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Seismic Potential of the New Madrid Seismic Zone's Reelfoot Fault: Collaborative Research With the University of Memphis and University of Kentucky

Roy Van Arsdale
Department of Earth Sciences
1 Johnson Hall
University of Memphis
Memphis, TN 38152
901-678-4356, FAX 901-678-2178, rvanrsdl@memphis.edu

Edward Woolery
Department of Earth and Environmental Sciences
101 Slone Research Building
University of Kentucky
Lexington, KY 40506-0053
859-257-3016, FAX 859-257-1147, ewoolery@uky.edu

Matthew Geenwood
Department of Earth Sciences
1 Johnson Hall
University of Memphis
Memphis, TN 38152
865-207-1310, FAX 901-678-2178, mlgrnwod@memphis.edu

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Abstract

A pressing New Madrid seismic zone problem is whether the northwest-striking and southwest-dipping Reelfoot reverse fault is a single ~84 km long fault capable of generating a ~**M** 7-8 earthquake or whether it consists of two discrete faults – the 59 km Reelfoot North and ~25 km Reelfoot South faults – capable of generating a smaller maximum ~**M** 7-7.5 earthquake. Previous investigators have argued that the Reelfoot fault is divided into the Reelfoot North fault and the Reelfoot South fault and that the point of division is where the northeast-striking Axial fault zone passes through the Reelfoot fault. A surface scarp (monocline) clearly demarcates the Reelfoot North fault; however, there is no scarp along the Reelfoot South fault. In this current study six seismic soundings, two seismic reflection profiles, geologic mapping, and geomorphic mapping were conducted to map and determine the history of the Reelfoot South fault within the Mississippi River bluffs immediately southeast of where the fault appears to separate into two segments. The seismic reflection profiles revealed a southwest-dipping (81°) Reelfoot South fault to a depth of one km. The Reelfoot South fault displaces the top of the Paleozoic section 65 m, top of the Cretaceous 40 m, top of the Paleocene Porters Creek Clay 31 m, top of the Paleocene Wilcox Group 20 m, and top of the Eocene Memphis Sand 16 m.

The Tiptonville dome is a hanging wall horst that has been mapped in previous studies above the Reelfoot North fault. An unpublished north-south US Geological Survey seismic reflection line, acquired along the South Bluff road near Gratio, Tennessee in 2008, reveals a north-dipping (84°) up-to-the-north reverse fault 4.3 km south of the Reelfoot South fault. We interpret this fault to be the reverse fault, herein called a back thrust, which defines the southwest margin and southeast extension of the Tiptonville dome. This back thrust displaces the top of the Paleozoic section 20 m, top of the Cretaceous 10 m, and the top of the Memphis Sand 6 m.

A 10 km long geologic strip map was made of the top and bottom of the ~3.1 Ma Pliocene Upland Complex (ancestral Mississippi River terrace) within the Mississippi River bluffs. No exposed fault zone was found; however, the mapping indicates that the Upland Complex is displaced ~6 m up-to-the-south immediately east, and on strike with, the Reelfoot South fault imaged at depth in our seismic reflection profiles.

Geomorphic mapping using LiDAR data revealed strath terraces on some small Mississippi River tributaries within the Mississippi River bluffs. However, within the map area terraces are only found on the creeks that exist between the Reelfoot South fault and its back thrust. The terraces are 6 to 7 m above their respective modern floodplains. Similarly, abandoned gravel pits within the Pliocene Upland Complex are restricted to the area between the Reelfoot South fault and its back thrust. The geologic, geomorphic, and gravel pit data support the conclusion that the stream terrace formation is due to ~6 m of uplift of the Tiptonville dome coincident with 6 m of uplift on the Reelfoot South fault and 3 m of uplift on the back thrust. The presence of a lower 2 m high terrace along Rock Branch creek suggests that there may have been two uplift events on the Tiptonville dome – an early 4 m uplift and a later 2 m uplift. The absolute age of the alluvium within the terraces is unknown, but the faulting that lifted the landscape to cause incision and terrace formation is probably Quaternary.

Introduction

The February 7, 1812 New Madrid earthquake occurred on the southwest-dipping Reelfoot reverse fault, which as most recently defined extends ~84 km from Dyersburg, Tennessee to 14.5 km northwest of New Madrid, Missouri (Figs. 1 and 2) (Van Arsdale et al., 2013). The purpose of this current research is to ascertain whether the Reelfoot fault consists of one 84 km long fault (Fig. 2) (Van Arsdale et al., 1999) or if it consists of two discrete faults – the 59 km long Reelfoot North fault and the 25 km long Reelfoot South fault (Fig. 3) (Csontos et al., 2008; Csontos and Van Arsdale, 2008; Van Arsdale and Cupples, 2013). The significance of this distinction is that two discrete faults with maximum rupture lengths of 59 km and 25 km would result in earthquakes with a maximum magnitude of ~**M** 7-7.5 (59 km) as opposed to a single fault with a rupture length of 84 km that is capable of producing a ~**M** 7-8 earthquake (Cramer and Boyd, 2014). Two discrete faults would also permit different fault/earthquake histories and recurrence intervals for each fault.

The Reelfoot reverse fault has been interpreted to be a compressional stepover between the Eastern and Western Reelfoot rift margin right-lateral strike-slip faults (Purser and Van Arsdale, 1998; Odum et al., 1998; Mueller and Pujol, 2001). Alternatively, the Reelfoot fault is a compressional stepover consisting of two segments (Csontos et al., 2008; Csontos and Van Arsdale; Van Arsdale and Cupples, 2013). The Reelfoot North fault extends from the Axial fault to the Western Reelfoot Rift margin faults and the Reelfoot South fault extends from the Axial fault to near the Eastern Reelfoot Rift margin faults. In cross section the Reelfoot North fault has been interpreted as a southwest dipping (72°) reverse fault in the uppermost 3.3 km and a southwest-dipping thrust fault (30°) at depths between 3.3 and 12 km (Chiu et al., 1992; Pursuer and Van Arsdale, 1998; Mueller and Pujol, 2001; Csontos and Van Arsdale, 2008) that apparently becomes horizontal at ~12 km depth where seismicity ceases (Van Arsdale, 2000) (Fig. 4). In this interpretation, the Lake County uplift is a hanging wall horst and the Tiptonville dome is a culmination (horst) on the eastern side of the Lake County uplift and both of these hanging wall horsts are bound on their western sides by northeast-dipping reverse faults (Purser and Van Arsdale, 1998; Van Arsdale, 2000). Although poorly constrained, the Reelfoot South fault has been interpreted to be a southwest-dipping (72°) reverse fault in the uppermost 3.7 km and a southwest-dipping thrust fault (44°) between 3.7 and 12 km (Chiu et al., 1992; Csontos and Van Arsdale, 2008) that also apparently becomes horizontal at ~12 km depth where seismicity ceases.

A number of seismic reflection lines have been acquired across the Reelfoot fault in previous studies (e.g. Hamilton and Zoback, 1982; Sexton and Jones, 1986; 1988; Odum et al., 1998; Stephenson et al., 1995; Van Arsdale et al., 1998; 1999). One of the lines was acquired along the southern margin of Reelfoot Lake in Tennessee (Fig. 2) (Van Arsdale et al., 1998). This reflection line reveals 70 m of displacement on the top of the Paleozoic, 60 m on the Cretaceous, 40 m on the Paleocene Midway Group, 30 m on the Eocene Wilcox Group, and 15 m on the Eocene/Quaternary unconformity that has been interpreted to reflect fault reactivation through time (Van Arsdale et al., 1998; Van Arsdale, 2000). Additionally, surface coring across the Reelfoot scarp near the southwest margin of Reelfoot Lake identified 3 m of structural displacement of the Quaternary alluvium at a depth of 3 m (Van Arsdale et al., 1995).

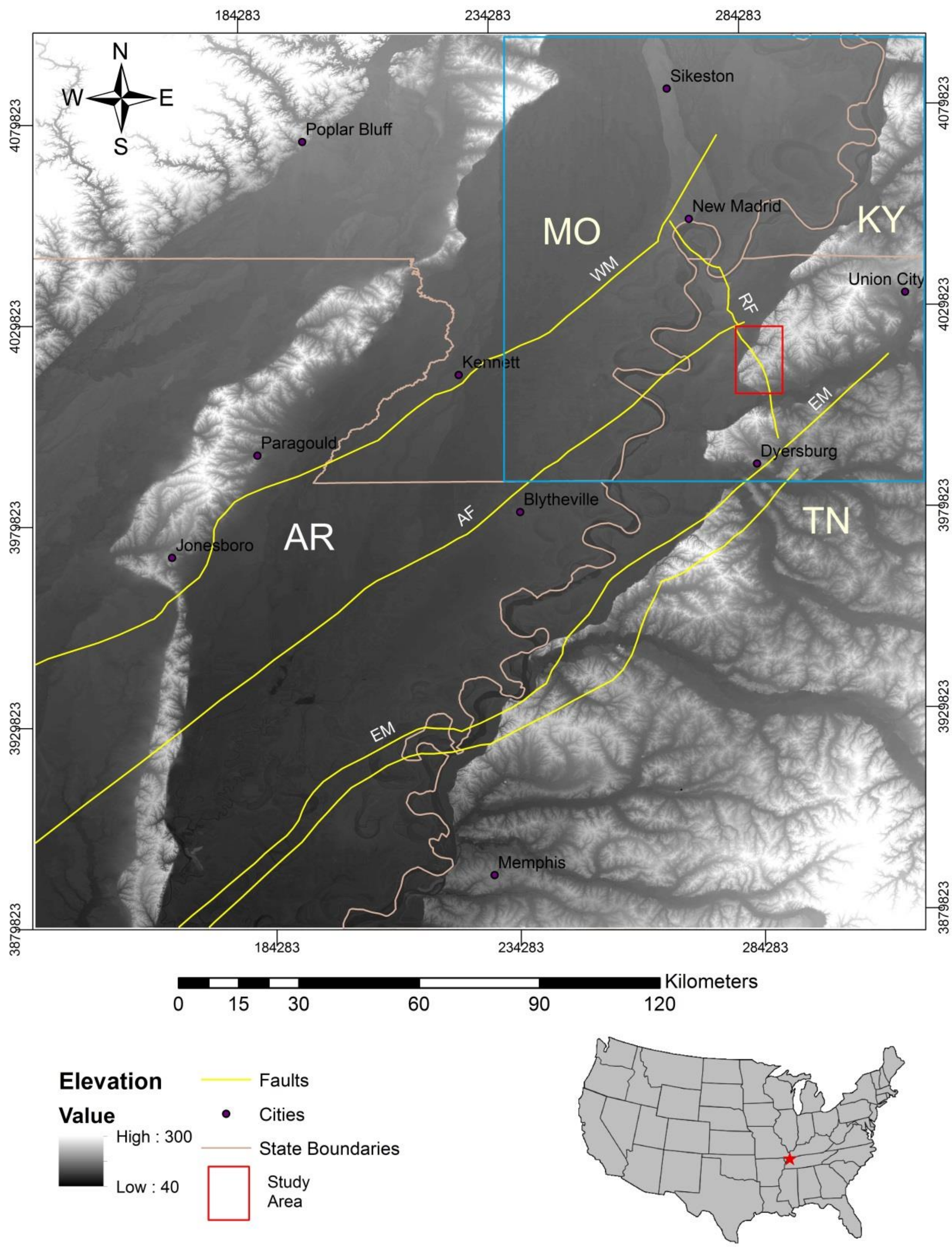

Figure 1. The central Mississippi River valley illustrating the principal faults of the Cambrian Reelfoot rift. Map coordinates are UTM. Blue box outlines area of Figure 2 and the red box outlines the study area in Figure 3. RF-Reelfoot fault, EM-Eastern Reelfoot rift margin faults, AF-Axial fault, WM-Western Reelfoot rift margin fault.

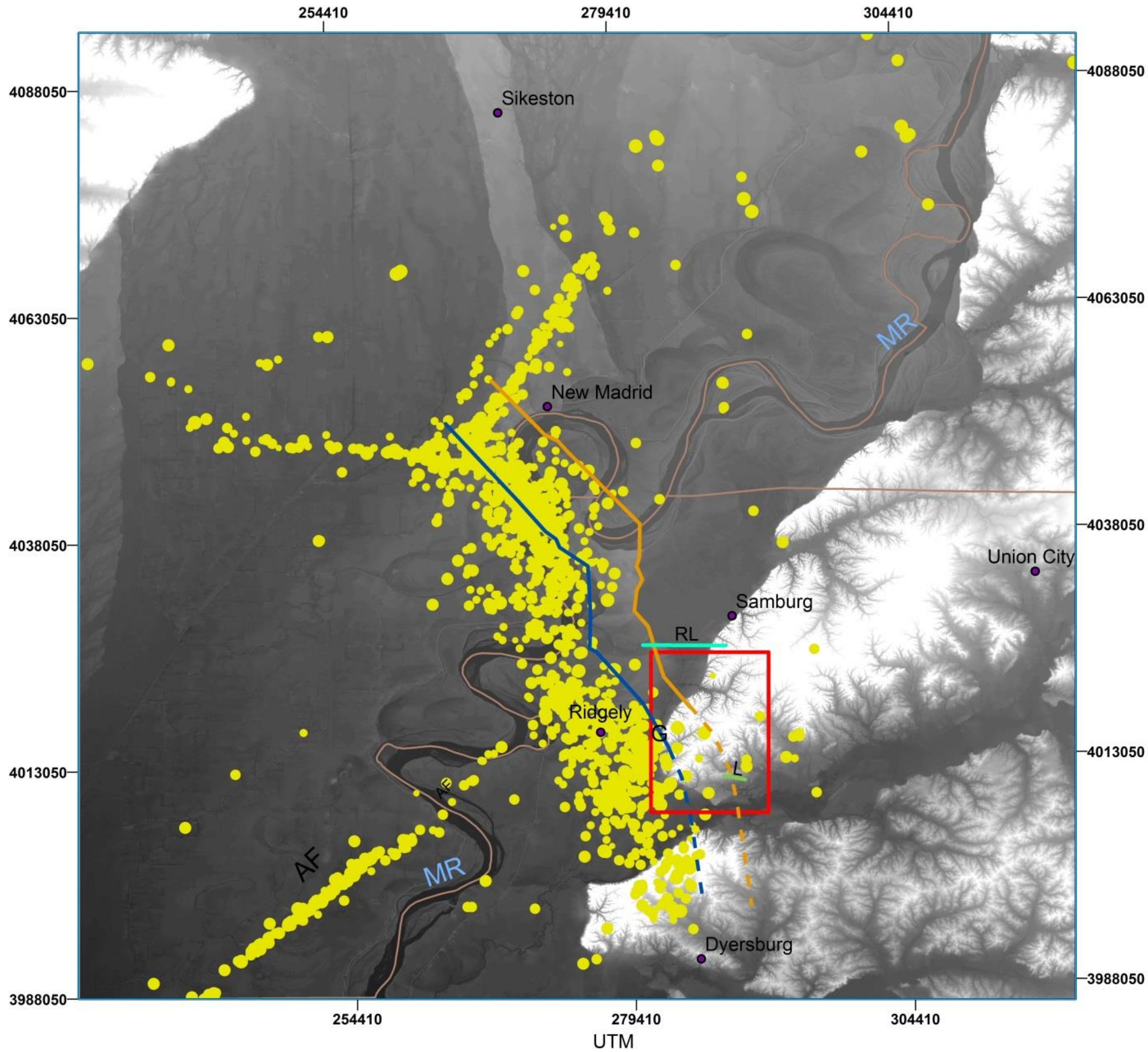

Figure 2. Yellow dots are microseismicity epicenters of the New Madrid seismic zone. Reelfoot fault (orange) and its back-thrust (dark blue) bound the Tiptonville dome. Red box is area of Figure 3. MR-Mississippi River, AF-Axial fault, G-Gratio, RL-Reelfoot Lake seismic reflection line (Van Arsdale et al., 1998), L-Lane seismic reflection line (Van Arsdale et al., 1999).

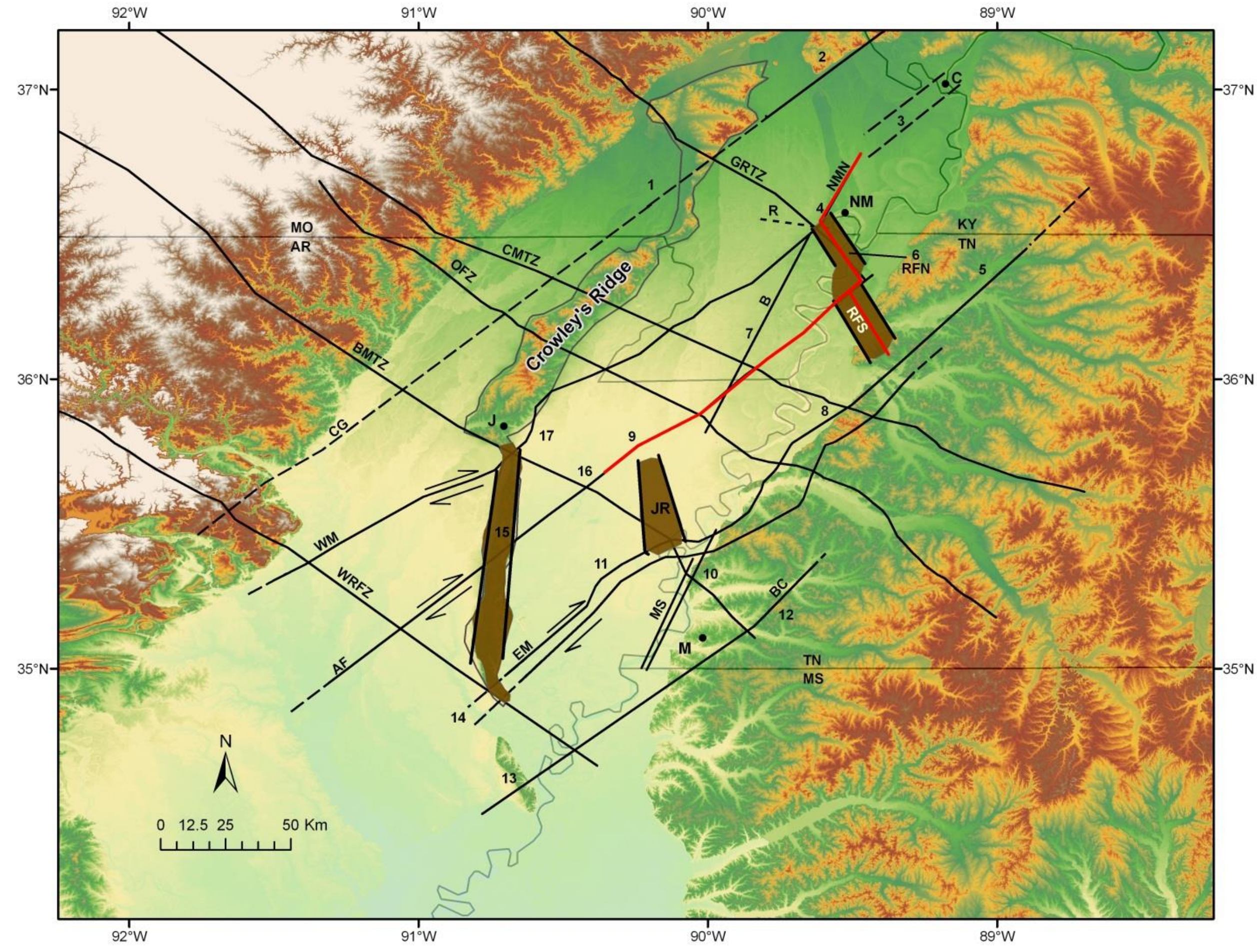

Figure 3. The Reelfoot fault mapped as two discrete faults. The Reelfoot North fault (RFN) and the Reelfoot South fault (RFS) are separated by the Axial fault (AF) (from Van Arsdale and Cupples, 2013). WM-Western Reelfoot rift fault, EM-Eastern Reelfoot rift faults, NMN-New Madrid North fault, NM-New Madrid, M-Memphis, J-Jonesboro, C-Cairo, CG-Commerce geophysical lineament/fault, MS-Meeman Shelby fault, BC-Big Creek/Ellendale fault, GRTZ-Grand Rapids tectonic zone, CMTZ-Central Missouri tectonic zone, OFZ-Osceola fault zone, BMTZ-Bolivar Mansfield tectonic zone, WRFZ-White River tectonic zone. Numbers represent locations where Quaternary deformation has been documented.

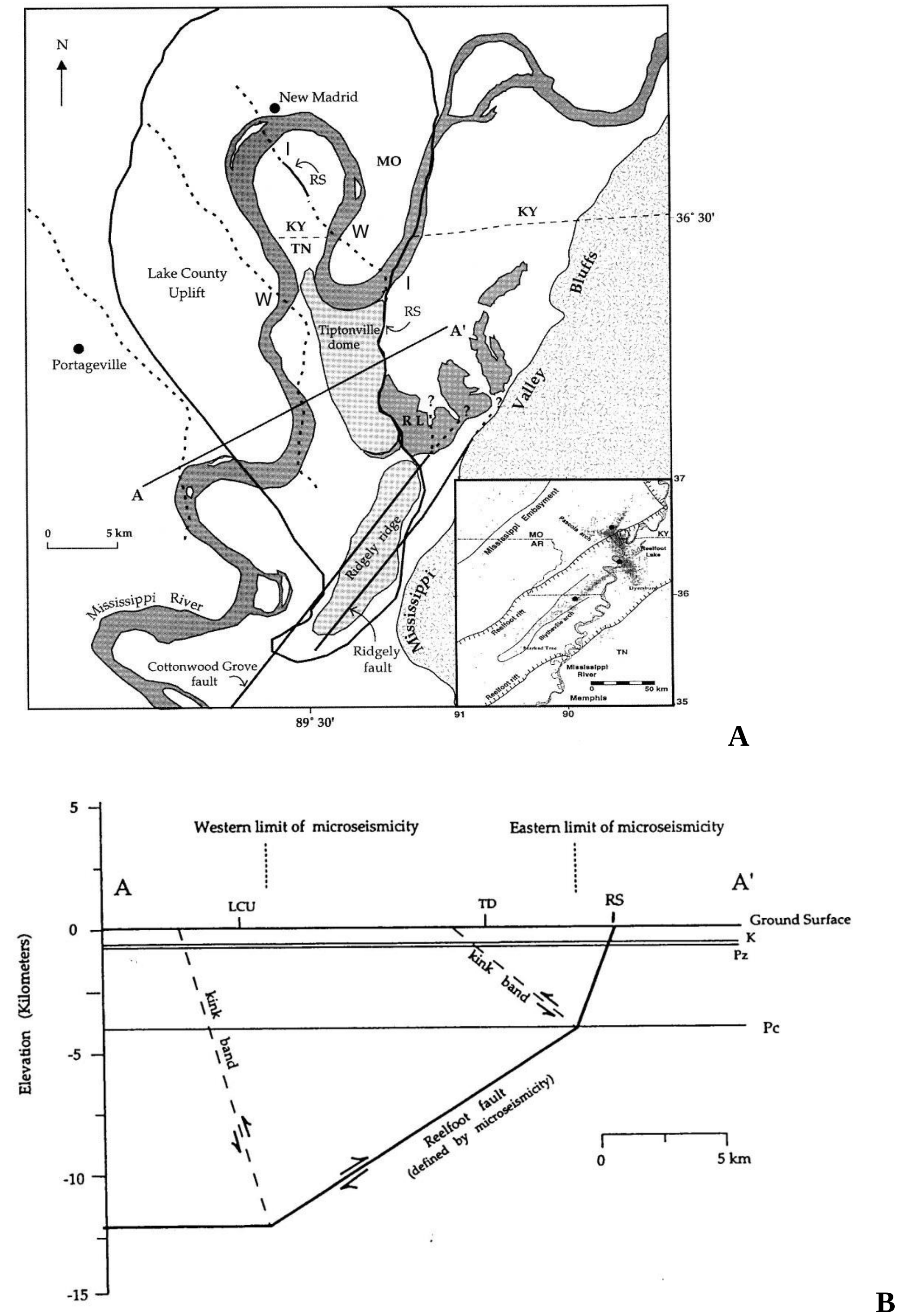

Figure 4. (A) Lake County uplift and its west-bounding back thrust (dashed), Tiptonville dome and its west-bounding back thrust (dashed), and the Reelfoot North fault with its discontinuous east-facing monocline scarp (RS). (B) Cross section A-A' across the Reelfoot fault with its hanging wall Lake County uplift (horst), and Tiptonville dome (horst), and their associated back thrusts here labeled kink band. R.L.-Reelfoot Lake, LCU-Lake County uplift, TD-Tiptonville dome, K-top of Cretaceous strata, Pz-top of Paleozoic strata, Pc-top of Precambrian (estimated).

Seismic reflection lines have also been collected in the immediate area of this current study. An unpublished seismic reflection line was acquired by the US Geological Survey in 2008 that extends 4.08 km north from Gratio, Tennessee along the South Bluff road (Fig. 5). Five kilometers west of Gratio the northeast-striking right-lateral strike-slip Cottonwood Grove and Ridgely faults within the Axial fault zone have been imaged with seismic reflection (Stephenson et al., 1995). Additionally, a seismic line imaged 40 m of down-to-the northeast reverse displacement on the top of the Paleozoic across the Reelfoot South fault near Lane, Tennessee 7 km southeast of this current study (Van Arsdale et al., 1999) (Fig. 2).

If the Reelfoot fault is one 84 km long fault then we would expect the fault can be traced continuously across the northeast-striking right-lateral Axial fault zone (Figs. 1 and 2) and that seismic reflection profiles across the Reelfoot fault on either side of the Axial fault zone should be very similar. Thus, to determine if the Reelfoot North and Reelfoot South faults are discrete and separate faults that act independently of each other it is necessary to determine if the Reelfoot North and Reelfoot South faults have different displacements and different displacement histories.

West of the Mississippi River bluff line, within the Eastern Lowlands, the near-surface geology consists of Quaternary Mississippi River floodplain alluvium overlying Eocene Claiborne Group sediments (Fig. 6). Exposed within the Mississippi River bluffs, the near-surface geology consists in descending order of buff colored Pleistocene loess, Pliocene Upland Complex (UC) red sand and gravel, and gray Eocene Jackson Formation (Hardeman, 1966). The Pleistocene loess consists of at least 3 discrete loess deposits (Markewich et al., 1998) and the UC is a terrace of the ancestral Mississippi/Ohio river system that has been Al-Be dated as ~3.1 Ma near Memphis, Tennessee (Van Arsdale et al., 2014). The Eocene sediments consist of partially lithified shallow marine and deltaic sands, silts, clays, and lignite. In the subsurface the stratigraphy with increasing depth consists of the Paleocene Wilcox Group, Paleocene Midway Group, Upper Cretaceous McNairy Sand, Demopolis Formation, and Coffee Formation, and Upper Cambrian carbonates (Fig. 6).

Methodology

This project involved six seismic soundings, two seismic reflection profiles (lines A and B), geologic mapping, and geomorphic mapping. Integrated seismic reflection (and refraction) walkaway soundings and common-midpoint (CMP) imaging were acquired starting 4 km north of Gratio and continued for 5 km north along South Bluff road (Fig. 5). The seismic surveys were performed in two phases along this transect. The first phase utilized serial P-wave walkaway soundings at 0.5 km intervals for identifying significant variation in the elevation of major stratigraphic boundaries. This methodology constrained the target area for the P-wave CMP reflection surveys seismic lines A and B (Fig. 5). A P-wave reflection survey line was acquired along South Bluff road, which is oriented nearly orthogonal to the prospective southeastern continuation of the Reelfoot fault zone (Fig. 7 line A). The CMP seismic surveys were collected with a 48-channel seismograph. Preliminary field matrix testing (sources and receivers) was performed to optimize the acquisition parameters. The P-wave data shown in line B of Figure 7 were collected using a 4 meter group interval and a standard 8 pound hammer source.

Data processing was performed on a Microsoft platform using VISTA12.0® and Parallel Geosciences SPW. A conventional CMP processing sequence was applied to the data (Baker, 1999). Front-end and surgical mutes were given special attention to ensure that coherent noise

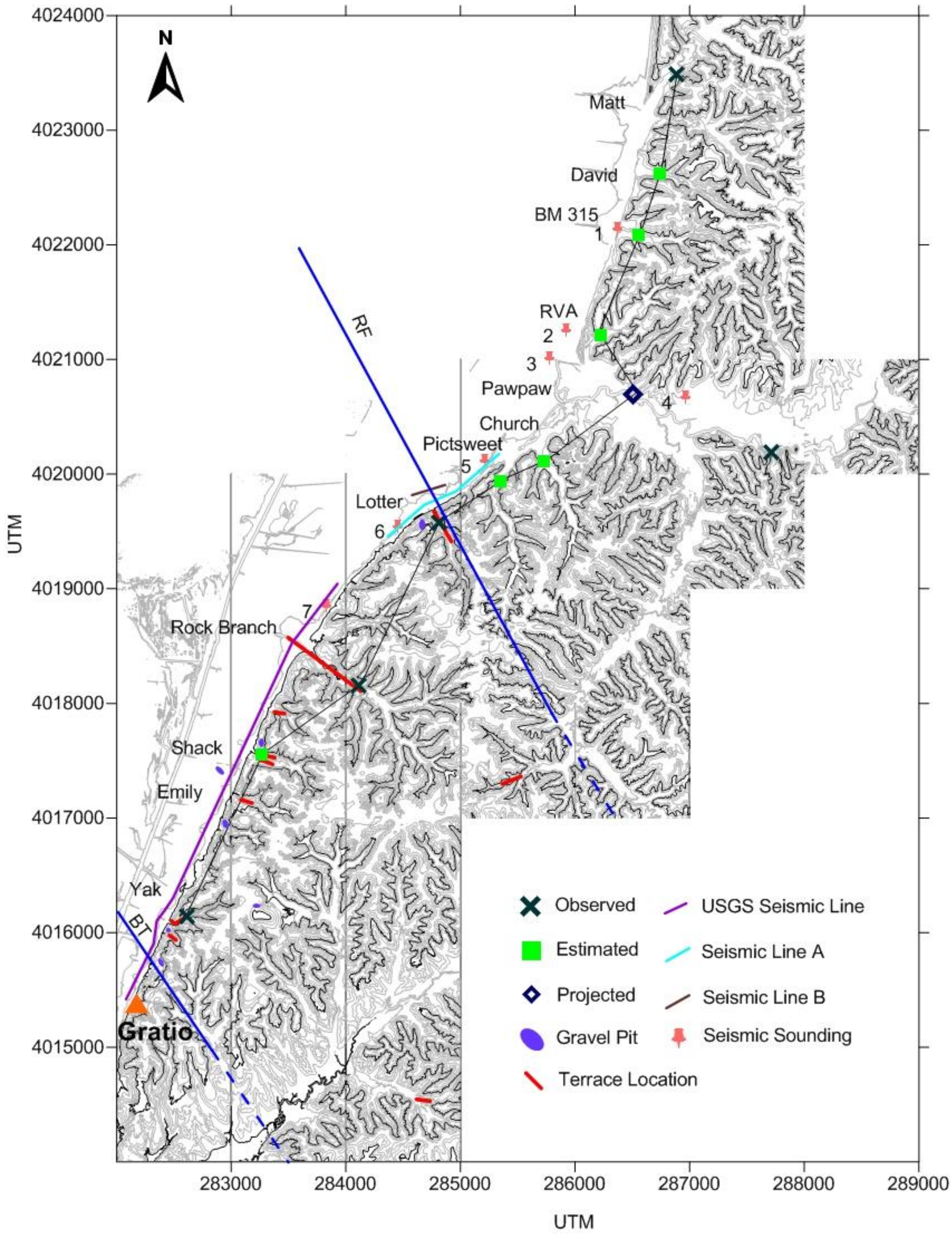

Figure 5. Study area located in Figures 1 and 2 red boxes. Dots represent observed, estimated, and projected UC exposures. RF-southwest-dipping Reelfoot reverse fault, BT-northeast-dipping back thrust. Most creek names (e.g. Shack) are informal names assigned in this study. Pawpaw and Rock Branch are official stream names.

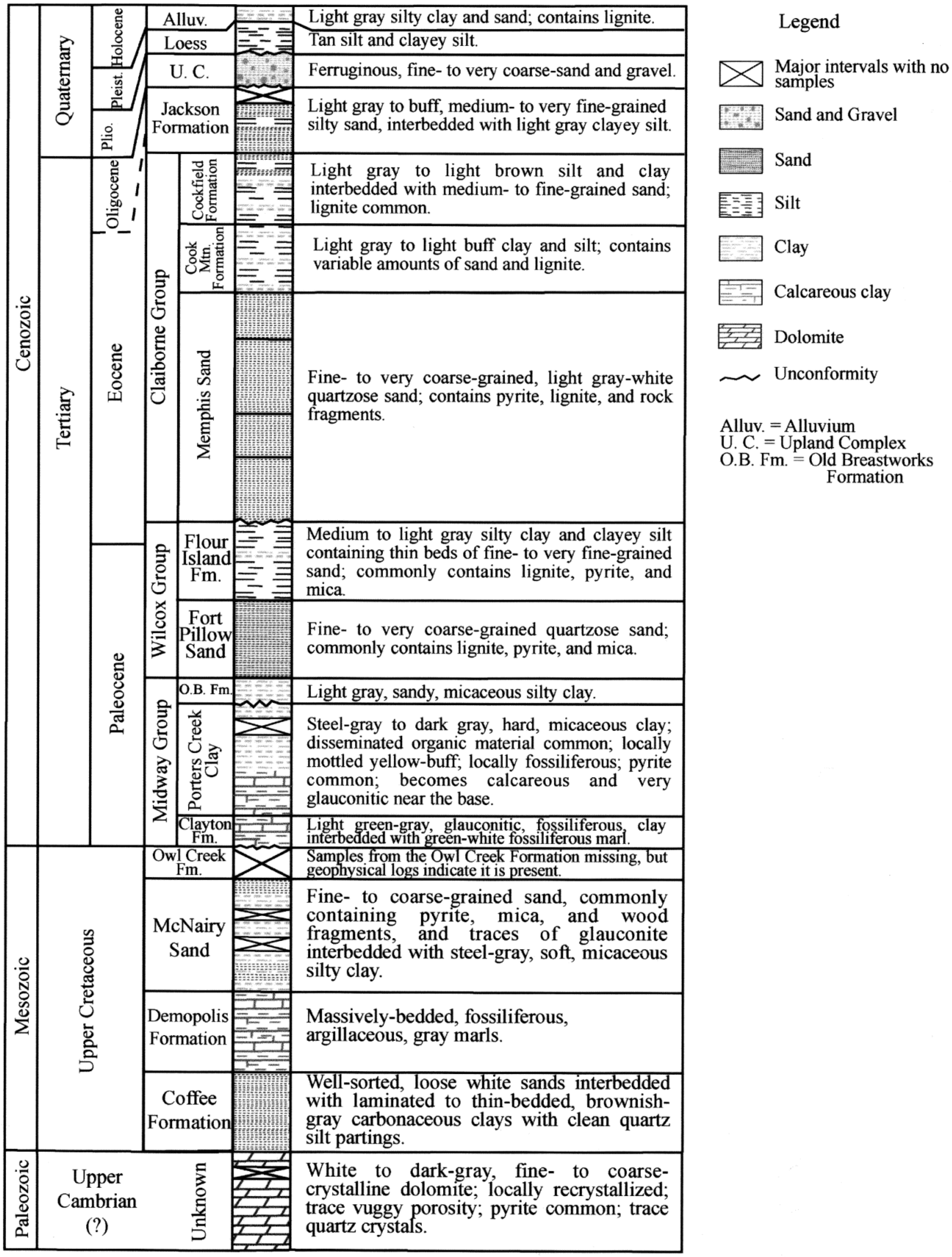

Figure 6. Stratigraphy of the New Madrid seismic zone region (modified from Crone, 1981).

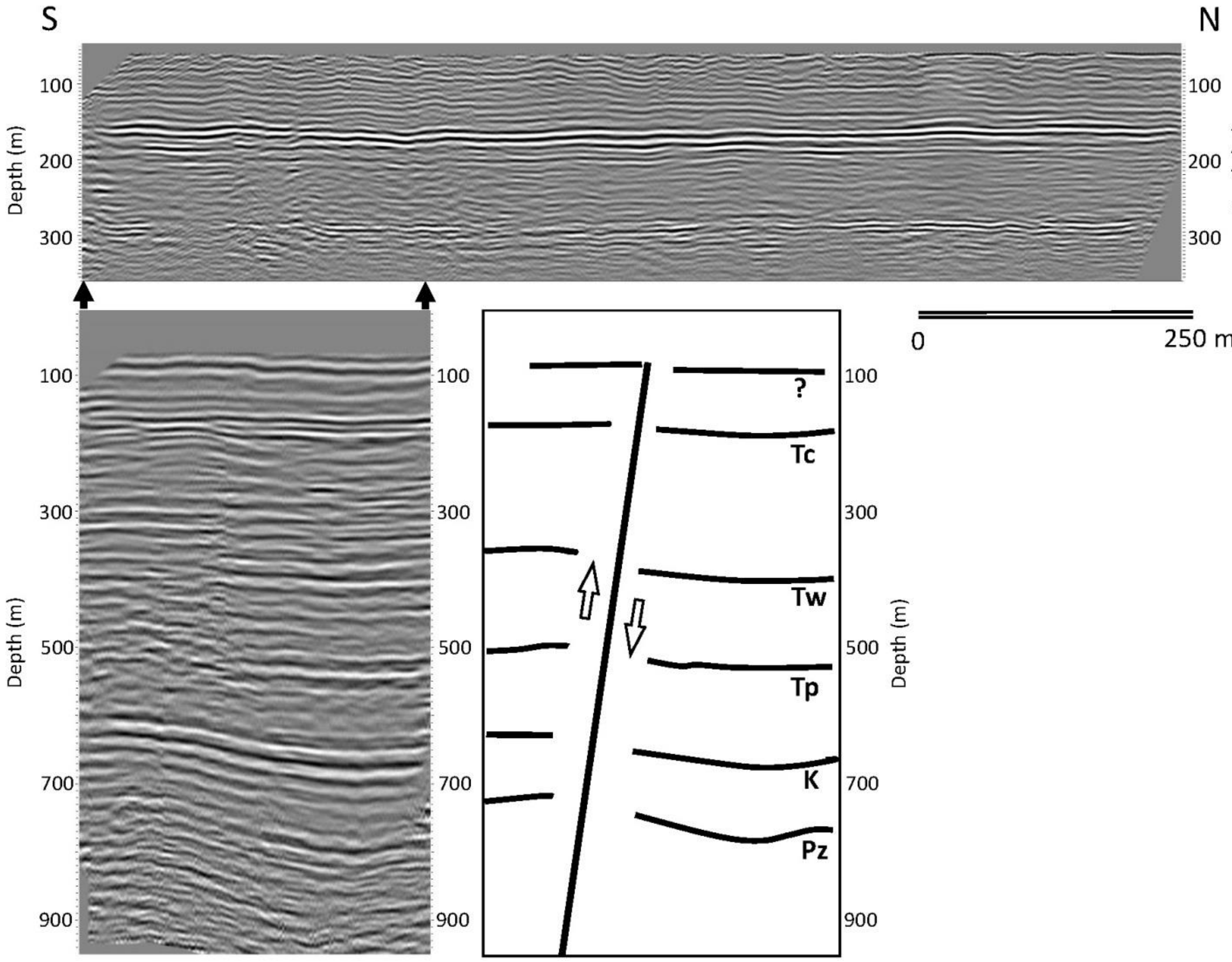

Figure 7. (Upper) P wave seismic reflection line A located in Figure 5. (Lower) P wave seismic reflection line B located in Figure 5 and its interpretation with lines representing stratigraphic tops. Tc-Tertiary Claiborne Group (Memphis Sand), Tw-Tertiary Wilcox Group, Tp-Tertiary Porters Creek Clay, K-Cretaceous, Pz-Paleozoic.

(i.e., refractions, ground roll, air wave, etc.) was not inadvertently stacked. Iterative velocity analysis was used to maximize resolution and coherency, as well as provide accurate depth migration.

The Reelfoot fault does not have a topographic expression southeast of the Axial fault zone and in-situ strata exposures are poor due to the thick (locally 30 m) surface loess. Thus, to identify near-surface faulting we mapped the top of the Eocene Jackson Formation strata and the top of the Pliocene UC strata (Van Arsdale et al., 2007; Cox et al., 2014) that are discontinuously exposed in creek banks within the bluff over an area 16 km north-south by 4 km east-west by walking creeks (only bluff section with exposed UC shown in Fig. 5). Light Detection and Ranging (LiDAR) data provided horizontal (± 1 m) and vertical (± 10 cm) control on the contact locations. Most creeks walked in this study were given informal names for this project (Fig. 5).

Geomorphic mapping was conducted using LiDAR data. Floodplains and terraces of small creeks (Mississippi River tributaries) were mapped within the bluff (Fig. 5). Pseudo three-dimensional landscape digital elevation model renditions and topographic profiles of the floodplains and terraces were constructed from the LiDAR data using Golden Software Surfer version 12 and Grapher version 10.

The UC is a local source of sand and gravel and there are abandoned quarries along the bluff line. We included abandoned quarry locations as one of our mapping layers.

Results

Seismic Reflection Data

Initial seismic soundings collected at 0.5 km spacing along South Bluff road (Fig. 5) revealed that the top of the Cretaceous apparently stepped up-to-the-south near Lotter Creek. Subsequently, a 1 km long north-south reflection line (line A) was acquired that indeed revealed an up-to-the-south reverse fault (Figs. 5 and 7). Reflection line (A) was collected along the shoulder of South Bluff road and the line traversed alluvial fans and colluvium at the base of the bluff. Consequently, seismic energy penetration was limited to the Tertiary section (uppermost 350 m). A second shorter parallel reflection line (B) was acquired in a field ~50 m west of line (A) (Figs. 5 and 7). Acquisition conditions were ideal and a clear image of the Reelfoot South fault zone was imaged into the Paleozoic section (900 m). Line (B) illustrates that the Reelfoot South fault displaces the top of the Paleozoic 65 m, top of the Cretaceous 40 m, top of the Paleocene Porters Creek Clay 31 m, top of the Paleocene Wilcox Group 20 m, and top of the Eocene Memphis Sand 16 m. Twenty five meters of stratigraphic thickening on the downthrown side of the fault within the Cretaceous, 9 m within the Paleocene Porters Creek Clay, 11 m in the Paleocene Wilcox Group, and 4 m in the Eocene Memphis Sand indicates that faulting was occurring during these times. Due to the acquisition parameters these reflection surveys could not resolve displacement higher in the section.

Our interpretation of an unpublished 2008 US Geological Survey seismic reflection line reveals a north-dipping, down-to-the-south, reverse fault located 4.3 km south of the Reelfoot South fault (Figs. 5 and 8). This fault has displaced the top of the Paleozoic section 25 m, Cretaceous 10 m, and the Memphis Sand 6 m. We interpret this to be the south-bounding fault (back thrust) of the Tiptonville dome (horst) like that illustrated in Figure 4 on the Reelfoot North fault.

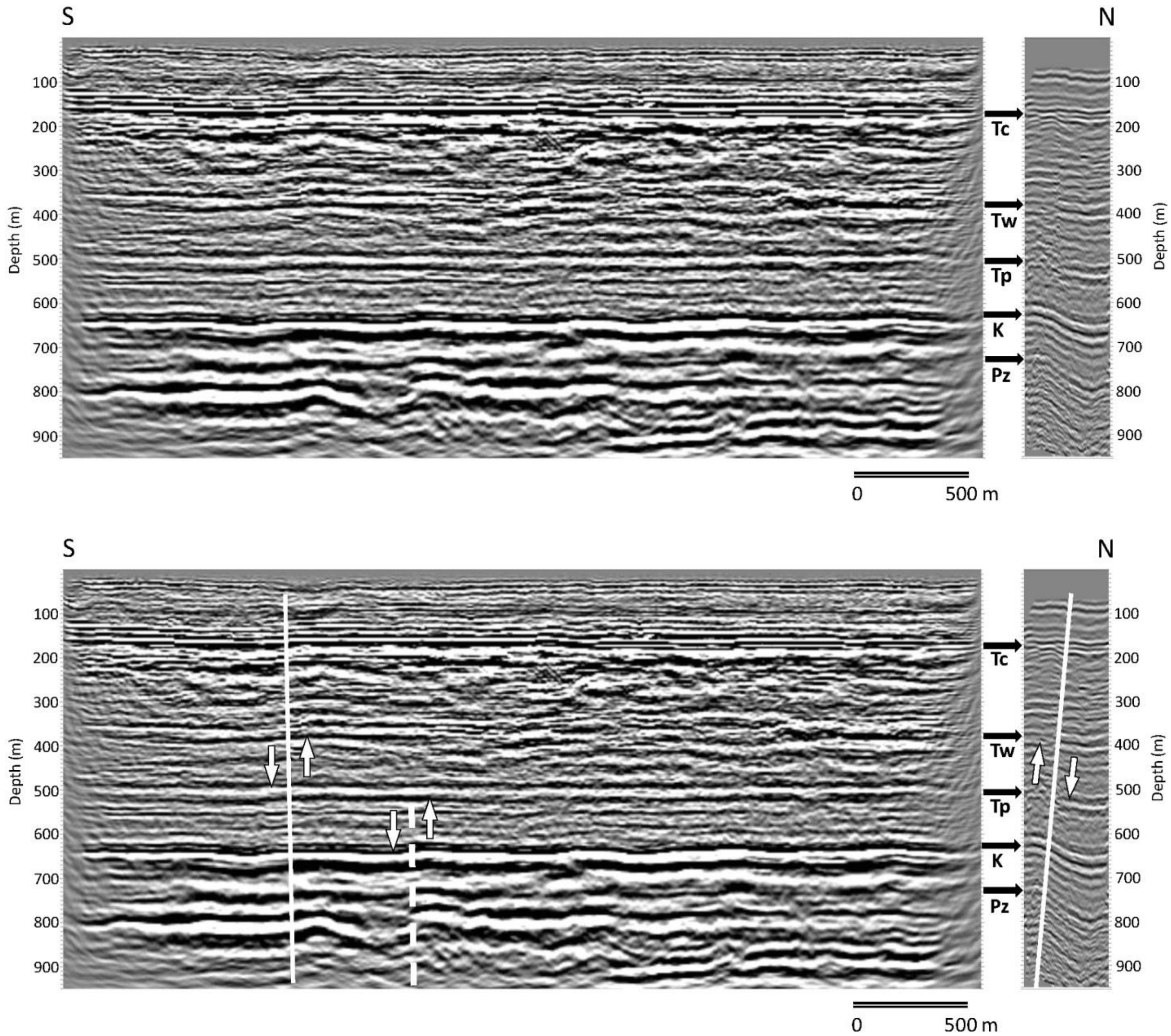

Figure 8. Uninterpreted and interpreted (Left) P-wave seismic reflection line acquired in 2008 by the USGS (Rob Williams, personal communication) with the northeast-dipping reverse fault interpreted to be the back thrust forming the southwestern margin of the Tiptonville dome (line located in Figure 5). (Right) P-wave seismic reflection line A illustrating the southwest-dipping Reelfoot fault that forms the northeastern margin of the Tiptonville dome (line located in Figure 5). Distance between the two seismic lines is 0.5 km. Arrows between seismic lines point to stratigraphic tops. Tc-Tertiary Claiborne, Tw-Tertiary Wilcox, Tp-Tertiary Porters Creek, K-Cretaceous, Pz-Paleozoic.

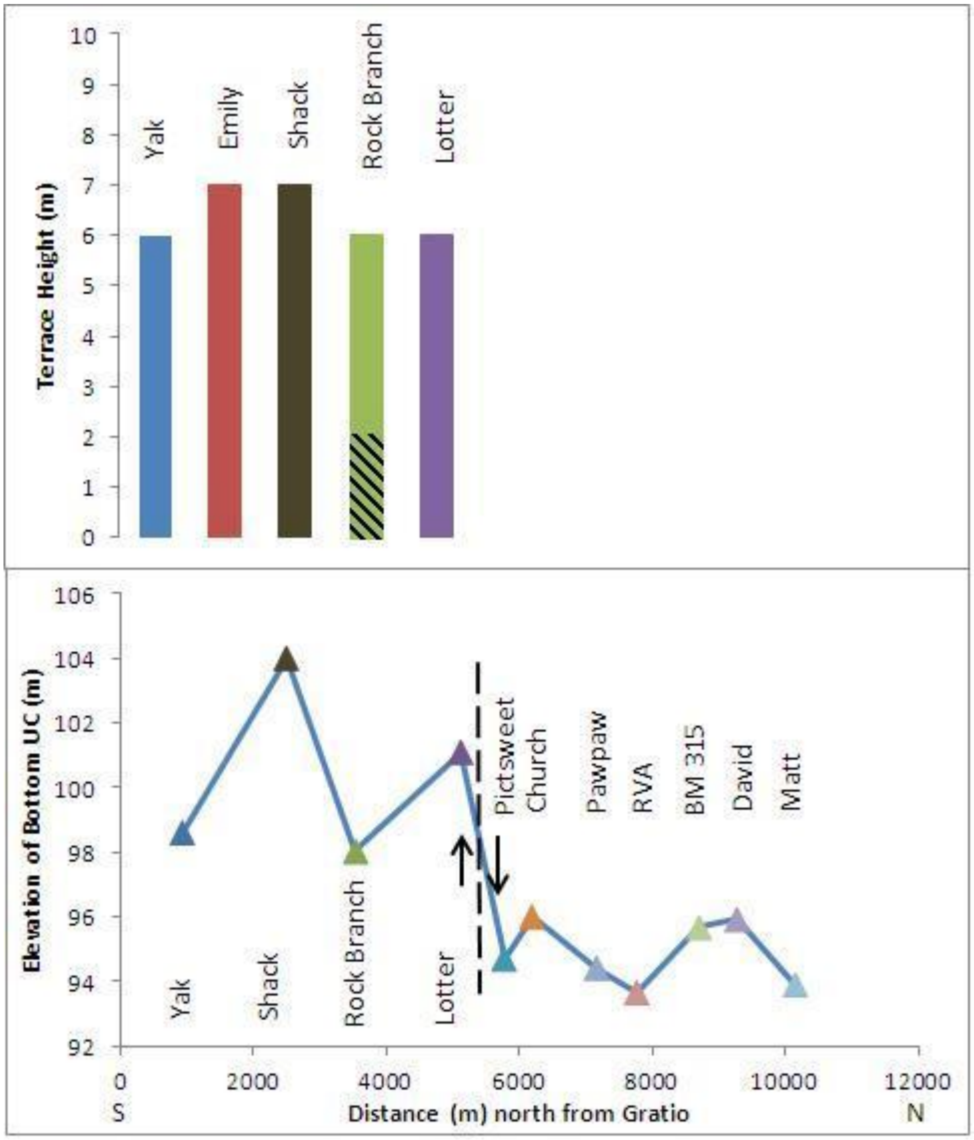

Figure 9. Lower diagram is elevation of the base of the Upland Complex in west-flowing creeks along the north-south line of section illustrated in Figure 5. Upper diagram is the height of stream terrace surfaces above their respective current floodplains. Rock Branch also has a 2 m terrace indicated with cross hatch. There are no terraces in the creeks north of Lotter creek or south of Yak creek.

Geologic and Geomorphic Mapping

Geologic mapping identified discontinuous exposures of the top and bottom of the UC within the Mississippi River bluffs along some west-flowing creeks north of Gratio (Fig. 5). A south-north cross section of the top and bottom of the UC was made from the contact exposures (only base of UC shown in Fig. 9). Due to the erosional irregularity of the top of the UC we herein consider the basal contact as an originally more planar datum for fault displacement determination and do not discuss the UC upper contact. A regression line fit to all the elevations of the base of the UC reveals a northerly slope, which is unreasonable because it is opposite to the regional slope of the ancestral Mississippi/Ohio river system. However, our cross section reveals that between Pictsweet Creek and Lotter Creek the base of the UC raises 6 m up-to-the-south and remains high south to Yak Creek. The UC was not found in creek exposures south of Yak creek.

Some of the small creeks within the map area have strath terraces (Figs. 5 and 9). The terraces occur along streams in the central portion of the map from Pictsweet creek south to Yak creek with two terraces east of the bluff line (Fig. 5). At one exposure along Yak creek the terrace alluvium was 4 m thick. Terrace surface heights above their respective modern floodplains along the bluff margin are from 6 to 7 m (Figs. 5 and 9). The largest stream, Rock Branch creek, has two terraces (Figs. 5 and 9). The major terrace is 6 m above the floodplain and its lower terrace is 2 m above the floodplain.

Included in Figure 5 is the distribution of old gravel pits in the UC. The gravel pit locations are coincident with the southeastern projection of the Tiptonville dome.

Alternative Terrace Formation Hypothesis - Discredited

An alternative explanation for the stream terrace formation is that a northeast-striking fault with up-to- the-west displacement passes through our study area, which caused local uplift and stream incision. To test this possible geology a seismic sounding was acquired east of the bluff margin at sounding #4 (Fig. 5). The elevation of the top of the Wilcox in sounding #4 is 28 m higher than at soundings 1, 2, 3, and 5. However, sounding #4 appears to have imaged a fault with down-to-the-west displacement (Fig. 10). We believe that if indeed there is a northeast-striking down-to-the-west fault within the bluffs as sounding #4 appears to reveal, that displacement sense could not produce uplift necessary for the formation of the stream terraces.

Conclusions

The seismic reflection profile conducted across Reelfoot North fault along the southern margin of Reelfoot Lake by Van Arsdale et al. (1998) (Fig. 2) revealed 70 m of displacement on the top of the Paleozoic, 60 m on the Cretaceous, 40 m on the Paleocene Midway Group, 30 m on the Eocene Wilcox Group, and 15 m on the Eocene/Quaternary unconformity that has been interpreted to reflect fault reactivation through time (Van Arsdale, 2000). In addition, shallow coring across the Reelfoot scarp near the southern margin of Reelfoot Lake identified 3 m of structural displacement of the Quaternary alluvium at a depth of 3 m (Van Arsdale et al., 1995). Near Lane, Tennessee (Fig. 2) the Reelfoot fault displaces the top of the Paleozoic 40 m (Van Arsdale et al., 1999).

Seismic soundings and north-south seismic reflection surveys conducted east of the Axial fault in this current study reveal the southwest-dipping (81°) Reelfoot South fault and a

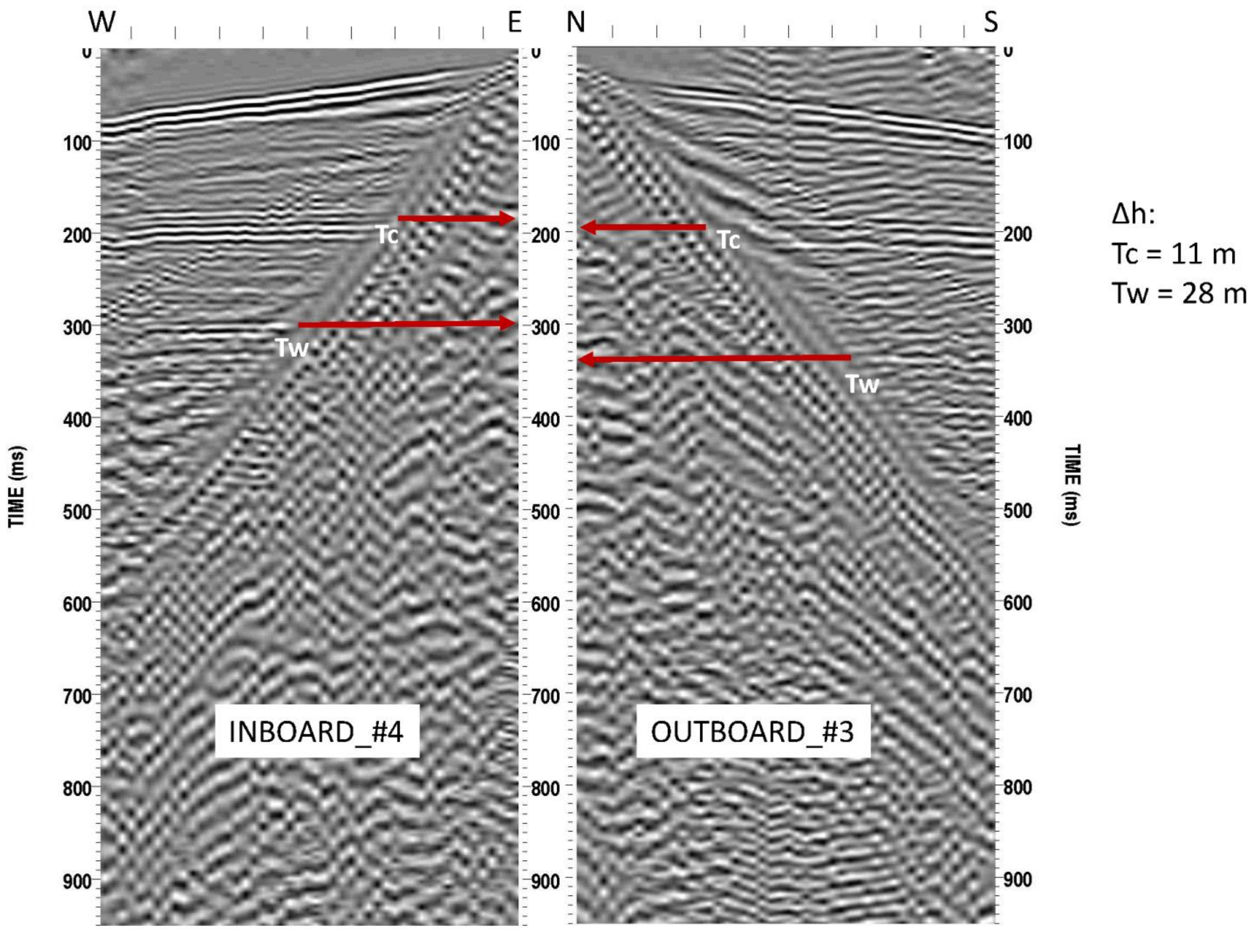

Figure 10. Seismic soundings #3 and #4 located in Figure 5. Tw = Wilcox Group top. Flexure in westernmost portion of #4 interpreted to be due to down-to-the-west faulting.

northeast-dipping (84°) back thrust in the uppermost 900 m (Fig. 8). Since no deformation is evident in the seismic reflection data between these two faults, the two reverse faults are apparently the bounding faults of the Tiptonville dome (horst). The back thrust displaces the top of the Paleozoic 25 m, Cretaceous 10 m, and the Memphis Sand 6 m. Reelfoot South fault displaces the top of the Paleozoic 65 m, Cretaceous 40 m, Paleocene Porters Creek Clay 31 m, Paleocene Wilcox Group 20 m, and Eocene Memphis Sand 16 m. Thus, the amounts of displacements on the principal reflectors, although similar in relative magnitudes, are less across the Reelfoot South fault than the Reelfoot North fault.

Geologic mapping reveals that the ~3.1 Ma Pliocene UC has been displaced ~6 m by the Reelfoot South reverse fault within the Mississippi River bluffs. Geomorphic mapping of small tributaries of the Mississippi River within the bluffs reveals that some of the creeks have terraces that are 6 m above their current floodplains. Rock Branch creek also has a lower terrace that is 2 m above its floodplain. These terraced streams are located where the Tiptonville dome (horst) passes southeast into the bluffs. We believe that the terraces along these streams formed as a consequence of uplift of the Tiptonville dome within the bluffs. Distribution of gravel pits in the UC further supports this interpretation. The gravel pits are restricted to the location of the Tiptonville dome probably because the post-UC dome uplift brought the UC gravel higher in the landscape thus making it more accessible for quarrying. The 6 m of Reelfoot South faulting and Tiptonville dome uplift is clearly post UC (~ 3.1 Ma) and was probably responsible for, and coincident with, creek incision and consequent terrace formation. Two terrace levels along Rock Branch creek suggest that there may be two Reelfoot South faulting events with an early displacement of 4 m and a more recent displacement of 2 m. The terrace alluvium has not been dated. However, we believe the faulting is Quaternary, and it is possible that the two terrace levels in Rock Branch correspond with the A.D. 1450 and 1812 faulting events previously documented on the Reelfoot North fault (Kelson et al., 1996; Tuttle et al., 2002).

Figure 11 illustrates possible geometries and evolution for the Reelfoot fault. The similar displacement magnitudes and histories revealed in the seismic line along the southern margin of Reelfoot Lake (Van Arsdale et al., 1998) and our seismic line B indicate one continuous Reelfoot fault through time as opposed to two discrete faults (North and South) with independent histories. Thus, Figure 11B fault evolution model is not appropriate. Diminished displacement on the top of the Paleozoic across the Reelfoot fault from the Reelfoot Lake seismic line (70 m) through our line (B) (65 m) to the Lane seismic line (40 m) supports the Figure 11A and 11C models. However, we believe that model 11C best depicts the fault's history since it appears that Reelfoot fault microseismicity, and thus the Reelfoot fault, is truncated by the Eastern and Western Reelfoot Rift margin faults (Fig. 1).

A second argument for one continuous fault is that the Reelfoot South fault and its back thrust within the Mississippi River bluffs are on strike with the Reelfoot North fault and its back thrust as mapped west of Reelfoot Lake (Fig. 2). Thus, there does not appear to be right-lateral displacement of the Reelfoot fault across the Axial fault. This current research supports the interpretation that the Reelfoot fault is one continuous fault across the Axial fault and may continue to the southeast for a total length of 84 km. Cramer and Boyd (2014) argue that the February 7, 1812 New Madrid earthquake on the Reelfoot fault was **M** 7.7, which we think is more compatible with a ruptured fault length of 84 km.

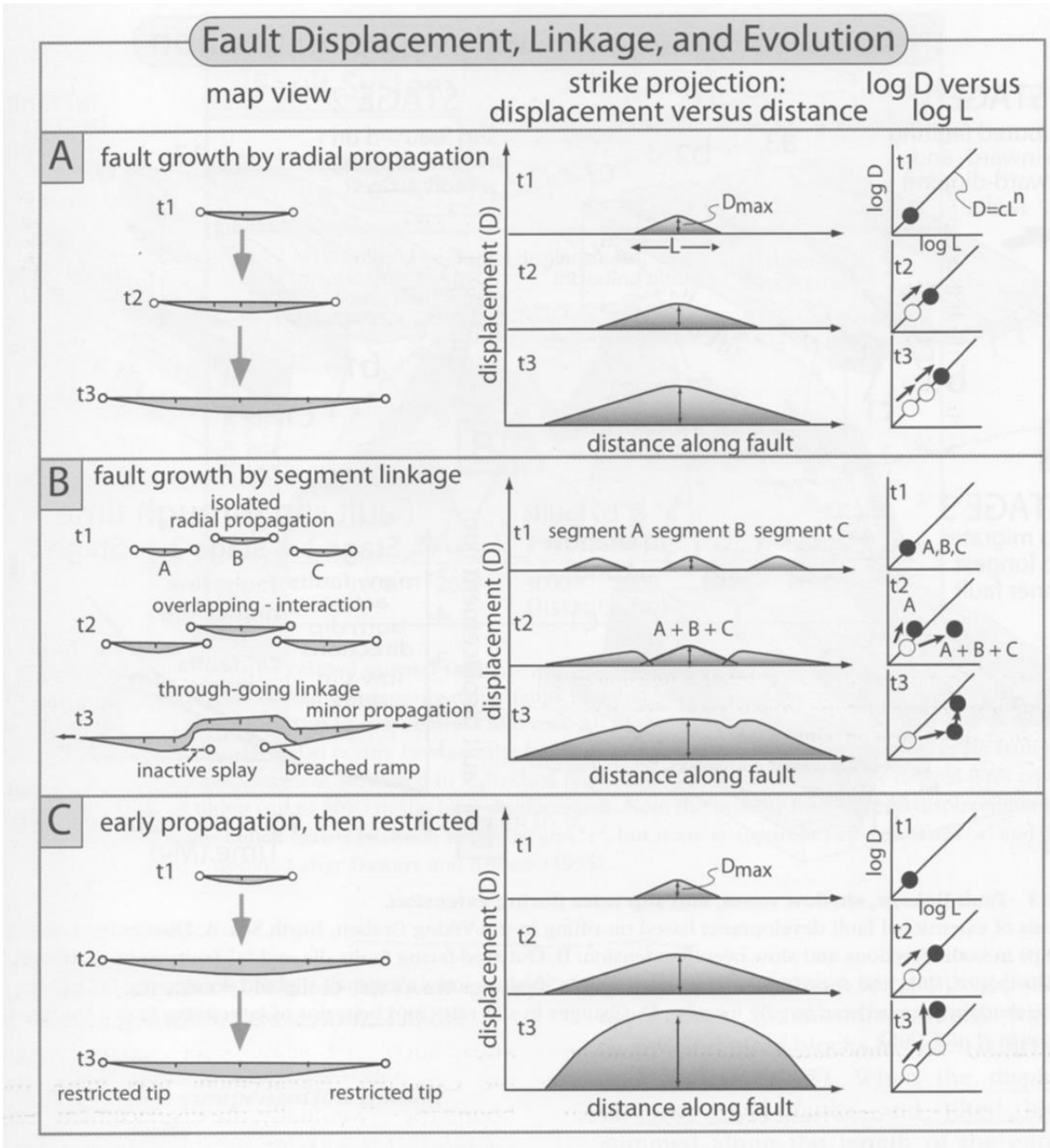

Figure 11. Three models for fault displacement, linkage, and evolution (from Burbank and Anderson, 2012).

Acknowledgements

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