Investigation of faulting beneath the city of Memphis and Shelby County, Tennessee

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## Abstract

A geologic investigation of the city of Memphis and southern Shelby County, Tennessee, reveals Quaternary faulting. Structure contour maps of the top of the Pliocene-Pleistocene Lafayette Formation (Upland Gravel), Eocene Upper Claiborne Group, and Eocene Lower Claiborne Group reveal two 20 m down-to-the-northwest faults. The western one is herein called the Memphis fault and the eastern, the Ellendale fault. Isopach maps reveal thinning of the Lafayette Formation and Upper Claiborne Group on the east (upthrown) side of the Ellendale fault also suggesting Quaternary faulting. Geomorphic analysis reveals an increase in surface elevation and river course changes across, and barbed tributaries along, the Ellendale fault trace. A comparison of modern drainage and Lafayette Formation paleodrainage suggests that the Wolf River and Nonconnah Creek have changed their courses since Lafayette time.

The Ellendale fault is projected to pass beneath the Wolf River flood plain in east Memphis. At this location, a cut bank exposes flood plain sands that are folded into an anticline with a wavelength of approximately 100 m, minimum amplitude of 4 m, and a hinge oriented $10^0$N$7^0$W. The folded sands are truncated by overlying, flat-lying, clayey silt overbank sediments. A 1 m wide liquefaction sand dike was found above the crest of the anticline, in the overbank sediments. $^{14}$C dates reveal that the folding occurred between 390 AD and 450 AD and the liquefaction occurred post 450 AD. Seismic reflection lines indicate that the fold extends to over 60 m depth into the Lower Claiborne Group, has a length of over 1 km, and is thus tectonic in origin. The reflection lines also reveal a N$25^0$E trending down-to-the-west fault with from 5 m to 10 m displacement in the Upper Claiborne Group that we believe is within the Ellendale fault zone. The anticline could have formed during approximately 5 m of right lateral strike slip on the Ellendale fault. If indeed the fold formed as a consequence of a single 5 m Ellendale faulting event, then an earthquake with an estimated moment magnitude 7.6 occurred beneath Memphis near 400 AD. Based on these observations, we believe that the Ellendale fault and perhaps the Memphis fault pose serious seismic threats to the city of Memphis and Shelby County, Tennessee.

# Introduction

Several research projects currently focused on the city of Memphis and Shelby County, Tennessee, address hazards related to a New Madrid seismic zone (NMSZ) earthquake (Fig. 1). However, the possible presence of Quaternary faults beneath Shelby County has not been addressed. The only detailed map of subsurface Shelby County is a U.S. Geological Survey Water-Resources Investigations map by Kingsbury and Parks (1993) that shows several faults displacing Eocene strata. In this current project, we geologically interpreted over 600 geotechnical borings and water wells of southern Shelby County and made structure contour maps of the tops of the Pliocene-Pleistocene Lafayette Formation (Upland Gravel), top of the Eocene Upper Claiborne Group, and the top of the Eocene Lower Claiborne Group to determine if they have been displaced by faulting. In addition, we present isopach maps of the Lafayette Formation and Upper Claiborne Group, seismic reflection lines, a drainage and paleodrainage analysis, and a logged portion of the Wolf River bank to evaluate tectonic structures in Shelby County.

## Geology of the Northern Mississippi Embayment and Shelby County, Tennessee

The Mississippi embayment (Figure 1 inset) is a broad south-southwest plunging shallow trough filled with poorly consolidated Late Cretaceous and Tertiary shallow marine and fluvial sediments (Bushchbach and Schwalb, 1984; Van Arsdale and Ten Brink, 2000). Beneath the northwestern portion of the Mississippi embayment is the Reelfoot rift (Fig. 1), a southwest-trending graben approximately 65 km wide and 320 km long. This rift is a late Precambrian-Early Paleozoic aulacogen (Ervin and McGinnis, 1975; Braile et al., 1982). The rift geometry has been defined primarily through gravity and magnetic surveys (Hildenbrand et al., 1977). Most NMSZ earthquakes occur within the rift (Fig. 1). However, the southeastern margin of the Reelfoot rift has been tectonically active in Quaternary time along the Crittenden County fault zone, 25 km northwest of Memphis (Crone, 1992; Luzietti et al., 1992; Williams et al., 1995). Additional Quaternary faulting has been identified within the southeastern margin of the Reelfoot rift at Porters Gap and it has been proposed that this rift margin may currently be accumulating strain (Cox et al., 2001).

The stratigraphy of the upper 1 km in the northern Mississippi embayment (Figure 2) consists of Cambrian carbonate rocks unconformably overlain by Upper Cretaceous marine and terrestrial sands, silts, and clays in turn overlain by Tertiary marine and terrestrial sands, silts, and clays (Van Arsdale and TenBrink, 2000). The shallow stratigraphy beneath the city of Memphis and Shelby County, Tennessee, consists of the Eocene Claiborne Group, which is subdivided in ascending order into the Memphis Sand, Cook Mountain Formation (clay, silt, and minor sand and lignite), and Cockfield Formation (sand, silt, and clay). The Eocene/Oligocene Jackson Formation exists beneath extreme northwest Shelby County and is included in the Upper Claiborne in this study. In the Mississippi River valley, the Upper Claiborne is overlain by Mississippi River alluvium, but beneath Memphis and Shelby County it is overlain by the Pliocene-Pleistocene Lafayette Formation (Upland Gravel) (Autin et al., 1991). This is a fluvial sand and gravel deposit of the ancestral Ohio River that has an erosional upper and lower contact. The Lafayette Formation is overlain by up to three Pleistocene loess deposits and locally by Late Pleistocene and Holocene alluvium of the Wolf River and Nonconnah Creek in southern Shelby County.

New Madrid Seismic Zone and Shelby County

The principal seismic activity within the upper Mississippi embayment is located in the Reelfoot rift along the NMSZ (Fig. 1). NMSZ seismicity occurs primarily along three trends that define a northeast-trending right-lateral strike-slip fault system with a compressional left-stepover zone (Russ, 1982; Schweig and Ellis, 1994). Geological and geophysical evidence for neotectonic activity in this area has been accumulating rapidly over the past two decades. The geological features indicative of earthquakes include liquefaction of subsurface sands, faulting, and warping of the ground surface (Schweig and Van Arsdale, 1996).

Shelby County, Tennessee, and the city of Memphis are located near the southeastern margin of the Reelfoot rift and the NMSZ (Fig. 1) and regional studies have proposed faults beneath Shelby County. Johnson et al. (1994) produced a basement fault map from geophysical data, in which Shelby County is transected by several basement tectonic structures. Kingsbury and Parks (1993) have mapped faults from water well data that displace the Eocene Upper Claiborne Group. One of their mapped faults corresponds with a recently identified northeast-striking down-to-the-west fault called the Ellendale fault. The Ellendale fault appears to displace the Lafayette Formation by up to 20 m (Yates et al., 2001; Velasco et al., 2002).

Numerous sand dikes formed by earthquake liquefaction have been found in cut banks along the Wolf and Loosahatchie rivers in Shelby County (Fig. 3) (Van Arsdale et al., 1998; Broughton et al., 2001). The dikes were probably emplaced during the 1811-1812 New Madrid earthquakes since the dikes show no weathering effects and some extrude onto the Wolf River flood plain surface (Broughton et al., 2001). However, it is also possible that this liquefaction was caused by more local earthquakes, perhaps in Shelby County (Broughton et al., 2001).

## Methods

The purpose of this study was to determine if the Ellendale fault does indeed displace Tertiary and Quaternary sediments as proposed by Yates et al. (2001) and Velasco et al. (2002). This was undertaken by interpreting over 600 geotechnical boring and water well logs and making structure contour maps, geologic cross sections, and isopach maps of subsurface geologic units. In addition, modern and paleostream patterns were analyzed, a portion of the Wolf River bank containing a large sand dike and anticline was logged, and seismic reflection profiles were acquired.

Structure Contour Maps, Geologic Cross Sections, and Isopach Maps

Over 600 geotechnical boring and water well logs were acquired from private geotechnical companies (Hall Blake and Associates, PSI, and Tristate), government organizations (U.S. Geological Survey, Tennessee Department of Transportation, Shelby County Health Department, U.S. Army Corps of Engineers, and the Tennessee

Department of Environment and Conservation), and from Ng et al. (1989). (These well and boring data are available at http://gwidc.gwi.memphis.edu/website/introduction.) Structure contour maps were made of the top of the Lafayette Formation, Upper Claiborne Group, and Lower Claiborne Group using ArcGIS and Arc/Info. The interpolation method used was inverse distance weighted (Velasco, 2002). Geologic cross sections were derived from the structure contour maps and constructed by exporting the ArcGIS format files into EXCEL for plotting. Isopach maps were made of the Lafayette Formation and Upper Claiborne Group to show the thickness and extent of the two units.

Southern Shelby County Drainage and Paleodrainage Analysis

An interpretation of the surface topography and drainage pattern was undertaken of southern Shelby County using the National Elevation Dataset (NED). These data were converted to an ArcGIS format and displayed for analyses in ArcMAP. A paleodrainage map was constructed from the top of the Upper Claiborne Group structure contour map reflecting the river patterns during Lafayette Formation deposition. The paleodrainage networks were created from an algorithm in ArcInfo that links the lowest points on the surfaces.

Wolf River Bank Log

A sand dike and anticline were found in Wolf River flood plain sediments in a cut bank in eastern Shelby County. The sand dike emanated from the crest of the anticline. The sand dike and anticline were logged and the flood plain sediments were $^{14}C$ dated.

Shallow Seismic Reflection Surveys

Three shallow S-wave seismic reflection lines were acquired. Two of the lines were recorded on a 24-channel Geometrics Strataview seismograph and one was recorded on a 12 channel engineering seismograph (Table 1). In both cases a 10 kg sledgehammer energy source and single component 4.5 Hz S-wave geophones were used. Three shallow P-wave seismic reflection lines were also acquired. These data were recorded on a 24-channel Geometrics Strataview seismograph using a 40 kg propelled energy source.

Seismic reflection field data were processed using WinSeis Turbo for Windows (Kansas Geological Survey, 1994). The processing scheme for both S-wave and P-wave data included the following steps: preprocessing and trace editing, common midpoint sorting and gather, band-pass filtering, scaling, automatic gain control, velocity analysis, normal moveout corrections, final stacking, post-stack processing, and gain applications.

Two way travel times are recorded on the seismic lines and reflector depths are presented in the discussion of the seismic lines presented below. These depths were calculated from normal moveout velocities and supported by depths below the surface calculated from our structure contour maps.

## Results

Structure Contour Maps, Geologic Cross Sections, and Isopach Maps

Structure contour maps were constructed of the top of the Lafayette Formation, Upper Claiborne Group, and the Lower Claiborne Group for southern Shelby County (Figs. 4-7). All three of these geologic surfaces slope from southeast to northwest. Additionally, these three surfaces have two 20 m down-to-the-west steps that strike approximately $N30^0E$ (Ellendale and Memphis faults). These steps are particularly well illustrated in the geologic cross sections (Figs. 8-10). The steps are prominent in the cross sections because of the high vertical exaggeration; however, this vertical exaggeration illustrates that the three contacts, separated in time by approximately 40 million years, are nearly parallel. Cross sections 1, 2 and to a lesser extent 3, illustrate that the loess is removed or thinned on the east (upthrown) side of the Ellendale fault. Isopach maps of the Lafayette Formation and Upper Claiborne Group (Figs. 11-12) also illustrate that both units are preferentially thinned east of the Ellendale fault.

Southern Shelby County Topographic, Drainage, and Paleodrainage Maps

The topography of southern Shelby County reveals a rather sudden increase in elevation across the Ellendale fault (Fig. 8). The modern Wolf River and Nonconnah creek flow from southeast to northwest across the county (Fig. 13). Upon closer inspection, it is apparent that the Wolf River and to a lesser degree Nonconnah Creek have three differently oriented reaches. Both streams flow westerly, turn and flow northwesterly, and then turn again to resume a western course to the Mississippi River. The northwest-oriented reach flows across and is at right angles to the Ellendale fault (Figs. 8 and 13). Mapping of lower order tributaries throughout southern Shelby County also reveals that these two streams have northeast-trending barbed tributaries on their southern sides. The barded tributaries occur along the Wolf River and Nonconnah Creek in their northwest-trending reaches (Velasco, 2002).

Paleodrainage interpreted on the top of the Upper Claiborne Group reflects the drainage pattern during Pliocene-Pleistocene Lafayette Formation deposition (Fig. 14). We believe the Lafayette Formation was deposited by a south flowing ancestral Ohio River and its tributaries. Thus, we would interpret the two major west-flowing paleodrainages in Figure 14 to be the ancestral Nonconnah Creek and ancestral Wolf River. During Lafayette time these streams apparently flowed northwest and merged near the location of the western step (Memphis fault) (Figs. 8 and 14).

Anticline and Liquefaction Sand Dike Exposed in the Northern Bank of the Wolf River

Field investigations conducted along the Wolf River identified flood plain sediments consisting of point bar sands overlain by an overbank clayey silt (Broughton et al., 2001). Canoeing of the Wolf River, across all of Shelby County, revealed two anticlines exposed in the northern bank of the Wolf River. The eastern anticline is located in the boxed area of Figure 3, more precisely located in Figure 15B, and is illustrated in Figure 15A. The basal point bar sand is folded into an anticline that has a wavelength of approximately 100 m, a minimum amplitude of 4 m (Fig. 15A), with a hinge oriented $10^0$N$7^0$W (Fig. 15B). An overlying horizontal clayey silt overbank unit truncates the anticline (Fig. 16B). A 1 m wide sand dike (now eroded away) was found in the crest of the anticline. The dike sourced from the point bar sand and intruded into the flat lying clayey silt to within 89 cm of the ground surface (Fig. 17). Radiometric dates obtained from the flood plain sediments reveal that the youngest folded point bar sand is 1610±60 BP and the flat lying clayey silt is 1550±40 BP (Fig. 16A).

Seismic Reflection Profiles

A total of six seismic reflection profiles were acquired to determine if the anticline exposed in the Wolf River bank extends to depth and to determine if there are any faults beneath or adjacent to the anticline that may be within the Ellendale fault zone (Fig. 15B). The site is very noisy, since it is adjacent to a highway, and the loose flood plain sediments reduced our ability to get energy into the ground. Only the four highest quality lines are presented here.

Wolf1 is a 450 m long S-wave line that was acquired on the south side of the Wolf River within 100 m of the river bank anticline (Fig. 18). The upper highlighted reflector is at 120 msec TWTT (~ 15 m depth) and is interpreted to be the top of the Upper Claiborne Group. The lower highlighted reflector is at 300 msec TWTT (~ 40 m depth) and is within the Upper Claiborne Group. An anticline is visible at CMP 175 that increases in amplitude and wavelength with depth. At CMP 210 the deeper reflector appears to be truncated by a fault.

The Midfield P-wave line is 600 m long and we have highlighted a reflector at 70 msec TWTT (~35 m) and a deeper one from 90 to 110 msec TWTT (~45 to ~55 m) (Fig. 19). The 35 m deep reflector is within the Upper Claiborne Group and the 45-55 m deep reflector is probably the top of the Lower Claiborne Group. The western portion of the line is of poor quality; however, there is a suggestion of an anticline west of CMP 145. There also appears to be a down-to-the-west fault at CMP 75 with about 10 m of displacement on the top of the Lower Claiborne Group.

Shelby 01 is a 720 m long S-wave line (Fig. 20). In this northern line, we highlight reflectors at 120 msec and 240 msec TWTT (~15 m and ~30 m). The 15 m deep reflector is interpreted to be the top of the Upper Claiborne Group and the 30 m deep reflector is within the Upper Claiborne Group. A prominent anticline with a wavelength of 100 m and minimum amplitude of 5 m is evident from CMP 350 to the western end of the line. At CMP 145 the 30 m deep reflector is displaced about 5 m down-to-the-west and the overlying reflector at 15 m depth is anticlinally folded.

Agricenter is a shallow P-wave reflection profile that was shot along the same route as Shelby01 to achieve a greater depth of penetration (Figs. 15B and 21). An anticline is evident on the western end of the line that can be identified to a minimum depth of 60 m, within the Lower Claiborne Group. The fault identified on Shelby01 is not apparent on this line probably because of the lower resolution of the P-wave line.

## Discussion and Conclusions

A geologic investigation of southern Shelby County, Tennessee, was undertaken to determine if the area had experienced Quaternary faulting. Structure contour maps of the top of the Lafayette Formation, Upper Claiborne Group, and Lower Claiborne Group reveal two down-to-the-west 20 m steps that we herein call the Ellendale (eastern) and Memphis (western) faults (Fig. 8). Although it is possible that these steps are ancestral Ohio River terraces we believe this is highly unlikely because the deepest steps are on the top of the Lower Claiborne and if erosional would be Eocene in age. The Claiborne Group is a deltaic sequence that should not have terraces. It also appears that the faults have been active since the Eocene. The displacement on the top of the Lower Claiborne is generally greater than on the overlying Lafayette and the isopach maps of the Upper Claiborne and Lafayette show thinning on the upthrown eastern side of the Ellendale fault. The structure contour maps thus suggest post Lafayette Formation Quaternary fault reactivation in southern Shelby County. Even more significantly, Pleistocene loess is absent east of the Ellendale fault suggesting late Pleistocene or Holocene displacement.

Topographic, drainage, and paleodrainage analyses of southern Shelby County suggest Quaternary activity on the Ellendale and Memphis faults. Surface elevation rises eastward across the Ellendale fault zone. Additionally, the Wolf River and Nonconnah Creek change to a northwest flow direction that is perpendicular to the underlying Ellendale fault. In these northwest-trending reaches, northeast-trending barbed tributaries to these streams suggest that fault(s) or fault parallel joints may locally control the tributary courses. Comparison of the modern surface drainage pattern and the paleodrainage pattern on the top of the Upper Claiborne Group suggests that the drainage pattern has changed since Pliocene-Pleistocene Lafayette Formation deposition. The paleodrainage pattern reveals that the Wolf River and Nonconnah Creek merged in the proximity of the Memphis fault during Lafayette time and that the streams now follow two distinct, but parallel courses. We speculate that Quaternary displacement on the Memphis and Ellendale faults may be responsible for the topographic rise, barbed tributaries, and paleodrainage alteration.

A Wolf River flood plain bank exposure, near the surface projection of the Ellendale fault, revealed a $N7^{0}W$ trending anticline with a wavelength of about 100 m and an amplitude greater than 4 m. Prior to recent erosion, a 1 m wide liquefaction sand dike emanated from the crest of the fold. $^{14}C$ dates of the flood plain sediments reveal that the folding occurred between 390 AD and 450 AD and that the liquefaction dike was injected after 450 AD (Fig. 16).

East-west oriented shallow seismic reflection profiles were obtained to image the Ellendale fault and to determine if the fold exposed in the Wolf River bank extended below the flood plain sediments into the Eocene strata. The southern Wolf1 S-wave line shows folding that extends to a minimum depth of 40 m and the northern Shelby01 S-wave line reveals folding to at least 30 m. The P-wave Agricenter line, which was shot at the same location as Shelby01, reveals folding to a depth of at least 60 m. This fold extends down through the Holocene Wolf River flood plain alluvium, Pliocene-Pleistocene Lafayette Formation, Eocene Upper Claiborne Group, and into the Eocene Lower Claiborne Group. The fold trends $N7^{0}W$ and is essentially perpendicular to the Wolf River flood plain. Considering the fold's wavelength, amplitude, length (>1 km), depth of folding, and trend, the fold could not be a Holocene sand bar, liquefaction deposit, or landslide feature. The best interpretation is that the fold is tectonic in origin.

Faulting is revealed in seismic lines Wolf1, Midfield, and Shelby01. Connecting these displacements suggests a down-to-the-west fault that strikes N25$^0$E (Fig. 15B). The 10 m maximum displacement observed in the Midfield reflection line is less than the 20 m of down-to-the-west displacement across the Ellendale fault observed in the structure contour maps. Thus, we believe that our seismic lines are on the eastern flank of the Ellendale fault zone. The anticline exposed in the Wolf River bank and projected for over one kilometer has a hinge oriented 32$^0$ counter clockwise from the fault trace (Figs. 15B and C). This angular relationship suggests that the anticline was formed due to right lateral strike slip motion (Harding, 1974; Lowell, 1985) on the underlying Ellendale fault. To produce an anticline with a wavelength of 100 m and amplitude of 4 m requires approximately 3 m of shortening. If the folding is due to strike slip movement on the Ellendale fault, then the Ellendale fault has undergone 20 m of Quaternary dip slip displacement and at approximately 400 AD, 5 m of right lateral offset (Fig. 15C). If the 5 m of offset occurred in one earthquake then the estimated moment magnitude of the event would be M 7.6 (Wells and Coppersmith, 1994).

We have not identified any fault scarps or other tectonic landform in Shelby County, but the area is urbanized and so there has been extensive cut and fill. Even though Shelby County is aseismic (Fig. 1), we believe that the geologic data support the conclusion that the Ellendale and Memphis faults represent a significant seismic hazard to the city of Memphis and Shelby County.

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Table 1. Data Acquisition Parameters for Seismic Reflection Surveys.

| **Parameter** | **Description** |
|---|---|
| Sources | 10 kg sledgehammer (S-wave survey)<br>40 kg propelled energy source (P-wave survey) |
| Source intervals | 2.5 m (S-wave survey)<br>5 m (P-wave survey) |
| Receivers | 4.5 Hz S-wave geophones<br>30 Hz P-wave geophones |
| Receiver intervals | 3 m (S-wave survey)<br>5 m (P-wave survey) |
| Spread configurations | Off-end, 3 m offset (S-wave survey)<br>Off-end, 5 m offset (P-wave survey) |
| Recording systems | Geometrics Strataview (24-channel)<br>Bison 5012 (12-channel) |
| Maximum Fold | 6 (S-wave)<br>12 (P-wave) |
| Field Filters | None |
| Record length | 1024 msec (0.25 msec sampling interval) |

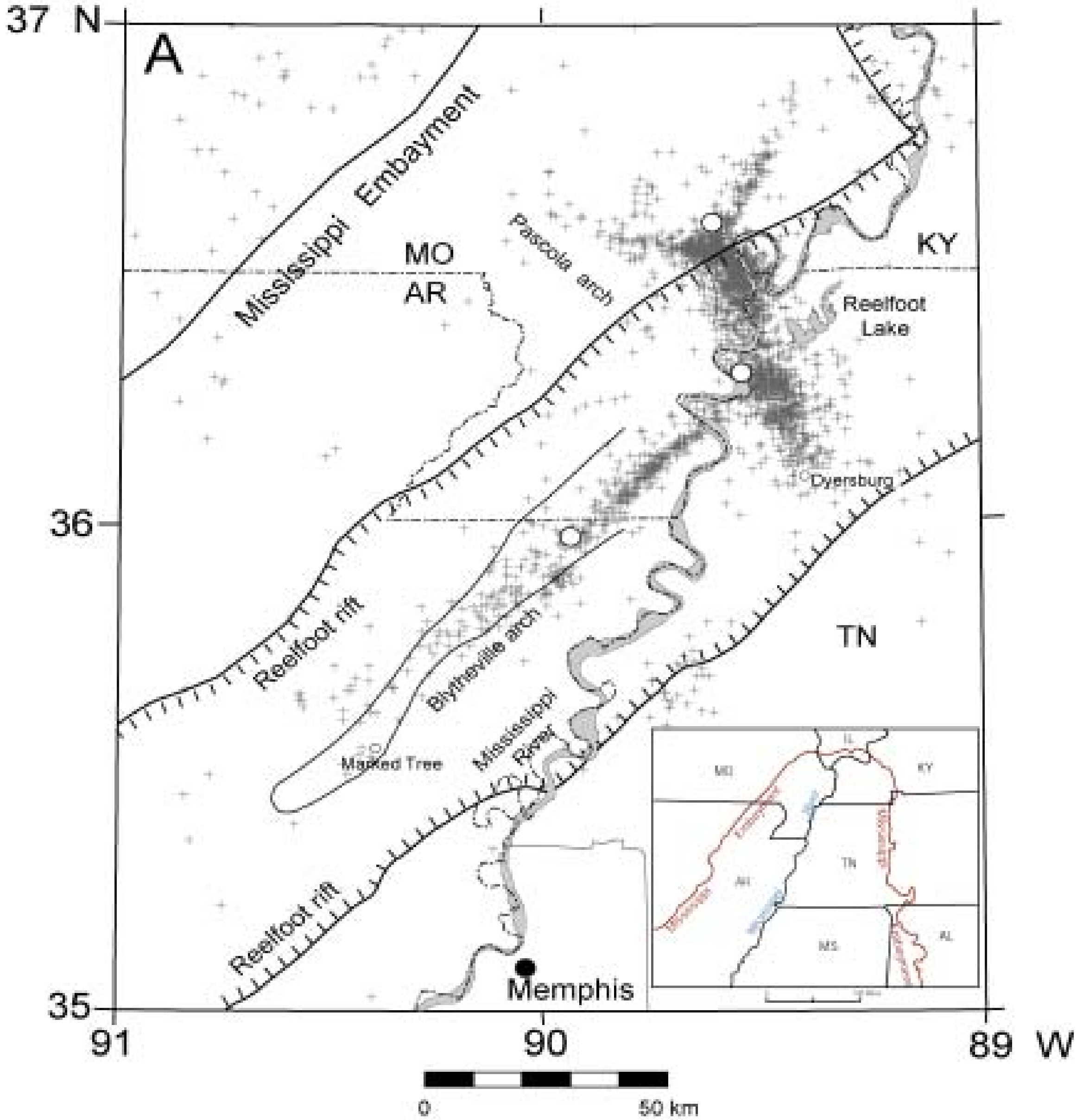



Figure 1. Map of the Reelfoot rift and New Madrid seismic zone within the Mississippi Embayment (inset). The microseismicity is represented by small crosses and the white circles indicate the estimated locations of the three great 1811-1812 New Madrid earthquakes (Johnston and Schweig, 1996).

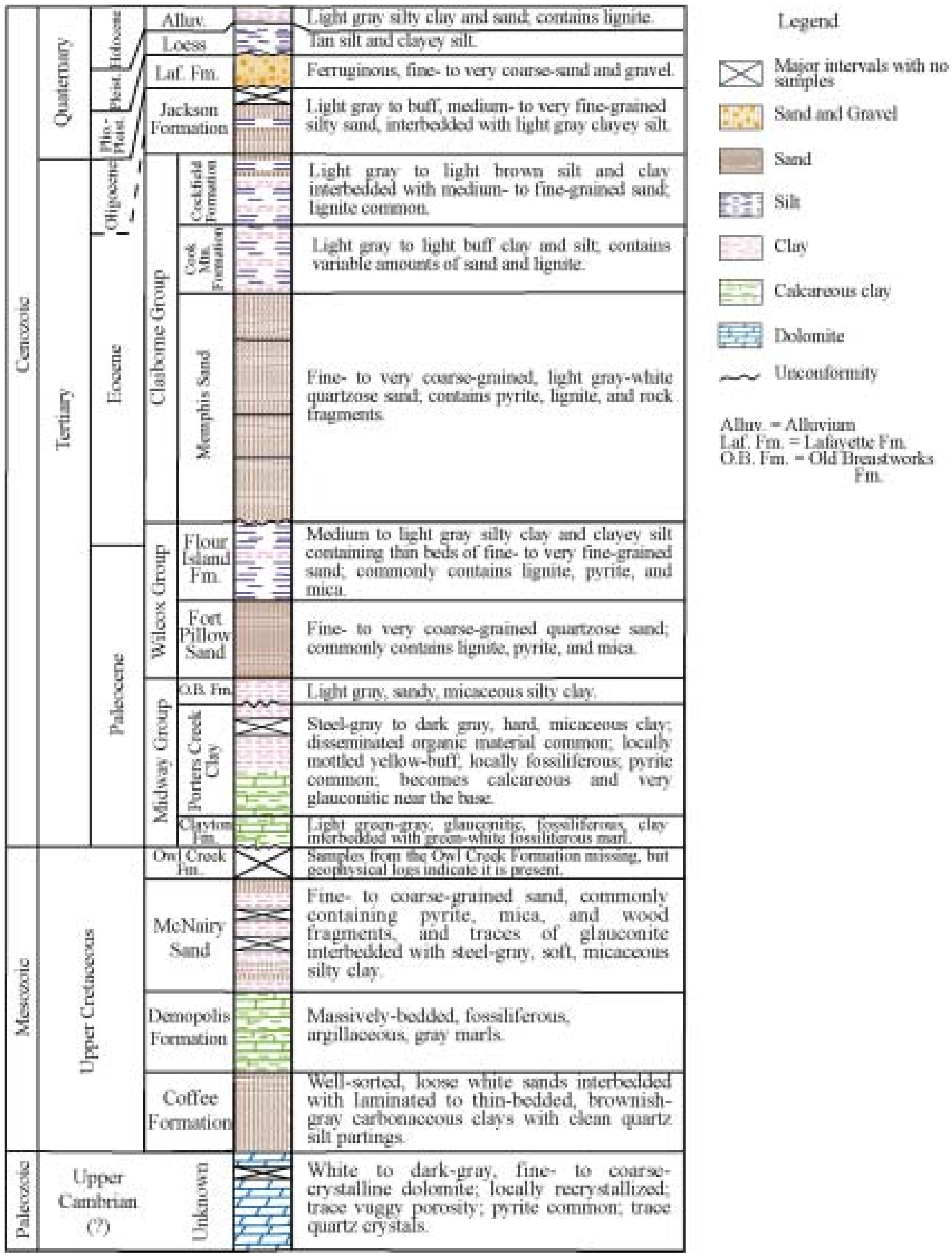



Figure 2. Stratigraphic column of the northern Mississippi embayment (modified from Crone, 1981).

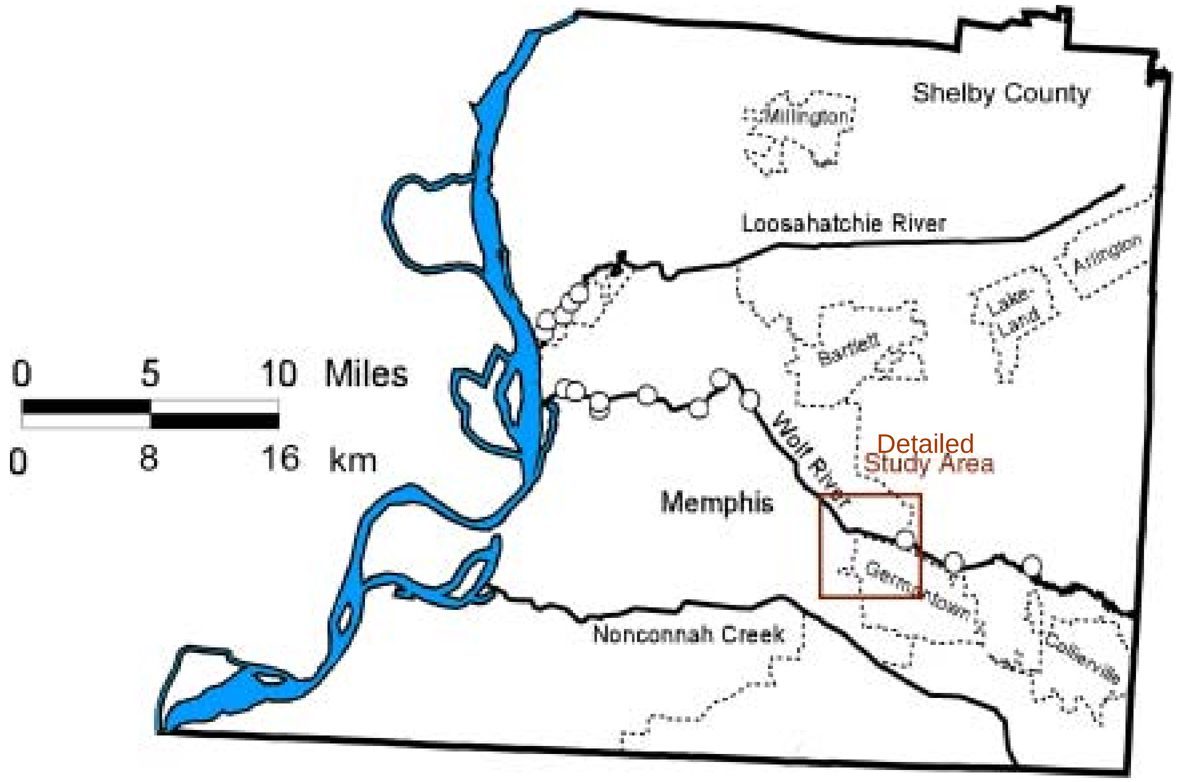



Figure 3. Shelby County liquefaction sand dikes (white circles) that probably formed during the 1811-1812 earthquakes (Broughton et al., 2001). Box outlines area of Figure 15.

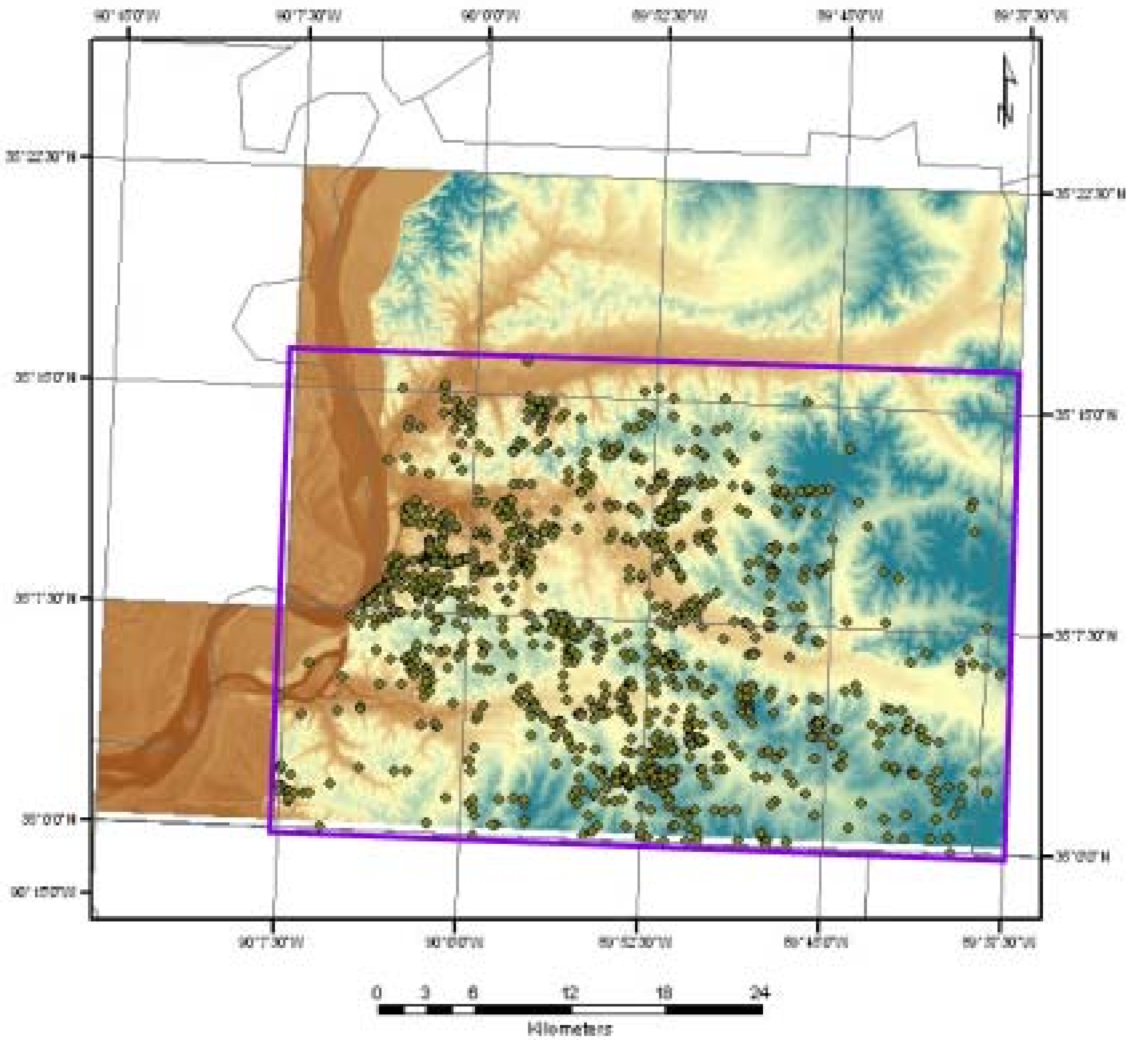



Figure 4. Digital Elevation Model map showing geotechnical boring and water well locations in southern Shelby County. Boundary of following structure contour maps indicated in purple rectangle. Blue is highest elevation.

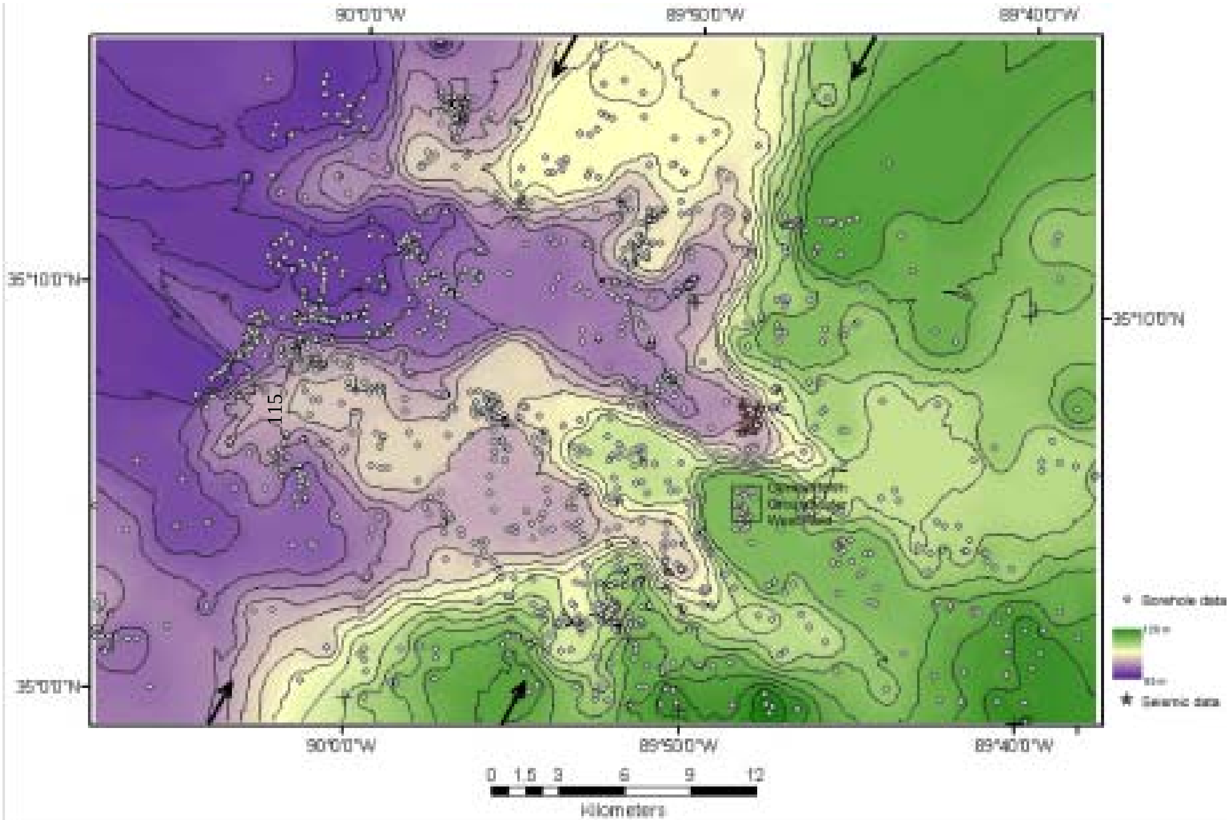



Figure 5. Structure contour map of the top of the Lafayette Formation (Upland Gravel) (CI = 5 m). Circles indicate boring and water well locations. Black arrows show the locations of the steps discussed in text. NE corner poorly constrained.

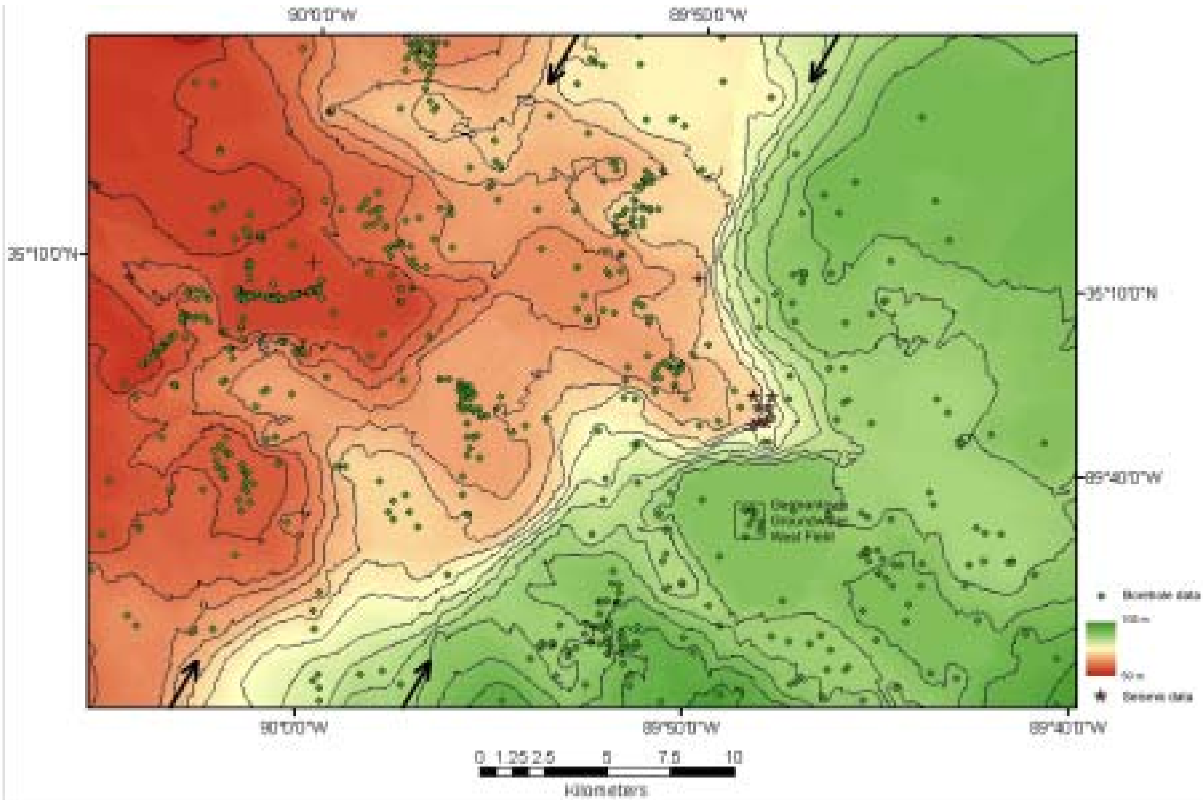



Figure 6. Structure contour map of the top of the Upper Claiborne Group. CI = 3 m. Circles indicate boring and water well locations used to construct this map. Black arrows show the locations of the steps discussed in text. NE corner poorly constrained.

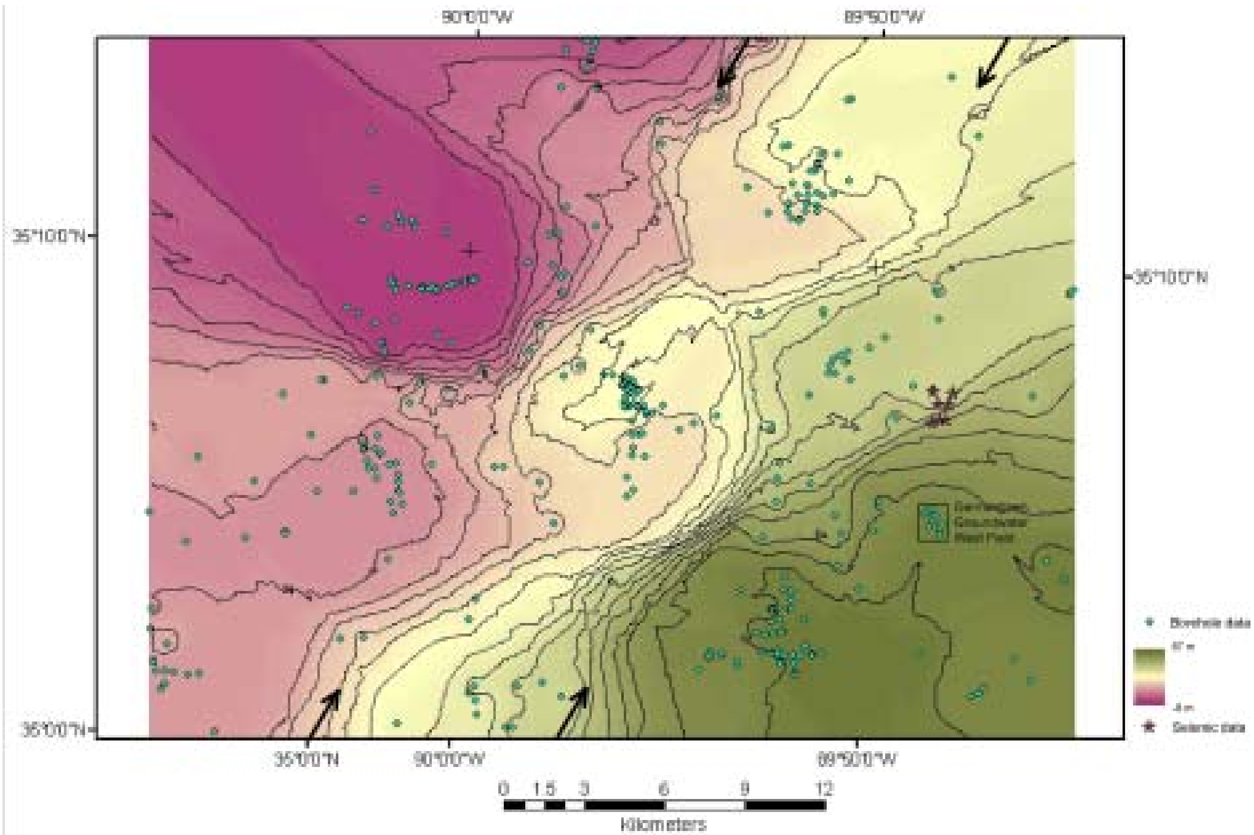



Figure 7. Structure contour map of the top of the Lower Claiborne Group. CI = 3 m. Black arrows show the locations of the steps discussed in the text. NE corner poorly constrained.

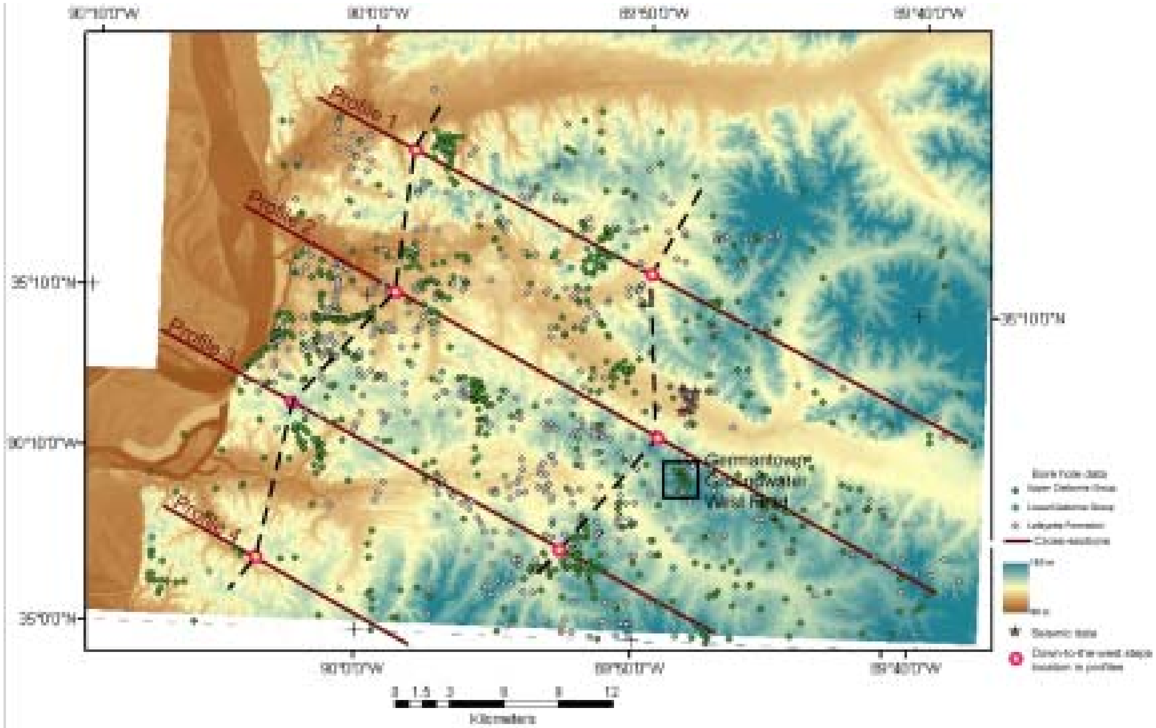
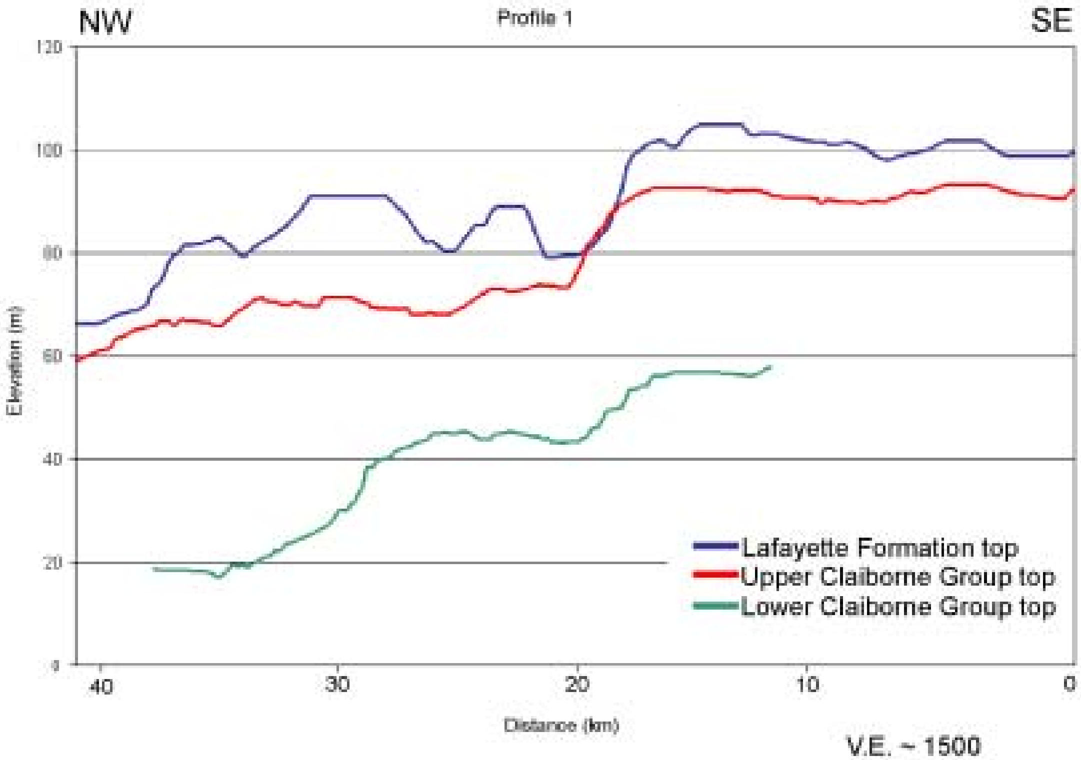



Figure 8. Surface topography and location of the cross-sections shown in Figures 9 and 10. Black dashed lines show the locations of the steps observed in the cross sections. The eastern dashed line is the Ellendale fault and the western dashed line is the Memphis fault.


NW
Profile 1
SE
120
100
80
60
40
20
0
Elevation (m)
Lafayette Formation top
Upper Claiborne Group top
Lower Claiborne Group top
40
30
20
10
0
Distance (km)
V.E. ~ 1500

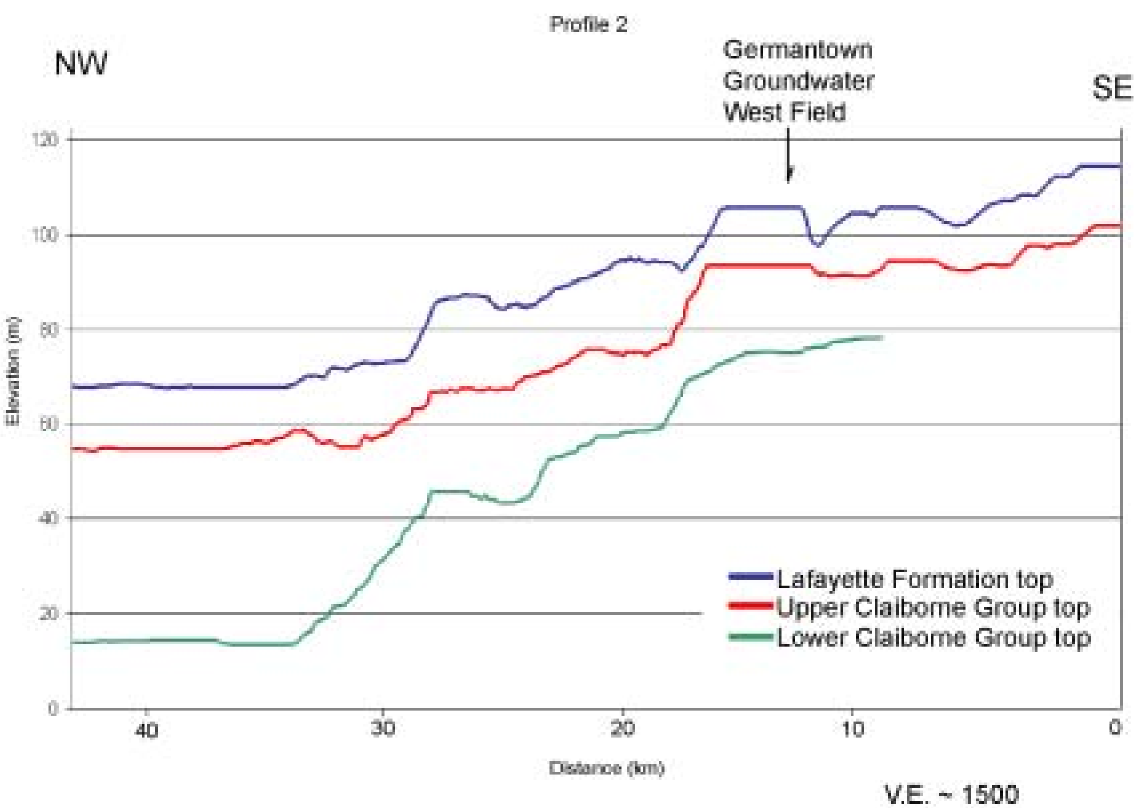

Profile 2
Germantown
Groundwater
West Field
NW
SE
120
100
80
60
40
20
0
Elevation (m)
Lafayette Formation top
Upper Claiborne Group top
Lower Claiborne Group top
40
30
20
10
0
Distance (km)
V.E. ~ 1500

Figure. 9. Cross sections 1 and 2 of Figure 8.

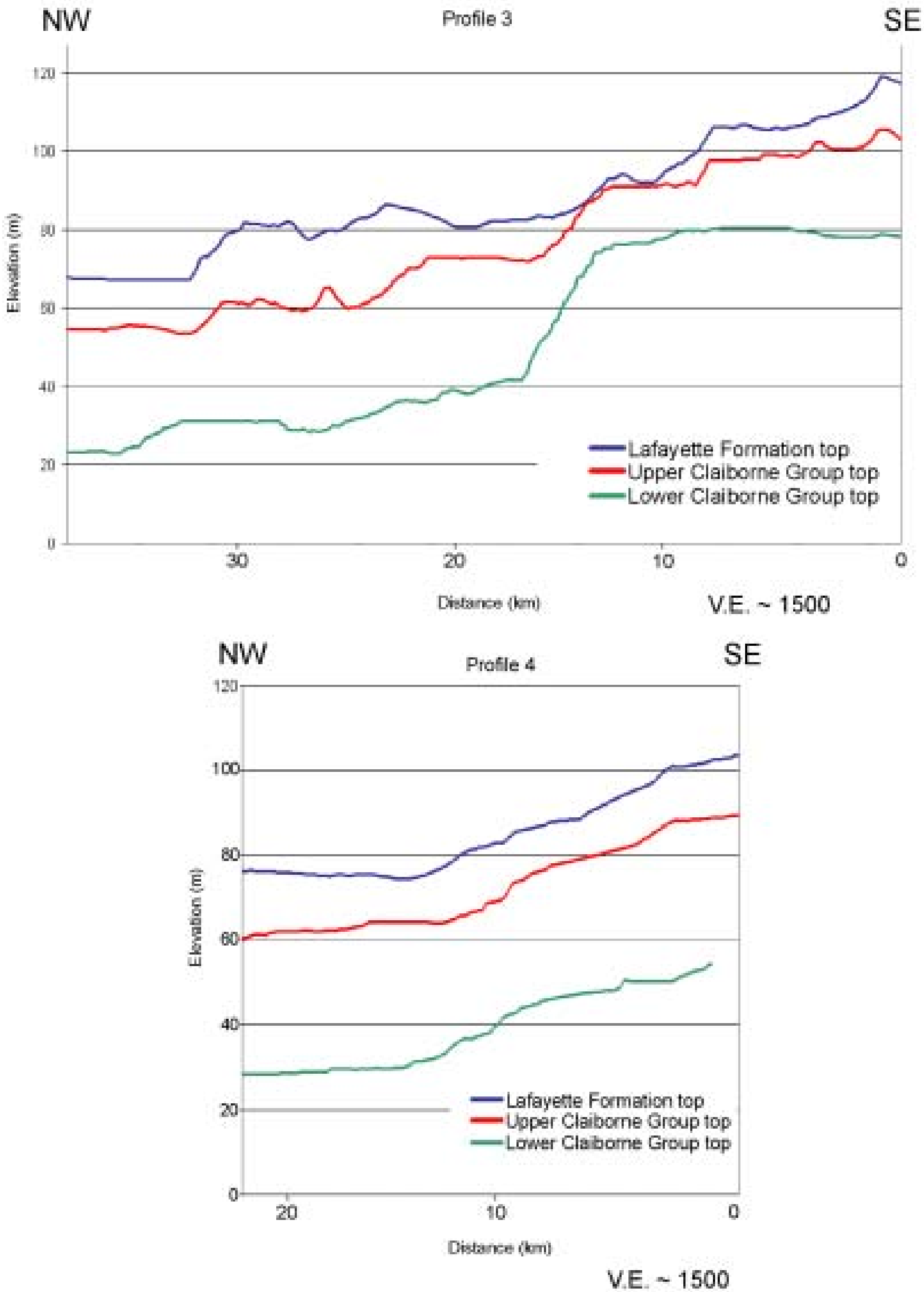



Figure 10. Cross sections 3 and 4 of Figure 8.

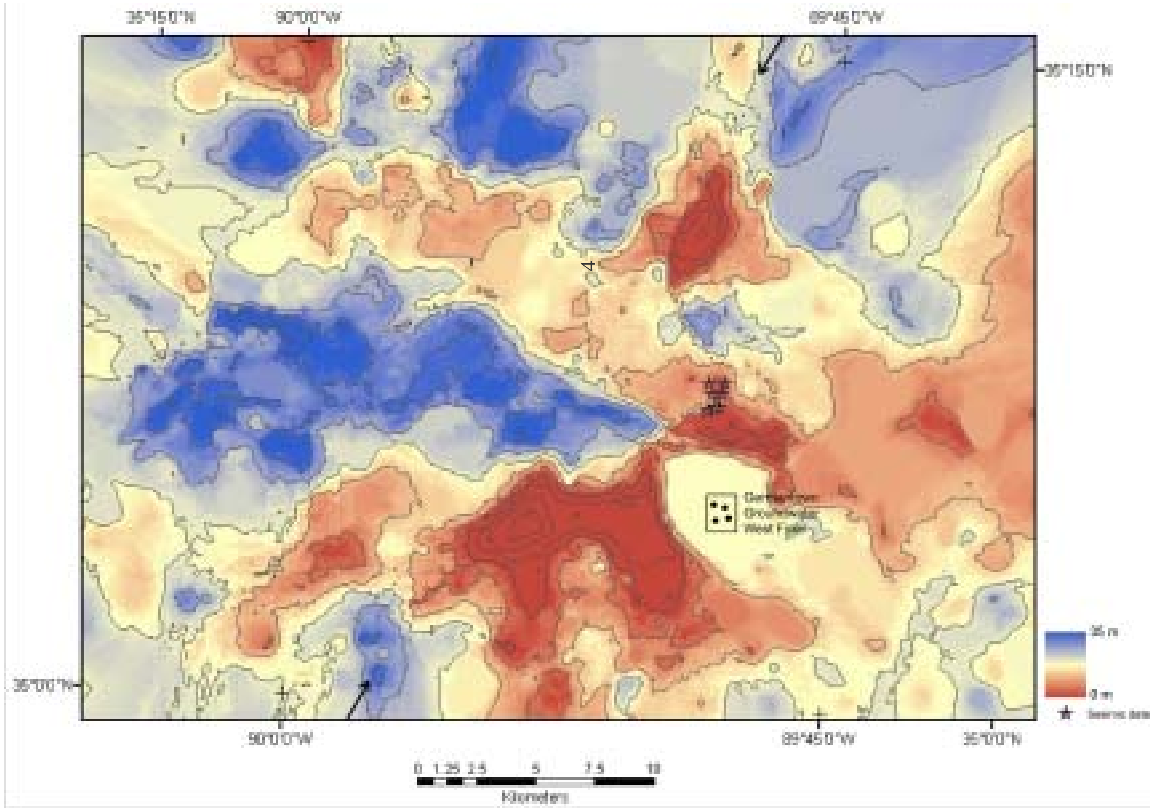



Figure 11. Isopach map of the Lafayette Formation (Upland Gravel). CI = 4 m. Black arrows show the location of the Ellendale fault. Northeast corner is poorly constrained.

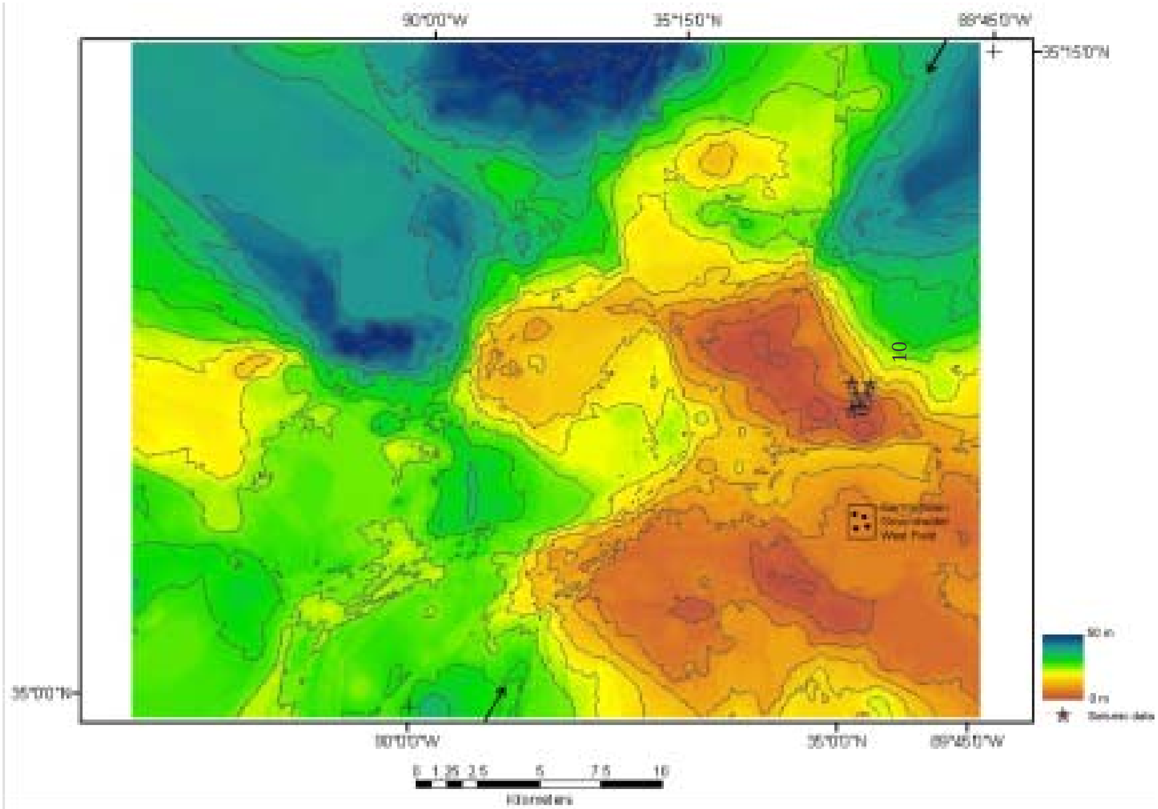



Figure 12. Isopach map of the Upper Claiborne Group. CI = 5 m. Black arrows show the location of the Ellendale fault. Northeast corner is poorly constrained.

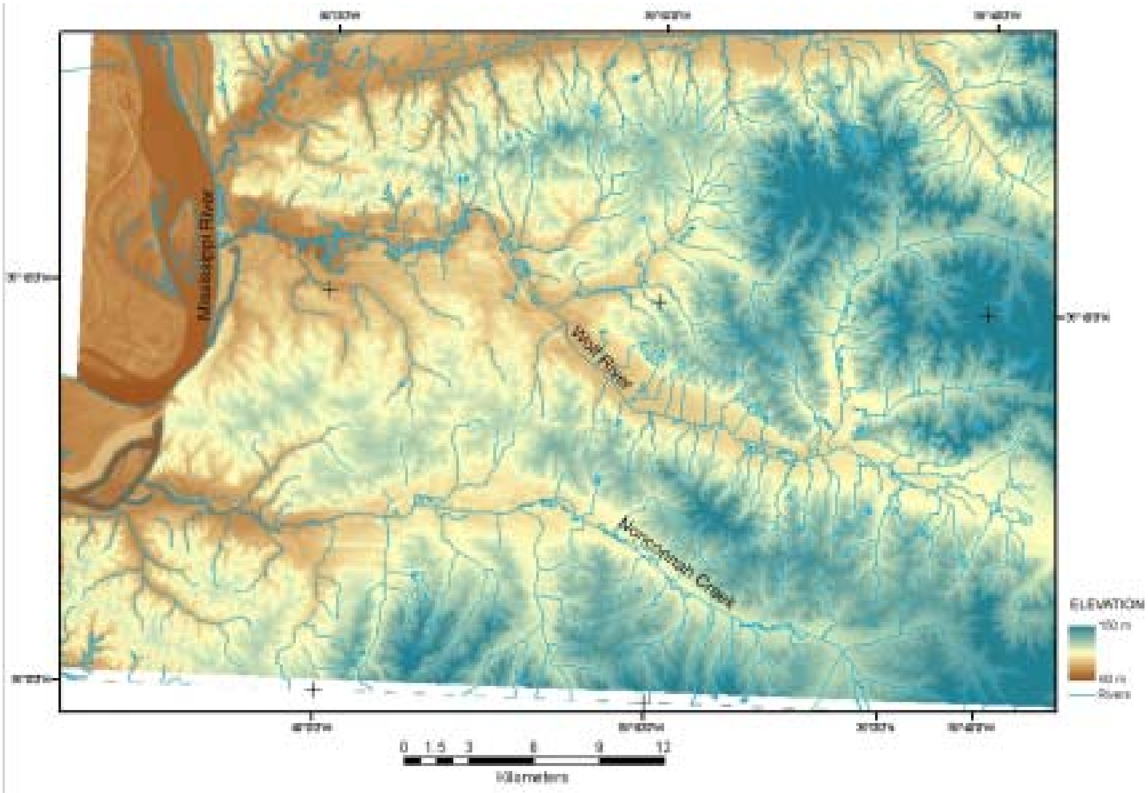



Figure 13. Surface topography and drainage system of southern Shelby County.

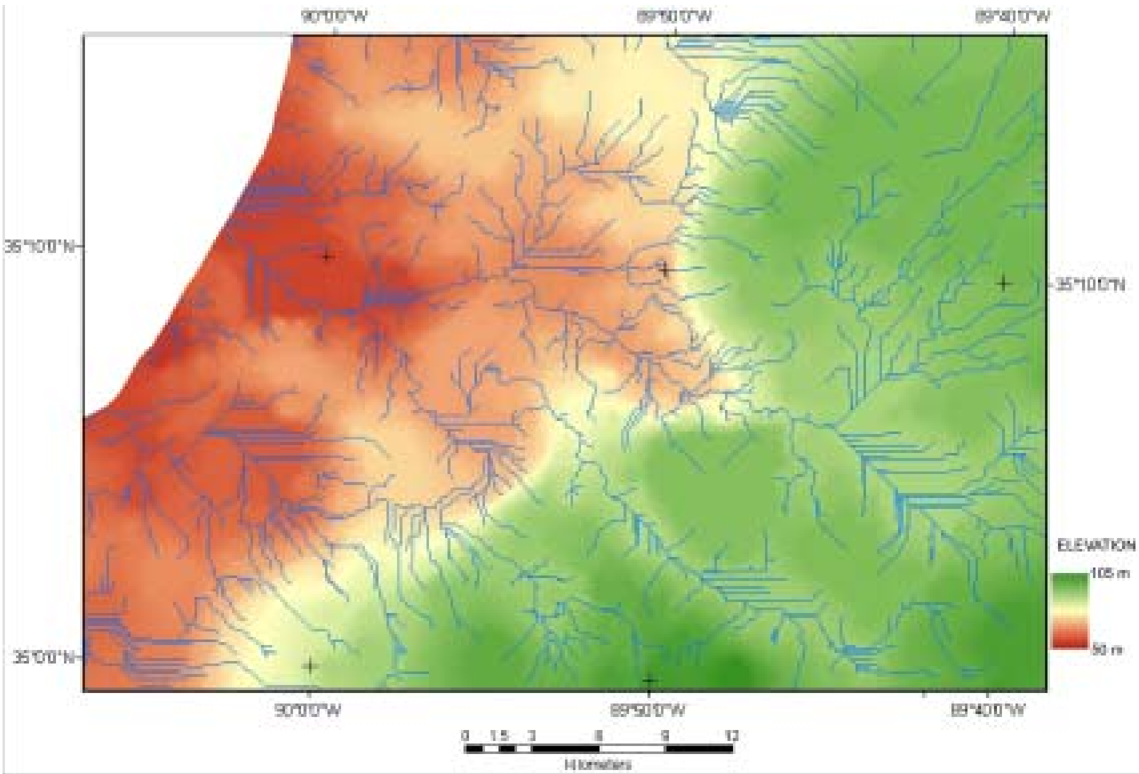



Figure 14. ArcGIS generated paleodrainage (blue) map on the top of the Upper Claiborne Group.

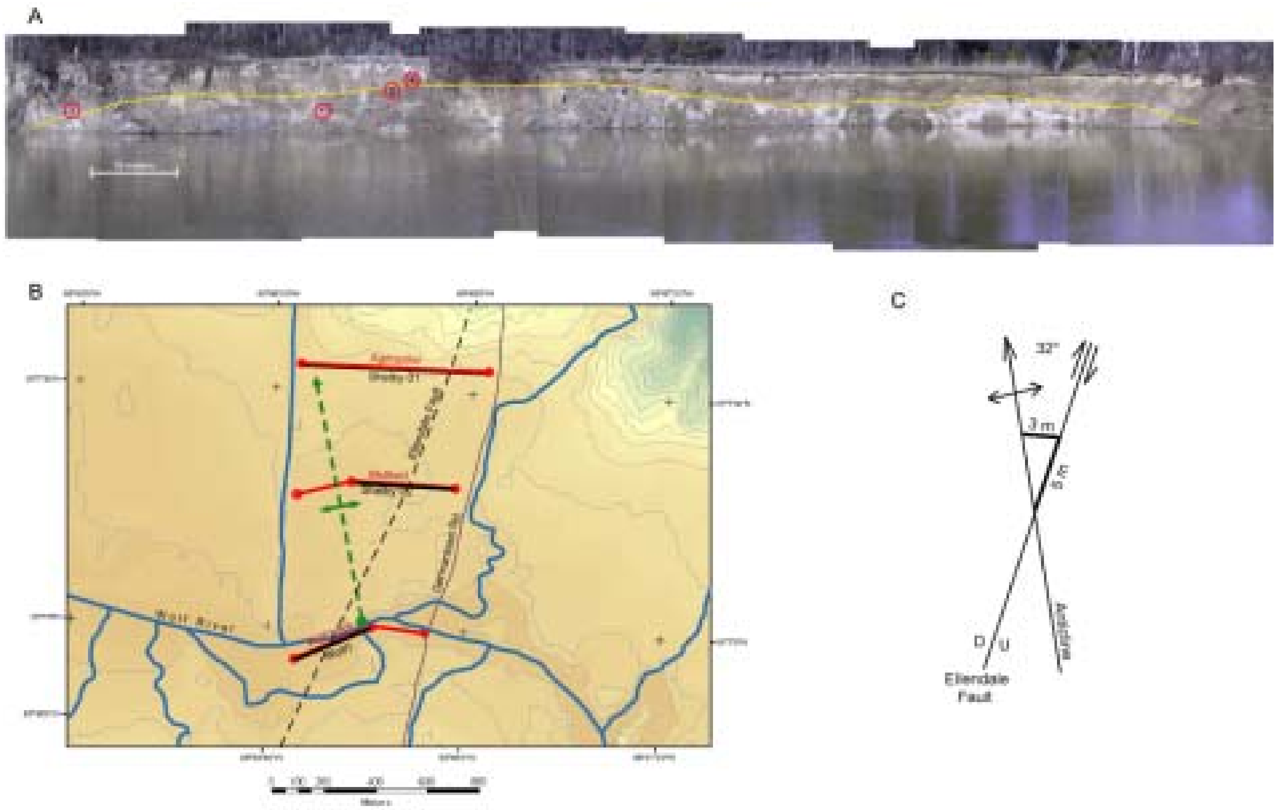



Figure 15. A. Anticline exposed along the northern bank of the Wolf River. Yellow line marks top of folded white sand bed. Circles are 14C sample sites presented in Figure 16.

B. Location of the anticline (green dot), fold hinge projection (green dashed line), and the location of a down-to-the-west fault (black dashed line) identified on the seismic lines.

C. Three meter anticlinal shortening due to 5 m of strike slip offset.

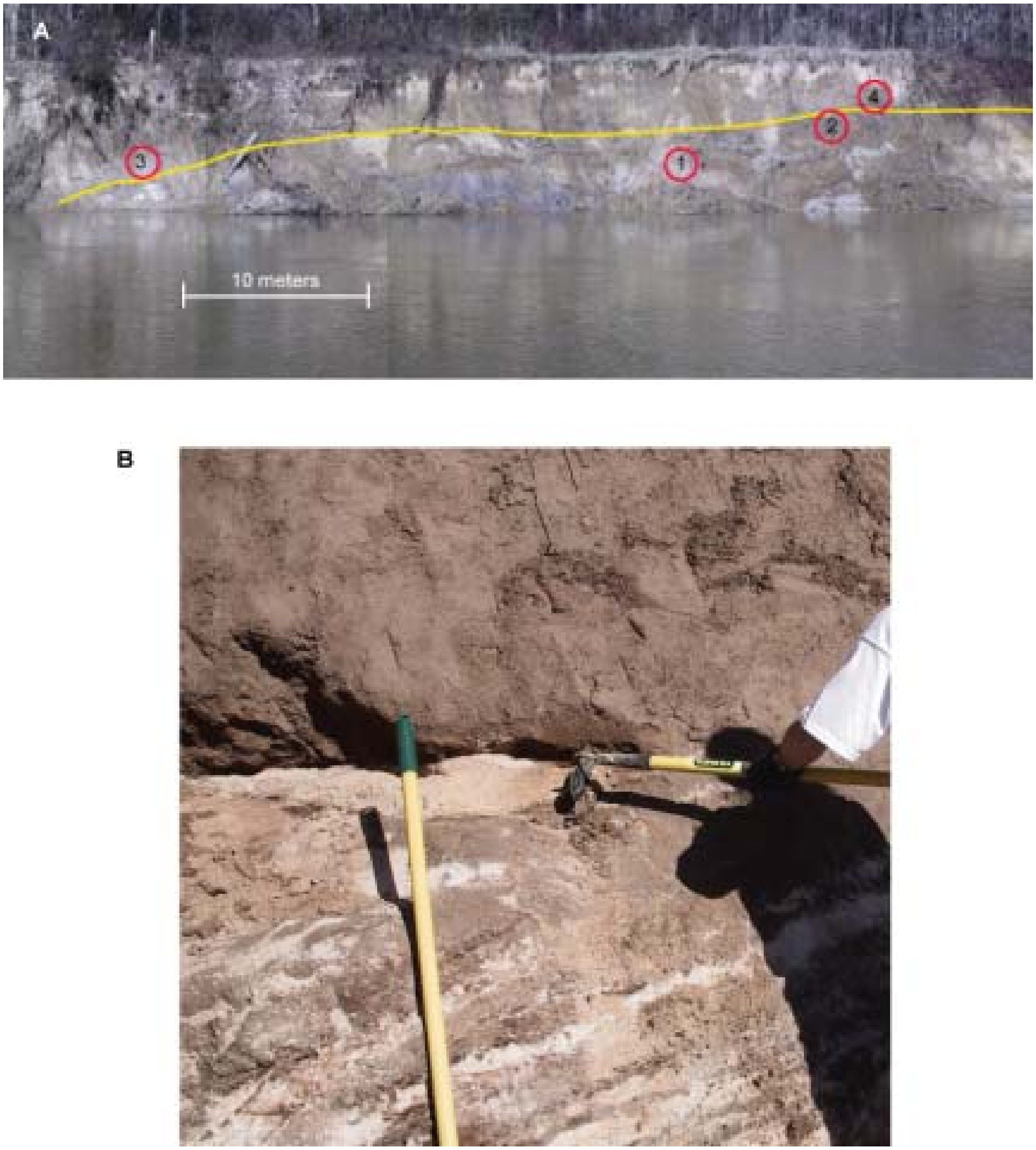



Figure 16. A. Location of radiocarbon samples (1 = 4000 $\pm$ 60 BP), (2 = 2130 $\pm$ 50 BP), (3 = 1610 $\pm$ 60 BP), (4 = 1550 $\pm$ 40 BP) (Velasco, 2002). Yellow = contact of white and overlying white and brown sand.
B. Truncation of anticline by overlying flat clayey silt containing $^{14}C$ sample number 4.

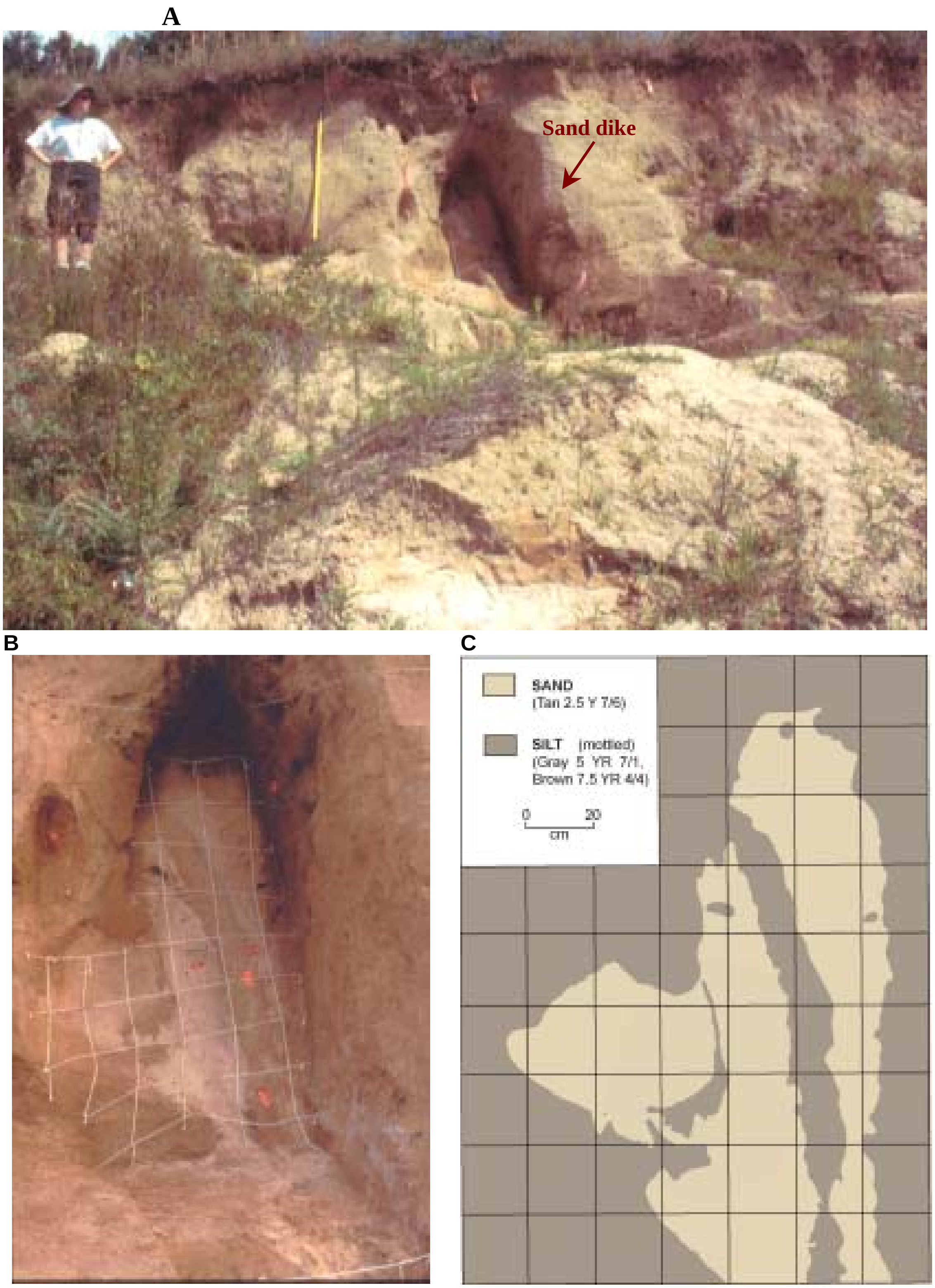



Figure 17. A. Liquefaction-induced sand dike above anticline crest in Figure 15.
B. Close-up of the sand dike. C. Log of the sand dike.

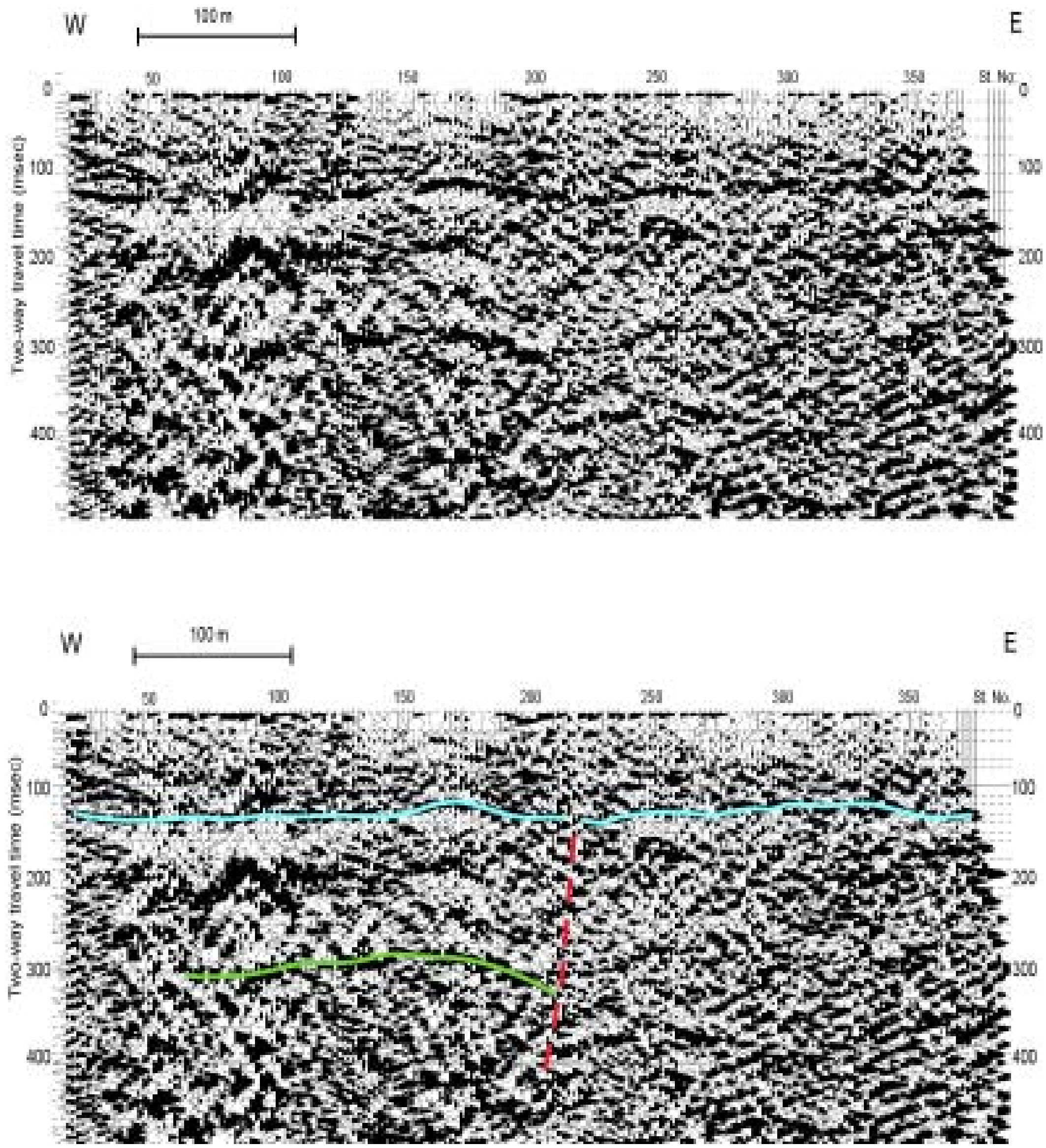



Figure 18. Stacked section of S-wave reflection line Wolf1 (located in Figure 15), with interpreted bottom figure. Upper highlighted reflector is top of Upper Claiborne Group and lower highlighted reflector is within the Upper Claiborne Group. Dashed vertical line is a possible fault.

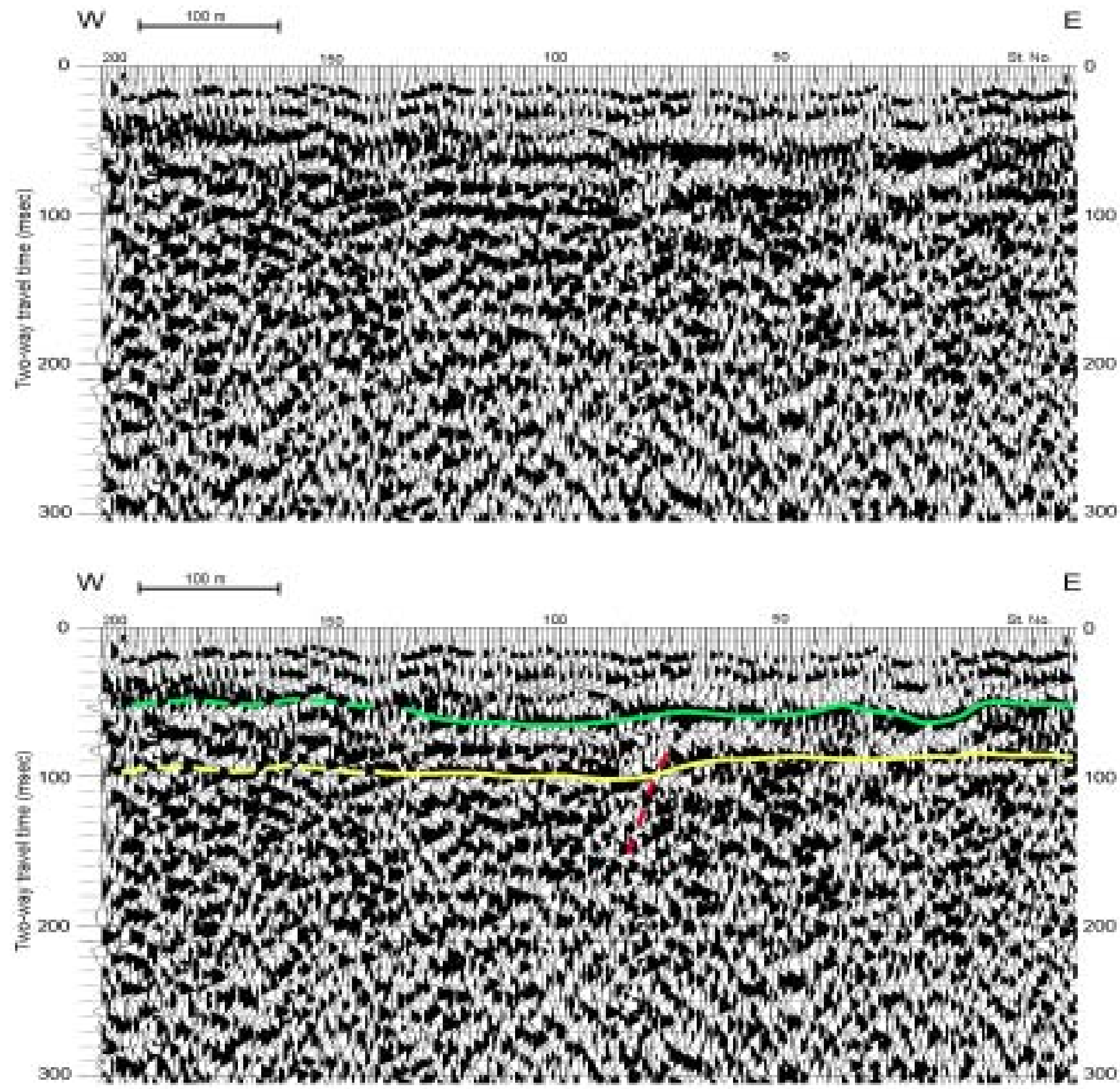



Figure 19. Stacked section of P-wave seismic reflection Midfield line (located in Figure 15), with interpreted bottom figure. Highlighted lines are reflectors within the Upper Claiborne Group (upper) and top of the Lower Claiborne Group (lower). Near vertical line is a fault.

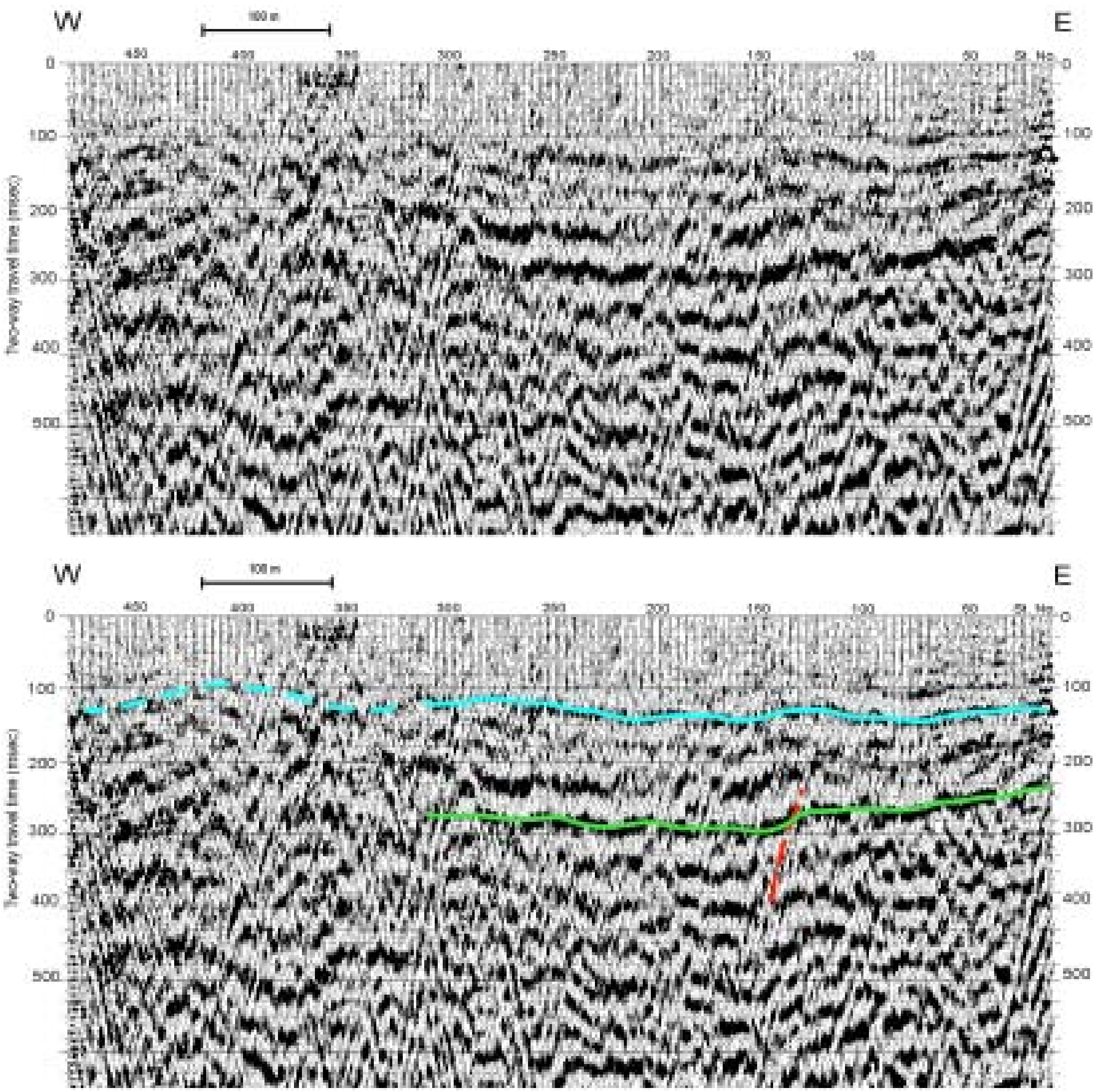



Figure 20. Stacked section of the S-wave seismic reflection line Shelby 01 (located in Figure 15), with interpreted bottom section. Upper highlighted line is the top of the Upper Claiborne Group and the lower highlighted line is within the Upper Claiborne Group. Near vertical line is a fault.

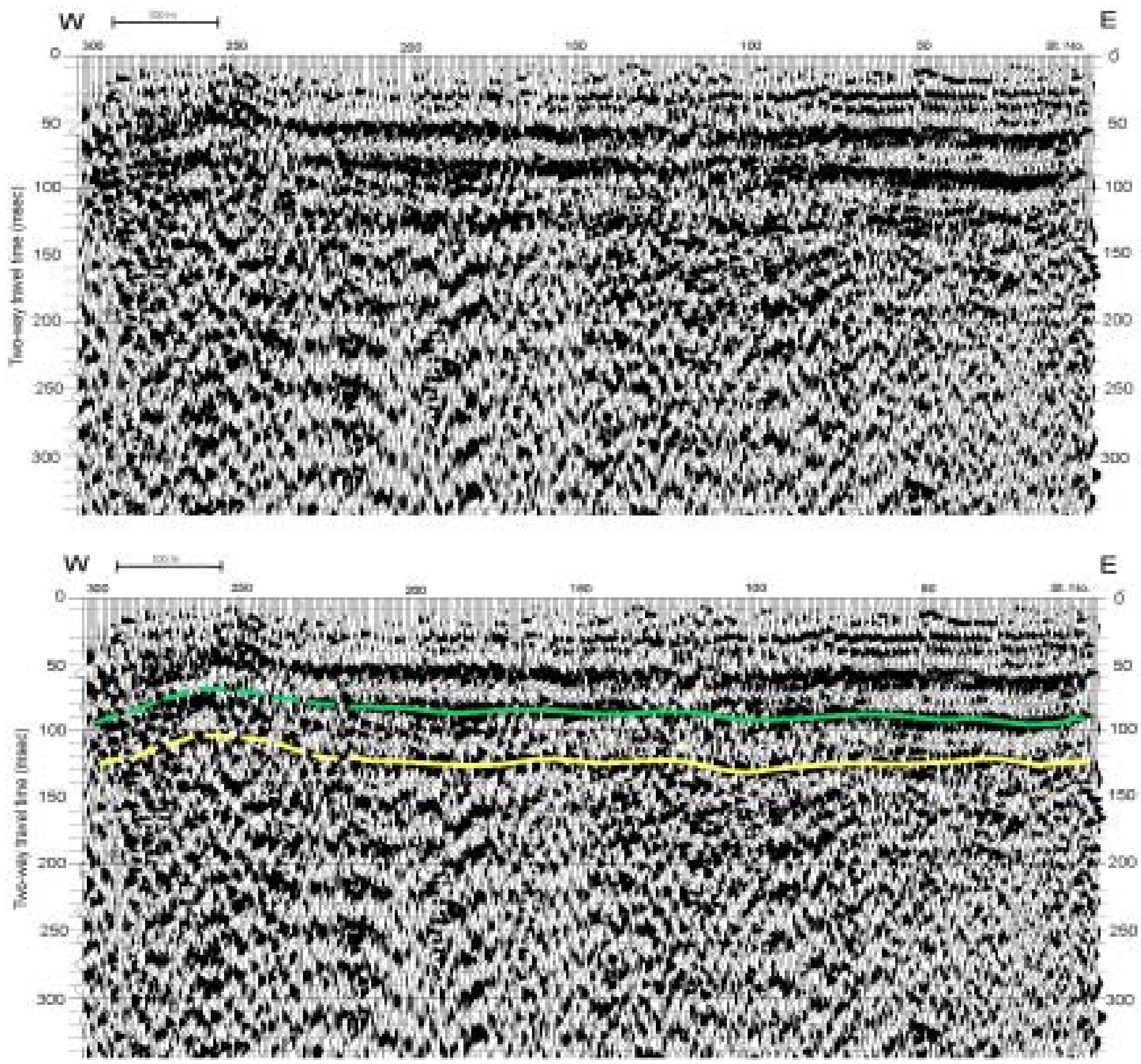



Figure 21. Stacked section of the P-wave seismic reflection Agricenter line (located in Figure 15), with interpreted bottom section. Highlighted lines are reflectors within the Upper Claiborne Group (upper) and the Lower Claiborne Group (lower).