Reelfoot rift and its impact on Quaternary deformation in the central Mississippi River valley

Ryan Csontos
University of Memphis, Ground Water Institute, 300 Engineering, Memphis, Tennessee 38152, USA

Roy Van Arsdale
Randel Cox
University of Memphis, Earth Sciences, 1 Johnson Hall, Memphis, Tennessee 38152-3430, USA

Brian Waldron
University of Memphis, Civil Engineering, 110D Engineering Science Building, Memphis, Tennessee 38152, USA

ABSTRACT

Geophysical and drill-hole data within the Reelfoot rift of Arkansas, Tennessee, Missouri, and Kentucky, USA, were integrated to create a structure contour map and three-dimensional computer model of the top of the Precambrian crystalline basement. The basement map and model clearly define the northeast-trending Cambrian Reelfoot rift, which is crosscut by southeast-trending basement faults. The Reelfoot rift consists of two major basins, separated by an intrarift uplift, that are further subdivided into eight subbasins bound by northeast- and southeast-striking rift faults. The rift is bound to the south by the White River fault zone and to the north by the Reelfoot normal fault. The modern Reelfoot thrust fault, responsible for most of the New Madrid seismic zone earthquakes, is interpreted as an inverted basement normal fault.

Geologic interpretation of 5077 shallow borings in the central Mississippi River valley enabled the construction of a structure contour map of the Pliocene–Pleistocene unconformity (top of the Eocene–base of Mississippi River alluvium) that overlies most of the Reelfoot rift. This map reveals both river erosion and tectonic deformation. Deformation of the Pliocene–Pleistocene unconformity appears to be controlled by the northeast- and southeast-trending basement faults. The northeast-trending rift faults have undergone and continue to undergo Quaternary dextral transpression. This has resulted in displacement of two major rift blocks and formation of the Lake County uplift. Joiner Ridge and the southern half of Crowley’s Ridge as compressional stepover zones that appear to have originated above basement fault intersections. The Lake County uplift has been tectonically active over the past ~2400 yr and corresponds with a major segment of the New Madrid seismic zone. The aseismic Joiner ridge and the southern portion of Crowley’s Ridge may reflect earlier uplift, thus indicating Quaternary strain migration within the Reelfoot rift.

Keywords: Reelfoot rift, Mississippi embayment, New Madrid seismic zone, Mississippi River alluvium, geomorphology.

INTRODUCTION

The Reelfoot rift (Mississippi Valley graben), beneath the northern Mississippi embayment, has been interpreted as a Cambrian aulacogen (Ervin and McGinnis, 1975; Thomas, 1991) (Fig. 1). Buried under as much as 8 km of Phanerozoic sediments, the crystalline basement rocks defining the rift have been mapped from gravity, aeromagnetic, seismic refraction, seismic reflection, and a few deep petroleum exploration wells (Hildenbrand et al., 1977; Howe and Thompson, 1984; Howe, 1985; Hildenbrand and Hendricks, 1995; Langenheim and Hildenbrand, 1997; Dart and Swolfs, 1998; Parrish and Van Arsdale, 2004; Csontos, 2007). The northern end of the rift near the town of New Madrid, Missouri, was the site of the great 1811–1812 New Madrid earthquakes and it remains the most seismically active area east of the Rocky Mountains (Johnston and Schweig, 1996) (Fig. 1). This seismicity ranges from 4 to 14 km in depth (Pujol et al., 1997) and has been attributed to reactivation of Reelfoot rift basement faults (Kane et al., 1981; Braile et al., 1986; Dart and Swolfs, 1998; Csontos, 2007). Specifically, the earthquakes are occurring on a compressional left stepover within a right-lateral strike-slip fault system (Russ, 1982; Schweig and Ellis, 1994).

The general geometry of the Reelfoot rift was mapped by Dart and Swolfs (1998) (Fig. 2); however, here we integrate a more recent and extensive data set (Csontos, 2007) to better map the rift. In addition, the base of the Mississippi Valley alluvium (Pliocene–Pleistocene unconformity) is mapped using 5077 shallow borings. Comparison of the Pliocene–Pleistocene unconformity with the Reelfoot rift structures indicates Quaternary fault reactivation far beyond the footprint of the New Madrid seismic zone.

GEOLOGY OF THE REELFOOT RIFT REGION

The geologic history of the Reelfoot rift region is poorly understood because the basement rocks are largely buried beneath Phanerozoic sediments, including Mississippi River alluvium. However, regional mapping indicates that the central United States is underlain by several Precambrian terranes (Fig. 3). These terranes include the Superior Province (2700 Ma), Penokean orogen (1800–1830 Ma), Northern Central Plains orogen (1800–1700 Ma), Southern Central Plains orogen (1700–1600 Ma), Eastern Granite-Rhyolite Province (1470 ± 30 Ma), Southern Granite-Rhyolite Province (1370 ± 30 Ma), and Grenville Province.

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Figure 1. Reelfoot rift and New Madrid seismic zone earthquakes. CR—Crowley’s Ridge. DEM—digital elevation model. AL—Alabama; AR—Arkansas; IL—Illinois; KY—Kentucky; MS—Mississippi; TN—Tennessee.
Proterozoic rocks of the Reelfoot rift region consist primarily of granite, granite porphyry, and dioritic gneiss as determined from drill cores (Thomas, 1985; Dart, 1992; Dart and Swolfs, 1998). Rocks of similar age in the Eastern Granite-Rhyolite Province are exposed in the St. Francois Mountains in southeastern Missouri (Thomas, 1985; Dart and Swolfs, 1998).

The Reelfoot rift is part of the Reelfoot rift–Rough Creek graben–Rome trough intracratonic rift zone that formed during the disassembly of Rhodinia and opening of the Iapetus Ocean (Thomas, 1976, 1983, 2006). Several authors have proposed that the Reelfoot rift may have formed along the boundary between adjacent Proterozoic terranes beneath the Eastern Granite Rhyolite Province (Kane et al., 1981; Hildenbrand, 1985; Hendricks, 1988; Nelson and Zhang, 1991; Dart and Swolfs, 1998).

Initiation of Reelfoot rifting may have been due to mantle plume upwelling that occurred along terrane boundaries (Dart and Swolfs, 1998). Alternatively, the Reelfoot rift may be a consequence of right-lateral strike-slip motion along a northwest-oriented transform fault that formed the Paleozoic continental margin of southeastern Laurentia (Thomas, 1985, 1991). Whatever the mechanics, intracratonic extension ultimately succeeded in creating the Reelfoot rift with an estimated extension between 17% (Nelson and Zhang, 1991) and 33% (Hildenbrand, 1985).

Cambrian Reelfoot rifting occurred primarily along large normal faults that appear to become listric with depth (Howe and Thompson, 1984; Howe, 1985; Nelson and Zhang, 1991). However, the exceptionally straight margin faults suggest that these northeast-trending rift structures originated as strike-slip faults (Hildenbrand, 1985). During rifting the Reelfoot graben accumulated a maximum of 7 km of sediment, while outside the rift only 1.5 km of contemporary sediments accumulated (Howe and Thompson, 1984; Howe, 1985). Local erosion of nearby granite-rhyolite rocks provided Early Cambrian basalt arkosic sediments (Crone et al., 1985; Dart and Swolfs, 1998). Howe and Thompson (1984) suggested that faulting occurred syndepositionally within and along the Rift margins up to Middle Cambrian time. After this, deposition within the rift shifted from subaerial to marine and as much as 6 km of marine Upper Cambrian Lamotte Sandstones, Bonterre Formation limestones, Elvins Group shales, and the Potsdam Supergroup were deposited (Thomas, 1985; Howe, 1985). Deposition kept pace with regional subsidence during Late Cambrian–Middle Ordovician time (Howe and Thompson, 1984; Howe, 1985; Dart and Swolfs, 1998), resulting in the thick, shallow-marine Knox (Arbuckle) carbonate Supergroup that overlies the rift (Thomas, 1985; Howe, 1985). From Middle Ordovician to Pennsylvania time, subsidence and uplift alternated due to distal effects of the Taconic, Acadian, and Alleghanian orogenies (Howe, 1985). Structural reactivation within the Reelfoot rift began during the late Paleozoic with the assembly of Pangaea (Thomas, 1985; Howe, 1985). Middle Ordovician to mid-Cretaceous rocks are largely missing above the rift, partly due to nondeposition (Permian–Late Cretaceous) and partly due to late Paleozoic and/or mid-Cretaceous uplift and erosion, which produced a major unconformity at the top of the Paleozoic section. Many normal faults within the central United States were inverted during the Paleozoic collisional processes (Howe and Thompson, 1984; Howe, 1985; Marshak and Paulsen, 1996).

Cox and Van Arsdale (1997, 2002) proposed that regional mid-Cretaceous uplift and subsequent Late Cretaceous subsidence of the Mississippi embayment occurred because the North American plate drifted over the Bermuda hotspot. The thermally uplifted area formed a north-trending arch from which ~2 km of Paleozoic strata were eroded during the mid-Cretaceous (Cox and Van Arsdale, 1997). Following the North American plate's migration off the hotspot during the Late Cretaceous, the eroded mid-Cretaceous arch subsided as it cooled, forming the Mississippi embayment trough. Late Cretaceous and Cenozoic sediments record transgressive-regressive sequences within the trough that include the McNairy, Clayton, Porters Creek, Fort Pillow, Flour Island, Claiborne Group, Upland Complex, and the Mississippi River alluvium (Howe and Thompson, 1984; Thomas, 1985).
The Mississippi River Valley within the Mississippi embayment is a broad alluvial lowland (Fig. 1). Notable in eastern Arkansas is the 320-km-long Crowley’s Ridge, a northerly trending topographic high that divides the valley into the Western and Eastern Lowlands. The ridge ranges in width from 1.6 to 19 km and averages 60 m above the surrounding lowlands. It is composed in ascending order of Eocene Wilcox and Claiborne Groups (Meissner, 1984), Pliocene Upland Complex (Van Arsdale et al., 2007), and Pleistocene loess (Guccione et al., 1990).

Crowley’s Ridge formed due to erosion of the Western Lowlands by the ancestral Mississippi River, erosion of the Eastern Lowlands by the ancestral Ohio River, and by Quaternary reactivation of ridge-bounding faults (Van Arsdale et al., 1995). Depositional environments within the valley were fluvial during the Pliocene. This resulted in deposition of the Upland Complex, a terrace of the ancestral Mississippi–Ohio river system (Van Arsdale et al., 2007). Repeated periods of glacial melt-water escape, sea-level change, loess deposition, and structural deformation have produced various river terraces, river courses, lakes, and areas of warping during the Quaternary (Autin et al., 1991; Schweig and Van Arsdale, 1996). These landforms are dominated by glacio-fluvial processes and sediments that produced Pliocene and Pleistocene landforms consisting mostly of terraces and valley trains (Saucier, 1974; Autin et al., 1991). Repeated changes in late Pliocene and Pleistocene base level have controlled much of the Mississippi Valley’s landforms and deposits through repeated degradation and aggradation. Four processes especially influenced base level through the Quaternary: glacio-eustatic sea-level changes, variations in rates and patterns of sediment yield, climatic changes, and tectonic activity. Pleistocene rivers carrying coarse-grained sediment were dominantly braided, in contrast to the high silt and clay sediment load of the Holocene rivers that now occupy meandering channels.

Structural features affecting regional Quaternary stratigraphy within the Mississippi River valley include the Jackson Dome, Lake County uplift, Monroe uplift, Ouachita fold and thrust belt, Wiggins arch, and several fault zones (Autin et al., 1991; Schweig and Van Arsdale, 1996; Cox et al., 2000). Based on shallow alluvial cores, Mihills and Van Arsdale (1999) recognized modern topographic relief mirroring the Pliocene–Pleistocene unconformity (base of Mississippi River alluvium), reflecting deformation of the Lake County uplift, Reelfoot Lake basin, and the northeast Arkansas sunklands. Some of these structures have modified local stream gradients and sedimentary processes during the Quaternary (Holbrook et al., 2006).

FAULTING WITHIN THE REELFOOT RIFT

Bounding faults of the Reelfoot rift (Fig. 1) have large normal displacements (Howe 1985; Nelson and Zhang, 1991; Parrish and Van Arsdale, 2004). The northwestern margin of the rift is delineated by a steeply southeastward-dipping normal fault, displacing the Precambrian erosional surface as much as 3 km (Howe, 1985; Nelson and Zhang, 1991). The southeastern rift margin consists of a pair of down-to-the-northwest steep normal faults with as much as 3 km normal displacement on the more western fault, and 0.5 km on the more eastern fault in western Tennessee (Howe, 1985; Parrish and Van Arsdale, 2004).

Several faults have been identified within the Reelfoot rift (Fig. 1). The Reelfoot reverse fault, coincident with the northwest-trending seismic zone in Figure 1, produces most of the current seismicity. Surface deformation occurred along this fault during the February 1812 earthquake. The White River fault zone is an up-to-the-south normal fault, based upon gravity, magnetic (Hildenbrand and Hendricks, 1995; Langenheim and...
Hildenbrand, 1997), and seismic reflection data (Howe, 1985), that may form a southern terminus to the Reelfoot rift. The Axial fault, a vertical fault (Howe, 1985) that trends down the center of the rift, is the locus of the northeast-trending seismicity in Figure 1.

A number of southeast-trending strike-slip faults in southeastern Missouri and northeastern Arkansas may cross the Reelfoot rift (McCracken, 1971; Guinness et al., 1982; Zietz, 1982; Hildenbrand, 1985; Howe, 1985; Simpson et al., 1986; Sims et al., 1987; Cox, 1988; Dart and Swolfs, 1998). Stark (1997) suggested that major thrusting and transpressive deformation during the Late Proterozoic Grenville orogeny modified the rift region, resulting in orthogonal basement faults with southeast and northeast strikes. Many of these southeast-trending faults displace Paleozoic strata and thus have been active during the Phanerozoic (Stark, 1997).

METHODS

A number of data types and mapping techniques were applied in this research. Picks for the unconformity on the top of the Precambrian crystalline basement were obtained from depth-converted seismic reflection lines (Howe and Thompson, 1984; Howe, 1985; Nelson and Zhang, 1991; Parrish and Van Arsdale, 2004) and petroleum exploration wells (Dart and Swolfs, 1998; Van Arsdale and ten Brink, 2000). Earthquake hypocenter data were provided by J. Pujol (2006, personal commun.). Pliocene–Pleistocene unconformity (base of Mississippi River alluvium) data were obtained by geologically interpreting 3546 North American Coal Company lignite exploration geologic shallow well logs and combining these with 1531 picks that were previously made by the U.S. Army Corps of Engineers (Mihills and Van Arsdale, 1999). These data were imported into a database, mapped, and projected to a transverse mercator projection. The projection was centered at long 90°W and lat 35°N to minimize distortion of the map area (Csontos, 2007).

The Precambrian database was maintained and interpreted in the ArcGISTM and Landmark GraphicsTM software packages. These packages each offer unique advantages for interpolation and interpretation of the data. The top of the crystalline Precambrian was interpolated using ordinary kriging. Ordinary kriging is an interpolation algorithm typically used with geologic data. This algorithm calculates any overriding trend to the data, and models these data as a polynomial. The measured data are interpolated following removal of the trend. After interpolation, the random errors are assessed and the trend polynomial is added back into the interpolated surface to yield a meaningful result. Both LandmarkTM and ArcGIS™ have this capability, yet only ArcGIS™ offers a visual inspection of the semi-variogram and an interactive means of minimizing error through adjustment of the semi-variogram parameters, while only Landmark offers the capability to incorporate fault and break-line information into the interpolation. The semi-variogram model parameters determined in ArcGIS™ were entered into Landmark™ZmapTM package. Unfaulted interpolation schemes were built in tandem within ArcGIS™ and Landmark Zmap™ for comparison.

Faults were subsequently inserted into the Zmap™ model as break lines and polygons to the interpolated Precambrian surface. These faults were obtained from published seismic reflection lines (Howe and Thompson, 1984; Howe, 1985; Nelson and Zhang, 1991; Parrish and Van Arsdale, 2004), gravity and magnetic lineaments (Hildenbrand, 1985; Hildenbrand and Hendricks, 1995; Langenheim and Hildenbrand, 1997), mapped faults (McCracken, 1971; Zietz, 1982; Kisvarsanyi, 1984; Simpson et al., 1986; Sims et al., 1987; Haley et al., 1993), and hypocenter alignments (J. Pujol, 2006, personal commun.; Csontos, 2007). Hypocenters were viewed within a Landmark Geoprobe™ three-dimensional (3-D) model to identify fault planes. Hypocenter clusters appearing to follow planar surfaces were grouped into subsets and planar trend surfaces were created using ArcGIS™ and Landmark Zmap™. The Eastern Rift margin, Western Rift margin, and Reelfoot faults were assigned dip angle, dip azimuth, heave, and throw values where available with Zmap™. The southeast-striking Ozark Plateau faults and Axial fault were assigned vertical dips with no throw values where available with Zmap™. The southeast-striking Ozark Plateau faults and Axial fault were assigned vertical dips with no throw. Surface interpolation then utilized faults with dip, throw, and heave data to produce fault plane polygons, while faults without these data were treated as vertical break lines. These fault polygons and break lines were used to interrupt the contouring algorithm at the fault planes and continue interpolation on the opposite side of the fault using a new trend surface created for the fault-bound data subset. These faults were then incorporated into the Zmap™ interpolation algorithm to produce a Precambrian surface structure contour map displaced by faults.

The Pliocene–Pleistocene unconformity surface was mapped using ArcGIS™. Universal kriging was used to interpolate the surface, and then the surface was clipped along the periphery data points.

Owing to the regional extent of these surfaces and their three-dimensionality, visual comparison of these surfaces to control data (drill hole, seismic reflection data) was made easier through viewing them stereoscopically in Geoprobe™. Both ArcGIS™ and Landmark™ provide 3-D stereoscopy through the extensional packages ArcScene™ and Geoprobe™, respectively, and using Sharper Technology Incorporated Crystal-eye stereo goggles, an emitter, and a DepthQ Stereo3D projector.

RESULTS

Top of Precambrian Crystalline Basement Structure Contour Maps

The top of the Precambrian crystalline basement unconformity, including the Reelfoot rift and Rough Creek graben, is illustrated in Figure 4. In this map, no faults have been incorporated into the model to displace the surface. The obvious features are the Reelfoot rift, Rough Creek graben, the high between these down-dropped areas, southern and northern closure of the Reelfoot rift, and a structural high in the center of the Reelfoot rift.

Figure 5 focuses on the Reelfoot rift and adds into the model faults with their correct dips and displacements. These faults include the down-to-the-northwest Eastern Rift Margin normal faults (Parrish and Van Arsdale, 2004), down-to-the-southeast Western Rift Margin normal fault (Nelson and Zhang, 1991), vertical Axial fault with no displacement (Howe, 1985), and a down-to-the-southwest Reelfoot fault. In this model, the Reelfoot fault bounds the Reelfoot rift on the north and is interpreted to be a down-to-the-southwest normal fault. Seismicity reveals that the Reelfoot fault is currently a thrust fault at depth and seismic reflection profiles indicate that it steepens to a reverse fault in the upper 4 km (Purser and Van Arsdale, 1998; Csontos, 2007). However, the top of the Precambrian surface suggests that the southwestern side is down-dropped and thus the Reelfoot fault probably has normal separation at this level. We therefore have modeled the Reelfoot fault as an inverted Cambrian rift-bounding normal fault. As is apparent in Figure 5, there are also subbasins within the Reelfoot rift.

In the final Reelfoot rift basement model (Fig. 6; Animation 1), we extend one of the Eastern Margin faults north to include a Quaternary fault scarp near Union City, Tennessee (Cox et al., 2006), extend the Western Margin fault north to include the current seismicity trend north of New Madrid, Missouri (Baldwin et al., 2002), and extend the southeast-trending vertical Grand River tectonic zone, Central Missouri tectonic zone, Osceola fault zone, Bolivar-Mansfield tectonic zone, and White River fault zone through the Reelfoot rift. These southeast-striking faults were projected across the Reelfoot rift by connecting mapped faults exposed
Figure 4. (A) Precambrian unconformity data points (red dots and lines) from Howe (1985), Wheeder et al. (1997), Dart and Swolfs (1998), and Parrish and Van Arsdale (2004). AL—Alabama, AR—Arkansas, IL—Illinois, KY—Kentucky, MO—Missouri, MS—Mississippi, TN—Tennessee. (B) Precambrian unconformity structure contour map from A including the Reelfoot rift (RR) and the Rough Creek graben (RCG). NM—New Madrid. Yellow box denotes location of Figures 5 and 6. Elevation datum is sea level.
Figure 5. Precambrian unconformity structure contour map with the addition of the two Eastern Rift Margin faults (EM), Axial fault (AF), Western Rift Margin fault (WM), and the Reelfoot fault (RF). NM—New Madrid. Elevation datum is sea level.

Figure 6. Precambrian unconformity structure contour map with the addition of southeast oriented faults. GRTZ—Grand River tectonic zone; CMTZ—Central Missouri tectonic zone; OFZ—Osceola fault zone; BMTZ—Bolivar-Mansfield tectonic zone; WRFZ—White River fault zone. EM—Eastern Rift Margin faults, AF—Axial fault, WM—Western Rift Margin fault, RF—Reelfoot fault, NM—New Madrid. Elevation datum is sea level.
in the Ozark Plateau with similar on-strike faults and geophysical lineaments mapped in western Tennessee (Howe, 1985; Hildenbrand, 1985). The southeast-trending faults are along the sub-basin margins of Figure 5 and break the Precambrian surface into nearly orthogonal fault-bound blocks, as described by Stark (1997). For example, the relatively high central area of the Reelfoot rift is bound on the north by the Osceola fault zone and on the south by the Bolivar-Mansfield tectonic zone. There are also very close correlations between the northern closure of the Reelfoot rift and the Grand River tectonic zone and between the southern closure and the White River fault zone.

**Pliocene–Pleistocene Unconformity**

In this study, 5077 geologic bore holes located within the central Mississippi River valley were interpreted to record the elevation of the Pliocene–Pleistocene age unconformity (top of the Eocene–base of the Mississippi alluvium) (Fig. 7). The data were initially split into the Eastern Lowlands and Western Lowlands and contoured separately utilizing universal kriging within ArcGIS™. Surfaces were cropped based upon the data extent and flood plain limits.

Relief on the Pliocene–Pleistocene unconformity suggests the presence of both erosional and tectonic features (Fig. 8). A prominent low extends along the eastern side of Crowley’s Ridge that we believe is due to Pleistocene ancestral Mississippi or Ohio River incision as described by Saucier (1994). This river course can be traced beneath Sikeston Ridge at right angles to the trend of that ridge (Figs. 8 and 9). Since there is no evidence that this river course has been altered by tectonic uplift, we conclude that the overlying Sikeston Ridge is predominately erosional in origin. A topographic high trends southeast close to New Madrid, Missouri, that coincides with the Lake County uplift structure (Russ, 1982; Purser and Van Arsdale, 1998) and Reelfoot fault seismicity (Mueller and Pujol, 2005). Immediately east of this high is a low that corresponds with the tectonically down-dropped Reelfoot Lake basin (Russ, 1982). A second high extends southwest from the Lake County uplift to near Marked Tree, Arkansas, that is coincident with the Blytheville arch in the underlying Paleozoic strata (Johnston and Schweig, 1996) and the southern arm of New Madrid seismic zone seismicity (Fig. 1). This same high appears to bound the southern ends of Big Lake and Lake St. Francis sunkenlands. A third high on the unconformity surface that we have named Joiner ridge, after Joiner, Arkansas, can be traced northwest from the corner of Shelby County, Tennessee (Fig. 8).

In the Western Lowlands there are elevation changes on the Pliocene–Pleistocene unconformity surface. A 10-m-deep northeast-trending closed depression is in the central portion of the Western Lowlands that does not appear to be related to Quaternary river erosion. Bounding this low on the southeast is a high region, and still farther southeast there is a second low that may be related to river erosion.

**DISCUSSION**

**Precambrian Unconformity Surface**

The Precambrian unconformity surface beneath the central Mississippi River valley probably caps eroded 1.47 Ga Eastern Granite Rhyolite Province rocks (Fig. 3). Rifting of this landscape formed the northeast-trending Reelfoot fault (Mississippi Valley graben). However, it appears that southeast-trending faults also were active during rifting because some of these faults are evident on seismic reflection lines within the rift. These southeast-trending faults have been mapped in the Ozarks of Arkansas and Missouri as Proterozoic basement faults that predate Reelfoot rifting (Sims et al., 1987). Stark (1997) proposed that these southeast-trending faults originated within the 1.8 Ga Central Plains orogen basin.

The Reelfoot rift is subdivided into eight fault-bound blocks (Fig. 6). At the largest scale, the rift consists of two basins divided by a structural high. This intrarift high is bound on the north by the Osceola fault zone and on the south by the Bolivar-Mansfield tectonic zone. Major changes in strike of the Eastern Rift Margin and Western Rift Margin faults occur near their intersection with the Bolivar-Mansfield tectonic zone and the Osceola fault zone, also indicating that these southeast-trending faults influenced the geometry of the Reelfoot rift.

Although we do not have well or seismic data between the Reelfoot rift and the Rough Creek graben, regional depth to magnetic basement maps (Hildenbrand, 1985; Langenheim and Hildenbrand, 1997) suggest that the basement rises between these two down-dropped structures (Fig. 4). Thus, we have chosen to close the Reelfoot rift at its northern end with a down-to-the-southwest normal fault (Fig. 6). This fault coincides in location with the Reelfoot thrust and reverse fault. However, the only displacement information we have on the Reelfoot fault shows that there is 70 m of reverse displacement on the top of the Paleozoic section that diminishes ups section (Van Arsdale, 2000). We thus propose that the Reelfoot fault was a normal fault during Reelfoot rifting, but was subsequently inverted and is a reverse fault in the post-Paleozoic section. The southern end of the Reelfoot rift appears to be closed by the up-to-the-southwest White River fault zone. Our data are also limited in this area and it is possible that the Reelfoot rift continues south beneath the Appalachian-Ouachita thrust belt.

Extending down the center of the Reelfoot rift is the Axial fault. Although we have modeled the Axial fault as terminating against the Reelfoot fault, this is speculative. The Axial fault appears to have undergone both dip-slip and strike-slip movement. The northwestern side of the fault is generally downthrown relative to the southeastern side (Howe and Thompson, 1984). Left-lateral strike-slip offset is also suggested by a series of offset ridges and depressions on the Precambrian surface (Fig. 6).

**Reelfoot Rift Faults Projected to the Pliocene–Pleistocene Unconformity Surface**

In Figure 9 we project the Reelfoot Rift base fault to the Pliocene–Pleistocene unconformity surface. In addition, we have included the base of the Pliocene Upland Gravel on Crowley’s Ridge in our Pliocene–Pleistocene unconformity surface. Thus, the Eastern and Western Lowlands and Crowley’s Ridge were contoured together in Figure 9. The Pliocene–Pleistocene unconformity surface is an erosional surface that has been tectonically modified. In the Eastern Lowlands, Quaternary uplift has occurred along the Reelfoot fault (Grand River tectonic zone) to form the Lake County uplift, along the Axial fault to affect regional drainage, and along Joiner ridge. Tectonic subsidence in the Eastern Lowlands has occurred beneath Reelfoot Lake, northwest of the Axial fault, and perhaps immediately east of Joiner ridge. In the Western Lowlands there are one
and perhaps two major structural basins that are separated by an apparently uplifted block bound by the Axial fault and a possible extension of the Eastern Margin faults southwest of the White River fault zone. Perhaps most dramatic in Figure 9 is the elevation of Crowley’s Ridge. Upon viewing Figure 9 stereoscopically (see Animation 2), it becomes apparent that most of the basement faults produce saddles, or appear to divide Crowley’s Ridge into sections, as one would expect if the faults were active during the Quaternary.

Hence, based on Figure 9 and neotectonic studies conducted in the Eastern Lowlands, it appears that the entire Reelfoot rift has been tectonically active during the Quaternary (Fig. 10). Specifically, we believe that the southeastern half of the Reelfoot rift (south of the Axial fault) has undergone Quaternary uplift. Cox et al. (2001, 2006) documented that the Eastern Rift Margin faults have undergone up-to-the-northwest Quaternary displacement. Relative up-to-the-southeast Quaternary displacement along the Axial fault appears to have been responsible for local impoundment of the St. Francis and Little Rivers to form Lake St. Francis and Big Lake respectively, within the general
Figure 8. Pliocene–Pleistocene unconformity structure contour map. B—Big Lake, S—Lake St. Francis, J—Joiner ridge. AR—Arkansas, IL—Illinois, KY—Kentucky, MO—Missouri, MS—Mississippi, TN—Tennessee.
Figure 9. Pliocene–Pleistocene unconformity surface with Precambrian Reelfoot rift faults. B—Big Lake, S—Lake St. Francis, CR—Crowley’s Ridge, J—Joiner ridge, GRTZ—Grand River tectonic zone; CMTZ—Central Missouri tectonic zone; OFZ—Osceola fault zone; BMTZ—Bolivar-Mansfield tectonic zone; WRFZ—White River fault zone. EM—Eastern Rift Margin faults, AF—Axial fault, WM—Western Rift Margin fault, RF—Reelfoot fault, NM—New Madrid. AR—Arkansas, IL—Illinois, KY—Kentucky, MO—Missouri, MS—Mississippi, TN—Tennessee. Tiptonville dome is a culmination on the Lake County uplift. Crowley’s Ridge south of lat 35°N not shown.
area called the sunklands (Van Arsdale, 1998; Mihills and Van Arsdale, 1999; Guccione et al., 2000). In the Western Lowlands, our proposed Quaternary uplift of the southeastern half of the Reelfoot rift is coincident with the high that is bound by the Axial fault and the southwestern projection of the Eastern Margin faults (Fig. 9). Similarly, it appears that the northwestern half of the Reelfoot rift has undergone Quaternary subsidence. This interpretation is supported by the basin in the Western Lowlands that is bound by the Axial and Western Margin faults and down-to-the-southeast displacement on the Western Rift Margin fault near Jonesboro, Arkansas (Van Arsdale et al., 1995) and near New Madrid, Missouri (Baldwin et al., 2005).

The New Madrid seismic zone has been explained as being caused by right-lateral shear along the Axial fault and the Western Margin fault north of New Madrid, Missouri, with a left-stepping compressional stepover being the Reelfoot fault. However, the Reelfoot thrust earthquakes and deformation continue southeast beyond the Mississippi River valley beneath a thick loess blanket to near the Eastern Rift Margin faults (Figs. 1 and 10) (Van Arsdale et al., 1995; Cox et al., 2001). Thus, a more accurate assessment would be that there is either one large stepover zone from the Eastern Margin faults to the Western Margin fault or two stepovers separated by the Axial fault. In assessing the remaining Reelfoot rift area, it appears that there are an additional two aseismic north-trending left stepovers. The most obvious one is the southern half of Crowley’s Ridge, which is documented as being bound by young faulting (Van Arsdale et al., 1995), and the second one is Joiner ridge. Crowley’s Ridge steps between the West Rift Margin fault and the East Rift Margin faults, whereas Joiner ridge steps over between the East Rift Margin faults and the Axial fault. We propose that these three stepovers are associated with Reelfoot rift fault intersections; thus, the fault intersections have acted as initiation points for the stepovers (Talwani, 1999; Gangopadhyay and Talwani, 2005).

CONCLUSIONS

Late Proterozoic through Cambrian rifting across southeastern North America created the northeast-trending Reelfoot rift. Proterozoic southeast-trending faults of the Ozarks appear to pass through the Reelfoot rift and were active during rifting (Fig. 6). We speculate that the southeast-trending faults may have propagated upward from Central Plains orogen rocks through the overlying granites and rhyolites of the Eastern Granite Rhyolite Province, as proposed by Stark (1997) (Fig. 3). The northeast- and southeast-trending faults that bound the Reelfoot rift and interior subbasins locally have as much as 3 km of vertical displacement (Parrish and Van Arsdale, 2004). The Rift appears to step up to the north at its northern end across the Grand River tectonic zone (Reelfoot normal fault), has a central intrarift uplifted block bound by the Osceola fault zone and Bolivar-Mansfield tectonic zone, and steps up to the

Figure 10. Interpreted deformation of the Pliocene–Pleistocene unconformity surface. Black lines—faults, J—Joiner ridge, GRTZ—Grand River tectonic zone; CMTZ—Central Missouri tectonic zone; OFZ—Osceola fault zone; BMTZ—Bolivar-Mansfield tectonic zone; WRFZ—White River fault zone, EM—Eastern Rift Margin faults, AF—Axial fault, WM—Western Rift Margin fault, RF—Reelfoot fault, AR—Arkansas, KY—Kentucky, MO—Missouri, MS—Mississippi, TN—Tennessee. Inset map shows a restraining bend (van der Pluijm and Marshak, 2004).
south across the White River fault zone. Thus, the southeast-trending faults appear to be fundamental structures that were involved in the formation of the Reelfoot rift. 

The Pliocene–Pleistocene unconformity beneath the Mississippi River alluvium is an erosional unconformity that has been tectonically altered at different scales. On a regional scale, local field studies and inspection of Figure 9 suggest that the southeastern half of the Reelfoot rift has undergone Quaternary uplift while the northwestern half has undergone subsidence. On a more local scale, tectonic uplift has occurred on the Lake County uplift, along the Axial fault, along the southern half of Crowley’s Ridge, and on Joiner ridge. Tectonic subsidence has occurred east of the Lake County uplift at Reelfoot Lake and perhaps on the eastern sides of Joiner ridge and the southern half of Crowley’s Ridge. Any tectonic low east of Crowley’s Ridge, however, is masked by the Pleistocene river channel.

Right-lateral strike slip on the Axial and Western Rift Margin faults near New Madrid, Missouri, has been explained as causing the Reelfoot thrust stepover between these faults. We wish to extend this explanation to propose that the southeastern half of the Reelfoot rift and New Madrid North faults in the northern New Madrid seismic zone, central United States: Seismological Research Letters, v. 73, p. 393–413.


Kisvarenyi, E.B., 1984, The Precambrian tectonic framework of Missouri as interpreted from magnetic anomaly map: Missouri Department of Natural Resources Contributions to Precambrian Geology, no. 14, p. 19.


Reelfoot rift and Quaternary deformation in the Mississippi Embayment


Kisvarenyi, E.B., 1984, The Precambrian tectonic framework of Missouri as interpreted from magnetic anomaly map: Missouri Department of Natural Resources Contributions to Precambrian Geology, no. 14, p. 19.


