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Seismotectonic implications of sand blows in the southern Mississippi Embayment

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Abstract

We explore seismically-induced sand blows from the southern Mississippi Embayment and their implications in resolving the question of near or distal epicentral source region. This was accomplished using aerial photography, field excavations, and cone penetration tests. Our analysis shows that three sand blow fields exhibit a distinct chronology of strong ground motion for the southern embayment: (1) The Ashley County, Arkansas sand blow field, near the Arkansas/Louisiana state border, experienced four Holocene sand venting episodes; (2) to the north, the Desha County field experienced at least three episodes of liquefaction; and (3) the Lincoln–Jefferson Counties field experienced at least one episode. Cone penetration tests (CPT) conducted in and between the sand blow fields suggest that the fields may not be distal liquefaction associated with New Madrid seismic zone earthquakes but rather are likely associated with strong earthquakes on local faults. This conclusion is consistent with the differences in timing of the southern embayment sand venting episodes and those in the New Madrid seismic zone. These results suggest that active tectonism and strong seismicity in intraplate North America may not be localized at isolated weak spots, but rather widespread on fault systems that are favorably oriented for slip in the contemporary stress field.

Keywords: Paleoseismology; Liquefaction; Intraplate; Mississippi Embayment; Earthquake magnitude

1. Introduction

Reducing earthquake loss in the central and eastern United States, as with other intraplate regions, is complicated by the relatively long recurrence intervals for strong ground motion. Large damaging earthquakes are not a part of the disaster memory of engineers, planners, policy makers, or of the public. The New Madrid seismic zone (NMSZ) of the northern Mississippi Embayment (Fig. 1) is the area of greatest intraplate seismic activity in North America (Johnston, 1989; Johnston and Schweig, 1996; Schweig and Van Arsdale, 1996; Frankel et al., 2002), and although the NMSZ vicinity has been the site of extensive investigations of intraplate deformation and associated seismic hazard, its seismic sources and their driving mechanism remain poorly understood (for a review of ideas on NMSZ driving mechanisms see Cox et al., 2006). Field studies related to the location and timing of strong Quaternary earthquakes in the central

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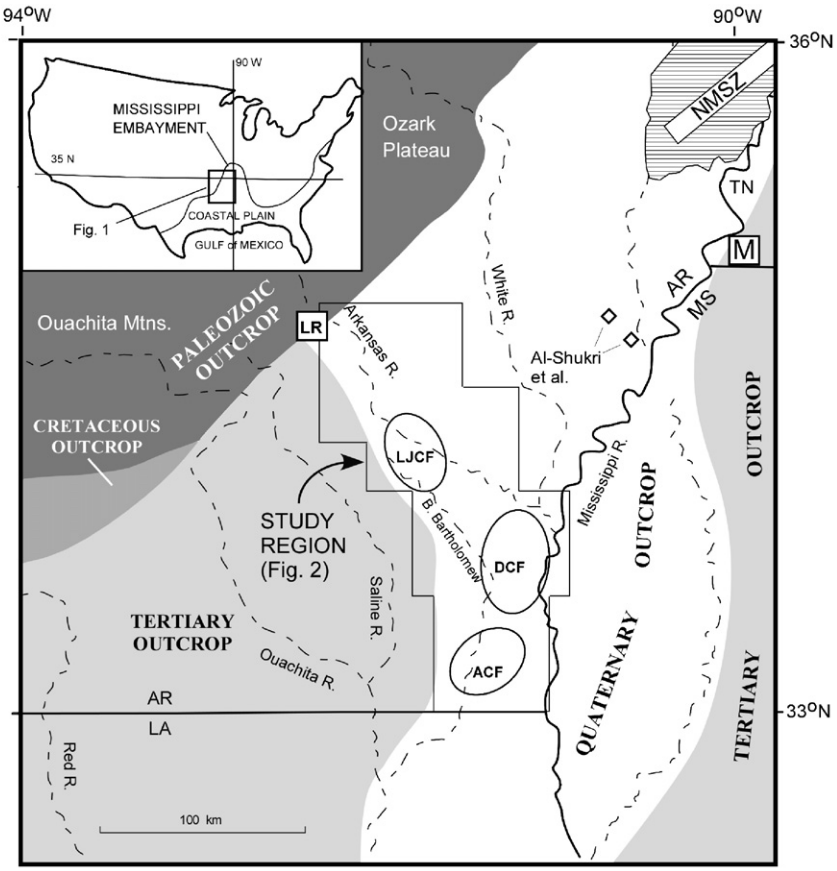

Fig. 1. Regional map showing the geologic and structural/tectonic setting of the study area in the southern Mississippi Embayment. Generalized surficial geology of the region. Ellipses denote southern embayment sand-blow fields: ACF = Ashley County field; DCF = Desha County field; LJCF = Lincoln/Jefferson Counties field. NMSZ = New Madrid seismic zone. Horizontally ruled area shows sand-blow field of the NMSZ. Diamonds show liquefaction trenching sites of Al-Shukri et al. (2005). M = Memphis, Tennessee; LR = Little Rock, Arkansas.

U.S. beyond the limits of the NMSZ are required to understand and constrain the long-term seismotectonics across this intraplate setting. To the north of the NMSZ in southern Illinois and Indiana (where historic seismicity has been <M5.5), a significant body of paleoseismological work documents numerous M6 to M7+ Late Pleistocene and Holocene earthquakes (Obermeier et al., 1991; Munson et al., 1992; Obermeier et al., 1993; Munson et al., 1995; Munson and Munson, 1996; Munson et al., 1997; Pond and Martin, 1997; Obermeier, 1998), but few paleoseismic data are available south of the NMSZ (Cox et al., 2004a; Al-Shukri et al., 2005; Tuttle et al., 2006). The field data presented herein help fill a void in the regional datasets of paleoearthquakes the southern Mississippi Embayment.

The southern embayment is characterized by only moderate historic seismicity (<M4.5), but it has a strong signature of tilt-block tectonics active throughout the Quaternary (Schumm et al., 1982; Burnett and Schumm, 1983; Cox, 1994). The data we present herein and our estimates of the timing, spatial extent, magnitude range, and probable sources of strong ground motion associated with sand blow fields in the southern embayment are important to the assessment of the driving mechanisms of strong seismic sources in the mid-continent (including the NMSZ). For example, passage of a continental ice-sheet fore bulge following a glacial retreat has been suggested as one mechanism of stress perturbation consistent with Late Pleistocene and Holocene timing of strong historic earthquakes and paleoseismicity in the upper Mississippi Embayment (Grollimund and Zoback, 2001), and the paleoseismicity of southern Indiana and Illinois may be readily accommodated by this driving mechanism. However, recognition of strong paleoseismicity in the southern embayment significantly farther from the ice margin may require that another mechanism is driving seismicity in the mid-continent in addition to or instead of glacial fore-bulge passage.

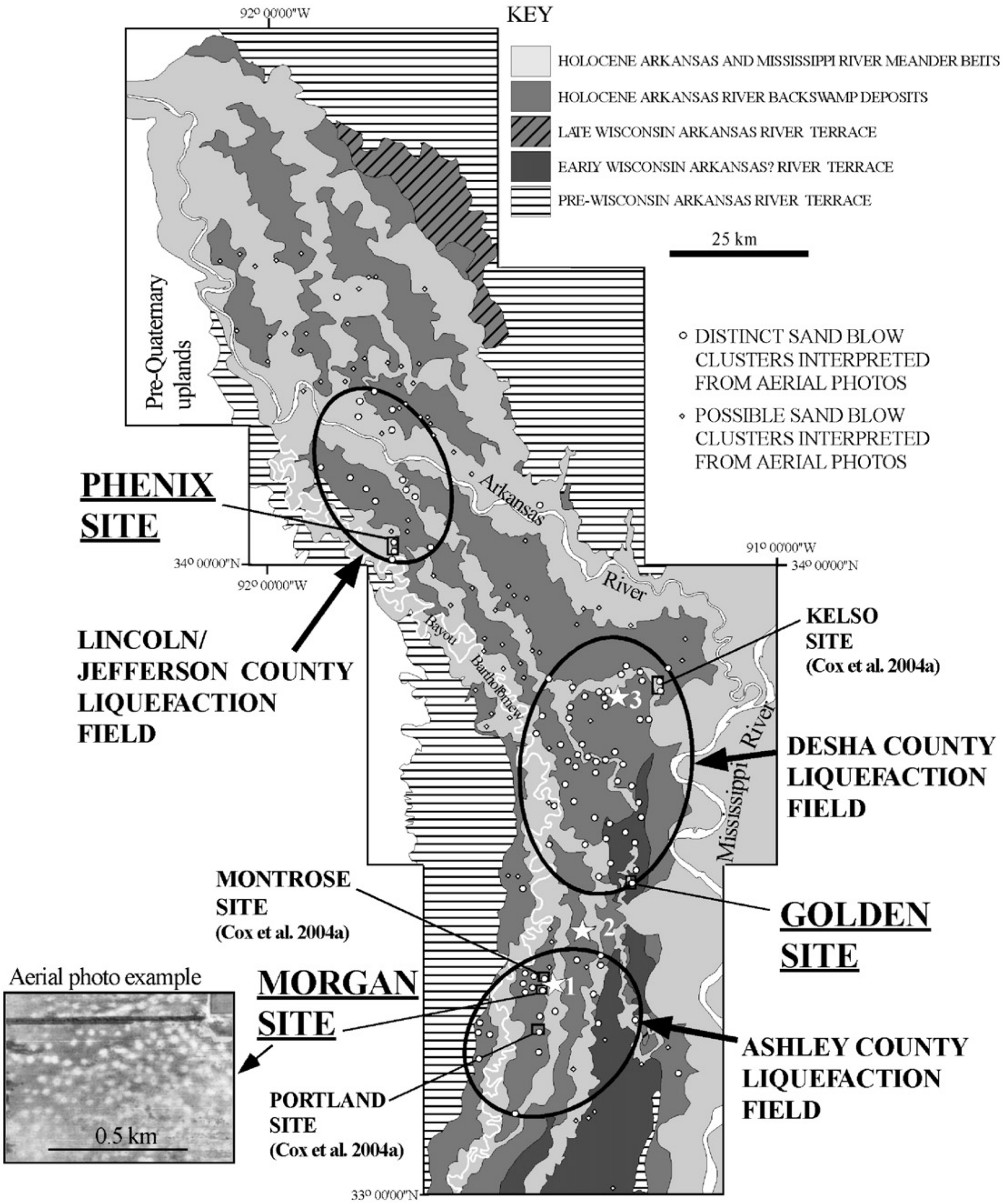

Fig. 2. Quaternary geology of the alluvial valley of the Arkansas River in southeast Arkansas (after Saucier, 1994). Each open circle denotes a section (640 acres) that contains circular to elliptical, light tonal anomalies on aerial photography that are characteristic of sand blows (circles denote many distinct anomalies; small diamonds denote few or vague anomalies). These anomalies have been shown to be liquefaction bodies of vented sand at the trench sites on the map (Cox et al., 2004a). Localities described in this report are underlined. Numbered stars denote localities of cone penetration test soundings (Fig. 9): 1 = AHY001 to AHY004; 2 = CCT001; 3 = DSA001 to DSA003.

To investigate the paleoseismicity of the southern Mississippi Embayment we examined circular to elliptical sand bodies that occur in three large areas (each ≥ 500 km^2) (Figs. 1 and 2): 1) the Ashley County field; 2) the Desha County field; and 3) the Lincoln–Jefferson Counties field. Previous field investigations (Cox, 2002; Cox and Larsen, 2004; Cox et al., 2004a) have shown these features to be Holocene and to conform to criteria for recognition of sand vented during seismically-induced liquefaction (sand blows) (for a review of these criteria see Obermeier et al., 2005). For example, blow sand overlies and is connected to sand dikes up to 0.5 m wide, some minor dikes branch upward, taper upward, and/or pinchout upward, and entrained clasts of dike host strata within sand dikes and dish structures of clay laminae near sand vents indicate upward sand transport. These sand blows have approximate dimensions of 1 m thick and 10 to 30 m across.

Sand blows and other liquefaction features provide evidence of strong ground motion, and delineating the extent and timing of such features reveals a chronology and frequency of earthquake occurrence in a region. Often however, determining the source of the strong ground motion is unclear where a distant, great event or a local smaller earthquake may both account for similar spatial patterns in sand blow distribution. These southern embayment liquefaction fields are ≥175 km southwest of the southern margin of the recognized liquefaction field of the NMSZ and ≥300 km southwest of the epicenters of the earthquakes responsible for the NMSZ sand blows. Southern embayment sand blows urge the question: are these far-field NMSZ liquefaction features or is there a local source generating strong ground motion in the southern embayment? Building on our previous investigations this work expands a chronology of strong ground motion in the southern Mississippi Embayment and provides additional geologic, geotechnical, and age data related to the location of strong Quaternary earthquakes in the mid-continent beyond the limits of the NMSZ.

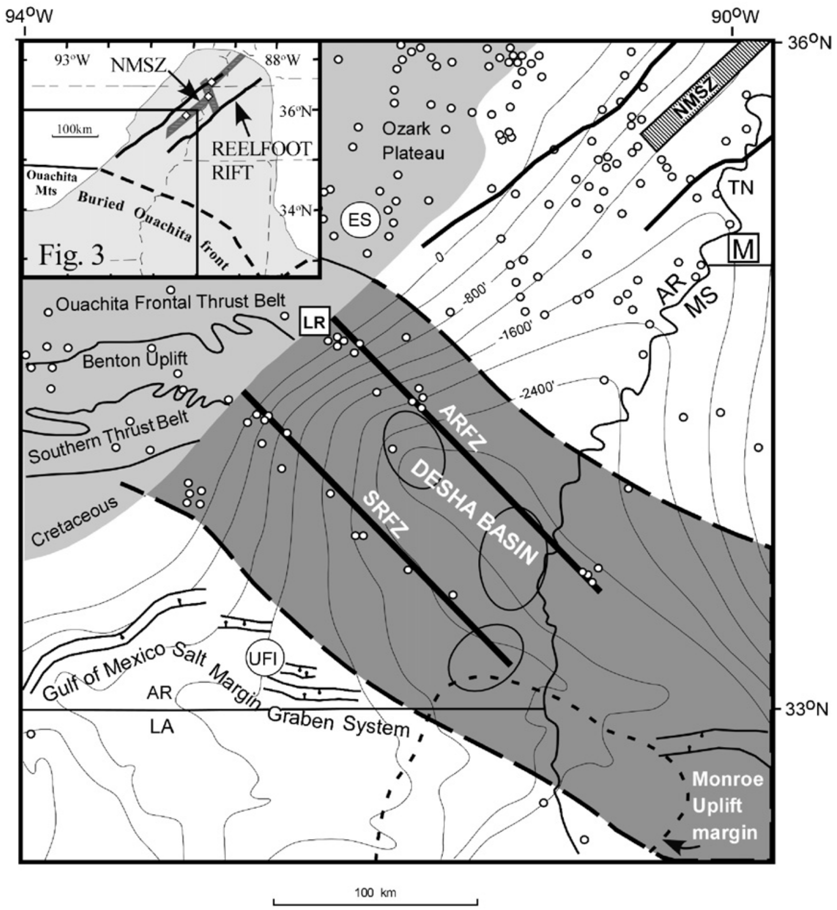

Fig. 3. Generalized structural and tectonic elements of the region. Structural contours are sub-sea elevations on the basal unconformity of the Mississippi Embayment sedimentary fill. Dark shading shows the location of the buried Paleozoic Ouachita thrust belt. Small circles are epicenters (historical and instrumental events through 2005, NCEER, ANSS, NEIC, and CERI earthquake catalogs). Individual epicenters are not shown for the New Madrid seismic zone (NMSZ), the Enola swarm (ES), and an area of earthquakes induced by underground fluid injection (UFI). SRFZ = Saline River fault zone; ARFZ = Arkansas River fault zone. Large ellipses denote liquefaction fields (see Fig. 2). M = Memphis, Tennessee; LR = Little Rock, Arkansas. Inset shows the proximity of the study area to faults defined by the NMSZ and to the Reelfoot Rift (Hildenbrand et al., 1982; Frankel et al., 2002). Diamonds denote estimated epicenters of the three largest events of the 1811–1812 NMSZ earthquake sequence (Johnston and Schweig, 1996).

2. Geology of study region

2.1. Surficial geology

This study was conducted within Holocene sediments of the lower Arkansas River valley (Figs. 1 and 2), where linear meander belt sands separated by backswamp deposits comprise a uniform alluvial architecture that persists from Little Rock (where the Arkansas River exits the Paleozoic outcrop) to the Arkansas/Louisiana state line (where the Holocene valley is constricted between Pleistocene terraces). With the exception of the active meander belt of the Arkansas River in the north of the study area, these Holocene sediments were deposited by former courses of the Arkansas River, and these abandoned courses are now occupied by smaller, sluggish streams ("bayous") or filled with slack-water clays and silts ("sloughs"). No significant tributary streams contribute alluvium to the Arkansas River valley within the study area.

Saucier (1994) identifies six separate Holocene meander belts within the lower Arkansas River valley, and sedimentary facies of each of these meander belts are alike. Within each belt, sand bodies deposited as point-bars, natural levees, and crevasse splays along former meander belts are typically 5 to 10 m thick and may be overlain by as much as 10 m of overbank silts and clays from adjacent younger meander belts (Bedinger and Reed, 1961). Sediment fill in oxbow cutoffs (as much as 13 m) and meander scroll swales (1 to 5 m) is primarily clays and silty sands. Backswamp deposits between meander belts typically consist of five to eight meters of silty clays and clays. Coarse sands and gravels presumed to be Pleistocene glacial meltwater deposits ("valley train" deposits) are encountered below Holocene sediments at a depth of approximately 20 meters. Quaternary alluvium is underlain by Eocene marine and deltaic units of the Jackson and Claiborne Groups that include sands, silts, clays, lignites, and marls (Wilbert, 1953; Bedinger and Reed, 1961; Saucier, 1994).

2.2. Structure and tectonics

The NMSZ in the northern Mississippi Embayment (Fig. 1) is related to the buried early Paleozoic Reelfoot

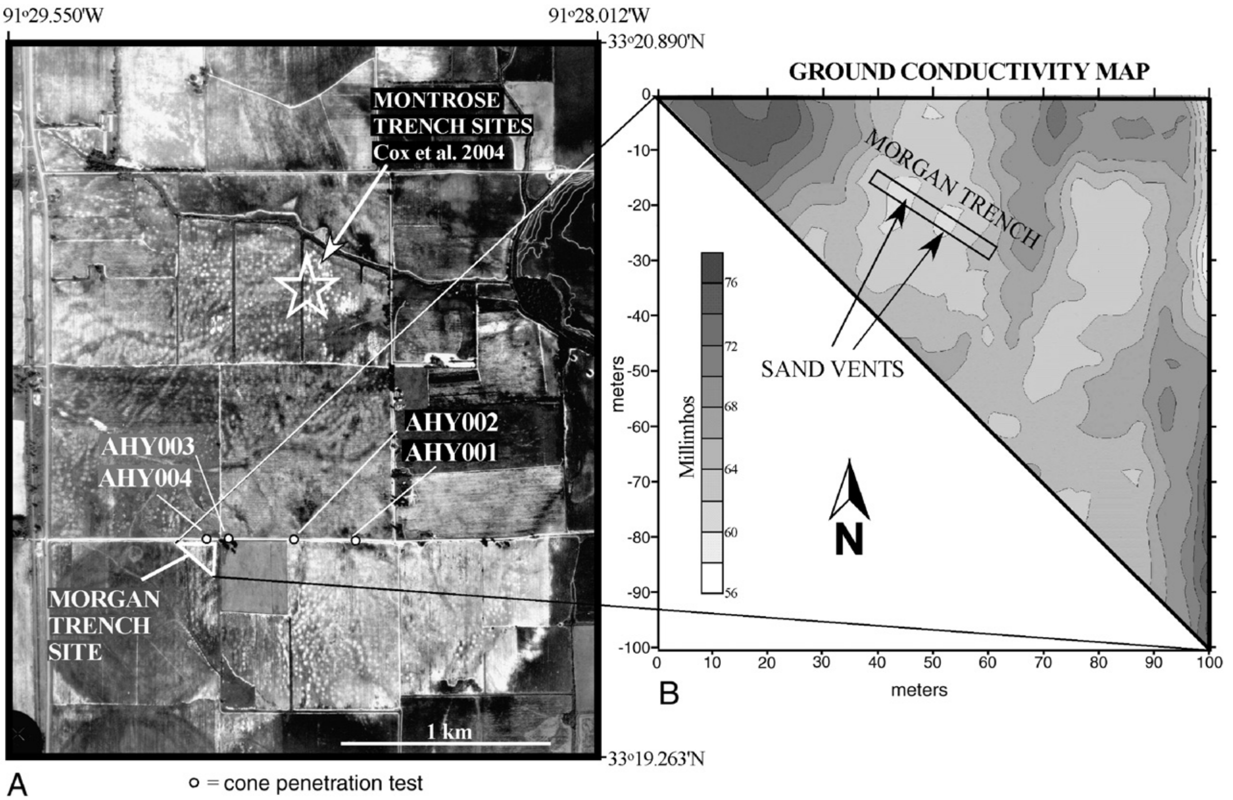

Fig. 4. Morgan site in the Ashley County sand blow field (see Fig. 2 for location). A) Aerial photo of the site and vicinity shows densely-spaced sand blows that appear to be aligned along buried paleo-crevasse splay channels. B) A ground conductivity map of site, showing sand blow vents and deposits as low value anomalies, was used to site the trench. AHY001 to AHY004 denote cone penetration test soundings (see Fig. 9).

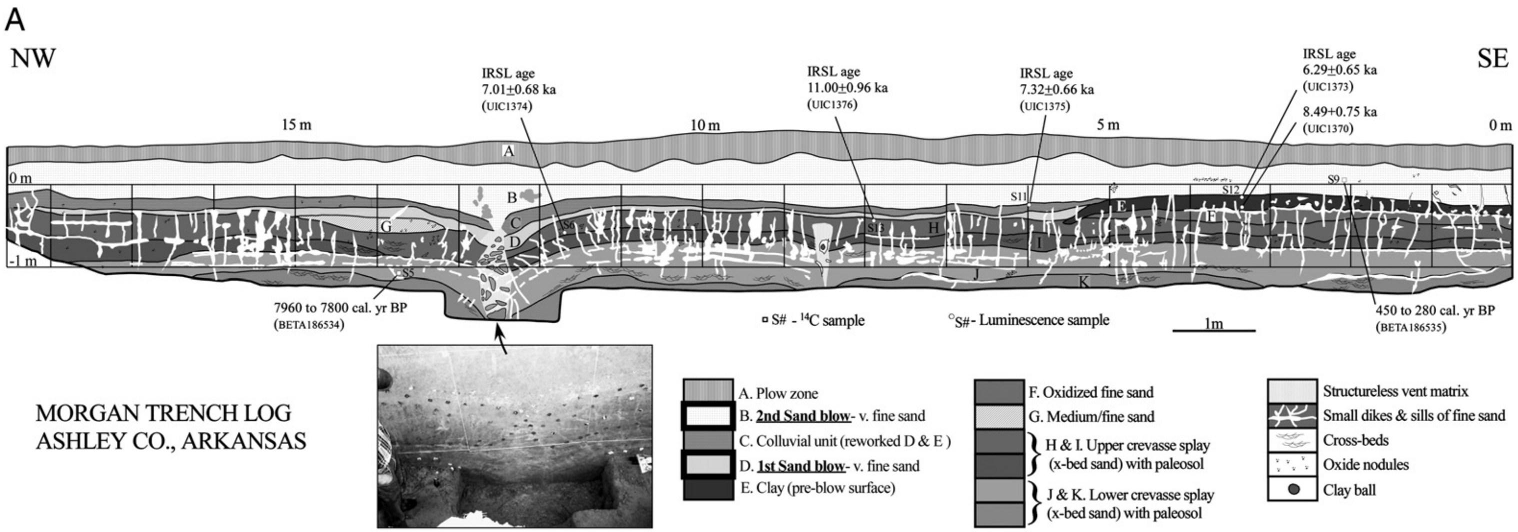

Fig. 5. A) Log of northeast trench wall at the Morgan site, northern Ashley County field showing at least two sand-venting episodes. Inset is a photograph of the principal vent at meter 12 to 13. The opposite wall was beveled and not logged. Radiocarbon and IRSL age data are listed in Tables 1 and 2. B) Soil profile at the southeast end of the Morgan trench.

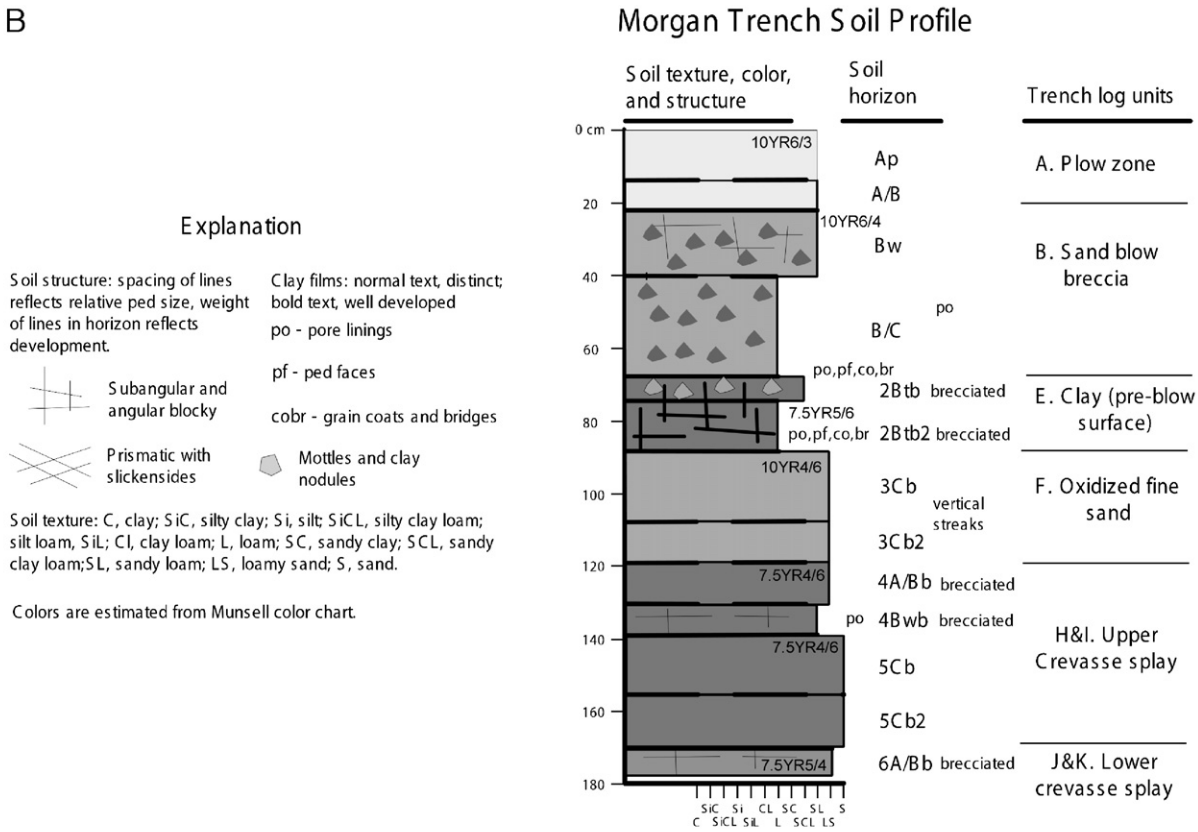

Fig. 5 (*continued*).

rift (Fig. 3). The Mississippi Embayment geologic province is a broad, southwest-plunging trough filled with Late Cretaceous and early Tertiary fluvio-marine sediments and Pliocene and Quaternary fluvial sediments (Ervin and McGinnis, 1975; Kane et al., 1981; Braile et al., 1997; Cox and VanArsdale, 1997, 2002). Patterns of microseismicity in the southern embayment are poorly understood because the region is outside the low-magnitude detection range of the seismic networks operating in the Central and Eastern United States. However, moderate seismicity in the southern embayment shows alignments and clusters (Fig. 3) that, together with a strong geomorphic signature of neotectonism (Schumm et al., 1982; Burnett and Schumm, 1983; Cox, 1994), suggest seismogenic structures. Information on basement structure of the southern embayment is limited because well log control is sparse and few seismic surveys have been published. Mesozoic and Cenozoic sediments of the southern embayment bury the late Paleozoic Ouachita orogen (Fig. 3), characterized by southeast-striking, fault-bounded blocks of marine Paleozoic rocks. This orogenic belt controlled the structural grain of the southern embayment during initial rifting of the Gulf of Mexico basin and later subsidence of the embayment (Thomas, 1989; Viele and Thomas, 1989).

3. Methods

Seismically-induced liquefaction causes sand intrusions and eruptions (“dikes” and “blows”) which result from an increase of pore pressures to near-lithostatic conditions in saturated sand at less than 30 m depth both during and immediately after a strong earthquake (Holzer et al., 1989). Field inspection of sand dikes and blows and age analysis of related deposits have been highly successful for the establishment of a chronology of strong paleoseismicity in the eastern U.S. (e.g., Obermeier et al., 1985, 1990, 2002, 2005; Talwani, 1989, 1996; Munson et al., 1992, 1995, 1997; Munson and Munson, 1996; Tuttle and Schweig, 1996; Tuttle et al., 1998, 2002; Tuttle, 2001). Following previously successful field practices for the southern embayment (Cox et al., 2004a), target excavation sites were selected from vintage air photos and then characterized by field inspection, ground conductivity surveying, push coring, and hand augering. If a site seemed suitable for finding

Table 1
Results of ^{14}C analyses

Sample	Lab No. [a]	Sample Material	Technique	Radiocarbon age ±1σ yr BP	$\frac{^{13}C‰}{^{12}C}$	Calibrated 2σ age yr BP	Mid-point 1σ age on Fig. 12
Morgan							
M03-C5	186534	Organic sediment	AMS	7070±40	−24.7	7960 to 7800	7890
M03-C9	186535	Organic sediment	AMS	280±40	−23.1	450 to 280	360
Golden							
G03-C1	183652	Organic sediment	AMS	100.71±0.38 [b]	−27.6	N/A	N/A
G03-C2	183653	Organic sediment	Radiometric	340±50	−25.0 [c]	510 to 290	410

[a] All analyses conducted by BETA Analytic, Inc., Miami, Florida. See Figs. 5 and 7 for sampling locations within Golden and Morgan trenches, respectively.

[b] Reported result indicates an age of post 0 yr BP and has been reported as a % of the modern reference standard, indicating the material was living within the last 50 years.

[c] A $^{13}C/^{12}C$ was estimated as −25.0‰ based on typical sediment values in the region.

liquefaction deposits (i.e., there is a near-surface capping unit of alluvial or pedogenic clay and agricultural modification is minimal), we evaluated the areal extent of sand blows by making ground conductivity maps using a Geonics EM-31 (e.g., Fig. 4). An electrical ground conductivity survey of a portion of a sand blow field will define the limits of near surface (<4 m deep) sand blows that may be buried beneath alluvium or obscured by agricultural modification. A conductivity anomaly that extends beyond exposed sand indicates a composite sand blow that has soil development or overbank alluvium (valuable for age analysis) over the older parts of the deposit. Trenches were sited to transect low conductivity anomalies (sand bodies) and minimum values (sand vents below blow deposits).

Sand blows were excavated by backhoe, and trench walls logged in detail to establish the stratigraphic relationships of vented liquefaction deposits to alluvial deposits and to modern and buried soil horizons. Organic-rich soil units, along with wood and charcoal from substrate units, were collected for radiocarbon age analysis. In addition, buried silt and/or sand units were sampled for infrared stimulated luminescence (IRSL) age analysis. (For an in-depth discussion of protocol for IRSL sample collection see Forman et al., 2000). Radiocarbon analyses and luminescence analyses were

Table 2
Results of infrared stimulated lumunescence age analyses

Sample	Lab No. [a]	Equivalent Dose (Gy)	U (ppm)	Th (ppm)	K (%)	Dose Rate (Gy/ky)	IRSL age ±1σ (yr)	Comment [b]
Morgan								
M03-12B	UIC1370	31.31±0.74	2.40±0.44	9.22±1.26	2.19±0.02	3.82±0.20	8490±750	Underlying deposit Unit E
M03-12A	UIC1373	23.80±0.18	2.88±0.45	8.65±1.22	1.99±0.02	3.79±0.20	6285±560	Buried soil Unit E
M03-6B	UIC1374	34.46±0.12	3.48±0.68	15.20±1.96	2.09±0.02	4.91±0.33	7010±680	Buried soil Unit H
M03-11A	UIC1375	26.24±0.20	2.20±0.50	10.42±1.48	2.15±0.02	3.59±0.20	7320±660	Buried soil Unit C
M03-13A	UIC1376	38.01±0.44	2.41±0.40	7.47±1.11	2.09±0.02	3.46±0.17	11,000±960	Buried soil Unit H
Golden								
G03-6A	UIC1369	32.20±0.24	2.40±0.44	9.22±1.26	2.19±0.02	3.82±0.20	8490+750	Buried soil Unit F
G03-10A	UIC1371	30.66±0.31	3.04±0.47	8.32±1.34	2.00±0.02	3.83±0.20	8010+730	Buried soil Unit F
G03-10B	UIC1372	35.03±0.27	2.68±0.42	10.98±1.61	2.28±0.02	4.29±0.25	8170+750	Underlying deposit Unit F

Analyses were conducted on the 4–11 μm fraction under 880 nm stimulation following Singhvi et al. (1982) and Forman and Pierson (2002). Each sample had 15±5% moisture content.

[a] All analyses were conducted at the Luminescence Dating Research Laboratory, Department of Earth and Environmental Sciences, University of Illinois at Chicago (UIC). See Figs 5 and 7 for sampling locations within Golden and Morgan trenches, respectively.

[b] Buried soil horizon ages are interpreted as maximum limiting ages of surface exposure (i.e., age of burial by sand venting). Underlying deposit ages are interpreted as maximum limiting ages of sediment deposition. These ages are maximum estimates because they may have a component of inherited IRSL signal.

preformed at Beta Analytic, Inc, Miami, Florida and Luminescence Dating Research Lab, University of Illinois, respectively. Soil stratigraphic analysis has been found to be useful for establishing relative age relationships during paleoseismic studies (Munson and Munson, 1996; McCalpin and Nelson, 1996; Birkeland, 1999) and was used in our study to estimate the relative age of vented sand deposits for which numerical ages are poorly constrained. Field and laboratory data collected include soil color, texture, structure, pH, organic carbon content, and carbonate content.

In late 2004, the U.S. Geological Survey (USGS) CPT (Cone Penetration Test) truck collected data to a depth of 20 m in the Ashley County and Desha County sand blow fields and in an area without sand blows between the two sand blow fields. The CPT measured cone tip resistance and sleeve friction on a cylinder driven into the ground. In addition, shear-wave velocities were measured at 2 m depth intervals. Sediment horizons were assessed with respect to susceptibility to liquefaction using the Seed–Idriss simplified procedure (Youd et al., 2001) and the liquefaction potential index (LPI) of Toprak and Holzer (2003). Together, the CPT data and the shear-wave velocities were used to estimate the peak ground accelerations and earthquake magnitudes required to liquefy susceptible sediments and vent them to the surface.

4. Results

In this phase of the study, additional trenching built upon our preliminary investigations of two large areas (≥ 500 km^2) of intense sand venting (the Desha County field and the Ashley County field, Figs. 1 and 2) in the southern Mississippi Embayment (Cox et al., 2004a). Vintage 1937 to 1980 aerial photography of non-forested Holocene and late Pleistocene surfaces of the Arkansas and Mississippi Rivers in southeastern Arkansas was inspected for light tonal anomalies characteristic of sand venting associated with seismically generated liquefaction; in particular circular and elliptical anomalies were sought that are characteristic of discreet sand blows (see photo inset on Fig. 2). (Linear sand blows can be confused with fluvial sand deposits.) The densest clustering of such circular anomalies was found in eastern Ashley County, Arkansas, and two other fields of more sparsely

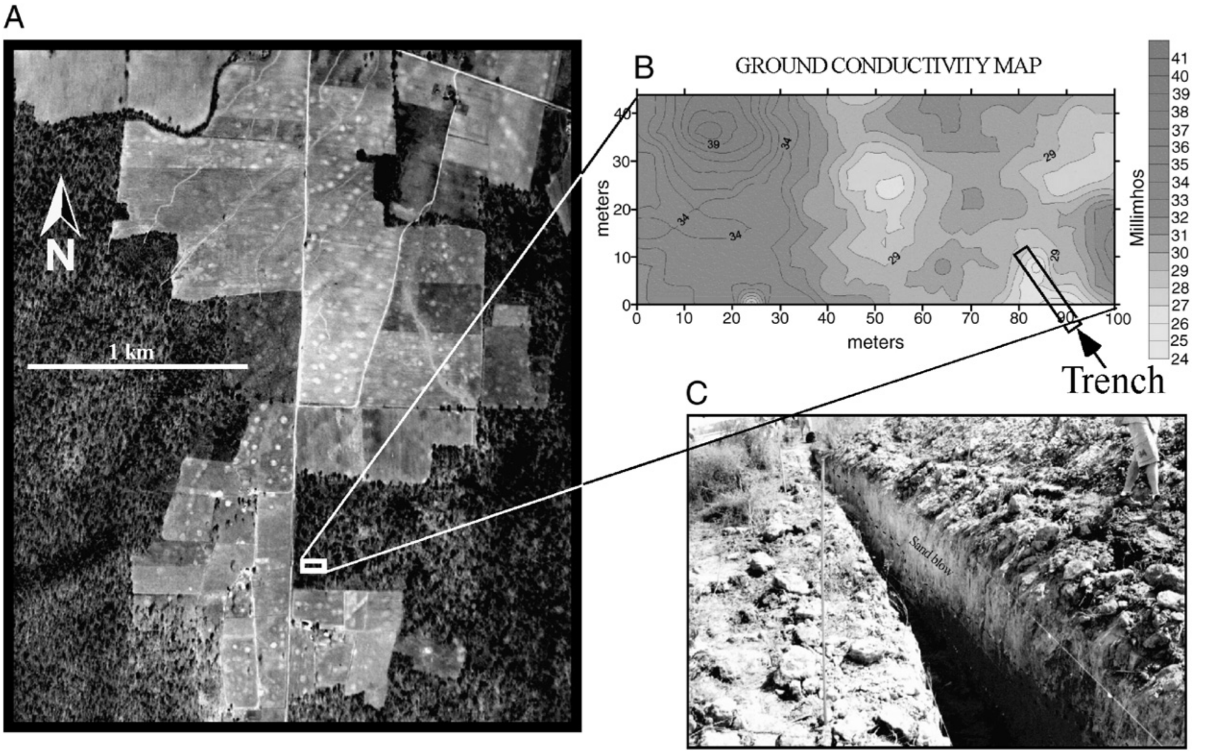

Fig. 6. Golden site near Halley, AR in the southern part of the Desha County sand blow field (see Fig. 2 for location). A) Aerial photo of the site and vicinity showing sand blows aligned along buried crevasse splay channels. B) Ground conductivity map of site showing low value anomalies of sand blows (this spot has been cleared of trees since aerial photo). Two strong low anomalies (center and lower right margin) indicate sand blows. We chose to trench the anomaly at the margin because values were lower. C) Photo of Golden trench showing champaign-glass shaped sand blow.

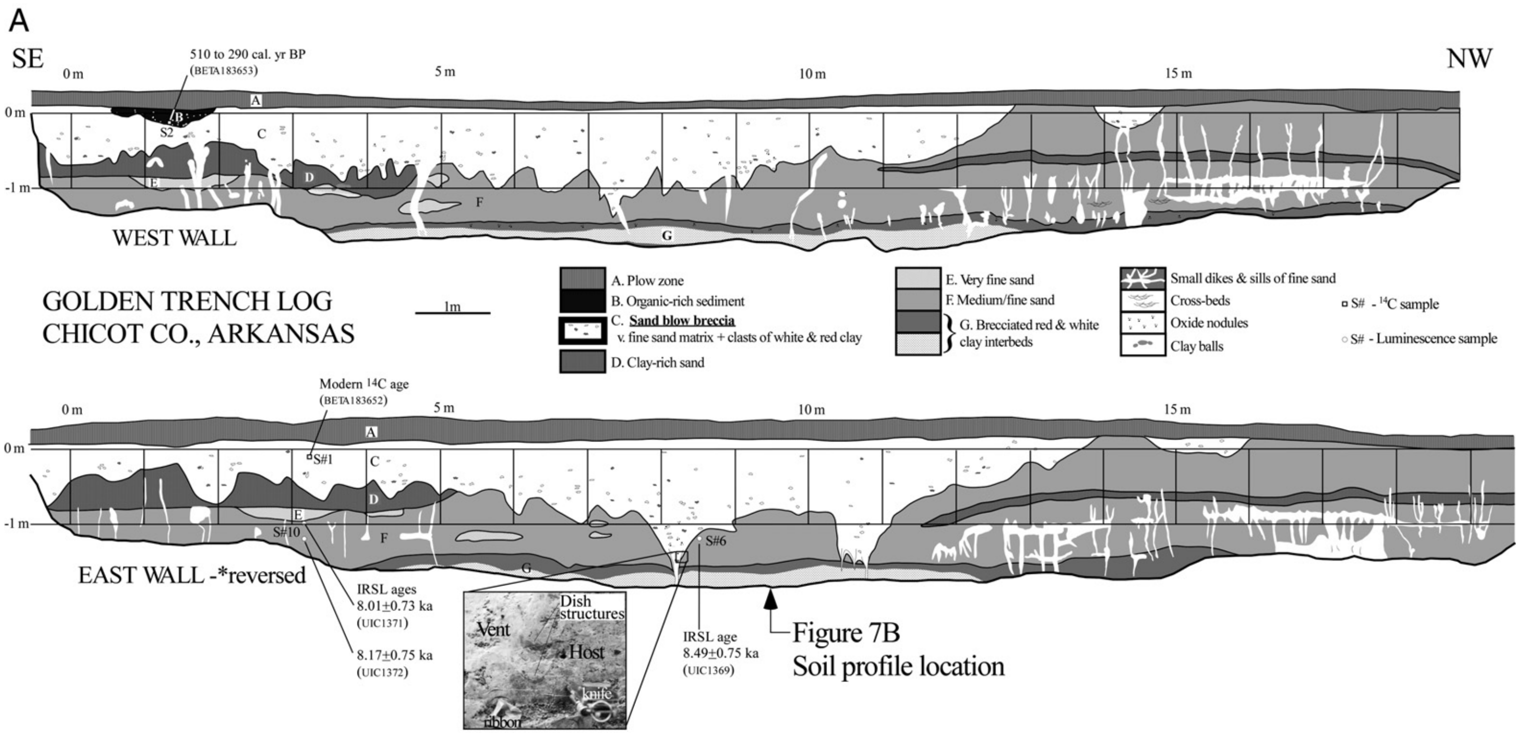

Fig. 7. A) Logs of trench walls at the Golden site showing at least one sand-venting episode. Note that the east wall (bottom log) has been reversed for ease of comparison to the west wall. Inset is a photograph of clay laminae "dish" structures indicating water escape at a sand vent (Lowe and LoPiccolo, 1974). Radiocarbon and IRSL age data are listed in Tables 1 and 2. B) Soil profile at the southeast end of the Golden trench.

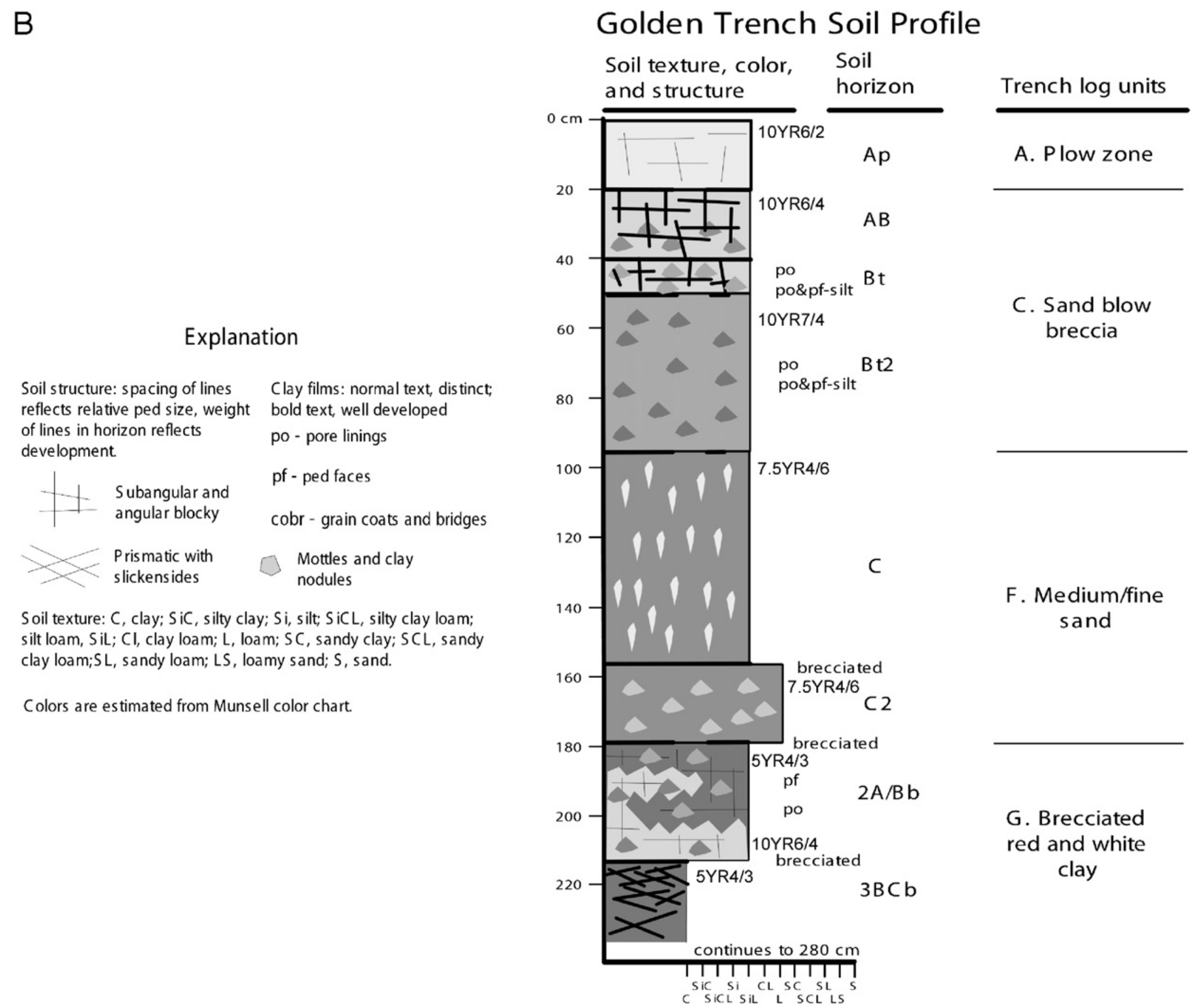

Fig. 7 (*continued*).

distributed anomalies were identified in Desha County and in Lincoln and Jefferson Counties (Fig. 2). Results of preliminary investigations in Ashley County and Desha County fields are reported in Cox et al. (2004a). On field inspection of these areas, the tonal anomalies were found to be surficial bodies of fine sand (~1 m thick), and trenching revealed the sand of each blow had been vented through multiple dikes. The sand blows typically range from 10 to 30 m in diameter and occur on overbank clays that bury sands of natural levees and crevasse splays of abandoned late Holocene courses of the Arkansas River. The absence of man-made levees precludes that this sand was extruded by sub-levee seepage, and the extremely low topographic relief of the meander belt precludes that sand was vented during artesian flow of groundwater driven by hydraulic head. Herein we report new observations from trenching at two sites, ground conductivity surveys at three sites, and cone penetration tests at three sites.

4.1. Ashley County, Morgan trench

Morgan trench site is located near Montrose, Arkansas just off of US highway 165 at 33°19.801′ N, 91°29.077′ W about1.3 km south of trenches previously excavated and reported upon (Montrose trenches of Cox et al., 2004a). A ground conductivity survey of the Morgan trench site (Fig. 4) revealed elliptical low-value anomalies consistent with sand blows. The Morgan trench (Fig. 5) exposed a principal vented deposit of loose fine sand with a weak Bw soil (unit B, Fig. 5) underlain by a colluvial clayey sand (unit C) that in turn is underlain by an older vented fine sand (unit D). A principal sand vent (35 cm-wide, Fig. 5A, inset photograph) and many subsidiary sand dikes (<5 cm-wide) were linked to the two sand blows and to many minor sand sills. Stratigraphy had subsided ~50 cm at the principal vent. However, 10 cm coherent blocks of substrate (units J and K) had been transported upward ~45 cm in a matrix of fine sand in the principal vent dike (Fig. 5A, inset photograph). Sediments underlying the vented sand comprise alternating sandy and sandy clay deposits associated with crevasse splay alluvial deposition. The clay-rich intervals are typically broken or brecciated, presumably from liquefaction processes. Weakly to moderately developed buried soil profiles are present in the crevasse splay deposits (Fig. 5B), and pedogenic modification is best developed in the finer grain parts of the crevasse–splay alternations, whereas the sandy portions are either massive or retain depositional structures (ripple cross-lamination). In general, the trench stratigraphy reflects a dominance of alluvial processes over soil development.

Timing of sand venting is constrained by a ^{14}C age of 450 to 280 cal. yr BP (meter 2) from the upper sand blow deposit and a ^{14}C age of 7960 to 7800 cal. yr BP (meter 14) from the crevasse splay deposits near the base of the trench (Fig. 5A, Table 1). IRSL ages of surfaces buried by the upper and lower sand blows are ~6300 yr BP (meter 3) and ~7000 yr BP (meter 12), respectively (Fig. 5A, Table 2). These IRSL ages are compatible with our ^{14}C ages and similar to those from alluvium buried by sand blows at the Montrose site of Cox et al. (2004a). Samples yielding older IRSL ages at meters 6 and 8 may have incorporated reworked vented material. We intrepret the Morgan site blows to be coeval with the earliest two sand blows at the Montrose site (Fig. 4).

4.2. Desha County, Golden trench

Golden trench is located in the southern part of the Desha County sand blow field near Halley, Arkansas on Lester Golden Road at 33°29.199′ N, 91°18.325′ W. As at the Morgan site, a ground conductivity survey (Fig. 6) revealed low-value elliptical anomalies consistent with sand blows. The Golden trench exposed a principal vented deposit of brecciated clay clasts suspended in a fine sand matrix having a weak Bt soil (unit C, Fig. 7). This blow, a champagne glass shape in cross-section (Fig. 7A), was fed by several dikes (~5 cm wide) that extend downward through a clay unit at the base of the

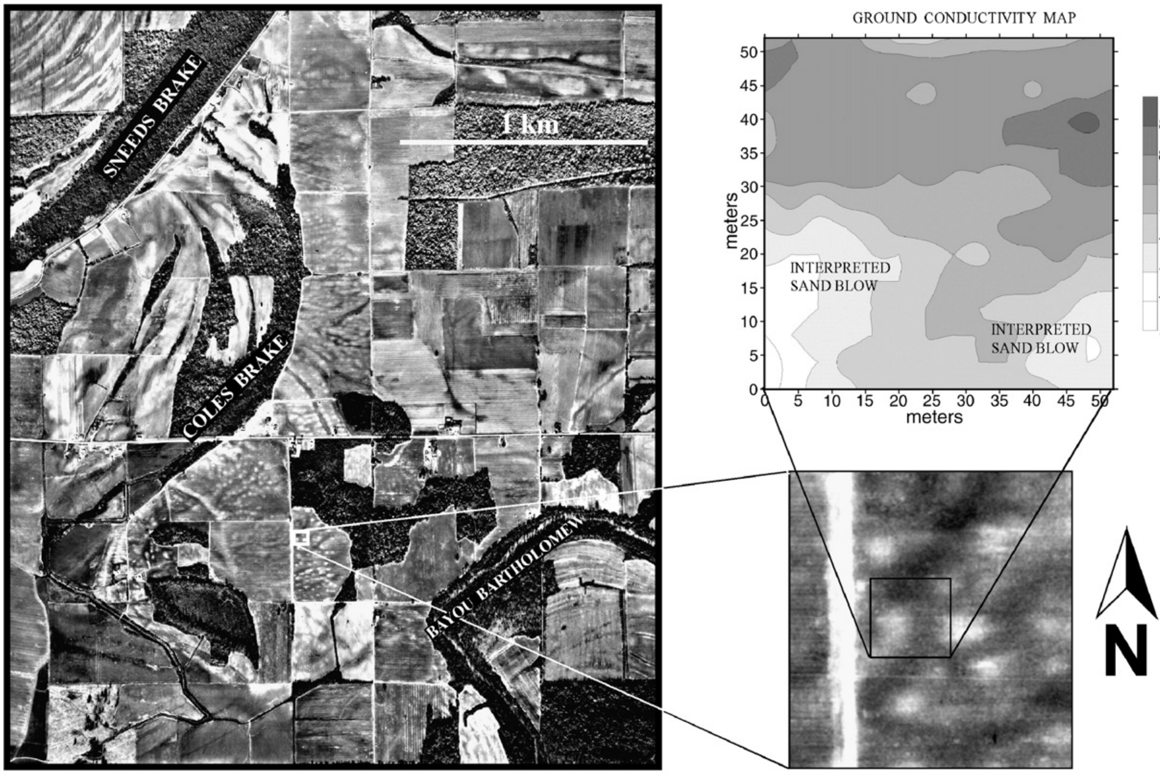

Fig. 8. Aerial photograph and ground conductivity map showing sand blows near Phenix, AR in the southern part of the Lincoln/Jefferson County sand blow field (see Fig. 2 for location). We have not excavated a trench in this field.

trench (unit G, Fig. 7A) that is the source of the clay clasts. Unit G is brecciated around the primary feeder dikes, and we interpret unit G as the capping clay that was hydraulically fractured during ground shaking. Dish structures near sand vents indicate upward water escape (e.g., Fig. 7A, inset photograph). A weak buried soil

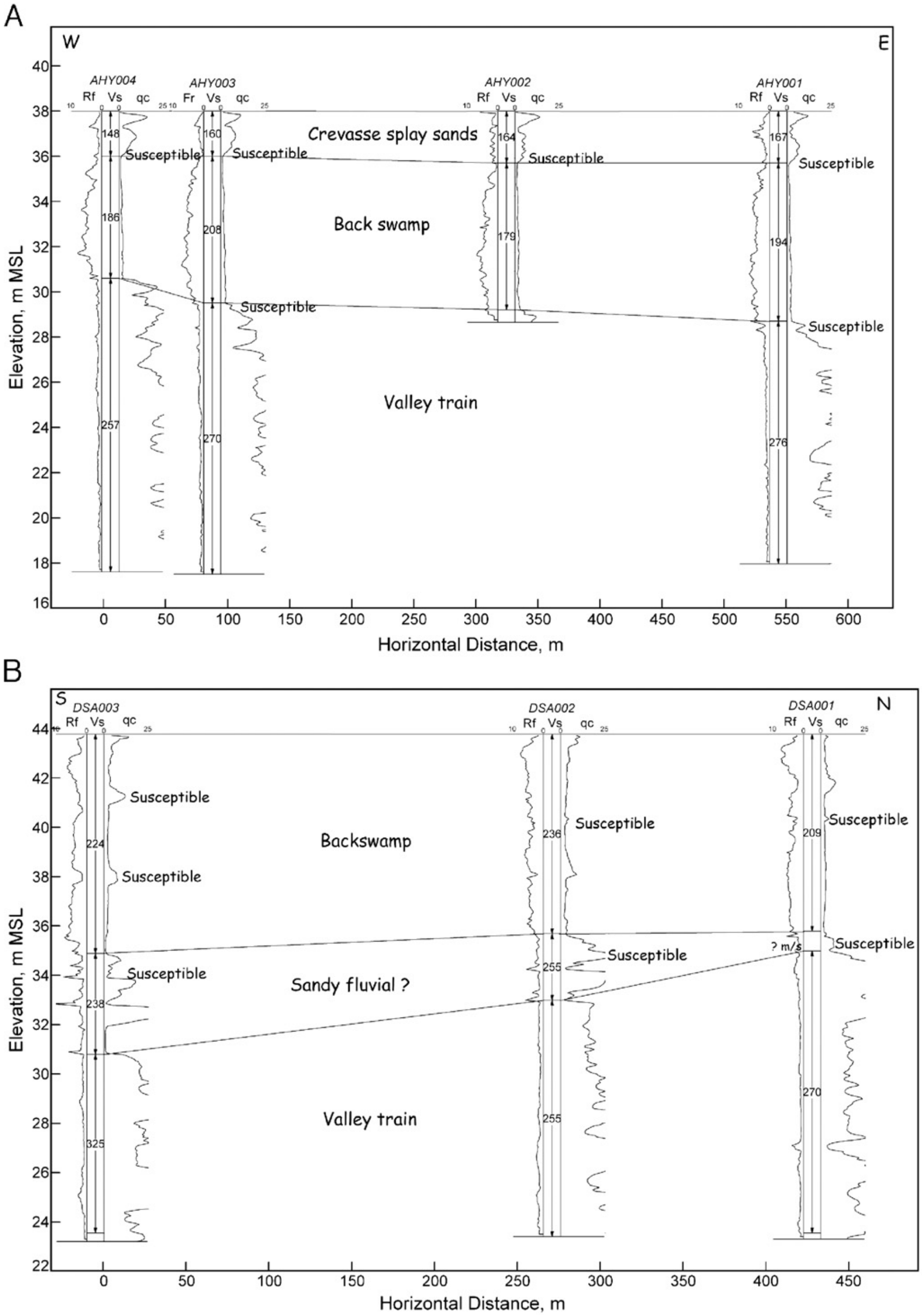

Fig. 9. Cone penetration test soundings (See Figs. 2 and 4 for locations of soundings). A) Ashley County cross section based on CPT's. The west end of the Ashley County sounding transect is at the Morgan trench site. B) Desha County cross section based on CPT's. Rf is friction ratio (%), Vs is shear wave velocity (m/s), and qc is tip resistance (MN/m^2).

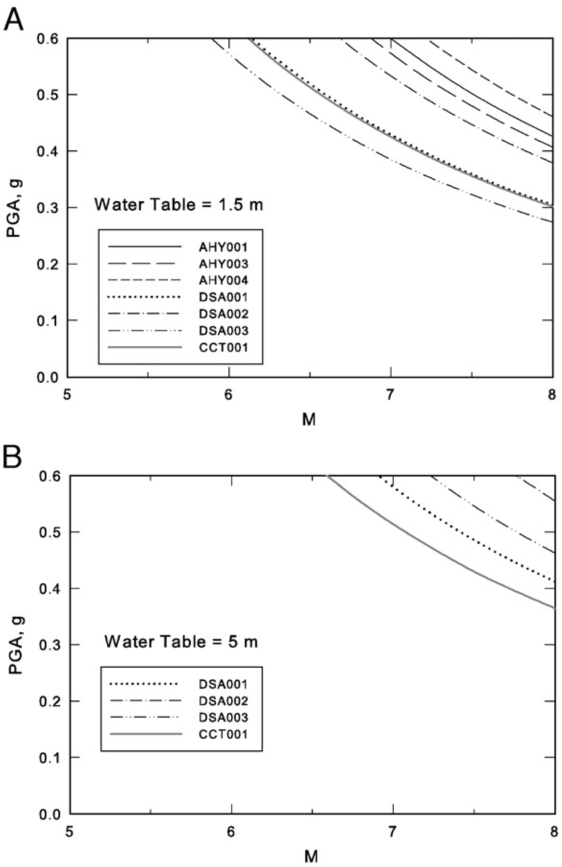

Fig. 10. A) Combinations of earthquake magnitude and PGA required to cause LPI = 5, which correlates with the occurrence of sand blows. Water table assumed to be at 1.5 m. B) Combinations of earthquake magnitude and PGA required to cause LPI = 5, which correlates with the occurrence of sand blows. Water table assumed to be at 5 m. Results for Ashley County soundings are not shown, i.e., they required PGA >0.6 g.

profile is developed on unit G (Fig. 7B). A network of smaller sand dikes (<0.5 to 3 cm width) and sills (<10 cm thick) is present below the flanks of the principal blow, and some of these dikes are linked to the principal blow.

Spatial relationships in the Golden trench suggest the sand dikes, sills, and blows formed during a single earthquake, but some of the "sills" and other sand lens (unit E) may be older buried blows (Fig. 7A). A lens of organic sediment post-dating venting (meter 1, unit B) gave a ^{14}C age of 510 to 290 cal. yr BP (Table 1), and the surface of unit F (meter 8) buried by the blow deposit gave an IRSL age of ~8500 yr BP (Table 2). An IRSL age of ~8000 yr BP of the surface of unit F below a sand lens of unit E (meter 3) is within the error of the IRSL age of unit F at meter 8 where buried by the principal blow (unit C). This age similarity suggests that the upper surface of unit F was eroded during venting of unit C and that the IRSL age of ~8500 yr BP is not an age of burial of a paleosurface by sand venting but rather a depositional age of unit F. The irregularity of the base of the blow deposit is consistent with this interpretation. Thus, the principal venting at Golden site occurred later, possibly coeval with major venting circa 5500 to 6000 yr BP at the Kelso site in the northern Desha County field (Fig. 2).

4.3. Lincoln–Jefferson Counties, Phenix site

Sand blows at the Phenix, AR locality in the Lincoln–Jefferson Counties field (Fig. 2) are less densely-spaced and more widely distributed than the Ashley County and Desha County liquefaction fields. We found patches of sandy soil at this site, but agricultural activity has obscured the original geomorphic expression of the tonal anomalies observed on vintage aerial photos. However, the areas having tonal anomalies have elliptical low ground conductivity anomalies (Fig. 8) that are characteristic of the seismically-induced sand blows at our previous excavation localities in Ashley and Desha Counties. No trenches have been opened in this area.

The Phenix "sand blows" show branching alignments suggesting they are vented crevasse splay sands adjacent to the Stage 3 paleocourse of the Arkansas River (Coles Brake, circa 6000 yr BP to 4500 yr BP) (Saucier, 1994) (Fig. 8). There are sand blows with similar branching alignments that appear to be inherited from source sands in alluvial fan channels at Carlsbad, California (see

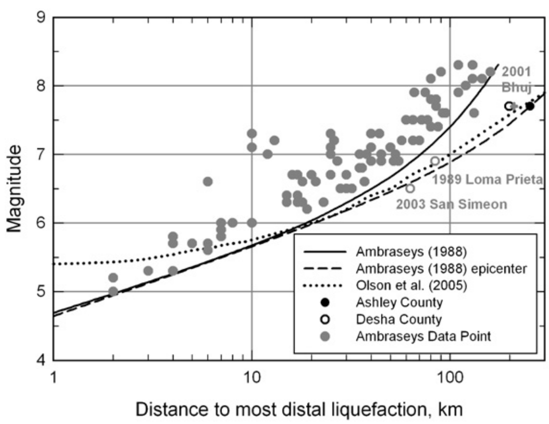

Fig. 11. Maximum distance to liquefaction from nearest point on seismic source zone (Ambraseys, 1988) with points added for the 1989 Loma Prieta and 2003 San Simeon earthquakes (Holzer et al., 2005) and 2001 Bhuj, India, earthquake (Jain et al., 2002). Boundaries for Olson et al. (2005) and Ambraseys (1988), respectively, are based on distances measured to the energy centroid and epicenter.

Kuhn, 2005, Fig. 5). The vented sands at Phenix appear to have been liquefied and vented after burial by Arkansas River Stage 2 paleocourse overbank deposits (Sneeds Brake, circa 4500 yr. BP to 3000 yr. BP). The final Stage 2 paleocourse, Bayou Bartholomew (circa 2200 yr. BP), appears to postdate the liquefaction event (i.e, earthquake).

4.4. Cone penetration tests

Two sets of seismic cone penetration tests (CPT) were conducted, one each in the Ashley and Desha County sand-blow fields, to identify source beds and evaluate liquefaction susceptibility. In addition, a single CPT sounding was conducted in Chicot County in an area without recognized sand blows. The general locations of the soundings are shown in Fig. 2.

The soundings in Ashley County were conducted near the Morgan site. Sounding AHY004 was adjacent to the trench. Fig. 9A is a 550-m-long cross section based on the soundings. Three major units can be traced across the profile. The uppermost unit is the crevasse splay deposit in which the 2-m deep Morgan trench was dug. It is underlain by a fine-grained backswamp deposit that

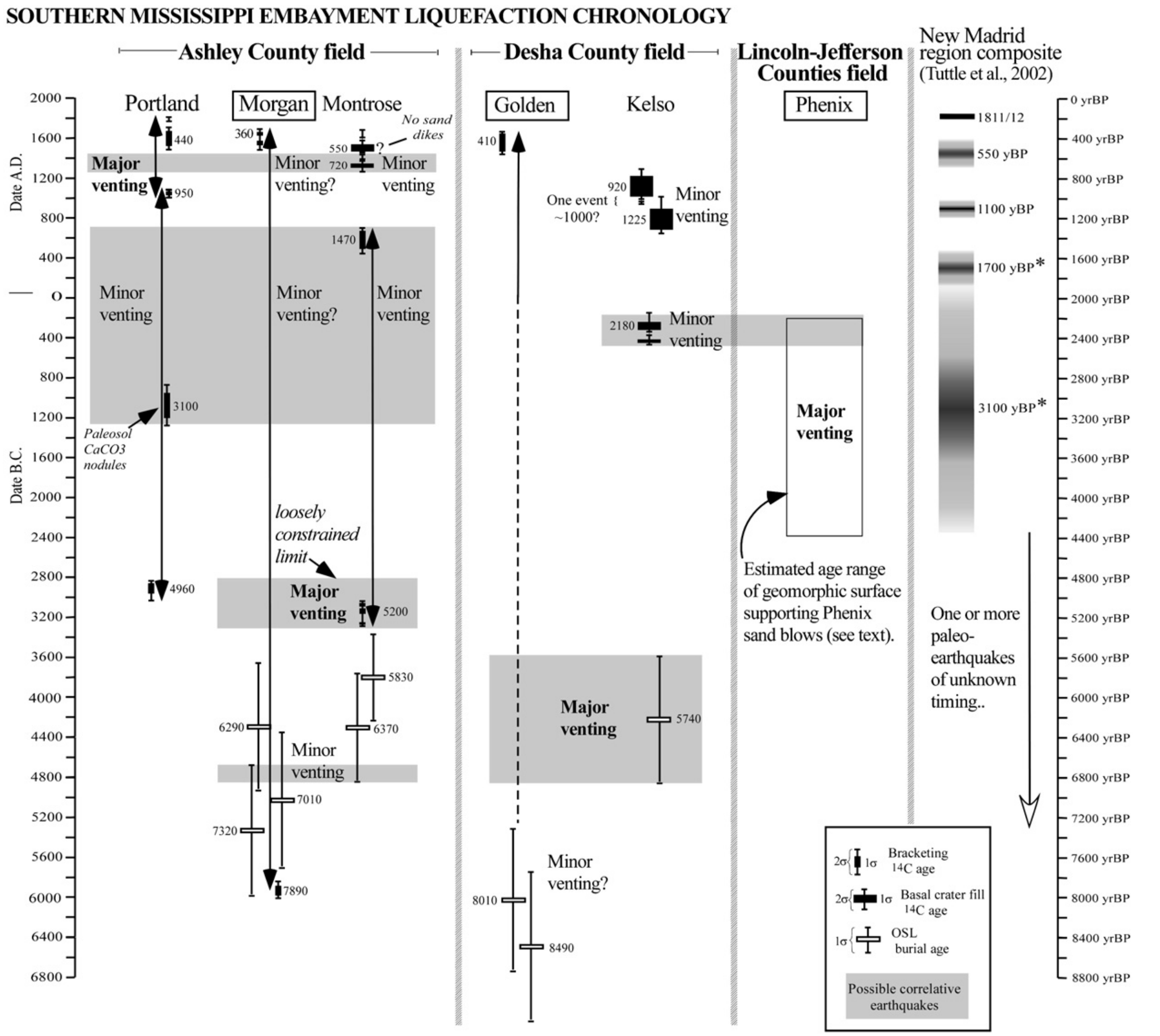

Fig. 12. Timing of sand venting episodes in the southern Mississippi Embayment. Age ranges are constrained by ^{14}C and IRSL dates. Investigation sites are arranged south (left) to north (right)(the names of sites described herein are in boxes). Vertical lines with arrowheads denote time intervals containing sand venting episodes that are bracketed by ^{14}C ages. The New Madrid seismic zone paleoearthquake chronology is shown on the right for comparison (earthquakes in the New Madrid region with an asterisk by the age are not documented in the southern or central parts of the New Madrid liquefaction field).

increases eastward in thickness from 5.4 to 7.0 m. A push core collected at the Morgan site next to AHY004 exposed sand dikes that cut the backswamp deposit at depths of 4 and 5.5 m. These units are underlain by Upper Pleistocene clean sandy valley train outwash deposits.

The soundings in Desha County were conducted in a sand-blow field 34 km from the Golden site and 8 km from the Kelso trench of Cox et al. (2004a,b). Fig. 9B is a 440-m-long cross section based on the three soundings. The shallowest unit is the fine-grained backswamp deposit, which ranges in thickness from 8 to 8.9 m. It is underlain by a sandy unit, presumably of fluvial origin, that increases southward in thickness from 0.8 to 4.1 m. This unit is underlain by valley train outwash deposits similar to those in the Ashley County cross section.

Subsurface sediment intervals that are liquefiable according to the Seed–Idriss simplified procedure (Youd et al., 2001) are labeled "susceptible" in Fig. 9A and B. We use the term "susceptible" as defined by Kramer (1996) to distinguish liquefiable from nonliquefiable deposits. In the Ashley County cross section, both the crevasse splay and upper part of the valley train deposits have susceptible intervals. The backswamp deposit is generally too fine-grained to liquefy. In the Desha county cross section, thin (<1 m) beds of susceptible sediment are present in the backswamp deposit. The buried sandy fluvial (?) unit also contains susceptible sediment.

Liquefaction potential at each CPT sounding was also assessed with the liquefaction potential index (LPI). Following the approach described in Toprak and Holzer (2003), the index is a weighted average to 20 m of one minus the liquefaction factor of safety inferred from the Seed–Idriss simplified procedure. LPI values can range from 0 for a sounding with no liquefiable material to 100 for a sounding where the liquefaction factor of safety is zero over the entire 20 m. Toprak and Holzer (2003) correlated LPI with surface manifestations of liquefaction and concluded sand blows are likely where LPI > 5. Holzer and others (2006a,b) use LPI as a basis for mapping liquefaction hazard and Holzer and others (2005) used it to infer levels of ground motion during the 2003 San Simeon, California, earthquake.

Fig. 10 shows the combinations of earthquake magnitude and peak ground acceleration (PGA), required at each sounding to produce LPI = 5. This PGA is the surface ground motion that would occur at the location of the sounding in the absence of liquefaction (See Youd et al., 2001, p. 831). Because the depth to the water table at the time of liquefaction is not known, Fig. 10A and B, respectively, are for a shallow (1.5 m) and deep (5 m) water table. For example, in Fig. 10A, the curve for DSA003 shows the combinations of earthquake magnitude and PGA at which LPI = 5, the threshold value estimated by Toprak and Holzer (2003) at which sand boils typically occur. Thus for a M7 earthquake, a PGA = 0.39 g is required for the surface manifestations of liquefaction to occur at DSA003.

5. Discussion

The results presented here represent an ongoing effort to identify the seismic source of the liquefaction features that we describe in the southern embayment. In the following we evaluate whether these sand blow fields may be distal liquefaction associated with NMSZ earthquakes 300 km to the northeast or with local seismogenic faults. If related to NMSZ earthquakes, these sand blows greatly expand the recognized limit of NMSZ liquefaction and hence the area of strong ground shaking.

5.1. NMSZ versus local seismic source

Radiocarbon and IRSL dates from our work show the Ashley County and Desha County liquefaction fields each experienced at least three earthquakes in the last 7000 years large enough to vent sand (Fig. 12). In the Lincoln–Jefferson Counties field, interpreted sand blows are present on natural levees and crevasse splays of early Stage 2 and older courses of the Arkansas River, but not on late Stage 2 or Stage 1 courses, suggesting these sand blows were triggered by a mid-Holocene earthquake ca. 2200 to 4500 yr BP. Discrepancies between this southern embayment chronology of sand venting episodes and NMSZ earthquakes (Fig. 12), suggest that they do not correlate with the timing of known NSMZ events and therefore were induced by local earthquakes. Moreover, the character of Holocene stratigraphy (meander belts, backswamp, and crevasse splays) is continuous between and within sand blow fields in the study area, and the area is underlain by similar pre-Quaternary geology (Figs. 2 and 3). Thus, geologic factors that influence sand venting (thickness, density, and grain size of source sand and of capping sediment, topography, elevation of water table, lithology and structure of underlying strata) are regionally uniform. Youd and Perkins (1987) report that given similar geologic factors, liquefaction is greatest near the seismic source and attenuates systematically away from the source. Thus, clustering of sand blows in the Arkansas River valley into three fields, and the occurrence of blows on both clay and sandy surfaces suggest that the principal control on sand blow distributions in this region is not geology (as would be expected if the distant NMSZ was the energy source), but rather proximity to a local seismic source.

A local seismic source is also indicated by CPT results that show the mechanical strength and 5-m thickness of the clay unit capping liquefiable sandy beds in this region require high ground accelerations from strong local earthquakes for venting of the observed sand blows. Both Fig. 10A and B indicate that high levels of PGA were required to produce the sand-blow fields observed in both Ashley and Desha Counties. Even for a shallow water table (1.5 m), a PGA > 0.3 g is required to produce the sand blows. In fact, all of the Ashley County soundings require PGA > 0.4 g. These high values of PGA are unlikely to be observed in the far field and thus, it is improbable that they could be generated in southern Arkansas by earthquakes like the 1811–1812 events in the New Madrid Seismic Zone (NSMZ). The Ashley and Desha County soundings, respectively, are approximately 200 and 250 km form the southernmost end of NMSZ as mapped by Frankel et al. (2002). In the area in Chicot County with no sand blows, which is between the Ashley and Desha County sand-blow fields (Fig. 2), Fig. 10 indicates sediments are at least as susceptible to liquefaction than sediment in the sand-blow fields, in accord with the uniformity of the Quaternary fluvial architecture of the lower Arkansas River valley. Absence of sand blows near the Chicot County sounding is consistent with a near-source shaking interpretation for the Ashley and Desha County fields, but we cannot draw strong conclusions from a single sounding.

An independent test of the plausibility that the source of the seismicity causing the sand blows is in the NMSZ is to plot their distances from the NMSZ on Ambraseys (1988) compilation of historic occurrences of liquefaction. This graph enables a comparison of the Ashley and Desha sand-blow fields with worldwide liquefaction occurrences. Fig. 11 shows Ambraseys's upper-bound distance. We assumed a M7.7 earthquake for the southern segment of the NMSZ in the 1811–12 New Madrid sequence based on Frankel et al. (2002). The figure also includes points added by Holzer et al. (2005) for the 1989 Loma Prieta and 2003 San Simeon earthquakes. Both of these points fall slightly outside Ambraseys's upper-bound distance. Holzer et al. (2005) reconciled the greater distance of these points by appealing to special seismological factors such as rupture directivity, local site amplification, and critical reflections off the Mohorovicic discontinuity. Comparison with these observations suggests that the Ashley and Desha County sand blows were not caused by earthquakes in the NMSZ. However, adding the most distant liquefaction observed during the 2001 Bhuj, India, earthquake as reported by Jain et al. (2002) adds a different perspective. This earthquake has been cited as an analog for the central United States. The location of the most distant liquefaction, which is along the Sabarmati River, is comparable to that of the southern Arkansas sand blows (assuming an epicenter at the southern end of the NMSZ) and implies that a distant NMSZ source cannot be precluded. Unfortunately, the description of the most distant liquefaction by Jain et al. (2002) is challenging to evaluate and distance is given from the earthquake epicenter, although we adjusted it to nearest distance to the source zone based on aftershocks. E.S. Schweig (written comm., 2006) described the distant liquefaction as minor.

It also is instructive to compare the distances for the Ashley and Desha County sites to the boundary curve recently proposed by Olson et al. (2005) for the Central United States (Fig. 11). However, one must be cautious in the comparison because the distance used for their curve is measured from the centroid of the seismic energy center. Distances plotted in Fig. 11 were measured from the end of the NMSZ. To properly compare the points to their curves in Fig. 11, we estimate approximately 65 km, half the length of the Frankel et al. (2002) fault trace, should be added to the distance plotted in the figure. This places the points outside of the Olson et al. (2005) boundary. We also include Ambraseys' (1988) curve for epicentral distance for comparison.

In summary, comparison of the Ashley and Desha County liquefaction locations with published boundary curves for maximum distance to liquefaction suggests that the NMSZ is not the likely source of the ground shaking. The points fall outside of these boundaries.

5.2. Local faults

Several fault systems in the southern embayment are possible local seismic sources. Below the Mesozoic/Cenozoic embayment sediments, a transform fault margin of the early Paleozoic North American craton strikes southeast in basement rocks that underlie the late Paleozoic Ouachita orogen, and the orogen conforms to the older continental margin (Thomas, 1989; Hale-Erlich and Coleman, 1993; Harry and Londono, 2004). Discontinuous subsurface distributions of early Mesozoic continental deposits define southeast-striking horsts and grabens that were formed during initial rifting of the Gulf of Mexico. The locations of these Mesozoic faults were controlled by faulted margins of the principal structural elements of the Ouachita orogen (the southern thrust belt, the Benton Uplift, and the frontal thrust belt, Fig. 3). Two of these southeast-striking faults, the Saline River fault zone (SRFZ) (Cox, 1994; Cox et al., 2000) and the Arkansas River fault zone (ARFZ) (Fisk, 1944; Cox, 1994), follow the margins of the Desha Basin (Fig. 3). The Desha Basin was the depocenter during Late Cretaceous and Paleogene filling of the Mississippi Embayment, and movement on the SRFZ and ARFZ probably accommodated subsidence of this basin. River bank exposures and trenches across the SRFZ reveal repeated Quaternary movements including Holocene activity (Cox et al., 2000, 2004b). The SRFZ and ARFZ are favorably oriented for left-lateral slip with a reverse component in the contemporary stress field (Zoback, 1992; Cox et al., 2000).

5.3. Magnitude estimates assuming a local seismic source

The limits of the Ashley County, Desha County, and Lincoln–Jefferson Counties sand blow fields, as interpreted from aerial photography, can be approximated by ellipses, and the epicenters of three earthquakes responsible for the sand blow fields can be estimated as the centers of the three ellipses. The long-axis radius of each ellipse gives an estimate of the distance from the epicenter of the respective earthquake to the farthest related liquefaction. The long-axis radii of the three fields are 16.5 km for Ashley County, 23.5 km for Desha County, and 16 km for Lincoln–Jefferson County. Magnitudes of paleoearthquakes associated with each of these sand blow fields can be estimated using a magnitude-bound empirical relationship of moment magnitude to epicentral distance to farthest liquefaction. Using magnitude-bound relationships from both a global data set (Ambraseys, 1988) (Fig. 11) and a central United States data set (Olson et al., 2005), estimated magnitudes of single earthquakes inducing the Ashley County field, the Desha County field, and the Lincoln–Jefferson Counties field are $M=5.8$, $M=6.1$, and $M=5.8$, respectively. These magnitudes may be too low due to underestimation of the size of these liquefaction fields, or they may be too high because these fields are actually composites of multiple liquefaction events of smaller radii. In addition, these relationships were not developed specifically for our study area, and thus they may not characterize the southern embayment accurately.

Field evidence along the SRFZ that suggests faulting events may have several meters of strike–slip movement (Cox et al., 2000), consistent with an event of magnitude 5.5 to 6.5 (Wells and Coppersmith, 1994) and in general agreement with the above estimates of magnitude from the size of these liquefaction fields. Results from CPT soundings indicate larger magnitude earthquakes ($M>7$) may have induced sand venting in the Ashley County field (see “Cone Penetration Tests” above), although there is uncertainty concerning bedrock response to seismic energy in this region.

5.4. More details of paleoseismic chronology

The principal sand-venting episode at the Morgan site shows similar mid-Holocene timing to the principal episode at the Montrose site to the north, and these blows are both preceded by relatively minor venting (Fig. 12). This timing differs from major late Holocene venting at the Portland site (Cox et al., 2004a) to the south (Figs. 2 and 12). We have recently acquired shallow seismic reflection profiles that show near-surface ruptures of the SRFZ 0.3 km to the north of the Montrose site (Cox et al., 2004b). We interpret the principal vented sand deposit at the Morgan and Montrose sites as a record of the first strong earthquake on the SRFZ following deposition of local mid-Holocene alluvium. Late venting at the Montrose site may record the major event recorded at the Portland site to the south. We suggest that this late event was larger in magnitude than the principal mid-Holocene Morgan–Montrose event and thus triggered liquefaction at a greater distance from the SRFZ than the mid-Holocene event. Sand venting may have been minor at the Montrose site and minor or absent at the Morgan site during these later events because the source sand had been largely vented and compacted during the mid-Holocene event.

The Golden site is at the southern periphery of the Desha County field. This site records a major mid-Holocene event probably correlative to the earliest event at Kelso (Fig. 12), but it does not record the minor late-Holocene venting episode seen at the Kelso site. We interpret this setting to be similar to the Ashley County field history in as much as the northern Desha County field is near the ARFZ projected trace (Kelso site) and shows a history of paleoseismicity that is longer and includes more events than the distal part of the field (Golden site) (see Fig. 12).

We do not know the chronology of paleoearthquakes in the Lincoln–Jefferson Counties field because we have not trenched those sand blows, but estimated ages of the geomorphic surfaces supporting these blows (Saucier, 1994) suggest at least one mid to late Holocene earthquake. This earthquake may have also induced the minor venting at the Kelso site in the Desha County field circa 2180 yr BP (Fig. 12). Indistinct tonal anomalies on aerial photography between the Lincoln–Jefferson

Counties field and the Desha County field (Fig. 2) have not been confirmed as sand blows, but these features may be blows induced by this earthquake. We do not correlate this venting episode with minor mid to late Holocene venting in the Ashley County field because no venting of this timing is recorded at the Golden site in southern Desha County.

The paleoseismic chronology of the NMSZ as recorded by sand blows (Tuttle et al., 2002) does not show a clear relationship to the southern embayment chronology (Fig. 12). NMSZ events circa 1700 yr BP and 3100 yr BP are only documented from the Cairo Lowlands of southeast Missouri in the northern NMZS, and thus it is unlikely these events correlate with southern embayment venting episodes. The well-constrained NMSZ event at 1100 yr BP may correlate with a minor venting episode at the Kelso site. However, this correlation requires that late Holocene sand blows at this site record two separate earthquakes even though their age ranges overlap, thus complicating the interpretation. We do not correlate the 550 yr BP NMSZ event with sand blows in Ashley County because no venting of this timing is recorded in Desha County. No sand blows coeval with the 1811–1812 NMSZ earthquake sequence have been found in the southern embayment. At least two large paleoearthquakes circa 5000 to 7000 years ago are recorded by sand blows between the Desha County field and the NMSZ in east-central Arkansas (Fig. 1, Al-Shukri et al. trench sites) (Al-Shukri et al., 2005; Tuttle et al., 2006), and these earthquakes may also have caused major sand venting in the Desha County field.

6. Summary and conclusions

Analyses and results presented support two primary conclusions: one, that strong ground motion in the southern embayment has occurred recently and repeatedly; and second, that the source of this ground motion is likely local. Radiocarbon and luminescence dates from our work show the Ashley County and Desha County liquefaction fields each experienced at least three earthquakes in the last 7000 years large enough to vent sand. Our new paleoseismic data from the Morgan and Golden trench sites are consistent with mid to late Holocene strong ground motions in southeast Arkansas. At the Morgan site, stratigraphy records two sand-blow events circa 6800 yr BP and 5800 yr BP. Lateral truncation of stratigraphy in the vent area suggest winnowing of material by vented water. Minor dikes "roll" into the vent area where stratigraphy is warped downward, suggesting these dikes pre-date subsidence associated with the principal venting episode. We recognize one significant sand-blow event at the Golden site that dates to ~6000 yr BP. Small lenticular sand bodies may be an earlier venting episode. As at the Morgan site, truncation of stratigraphy in the vent area may be due to winnowing of material by vented water or possibly by explosive cratering similar to that reported by Rydelek and Tuttle (2004) during the Bhuj Indian 2001 earthquake and by Youd and Keefer (1994) during the San Juan Province Argentinean 1977 earthquake. Stratigraphic horizons are warped downward immediately north of the vent area, suggesting subsidence accompanying venting. In the Lincoln–Jefferson County field no trenches were excavated, but sand blows are present on natural levees and crevasse splays of early Stage 2 and older courses of the Arkansas River and not on late Stage 2 or Stage 1 courses, suggesting these sand blows were triggered by a mid-Holocene earthquake ca. 2200 to 4500 yr BP.

The paleoseismic chronology, the clustered spatial distribution of sand blow fields, relationship between the sand blow fields and mapped Holocene surficial geology suggest that a local source of strong ground motion may provide the best explanation for generating these sand blow features. Within these liquefaction fields, sand blows are found on surfaces of contrasting geology (compare Morgan and Golden trench logs). These field relations suggest that the principal control on sand blow distributions in this region is not surficial geology, but rather proximity to a local seismic source (such as the Saline River fault zone (SRFZ) or Arkansas River fault zone (ARFZ); see Fig. 3). CPT results within the Ashley County and Desha County sand blow fields and an area in between are compatible with these conclusions, and the high ground accelerations that are indicated within the sand blow fields suggest strong local seismicity. Following the empirical relation of magnitude to liquefaction area presented in Ambraseys (1988), the areal extents of these sand blow fields suggest earthquakes of approximately M6.0 occurring within the limits of these fields. CPT results indicate possible stronger events of about M7, and future mapping of sand blow distribution may show these liquefaction fields are indeed of larger diameters characteristic of M7 earthquakes. Efforts to delineate, describe, and model the potential sources of strong ground motion in the southern embayment will continue. Such work will not only aid in the assessment of local seismic hazard relevant to pipeline infrastructure crossing the region as well as to vulnerable rural communities but also will support investigations of the tectonic and structural linkages between the northern and southern portions of the Mississippi Embayment. These efforts are critical to the evaluation of models of driving mechanisms for North American mid-continent seismicity. Thus, this work helps constrain seismotectonic models of intraplate North America and intraplate settings in general.

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