of sedimentary rocks were eroded from the crest of the Pascola arch. In Permian time, mafic igneous dikes and sills intruded the sedimentary rocks; radiometric dating of a mica-peridotite dike in a drill hole near Reelfoot Lake in north-western Tennessee yielded an age of 267 Ma. Near the end of the Mesozoic, probably beginning in early to middle Cretaceous time, regional subsidence occurred again. Also in early Cretaceous time, a series of igneous intrusions were emplaced along the margins of the rift; the emplacement of these intrusions is cited as evidence of reactivation of the rift, although extensional features are not known. During the late Cretaceous

and continuing through the Eocene, subsidence resulted in formation of the Mississippi embayment. The embayment was filled with a southward-thickening wedge of predominantly clastic marine and continental sediments. Oligocene sediments are generally absent in the northern Mississippi embayment. In late Quaternary time and probably in earlier episodes, tremendous volumes of glacial melt-water from much of North America flowed down the Mississippi-Ohio Rivers drainage system and through the northern embayment. Braided streams that transported the meltwater deposited outwash sand and gravel in the embayment that is typically tens of meters thick in the New Madrid region. In early Holocene time, the Mississippi River changed from a braided stream to a meandering regime and began developing the modern meander belt. As the river meandered, fine-grained overbank sediment that was deposited during annual floods spread across wide expanses of the modern river valley.

The contemporary seismicity and current deformation in the New Madrid region is controlled by a regional stress field in which the maximum compressive stress is oriented approximately east-northeast-west-southwest. Within this stress field, ancient faults, most of which originally formed as extensional features during rifting, have been reactivated mainly as strike-slip faults. The modern seismicity is concentrated into three major trends that form a zigzag pattern that has an overall northeasterly trend. The modern seismicity is largely associated with rift-related features. The southwesternmost trend is a narrow, linear, 120-km-long zone of earthquakes in northeastern Arkansas and extreme southeastern Missouri; this zone of earthquakes roughly coincides with the position of an axial fault zone that is commonly present along the center of most rifts. Focal mechanisms for earthquakes in this zone indicate mainly dextral slip (Herrmann and Canas, 1978 #732; Herrmann, 1979 #733). This zone of seismicity coincides with the Blytheville arch, which is an enigmatic subsurface structure that is only known from seismic-reflection data and is pre-middle Ordovician in age (Herrmann and Canas, 1978 #732; Crone and others, 1985 #728). At the northeastern end of this 120-km-long zone, the second seismicity trend extends north-northwestward from extreme north-western Tennessee to near the town of New Madrid, Missouri. This zone of earthquakes is referred to as the "cross-rift" trend of seismicity because it cuts obliquely across the northeasterly trend of the Reelfoot rift. Earthquakes in this trend form a diffuse pattern and have a variety of focal-mechanism solutions including reverse and normal

	faulting; recent studies suggest that many earthquakes in this cross-rift trend are occurring on southwesterly dipping reverse faults (Chiu and others, 1992 #730). The third prominent zone of earthquakes is a linear trend that extends northeasterly from the town of New Madrid and is close to the northwestern margin of the rift. Few earthquakes in this trend have yielded good focal mechanisms, but the available data indicate dextral slip on faults in this trend (Herrmann and Canas, 1978 #732; Herrmann, 1979 #733). Thus the current seismicity indicates that contemporary deformation in the New Madrid seismic zone is occurring on two left-stepping, en echelon, dextral slip faults.
Length (km)	km.
Average strike	
Sense of movement	Right lateral *Comments:* The sense of movement on active faults is derived from seismological data. These data indicate that the regional deformation is dominated by dextral slip in the two northeast-trending linear zones of seismicity. The two linear seismicity trends are linked by a zone of northwest-trending seismicity. Accurately located earthquakes in this northwesterly trend highlight the presence of a southwesterly dipping reverse fault (Chiu and others, 1992 #730). Modeling of deformation and comparison with geomorphic features are consistent with this interpretation. Based on combined information from seismological, seismic-reflection profiling, geomorphic, and geological studies, Reelfoot scarp is interpreted as an east-dipping moncline which is the surface expression of a fault-propagation fold associated with the underlying blind Reelfoot thrust fault (Van Arsdale and others, 1995 #3965; Kelson and others, 1996 #3811; Mueller and others, 1999 #3963; Van Arsdale, 2000 #3968). In the shallow subsurface, the scarp is composed of a series of flexures that collectively produce the total topographic relief on the scarp (Mueller and others, 1999 #3963).
Dip Direction	V *Comments:* Focal mechanisms and hypocenter locations indicate near-vertical dips for faults in the linear, northeasterly trending seismicity zones (Herrmann and Canas, 1978 #732; Herrmann, 1979 #733; Chiu and others, 1992 #730; Pujol and others, 1998 #3793). Hypocenter locations indicate dips of about 31?-48? SW

	on faults in the cross-rift trend (Chiu and others, 1992 #730), which is the down-dip extension of the Reelfoot fault. Thus, at depths of 7-14 km, the microseismicity indicates that the Reelfoot fault has a dip of about 34? (Chiu and others, 1992 #730). Upward toward Reelfoot scarp, this plane has a dip of about 55? between depths of 0.5 and 7 km, and at depths of less than 0.5 km, the fault plane probably has a dip of 16? or less (Mueller and others, 1999 #3963).
Paleoseismology studies	The first detailed studies of the 1811-1812 earthquakes and their surficial effects was conducted by M.L. Fuller nearly a century after the shocks (Fuller, 1912 #723). Since Fuller's pioneering work, numerous studies have examined diverse aspects of the geology, geomorphology, and tectonics of the New Madrid region. Many of those studies are cited in other parts of this discussion. Detailed studies of the Reelfoot scarp in northwestern Tennessee have documented evidence of three deformation events within the past 2,400 years and characterized the style of near-surface deformation associated with the scarp (Kelson and others, 1996 #3811). Late Holocene fluvial deposits are warped into an 8-m-high, east-facing monocline. Borehole data and trenches at three sites characterized the style of near-surface deformation associated with the scarp and constrain the timing of three deformation events on the scarp. The Crittenden County fault zone (feature 1023-6) in northeastern Arkansas has no known surface expression but extensive seismic-reflection studies suggest Quaternary sediments are deformed by movement on the fault (Luzietti and others, 1992 #705). The fault zone, in part, coincides with the southeastern margin of the Reelfoot rift and has a sense of vertical offset that is opposite to the net structural relief in the underlying rift (Crone, 1992 #706). Drill-hole and seismic-reflection data show that the top of Paleozoic rocks is vertically offset about 80 m across the fault zone and that shallower strata are offset progressively less (Luzietti and others, 1992 #705; Crone, 1992 #706). Deformation associated with the fault zone can be confidently traced through the Tertiary rocks that fill the Mississippi embayment (Luzietti and others, 1992 #705). Very high-resolution reflection data confirm that late Quaternary deposits are faulted, and a deformed reflector as shallow as 6-7 m could be resolved with these data (Williams and others, 1995 #3820). The lack of nearby

	stratigraphic control precluded determining if this reflector represented Holocene strata. An exploratory trench coincident with the very high-resolution reflection profile failed to find any unequivocal evidence of Holocene movement on the fault zone (Crone and others, 1995 #883).
Geomorphic expression	The geomorphology of the New Madrid seismic zone is dominated by the fluvial features of the Mississippi River and the latest Pleistocene braided stream terraces that are primarily composed of outwash sand and gravel. The most prominent geomorphic expression of the contemporary tectonism is the Lake County uplift (feature 1023-1), a teardrop-shaped uplift in extreme northwestern Tennessee that has a maximum length of about 50 km and maximum width of about 23 km (Russ, 1982 #722). Geomorphic studies indicate that recent deformation of the uplift has elevated the late Holocene fluvial sediments as much as 9 m. Part of the eastern margin of the Lake County uplift is defined by Reelfoot scarp (feature 1023-2), which separates the uplift from Reelfoot Lake on the east. The scarp is the only tectonic scarp in the entire seismic zone. A trench across the scarp exposed a group of normal faults at the scarp's base (Russ, 1979 #753), and seismic-reflection data show that the scarp coincides with the Reelfoot fault, a near-vertical down-to-the-east fault (Zoback, 1979 #731). Recent studies have revealed as much as 9 m of structural relief on the scarp (Mueller and others, 1999 #3963), which is the result of a monoclinal flexure, with secondary normal faulting across the crest of the flexure (Kelson and others, 1992 #729; Kelson and others, 1996 #3811). The surface expression of Reelfoot scarp is most distinctive along the western margin of Reelfoot Lake, even though the shallow sediments are only tilted to the east at slopes of 5-7? (Mueller and others, 1999 #3963). Original studies of the scarp traced its length for a distance of only 11 km, but recent work suggests that the scarp extends from west of New Madrid, Missouri, through the Kentucky bend, along the west side of Reelfoot Lake to just south of the lake: a total distance of about 32 km. Farther southeastward, no scarps are known, but on the basis of seismic-reflection and geomorphic data, Van Arsdale and others (1999 #3967) propose that the subsurface fault may be approximately 70 km long.

Initial studies of the surficial effects of the 1811-1812 earthquakes suggested possible uplift elsewhere in the New Madrid region (Fuller, 1912 #723), but geologic and geomorphic studies have yet to confirm the presence of these features. Fuller (1912 #723) also noted several areas where subsidence probably or possibly occurred during the 1811-1812 earthquakes. One area of probable subsidence is Reelfoot Lake (Van Arsdale and others, 1998 #3966). Historical accounts and geomorphic evidence indicate that the lake was enlarged as a result of the earthquakes (Russ, 1982 #722), but it is unclear if the enlargement was the result of subsidence beneath the lake, uplift of the Lake County uplift, which resulted in damming of drainage through Reelfoot Lake, or a combination of both processes.

Of the many "sunklands" described by Fuller (1912 #723), only two have been studied in sufficient detail to provide insight into their origin: the Big Lake (feature 1023-3) and the St. Francis (1023-4) "sunklands" in northeastern Arkansas (Guccione and others, 1988 #3809; Guccione and Hehr, 1991 #737; Guccione and others, 1994 #739). Bathymetric and sedimentologic evidence and radiocarbon dating suggest that these areas were drowned in a time frame that is consistent with subsidence induced by the 1811-1812 earthquakes. Other "sunk-lands", described by Fuller (1912 #723) and predicted by modeling, appear on old maps, but have not been studied.

A recently recognized, 135-km-long lineament named the Bootheel lineament (feature 1023- 5) has been speculated to be the surface expression of a coseismic fault related to the 1811-1812 earthquakes (Schweig and Marple, 1991 #725; Schweig and others, 1992 #726). The expression of the lineament varies along strike and is marked by (1) a distinct contrast in the density of sand blows and liquefied sand, (2) shallow linear depressions along the feature, (3) continuous and discontinuous linear sand bodies at the surface, and (4) meander scars that appear to truncate at the lineament (Schweig and Marple, 1991 #725; Schweig and others, 1992 #726). In detail, parts of the lineament are composed of individual, en echelon, linear segments. Locally there is as much as 1.0 m of topographic relief across the feature, but the sense of topographic relief varies, that is, in places the western side is high and elsewhere, the eastern side is high. Eight trenches have been excavated across the feature at four sites. These trenching studies have revealed that the lineament is typically associated with large-scale liquefaction features, especially major sand-blow feeder dikes (Schweig and Marple, 1991 #725; Schweig and others, 1992 #726; Crone and others, 1995 #883). The origin of the lineament is still unclear, but Schweig and Marple (1991 #725) speculate that it may mark the location of a lateral-slip fault even though little of the modern seismicity is spatially associated with it. Johnston and Schweig (1996 #3810), using historical descriptions of the effects of the 1811-1812 New Madrid earthquakes, suggest that the first large event occurred, in part, on the Bootheel lineament.

The most widespread expression of recent strong earthquakes in the New Madrid region is the abundant liquefaction features (sand blows and sand-filled fissures), which are concentrated in a 40- to 60-km-wide belt from near Charleston, Missouri on the northeast to south of Marked Tree, Arkansas (Obermeier, 1988 #3813). Geologic conditions in the New Madrid region are near optimum for the development of liquefaction features during strong earthquakes: a thin (2-8 m thick), fine-grained "topstratum" deposit overlies water-saturated, unconsolidated "sub-stratum" sand and gravel. Extensive liquefaction occurred during the 1811-1812 earthquakes; locally the ground surface was buried by more than 1 m of liquefied sand, and hundreds of square kilometers of the land surface have been mapped as being more than 25 percent covered by liquefied sand (Obermeier, 1988 #3813). Haller and Crone (1986 #718), Obermeier and others (1990 #717), Rodbell and Schweig (1993 #716), Wesnousky and Leffler (1992 #713), and Tuttle and Barstow (1996 #3815) describe the attributes of selected sand blows and liquefaction features from the 1811-1812 earthquakes.

The 1811-1812 earthquakes caused at least 221 landslides along the bluffs that define the eastern boundary of the Mississippi River alluvial plain (Jibson and Keefer, 1988 #715). The majority of the landslides are covered by mature vegetation, which indicates that they did not form within the last few decades and field evidence suggests that most of the landslides are approximately the same age (Jibson and Keefer, 1988 #715). This implies that most of the landslides were triggered by a single event, which is likely to have been the 1811-1812 earthquakes. Dynamic and static slope stability analyses of one landslide revealed that the landslide would be stable under all geologic conditions except those caused by strong earthquake-induced ground motion (Jibson and Keefer, 1992 #714).

Age of faulted surficial deposits	Late Holocene fluvial sediments are deformed in the Lake County uplift and along Reelfoot scarp; small-displacement reverse faults are associated with the scarp but it is not clear if these faults are directly connected to the Reelfoot fault at depth.
Historic earthquake	
Most recent prehistoric deformation	latest Quaternary (<15 ka) *Comments:* Some details of the chronology of prehistoric earthquakes in the New Madrid region are becoming clear after more than two decades of work. Although some earlier studies reported no definitive evidence of pervasive liquefaction similar to that which occurred in 1811-1812 in the region during the Holocene (Wesnousky and Leffler, 1992 #713; Rodbell and Schweig, 1993 #716), others, including all recent studies by the same investigators, have demonstrated repeated late Holocene paleoliquefaction on a regional scale. In the northern part of the seismic zone, Russ (1979 #753) described stratigraphic evidence of two prehistoric earthquakes that postdate the maximum age of 2,250 radiocarbon years for the fluvial sediments exposed in his trench across Reelfoot scarp (feature 1023-2). Subsequent trenching studies (Kelson and others, 1992 #729; 1996 #3811) have constrained the timing of the most recent paleoevent on the scarp to have occurred between A.D. 1310 and A.D. 1540 and have yielded equivocal evidence of a preceding event that occurred prior to about A.D. 900. Saucier (1991 #711) reported evidence of a strong earthquake north of New Madrid that occurred shortly before A.D. 539 and presents weaker evidence of a younger event about A.D. 991. Tuttle and others (1998 #3817) have found evidence from the central and northern parts of the seismic zone for an earthquake that occurred A.D. 1530?130yr. Tuttle and Schweig (1995 #3818; 1996 #3819) and Tuttle and others (1996 #3816; 1998 #3817) report widespread evidence throughout the New Madrid seismic zone of a prehistoric event around A.D. 900. They have also found scattered evidence for earlier events that caused less liquefaction. Thus, currently available paleoseismic data in parts of the New Madrid region suggests the occurrence of a penultimate event about 470 years ago, but the evidence is not uniform or widespread. However, evidence for an event at 1,000 years ago is widespread and well dated archeologically and with radiocarbon age determinations. Deformation on the scarp associated with the 1811-1812 New Madrid earthquake sequence produced extensive liquefaction,

	folded the fluvial sediments, and caused minor reactivation of small faults that bound an extensional graben in the uplifted (hanging wall) of the Reelfoot scarp (Kelson and others, 1996 #3811). The penultimate deformation event occurred between A.D. 1260 and 1650 (350-740 yr B.P.), produced about 1.3 m of throw in the graben-bounding faults, and caused folding and development of the scarp. The oldest documented event associated with the scarp occurred between A.D. 780 and 1000 (1000-1120 yr B.P.), and initially produced the small graben in the hangingwall of the Reelfoot fault.
Recurrence interval	*Comments:* Despite considerable efforts, reliable geologic data on the recurrence of strong, potentially damaging earthquakes in the New Madrid seismic zone has been elusive, and the currently available data are limited, inconclusive and contradictory. Paleoseismic studies (Russ, 1979 #753; Saucier, 1991 #711; Kelson and others, 1992 #729; 1996 #3811) have suggested a recurrence interval of about 500-1100 years for earthquakes that are large enough to produce significant surface deformation or liquefaction in various parts of the seismic zone. The most recent studies (Tuttle and Schweig, 1995 #3818; Tuttle and others, 1996 #3816; 1996 #3819; 1998 #3817) suggest that there were about 900 years between the last two New-Madrid-size events (A.D. 900 to A.D. 1811) and that widespread liquefaction occurs every few hundred years. However, the record studied thus far is too short to be used for a long-term recurrence rate. The detailed investigations of the Reelfoot scarp described above provide information that permitted Kelson and others (1996 #3811) to estimate a recurrence interval of 150-900 years, with a more likely range of about 400-500 years. It is not clear if these rate estimates reflect the overall behavior of major events for the entire seismic zone or only apply to the Reelfoot scarp. In the absence of better data for the entire seismic zone, we choose to categorize the recurrence interval as unknown.
Slip-rate category	Insufficient data *Comments:* In the absence of well-determined data on the timing of paleoevents and the amount of tectonic slip produced by those events, it is impossible to estimate reliable or even meaningful Holocene or late Quaternary slip rates. Despite the lack of well-constrained slip-rate data for specific faults in the New Madrid

	region, some general inferences can be made about general deformation rates using structural and stratigraphic data (McKeown, 1982 #709). A wide range of fault slip rates can be calculated in the New Madrid region depending on time intervals and datums that are being considered. Long-term slip rates of 0.001-0.0009 mm/yr result from measuring the amount of vertical displacement of various Paleozoic, Mesozoic and Cenozoic stratigraphic horizons and assigning an age for those horizons (McKeown, 1982 #709; Van Arsdale, 2000 #3968). Estimated short-term slip rates are much higher than these long-term values, and some of the short-term slip rates are comparable to the rates of major plate-boundary faults. Based on the amount of Holocene deformation associated with the Lake County uplift (feature 1023-1) and the Reelfoot scarp (1023-2), the calculated rate on the fault is as much as 6.1?0.7 mm/yr (Mueller and others, 1999 #3963). Based on the geometric relationship between the Reelfoot fault and faults along the main rift-axis zone of seismicity, Mueller and others (1999 #3963) compute a slip rate of 1.8-2.2 mmy/yr on the axial faults. Geodetic studies in the New Madrid seismic zone have yielded results that imply contrasting slip rates. One geodetic study in part of the New Madrid seismic zone yields a very high contemporary slip rate of 5-7 mm/yr (Liu and others, 1992 #708), but this high slip rate must be an anomalously high, very short-term rate, considering the lack of regional topography. Also, if sustained, these rates would have produced much more faulting and deformation in Paleozoic and Cretaceous rocks than actually exists. A more recent geodetic study has questioned whether the Liu and others (1992 #708) results are statistically significant (Newman and others, 1999 #3964). Geodetic data analyzed by Newman and others (1999 #3964) indicate virtually no significant deformation is currently occurring, that is, their results show that the measured rate does not differ significantly from zero. The significance of the divergent results from these two studies remains unresolved and is the subject of considerable discussion. Because various studies yield such diverse slip-rate estimates, we choose to define the slip rate for deformation in the New Madrid seismic zone as unknown.
Date and Compiler(s)	1994 Anthony J. Crone, U.S. Geological Survey, Emeritus Eugene S. Schweig, U.S. Geological Survey
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