# Mapping an aquitard breach using shear-wave seismic reflection

**B. A. Waldron · J. B. Harris · D. Larsen · A. Pell**

**Abstract** In multi-layered hydrostratigraphic systems, aquitard breaches caused by faulting or paleo-erosion can allow substantial quantities of water of differing quality to be exchanged between aquifers. Seismic reflection technology was used to map the extent and orientation of an aquitard breach connecting a shallow alluvial aquifer to the deeper semi-confined Memphis aquifer in southwestern Tennessee, USA. Geophysical well logs indicate the presence of the aquitard at borehole locations that define the beginning and end points on two seismic survey lines, which intersect at a borehole where the aquitard is absent. A SE–NW-oriented paleochannel, 350m wide and approximately 35–40m deep, is interpreted from the seismic reflection surveys. The paleochannel cuts through the aquitard and into the upper part of the Memphis aquifer, thus creating a hydraulic connection between the shallow unconfined and deeper, semi-confined aquifers. The results indicate the potential of the shear-wave seismic reflection methods to resolve shallow breaches through fine-grained aquitards given availability of sufficient well control.

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## Introduction

In groundwater systems comprising alternating unconsolidated aquifers and aquitards, interaquifer exchange of water influences water quality and assessment of water resource sustainability. The transfer of fresh water between aquifers depends on the aquitard integrity as well as hydraulic head distribution. An aquitard's ability to limit movement of water between adjacent aquifers may be compromised by cross-cutting faults or paleo-erosional features that provide localized short-circuiting. Contaminated water from a shallow aquifer may readily pass through sand and gravel fill of a paleovalley incised into a fine-grained confining unit to reach a deeper water-supply aquifer, for example. These localized discontinuities in an aquitard, termed breaches, can be difficult to identify without extensive subsurface geologic datasets.

Identification and mapping of aquitard breaches are important for source-water assessments and wellhead protection, especially if an aquifer with good water quality is receiving waters of poorer quality from, for example, an unconfined aquifer that is prone to contamination. Larsen et al. (2003a) determined through geochemical modeling and groundwater age-dating that as much as 30% of groundwater pumped from individual production wells in a confined aquifer proximal to a breach in the overlying aquitard came from the shallow aquifer that has water of much poorer quality. Similarly, Gerber and Howard (1996) used isotopic evidence to argue for localized downward vertical leakage through Late Wisconsinan till near Toronto, Ontario (Canada) raising concerns about possible contaminant transport from shallow surficial to deeper aquifers. Timms and Acworth (2002) described a sequence of fresh-water aquifers and aquitards in the Lower Murrumbidgee alluvial fan of the Murray Basin in Australia. Previous paleo-drainage features in this area were identified by van Dijk and Talsma (1964) from outcrop expression at ground surface. Results from Timms and Acworth (2002) using electrical image surveys revealed many more buried paleo-drainage features that were obscured at the surface by an overlying clayey deposit-van Dijk and Talsma (1964) paleo-drainage features account for only 5–20% Timms and Acworth's

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features. This significant increase in the identified number of paleo-drainage features is important as surface irrigation has raised concern regarding the migration of herbicides, pesticides and fertilizers through these aquitard breaches into the lower, partially saturated shallow aquifer.

Water transfer through an aquitard (leakage) can provide a significant source of water to a water-supply aquifer. Bradley and Phatare (1989) described the hydraulic connection between an unconfined aquifer within the Mehsana alluvial plains of the state of Gujarat, India, to underlying confined aquifers separated by a 40–50 m aquitard. The confined aquifers have been over-exploited for purposes of irrigation; therefore, causing a decline in the potentiometric surface and pronounced downward vertical gradient from the phreatic aquifer. Bradley and Phatare (1989) estimate that 90% of the extracted groundwater comes from vertical transfer of water from the phreatic aquifer with only 10% accounted for from lateral movement within the confined system. Brahana and Broshears (2001) developed a numerical model of the Mississippi Embayment in the south-central United States that evaluated groundwater production increases between 1886 and 1985. Mass balance and matching of observed-to-modeled heads were improved by allowing localized leakage through recognized aquitard breaches as well as regional leakage through the aquitard material. Zuber et al. (2000) stated that agreement between modeled and observed water levels in the Oligocene sandy aquifer of the Mazovian basin, Poland, could not be properly modeled without accounting for downward leakage

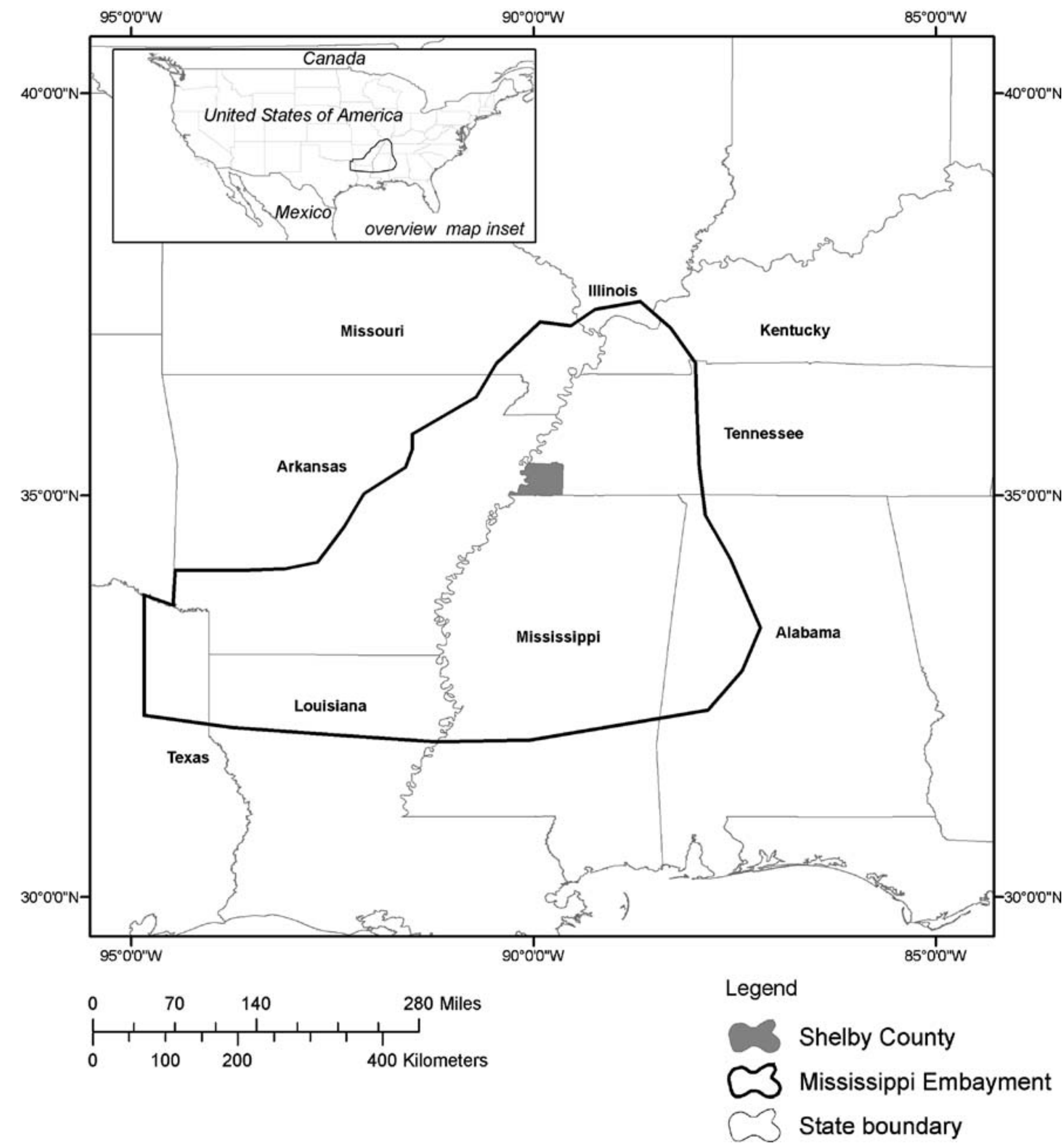


**Fig. 1** Location of Shelby County within the Upper Mississippi embayment

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| Era | System | Epoch | Geologic group | Geologic unit or formation | Hydrostratigraphic unit |
|---|---|---|---|---|---|
| Cenozoic | Quaternary | Holocene |  | Upper Alluvium | Leaky confining unit |
|  |  | ? |  |  |  |
|  |  | Pleistocene |  | Lower Alluvium | Shallow aquifer |
|  | Tertiary | Eocene | Claiborne | Cockfield | Upper Claiborne confining unit |
|  |  |  |  | Cook Mountain |  |
|  |  |  |  | Memphis Sand | Memphis aquifer |

**Fig. 2** Stratigraphic column of upper Mississippi Embayment for units of interest

through the aquitard; some of this occurring through deeply incised Pliocene deposits, thus connecting the Quaternary and the deeper aquifers. In Ontario, the Regional Municipality of Waterloo, servicing approximately 250,000 people, derives nearly 90% of its drinking water from the complex Waterloo Moraine groundwater system. A numerical model of the multiple aquifer sequence incorporated interaquifer exchange through breaches in the aquitards. Martin and Frind (1998) observed that although aquifer water levels were not sensitive to the presence of these breaches, the effect of this leakage on derived capture zones was profound.

Identification of interaquifer leakage between the shallow and the Memphis aquifers through natural breaches in the Upper Claiborne confining unit dates back

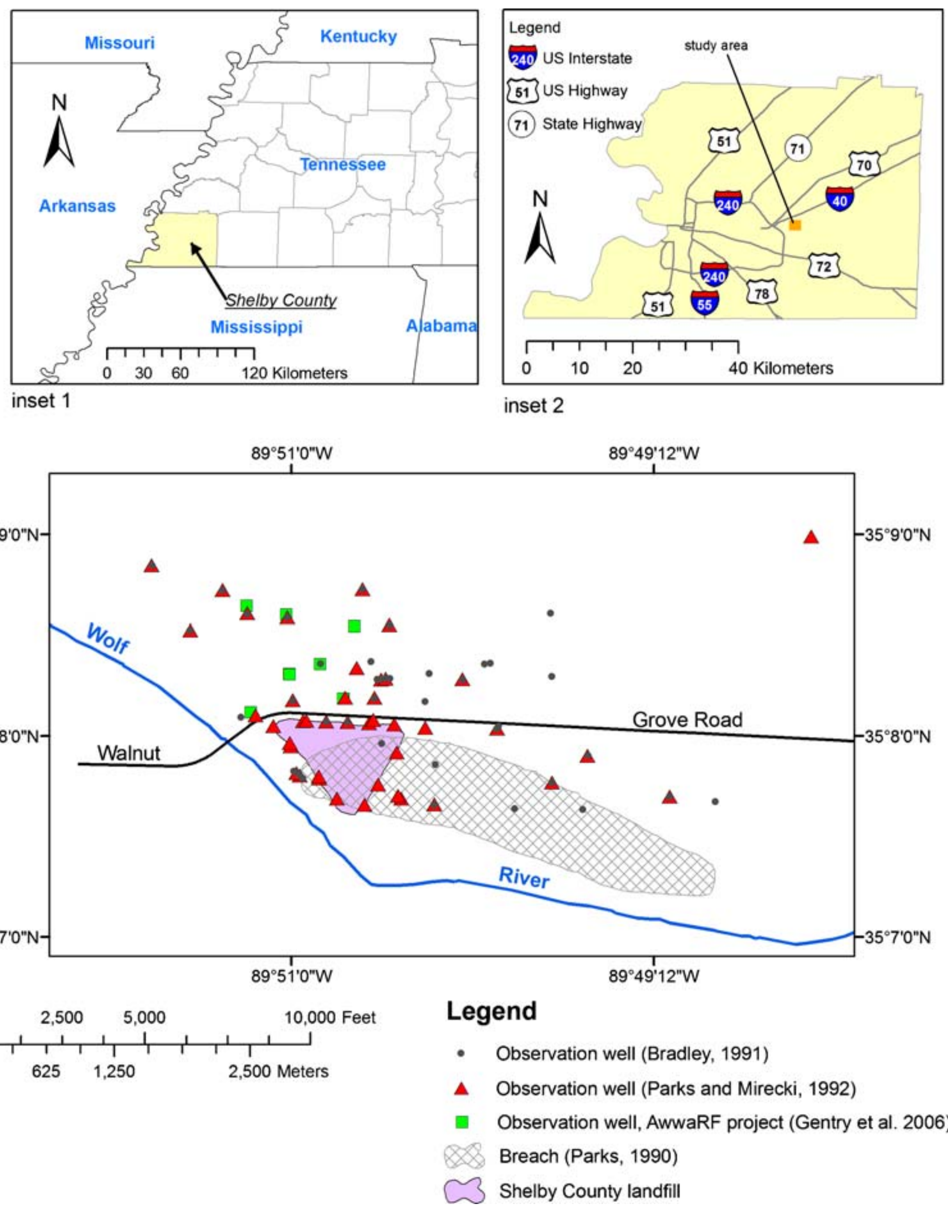


**Fig. 3** Study area at Shelby Farms Park in Memphis, Tennessee, north of the closed Shelby County landfill and Walnut Grove Road and east of the Wolf River. Observation wells were installed to monitor leachate migration from the landfill and map the aquitard breach


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to the early 1960s (Criner et al. 1964; Bell and Nyman 1968). Drilling has provided the best indication of the existence of such breaches, yet only serves to represent a point location and not an aerial extent. Analysis of geochemical analyses and environmental tracers using lumped parameter modeling can constrain locations of breaches (Ivey 2003), but again provides limited information on geometry of breaches. Anomalous water-table depressions provide additional means for breach characterization, providing information regarding plausible breach extent and orientation.

In this investigation, seismic reflection methods were used to refine the extent and orientation of an aquitard breach that had previously been identified using borehole, hydraulic, and geochemical data (Bradley 1991; Parks and Mirecki 1992; Gentry et al. 2003, 2006a, b). The seismic data also provide evidence regarding the origin of the aquitard breach that cannot be obtained from the previously employed methods. Seismic reflection methods have been useful in mapping subsurface stratigraphy and structure in regard to groundwater resources (Miller et al. 1994, 1999; Merey et al. 1992; Hammer et al. 2004; Jensen et al. 2002; Sharpe et al. 2003; Shtivelman and Goldman 2000). The results of this study further clarify the capabilities and limitations of seismic reflection methods in assessment of shallow subsurface stratigraphy, and illustrate the utility of the method for identifying the extent and origin of aquitard breaches.

## Hydrogeologic setting

The study area lies within the upper Mississippi embayment (Fig. 1), a shallow Cretaceous-Tertiary basin in the south-central United States that is underlain by Paleozoic rocks and filled with over 1,000 m of Cretaceous, Tertiary, and Quaternary sediments (Cushing et al. 1964; Van Arsdale and TenBrink 2000). The embayment sediments form a series of alternating sand aquifers and clay, silt, and sand confining units (Cushing et al. 1964).

Of interest in this study are the Eocene Memphis Sand, Eocene Cook Mountain and Cockfield formations, and various Pleistocene to Holocene loess and alluvial deposits (Fig. 2). The Memphis Sand is composed of fine- to very

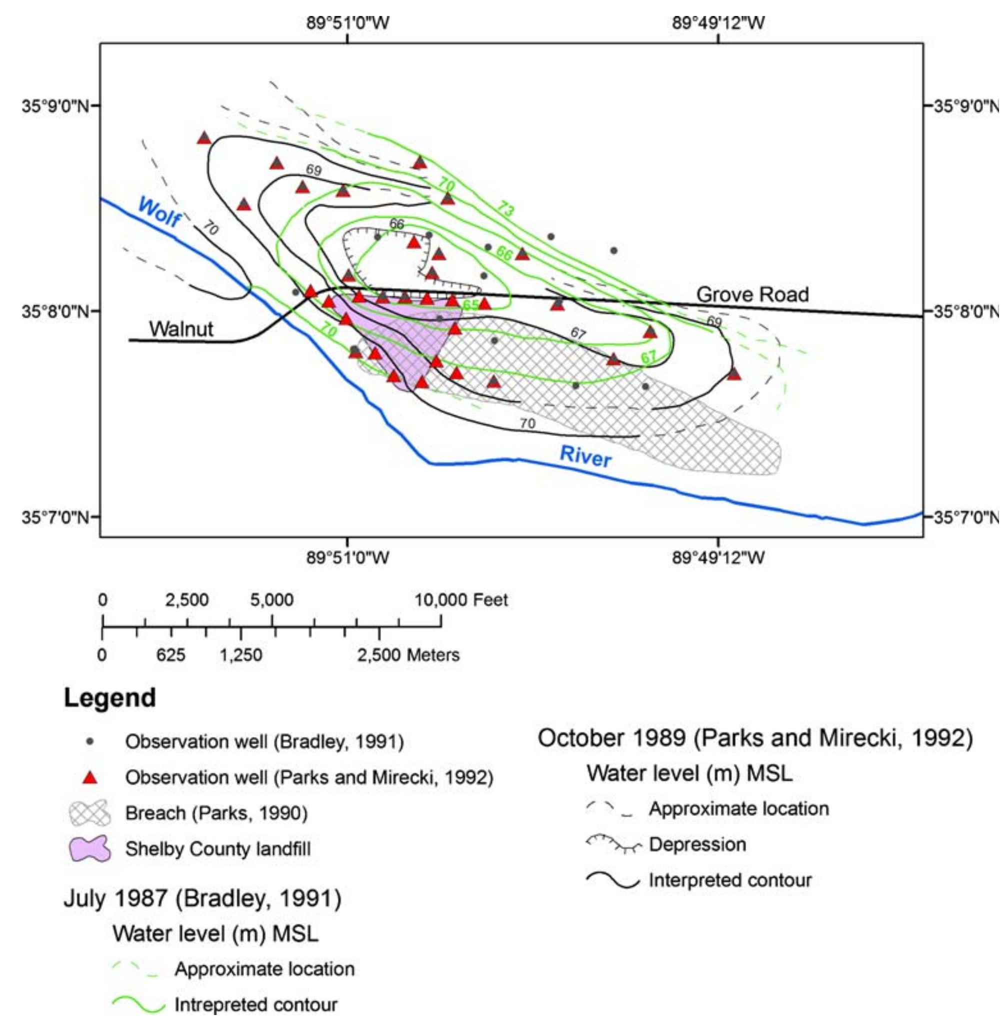


**Fig. 4** Water table elevations—m above mean sea level (m MSL)—across the study area of the shallow, unconfined aquifer. Note, contour intervals are not standardized

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coarse-grained sand with subordinate clay and is as much as 240-m thick. The Memphis Sand corresponds directly with the Memphis aquifer, a prolific aquifer that provides water to municipalities and industries throughout the Tennessee-Mississippi-Arkansas region. Overlying the Memphis Sand are mainly fine-grained strata of the Cook Mountain and Cockfield formations. These formations are composed primarily of silty clay interbedded with sand and silt. The Upper Claiborne formations comprise the Upper Claiborne confining unit, which provides confinement for the Memphis aquifer over much of the region; however, sand intervals are locally thick enough to be used as aquifers (Parks and Carmichael 1990) or provide hydraulic communication between the Memphis aquifer and overlying aquifer (Parks 1990; Larsen et al. 2003a, b, c). The Quaternary alluvial deposits include sand and gravel strata of the Pliocene(?) and Pleistocene terrace deposits in the upland areas and lower late Pleistocene and Holocene alluvium in the modern valleys (Carmichael et al. 1997; Larsen et al. 2003c). Blanketing the alluvial deposits is loess and reworked loess of thicknesses ranging from 25 m at the Mississippi bluff line to a few meters in the modern valleys. The Quaternary sand and gravel deposits form a regional shallow aquifer with the overlying loess providing leaky confinement.

## Site description

Of the ten identified breaches in the Upper Claiborne aquitard beneath Shelby County (Graham and Parks 1986; Parks 1990; Parks and Mirecki 1992; Parks et al. 1995), a breach identified north of a closed landfill at Shelby Farms was selected for the seismic survey for the following reasons: (1) good well control; (2) the site is part of a 2-$km^2$ park so surface-generated noise (rail, construction, vehicular traffic) is minimal; (3) geologic cross-sections exist for a portion of the study area; and (4) downward leakage is known to occur from the shallow aquifer to the Memphis aquifer (Fig. 3; Bradley 1991; Parks and Mirecki 1992). Bradley (1991) in cooperation with other agencies conducted a detailed study of the groundwater hydrology and potential leakage near the Shelby Farms landfill. Parks and Mirecki (1992) further investigated the groundwater chemistry proximal to the landfill for potential contamination of the Memphis aquifer. Gentry et al. (2006a, b) studied the groundwater transport process through the breach. A total of 69 observation wells or exploratory boreholes were completed as part of these investigations, thus providing a detailed understanding of the site hydrogeology.

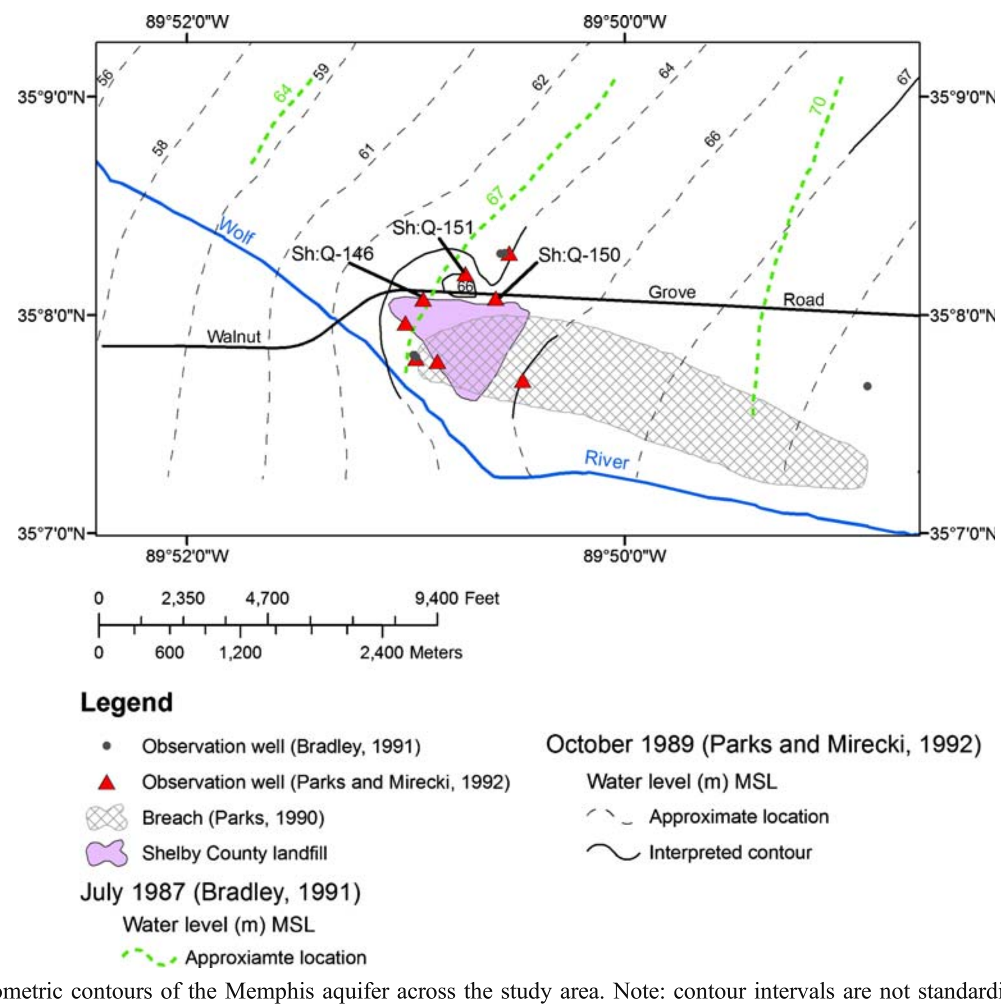


**Fig. 5** Potentiometric contours of the Memphis aquifer across the study area. Note: contour intervals are not standardized


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This study focuses on a cluster of wells surrounding well Sh:Q-151 in which the Upper Claiborne confining unit is absent (Fig. 3). The area land use is primarily agricultural with limited open grass field and forest areas. Approximately 3–5 m of loess overlie the shallow aquifer, which ranges from 14 to 17 m thick (Bradley 1988). The Upper Claiborne confining unit underlies the shallow aquifer and ranges in thickness from 0 to 18 m. The underlying Memphis aquifer is approximately 200 m thick.

## Past investigations

Water-level measurements were conducted in both the shallow and Memphis aquifers in July 1987 (Bradley 1991) and October 1989 (Parks and Mirecki 1992). The shallow aquifer water levels indicated a persistent depression in the water table north of Walnut Grove with interpreted contours elongated along the course of the Wolf River (Fig. 4). A gradient exists from the Wolf River to the depression in the water table, and flow is corroborated by a calculated reduction in the Wolf River discharge of 0.45 $m^3/s$—though this is within measurement error (Bradley 1991). Bradley (1991) indicated a gradual gradient in the piezeometric surface of the Memphis aquifer in a W–NW direction, whereas Parks and Mirecki (1992) suggested a slight mounding of the potentiometric surface in the Memphis aquifer north of Walnut Grove in proximity to Sh:Q-151 superimposed on the overall trend shown in Bradley (1991)(Fig. 5).

Parks and Mirecki (1992) constructed two cross-sections, one of which included the segment between wells Sh:Q-146, Sh:Q-151 and Sh:Q-150. All of these

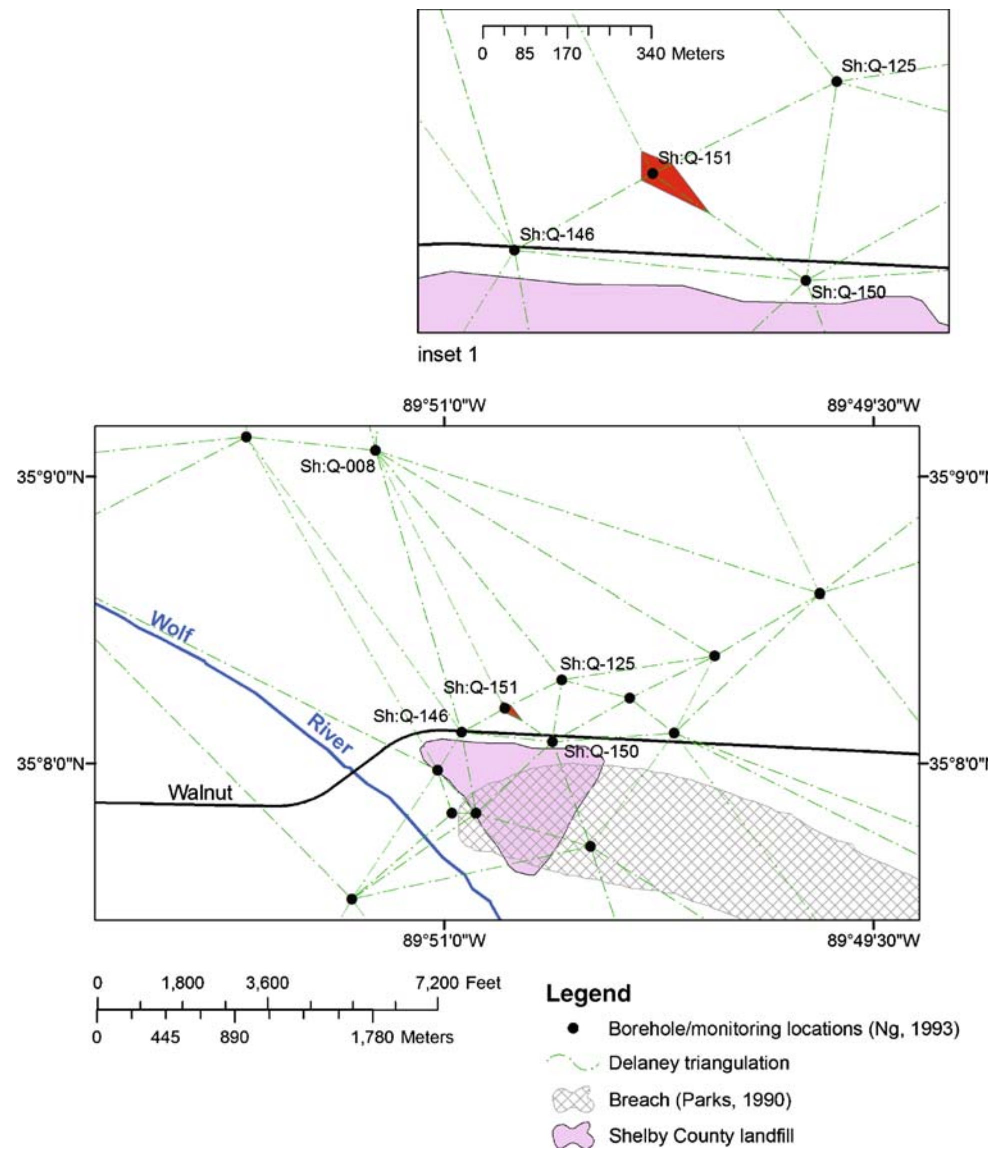


**Fig. 6** Delaney triangulation delineation for boreholes used by Ng (1993) to interpolate the thickness of the aquitard separating the shallow aquifer from the Memphis aquifer. *Inset* represents an enlarged view of the aquitard breach mapped by Ng

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observation wells are screened within the Memphis aquifer. Wells Sh:Q-146 and Sh:Q-150 (Fig. 5) indicate thicknesses of aquitard of 11 and 2.5 m, respectively. In their cross-section, the thickness of the confining unit is drawn as an assumed linear reduction in thickness from wells Sh:Q-146 and Sh:Q-150 to Sh:Q-151.

More recent investigations at the Shelby Farms landfill site were conducted by Ng (1993), Gentry (1998), and Gentry et al. (2003), all of whom used numerical modeling studies to estimate the extent of the aquitard breach and groundwater flux to the Memphis aquifer. As part of Ng's work, the extent of the breach north of the landfill, indicated by well Sh:Q-151, was determined through interpolation of well log data using Delauney triangulation (Fig. 6). Delauney triangulation results in breach geometry connecting well Sh:Q-008 with wells Sh:Q-146, Sh:Q-151 and Sh:Q-150 forcing long, thin triangles, an artifact that can limit the ability of the triangulation network to represent local variation (Watson and Philip 1984). Gentry et al. (2003) used a genetic algorithm (GA) to estimate recharge to the Memphis aquifer through the breach north of the landfill, again focusing on the area adjacent to well Sh:Q-151. Their model incorporated aspects of Ng's (1993) numerical model. At specified recharge rates, areas of accretion through suspected thinning or absence of the confining clay were determined with calculated levels of probable occurrence. The resulting area of accretion, which varied in size depending on the recharge rate, was somewhat circular with well Sh:Q-151 forming the centroid.

Gentry et al. (2006a, b) installed more wells at the breach site as well as at several downgradient locations in the Memphis aquifer. They conducted hydraulic testing, sedimentological analyses, chemical and isotopic tracer studies, and further GA modeling to assess groundwater flow rates and processes through the Shelby Farms landfill breach. Although the additional boreholes constrain the extent of the breach and provide additional information regarding its origin, the shape was not further clarified by these efforts.

## Seismic data acquisition and analysis

The area of seismic investigation focuses on the water-table depression encompassing well Sh:Q-151, as delineated by Bradley (1991) and Parks and Mirecki (1992) (Fig. 7). A large part of this area is used for crop production and, as a result, at times access to the area was limited. A pilot survey was used to determine if seismic reflection technology had the potential to depict the aquitard at shallow depths.

SH-wave (horizontally polarized) seismic reflection methods have been used to map shallow geologic features in unconsolidated, water-saturated sediments (Suyama et al. 1987; Hasbrouck 1991; Goforth and Hayward 1992; Harris et al. 2000; Young and Hoyos 2001). The choice of SH- as the preferred shear wave phase is based on the idea that SH- signals should be easier to identify because pure SH- energy reflects and refracts only as an SH-wave and, unlike P-waves (compressional wave) and SV-waves (vertically polarized shear wave), does not experience mode conversion. P-wave reflection data are highly influenced (both in quality and geologic significance) by

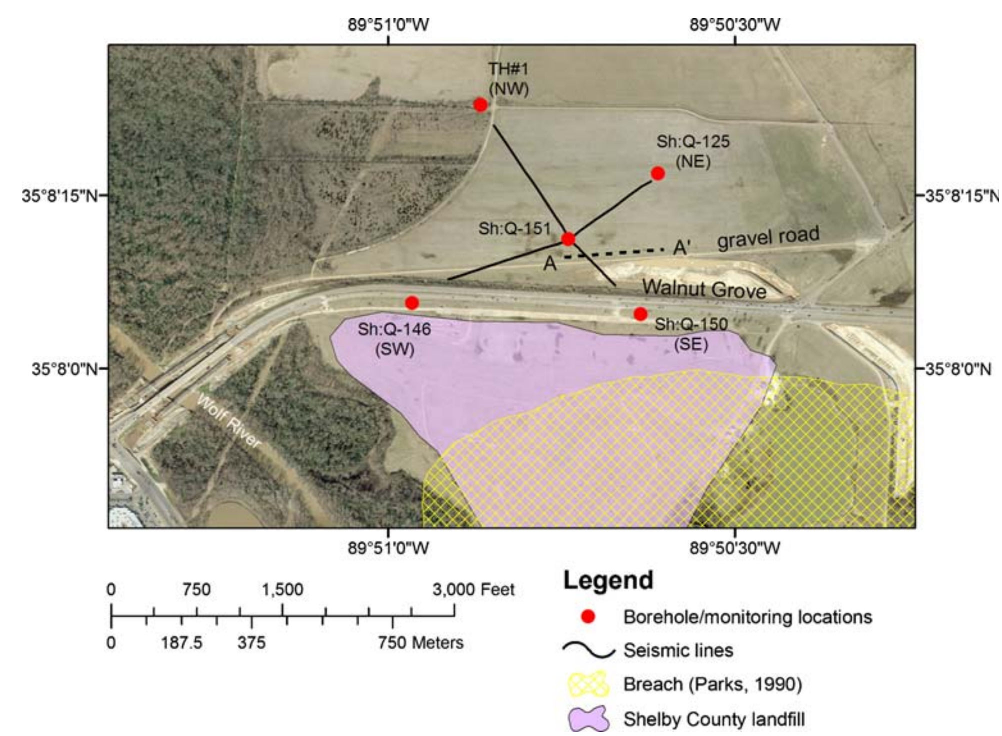


**Fig. 7** Aerial photo of study area overlain by the three seismic survey transects: *A–A'*, *SE–NW* and *SW–NE*

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the depth of water saturation in near-surface materials. Because S-waves travel with the velocity of the sediment framework, they are not greatly affected by the degree of saturation, and often lead to more consistent, high-quality data in unconsolidated, water-saturated sediment sequences. Due to the small target size for many shallow reflection surveys, seismic resolution is frequently the most important consideration when choosing a survey method. Although S-waves are rarely observed in the same frequency range as P-waves, in the authors' experience with shallow surveys in the Mississippi Embayment, S-waves commonly have frequencies of 0.5–0.25 to those of P-waves. For seismic energy of the same frequency and because S-waves travel with lower velocities than P-waves, shear wavelengths are shorter and resolution is higher. The higher resolution is particularly evident in water-saturated, alluvial material where the P-wave velocity is regularly 5–10 times higher than the S-wave velocity. Shallow reflections on S-wave field records from the Shelby Farms area show dominant frequencies of 40–50 Hz. Reflection (from shot gathers), refraction (Cramer 2005), and downhole (University of Memphis) S-wave data sets were integrated to develop the velocity functions used in stacking the reflection data. From the frequency and velocity observations, the vertical resolution for the Shelby Farms site was calculated to be between 1.5 and 2.5 m.

The shear (S)-wave seismic method was chosen for the pilot survey based on its ability to provide high-resolution images of near-surface geology in unconsolidated, water-saturated sediments such as those present in the Mississippi Valley (Harris et al. 1998). In addition, a previous study utilizing S-wave reflection methods (Larsen et al. 2003b; Pell et al. 2005) in the Sheahan well field of central Memphis, provided a high-quality image of an erosional swale in the shallow subsurface. The pilot survey (A–A′) was conducted along the shoulder of a gravel access road immediately south of well Sh:Q-151 (Fig. 7). The survey was positioned to cross over areas where the aquitard was present (well Sh:Q-125 with an aquitard thickness of 6 m) to where it was absent near well Sh:Q-151. From prior experience, horizontally polarized geophones were spaced at 2-m intervals, the source for the shear waves was a 1.8-kg sledge hammer struck horizontally against a 10-kg metal I-beam and the reflection data

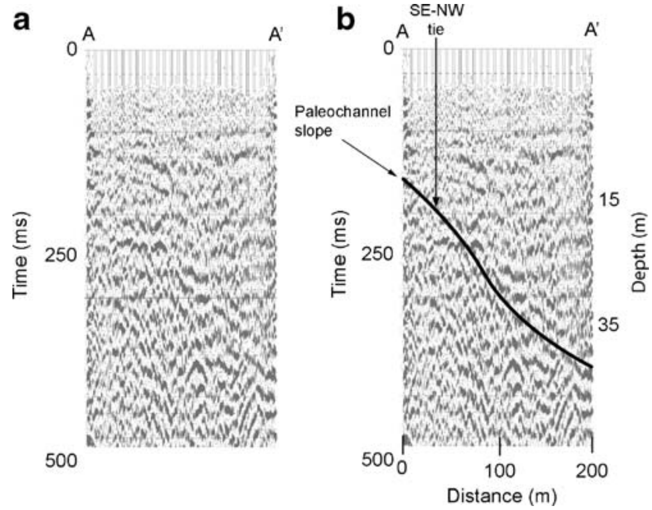


**Fig. 8** Seismic profile of transect A–A′ **a** without interpretation and **b** with interpretation

were recorded on a 24-channel engineering seismograph and processed using a standard sequence for shallow CMP (common midpoint) seismic reflection data (i.e., Baker 1999; see Table 1). Data processing followed these steps: reformat to SEGY (Society of Exploration Geophysicists format Y), bad trace edit, first arrival muting, CMP (common-midpoint) sorting, bandpass filter (20–80 Hz), automatic gain control (200 ms window), velocity analysis, normal moveout correction (NMO), and developing the CMP stack (12-fold).

The 12-fold stacked seismic profile indicates a possible erosional structure into the Memphis aquifer with semi-coherent reflection energy, primarily in the 100–350 ms range (10–50 m deep), visible along the length of the line (Fig. 8). Based on the results of previous shallow S-wave seismic reflection profiling in Mississippi valley (Harris et al. 1998), this data set can be considered to be of low to medium quality. The Upper Claiborne confining unit was anticipated to be observed at the eastern margin of the line, then thin and become absent toward the western edge. An east-dipping feature was mapped ranging from approximately 15 m on the west end of the profile to nearly 40 m on the east end of the profile, however. The down-sloping contact is interpreted to be the top of the

**Table 1** Seismic data acquisition parameters for pilot and full surveys

| Field parameter | Survey line | |
|---|---|---|
| | Gravel road (A–A′) | SE–NW and SW–NE |
| Energy source | 1.8-kg sledge hammer/I-beam (5 impacts) | 1.8-kg sledge hammer/I-beam (5 impacts) |
| Source interval | 2 m | 3 m |
| Receiver | 14-Hz horizontal geophones | 14-Hz horizontal geophones |
| Receiver interval | 2 m | 3 m |
| Spread configuration | split spread | split spread |
| Recording system | Seistronix RAS 24 | Seistronix RAS 25 |
| Sample interval | 0.25 ms | 0.25 ms |
| Maximum fold | 12 fold | 12 fold |
| Field filters | Out | Out |
| Record length | 500 ms | 1,000 ms |


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Memphis aquifer because the depth of the structure is well below the base of the confining unit interpolated from the four corner control points, boreholes TH#1, Sh:Q-125, Sh:Q-146, and Sh:Q-150. The structure resembles a paleo-erosional feature with horizontal reflections east of the feature boundary suggesting layered depositional fill of a channel. Although data quality was fair, the pilot survey illustrates the potential of seismic reflection to map the extent and possible orientation of the breach.

The full-scale survey was scheduled while the field was fallow. Two survey lines were chosen such that the SE–NW line followed the longitudinal orientation of the water table depression, the SW–NE line traversed the depression (Fig. 7), and the lines intersected at well Sh:Q-151. The NE and NW points were set at well Sh:Q-125 and borehole TH#1, respectively, both with geologic records that penetrated through the aquitard. The SE and SW points fall short of their intended control points, wells

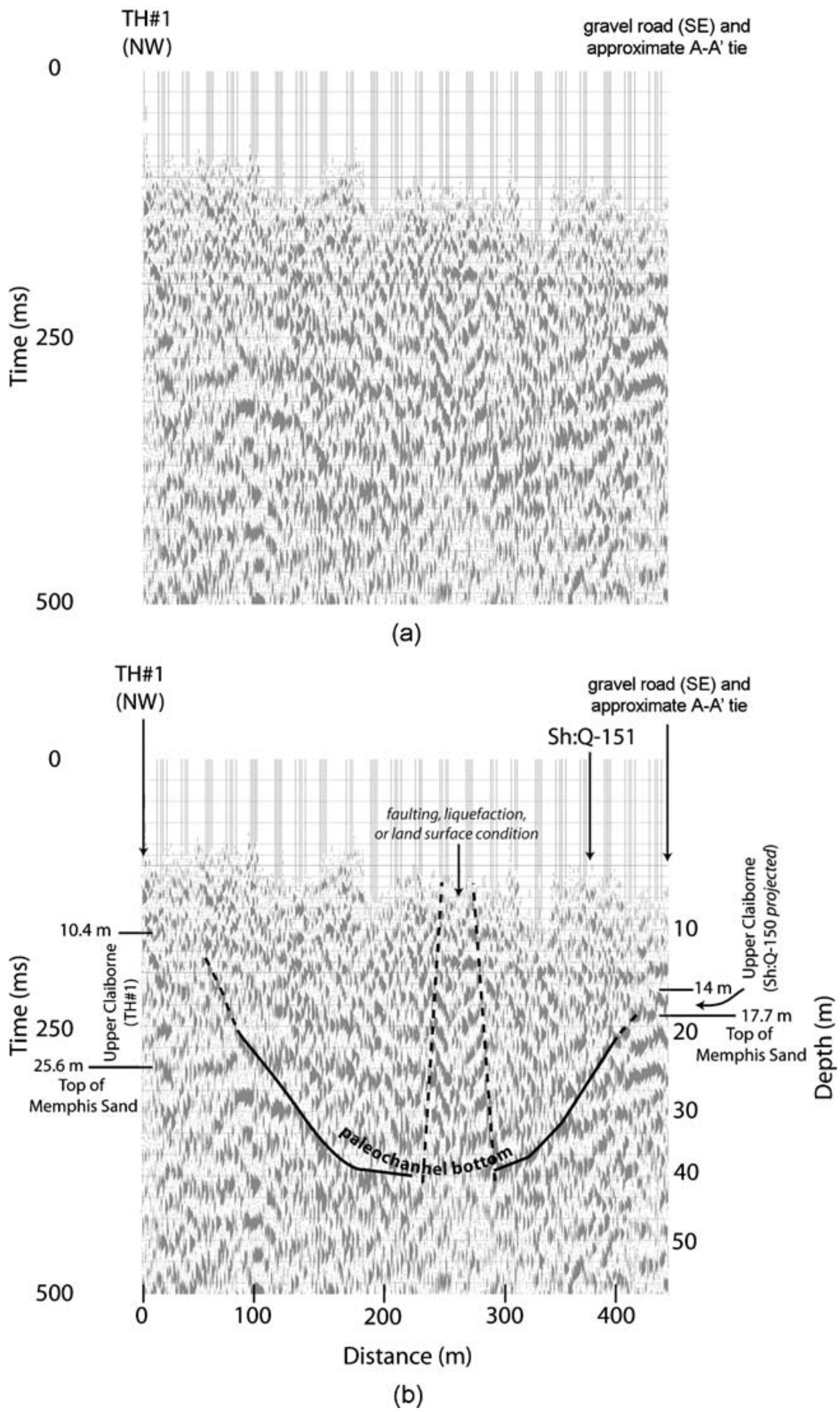


**Fig. 9** Seismic profile of transect SE–NW **a** without interpretation and **b** with interpretation. *Dashed lines* indicate possible paleochannel delineation


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ShQ-150 and Sh:Q-146, respectively, because the wells lie on the south side of Walnut Grove Road, a divided four-lane thoroughfare. Thus, the southern portions of the survey lines are truncated prematurely north of Walnut Grove.

The field at the time of the seismic survey was moist after many consecutive weeks of periodic rainfall events. There was concern that the soft soil may allow for slippage of the I-beam seismic source thus reducing energy coupling. There was also concern that wind-induced surface noise and/or traffic noise would negatively influence data quality; however, noise monitoring during the survey indicated a minimal impact. The only change in seismic data acquisition or processing from the pilot survey to the full-scale survey was the use of a 3-m geophone interval (see Table 1). Although overall data quality is fair, well control proximal to the survey line end points allowed the top of the Memphis aquifer to be identified on the profiles with relatively good consistency.

The SE–NW line (Fig. 9) shows strong reflections near the SE termination and weaker reflections approaching the NW control point, borehole TH#1, indicating that a paleochannel feature truncates the Upper Claiborne deposits and uppermost Memphis Sand. Sloping reflec-

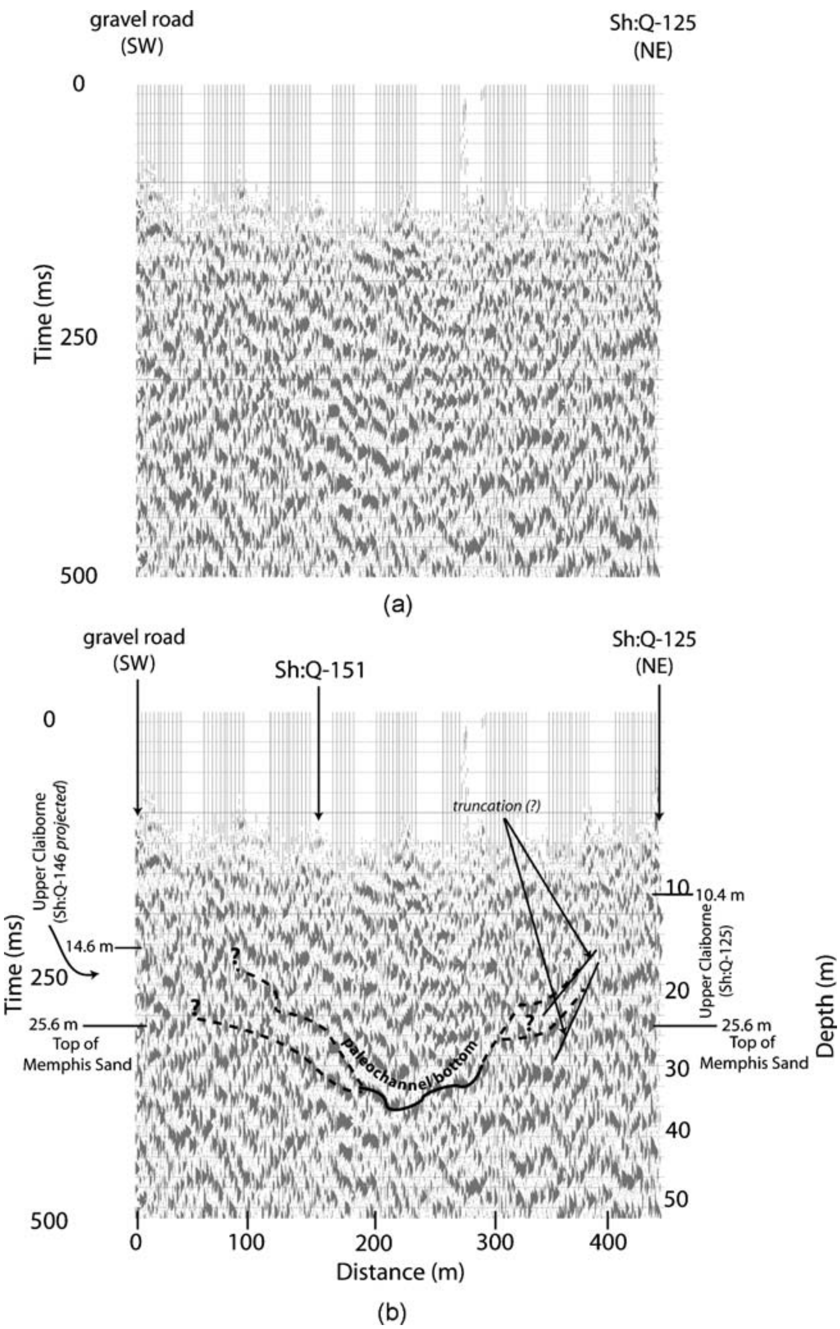


**Fig. 10** Seismic profile of transect SW–NE **a** without interpretation and **b** with interpretation. *Dashed lines* indicate possible paleochannel delineation


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tions within the paleochannel follow the general slope of the channel sides and may indicate depositional layering, similar to that observed in the pilot survey. The paleochannel along this orientation is approximately 325 m wide and 30 m deep. An anomalous zone approximately 50 m wide and extending to depth is observed between 200 and 300 m SE of borehole TH#1. The presence of diffractions in this vertically oriented zone suggests a possible geologic structure such as a fault zone or liquefaction vent. Shallow faults (Velasco et al. 2005) and liquefaction (Broughton et al. 2001) have both been identified within the Wolf River floodplain.

The SW–NE line was expected to transect a suspected SE-NW oriented paleochannel or erosional scar; thus, a cross-sectional profile would be revealed by the seismic reflection survey. However, a paleochannel structure is more difficult to interpret in the SW–NE line (Fig. 10). The best well control for this line is at the NE point at well Sh:Q-125. The Upper Claiborne in Sh:Q-125 is identified from the gamma log by two closely spaced, strong gamma signals at 10 m and 19 m (see strong reflector, Fig. 10) followed by a gradual gamma signal decrease (transition) until reaching the Memphis Sand at approximately 25 m. The top of the Memphis Sand in the profile is indicated by a strong reflection signal, then truncated approximately 50 m SW of well Sh:Q-125. Following the paleochannel bank is difficult to the SW, yet the base of the channel is estimated to be at 35 or 40 m below ground surface, thus corroborating the findings from the SE–NW line.

Mapping the paleochannel extent, dimensions and orientation with the pilot survey A–A′, a NW-SE oriented paleochannel is interpreted (Fig. 11), seemingly reversed from the hypothesized profile. The pilot survey begins just outside the western or southern margin of the paleo-erosional feature and terminates within the aquitard breach. The suggested base of the feature mapped in the pilot survey closely approximates the depth mapped in the SE–NW profile.

## Discussion

The results of the three seismic surveys have better defined the extent, orientation, and origin of the breach structure north of the Shelby Farms landfill, Memphis, Tennessee. The three seismic lines indicate a paleochannel structure incised through the Upper Claiborne strata and into the Memphis Sand. Drilling returns from borehole Sh: Q-151 (Parks and Mirecki 1992) and cores from adjacent boreholes (Gentry et al. 2006a, b) indicate that the paleochannel feature is filled with fine to medium sand, although some gravel horizons may exist. The paleochannel is approximately 300 m wide, 35–40 m deep and oriented in a SE–NW direction. The delineation of the breach by Ng (1993) using Delauney triangulation was much smaller than the interpreted paleochannel, yet Ng's mapping did indicate a SE–NW orientation. Although the S-wave seismic data quality was fair, seismic reflection in combination with well control and water-level data constrain the breach extent and clarify its fluvial origin.

The lateral continuity of the paleochannel cannot be assessed with the present survey data. Presence of clay in three surrounding boreholes toward the NW section suggests a possible termination; this inference is supported

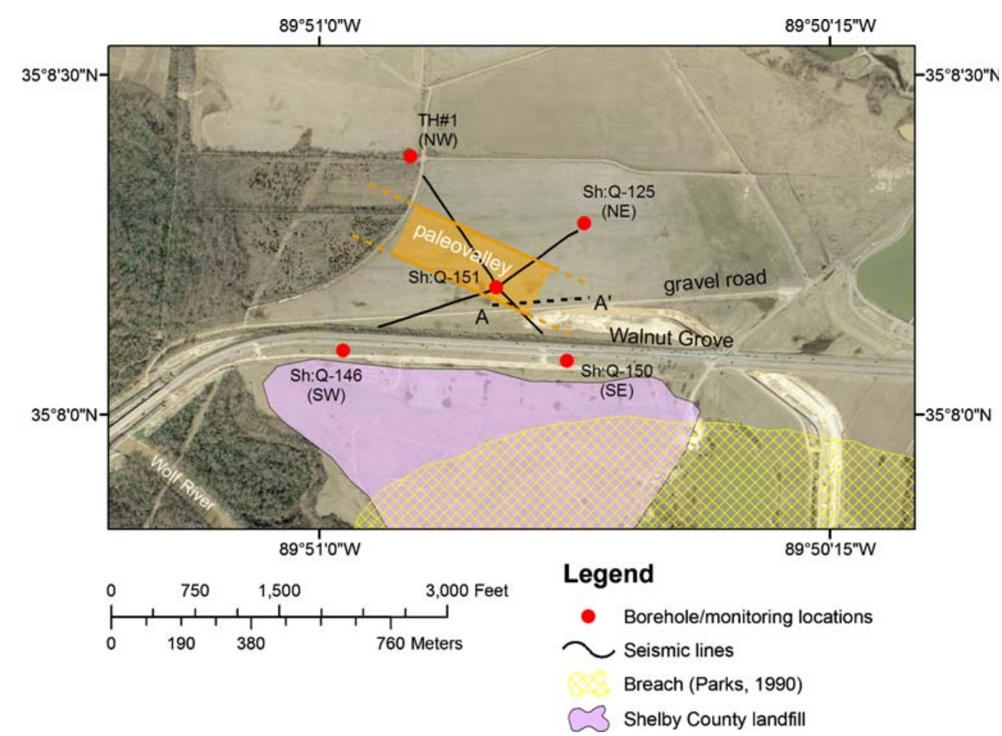


**Fig. 11** Location, extent and orientation of a paleochannel forming a breach in the aquitard separating the shallow aquifer from the Memphis aquifer. *Dashing* indicates probable extension of the paleochannel

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further by substantially different water levels in the alluvial and Memphis aquifers (Parks and Mirecki 1992; Gentry et al. 2006a, b). The lack of borehole control and similar water levels in the two aquifers to the SE of borehole Sh:Q-151 suggest that the breach extends or other breaches exist in this direction.

A possible explanation for the low signal-to-noise ratio of the S-wave data is a subsurface with laterally discontinuous units (such as a buried fluvial channel) that would not return strong reflections. More seismic reflection work in the area is required to more fully map the dimensions and path of the paleochannel. Thorough testing of various seismic energy sources in the area, including weight drop, projectile and vibratory sources that generate compressional and shear seismic waves, might improve future survey results and reduce interpretation error. Because low-fold, hammer-impact seismic reflection data commonly have signal-to-noise ratios that are not ideal, only basic processing steps were employed in order to minimize processing artifacts (and maximize interpretation confidence) produced by "over-processing" noisy data. Likewise, migration was not applied as it is not a common step used in processing shallow seismic reflection data (Black et al. 1994). The steep dips on the interpreted paleochannel boundaries are a result of high vertical exaggerations (8–12X) on the plotted seismic sections (Figs. 8, 9, and 10). Actual apparent dips are small, ranging from 6–9°, and migration is unlikely to affect the interpretation.

Beyond the Shelby Farms site, Parks (1990) delineated a number of aquitard breaches that vary in size and shape throughout Shelby County using primarily borehole data. With long-term water production from the Memphis aquifer resulting in a gradient reversal between water levels in it and the unconfined aquifer above, the aquitard breaches will continue to play a large role in the quality and supply of water to the Memphis aquifer. To accurately quantify the water transfer through these breaches in the aquitard and take proactive measures to monitor if not limit human activity in proximity to them, it is imperative that the extent, the origin (e.g., paleochannel, fault, liquefaction, etc.), and the spatial distribution be determined.

## Conclusions

A pilot S-wave reflection seismic survey and two full-scale S-wave reflection seismic transects were used to define the extent and origin of a breach through the Upper Claiborne confining at Shelby Farms in Memphis, Tennessee. Previous borehole, hydraulic, and sedimentological studies had established the presence of a breach through the Upper Claiborne confining unit at the site; however, the extent and origin of the breach were still unknown. Although the data quality for the surveys was low to medium, a paleochannel feature that incises through the confining unit and into the upper Memphis Sand was identified. The crossing transects allow determination of a SE–NW trending discontinuity in the fine-grained confining unit strata, which correlates well with stratigraphic control from borehole logs. The results indicate that shallow S-wave reflection seismic methods are useful for detailed characterization of breaches through confining units, especially where suitable borehole log and hydraulic data are available.

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