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INVESTIGATION OF THE MAGNITUDE AND TIMING OF PALEO-EARTHQUAKES IN SOUTHEAST ARKANSAS

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ABSTRACT

In order to assess the geographic extent of known Holocene sand blow fields in south Arkansas, we conducted a field investigation of the distribution of liquefaction features in Holocene alluvium along streams within a forested region between the known sand blow fields observed on aerial photography in agricultural areas (Ashley County field, Desha County field, and Bradley County field). Our results indicate that these sand blow fields are not continuous and do not reflect a single large liquefaction field related to paleo-earthquakes >M 6.5. However, the Desha County field may be significantly larger than presently mapped, and the distance from the center of the field to the farthest liquefaction may be ~35 km, corresponding to M 6.4 by the empirical relationship of magnitude and distance to farthest liquefaction. We found evidence for Holocene liquefaction that we interpret as resulting from strong ground shaking at five field sites that cluster near Pleistocene and Holocene surface ruptures of the Saline River fault zone, and we tentatively assign paleo-earthquakes related to this liquefaction to movements on that fault zone. We conclude that the Bradley County sand blow field is limited in extent and related to local surface faulting within the field. Our final conclusions await results of ^{14}C age analyses from the NSF-Arizona AMS Laboratory.

INTRODUCTION

The spatial distribution and recurrence intervals of large intraplate earthquakes in eastern North America are poorly understood, and some areas of significant seismic hazard have yet to be adequately characterized. Southeast Arkansas has a strong signature of active block tectonics, and regional rivers are aligned with the NW-SE structural grain of the deep basement (Fig. 1). Paleochannels and alluvial terraces show that throughout late Quaternary these rivers have been laterally migrating westward, against the eastward dip of strata into the Mississippi embayment (Schumm et al. 1982; Burnett and Schumm 1983; Cox 1994), and Pleistocene and Holocene alluvium is faulted and warped along these river alignments (Cox et al. 2000; Cox et al., 2012). Although the region is characterized by low historical seismicity, instrumentally-recorded and/or felt earthquakes (<M 4.5) in the region are aligned and clustered along southeast flowing rivers, and paleoseismic evidence indicates there were larger late Holocene earthquakes in the area (Cox et al. 2000; 2007; 2010; Cox et al., 2012).

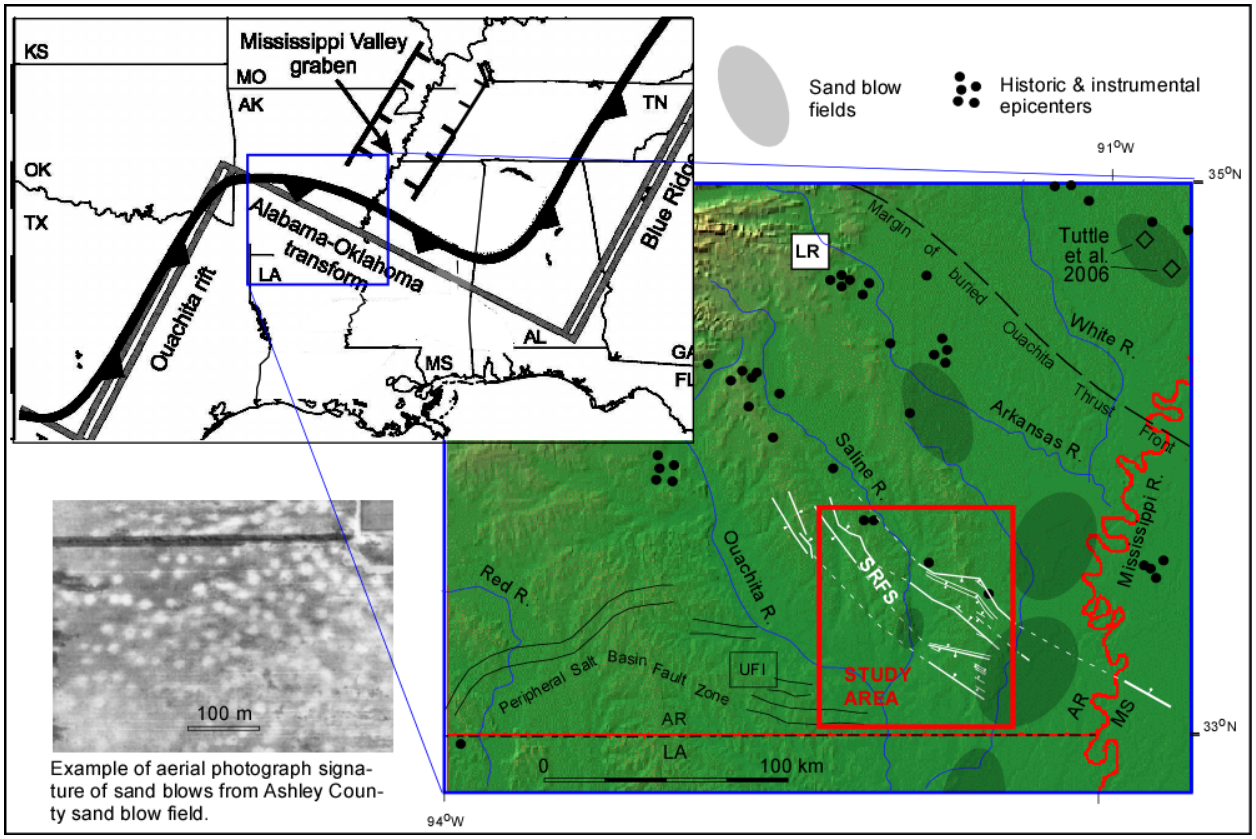

FIGURE 1. Location map showing the general tectonic setting, and an expanded shaded-relief map showing the study area. SRFS = Saline River fault system; UFI = an earthquake cluster related to underground fluid injection (Cox, 1991). Note that regional rivers are aligned with the NW-SE grain of the deep basement.

Constraints on the timing and location of paleo-earthquakes in the central United States has been greatly aided by the recognition and study of liquefaction features (e.g., sand blows and dikes) caused by earthquakes (Munson et al. 1992, 1997; Obermeier et al. 1993; Obermeier 1998; Tuttle and Schweig 1996; McNulty and Obermeier 1999; Tuttle 2001; Tuttle et al. 2002). There are abundant sand blows and other liquefaction features in southeast Arkansas on alluvial terraces and floodplains of the Arkansas River and tributaries (Cox et al. 2004, 2007, 2010). Several "fields" of sand blows are defined primarily by the areal extent of light tonal anomalies (characteristic of sand blows on over-bank clay) observed on aerial photography (e.g., Fig. 1 photo inset), but delineation of the geographic limits of these "fields" on aerial photography is hampered by broad areas of forest cover (west of dashed green line on Fig. 2).

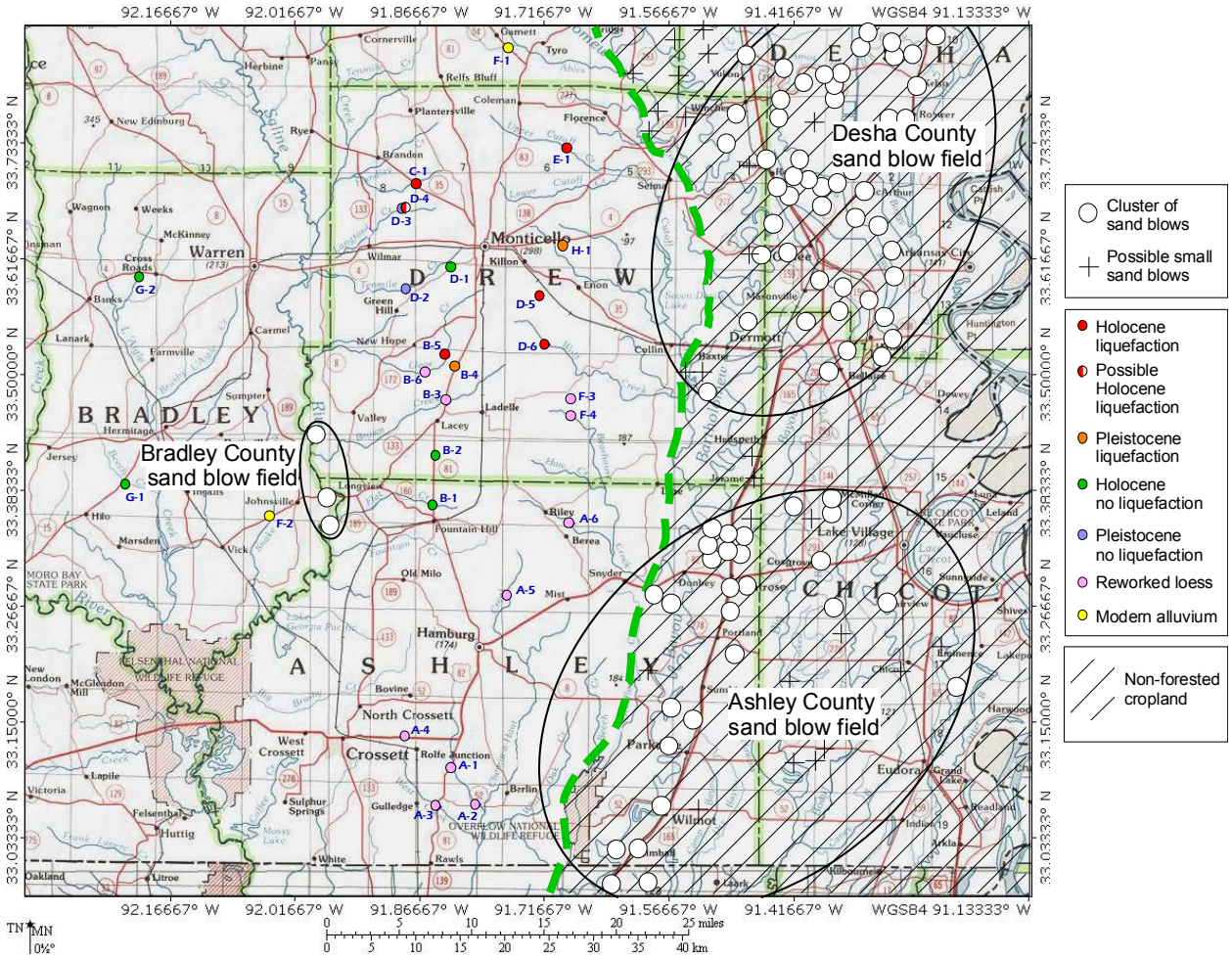

FIGURE 2. Map of study area showing the three sand blow fields of concern to this study. The green dashed line marks the eastern boundary of mostly forest cover in uplands and the western boundary of mostly agricultural fields of the Mississippi Valley. Letter-number labels by color-coded circles denote field sites listed in Table 1.

Table 1. Field sites.

Field site	Latitude	Longitude	Alluvium type	Liquefaction potential	Age category	Liquefaction features
A-1	33.10543	-91.82981	Reworked loess	Low	Holocene	None
A-2	33.06733	-91.80102	Reworked loess	Low	Holocene	None
A-3	33.0652	-91.14613	Reworked loess	Low	Holocene	None
A-4	33.13543	-91.8852	Reworked loess	Low	Holocene	None
A-5	33.27783	-91.76244	Reworked loess	Low	Holocene	None
A-6	33.35026	-91.68557	Reworked loess	Low	Holocene	None
B-1	33.36864	-91.8505	Bedded sand, gravel, clay	High	Holocene	None
B-2	33.41693	-91.84806	Bedded silt, gravel, clay	High	Holocene	None
B-3	33.47277	-91.83599	Reworked loess	Low	Holocene	None
B-4	33.50922	-91.82409	Bedded sand, gravel, clay	High	Middle Pleistocene	Sand dikes, convoluted beds, pinch/swell features, suspended blocks
B-5	33.52055	-91.836	Bedded clay, sand	High	Holocene	Sand dikes, foundered block, suspended blocks
B-6	33.50365	-91.85997	Reworked loess	Low	Holocene	None
C-1	33.69237	-91.87181	Bedded sand, gravel	High	Holocene	Sand intrusions, convoluted beds, pinch/swell features
D-1	33.60875	-91.83099	Bedded sand, gravel	High	Holocene	None
D-2	33.58621	-91.88271	Massive clay-rich sand	Moderate	Middle Pleistocene	None
D-3	33.66856	-91.88625	Massive sand	High	Middle Pleistocene	None
D-4	33.66931	-91.88531	Bedded sand, gravel, clay	High	Holocene	?Localized down-warped beds, minor pinch/swell features
D-5	33.57962	-91.72241	Bedded sand, gravel, clay	High	Holocene	Convoluted beds, pinch/swell features
D-6	33.53046	-91.7156	Bedded clay, sand	High	Holocene	Disrupted bedding, dish structures, suspended blocks
E-1	33.72764	-91.68954	Bedded clay, sand	High	Holocene	Sand intrusions, convoluted beds, suspended blocks
F-1	33.82934	-91.76145	Bedded sand, peat	High	Modern	None
F-2	33.35636	-92.04765	Massive sand	High	Modern	None
F-3	33.47069	-91.69711	Reworked loess	Low	Holocene	None
F-4	33.46138	-91.71356	Reworked loess	Low	Holocene	None
G-1	33.39285	-92.22405	Massive clay, sand	High	Holocene	None
G-2	33.60326	-92.20499	Massive & bedded sand	High	Holocene	None
H-1	33.62827	-91.69876	Bedded sand	High	Late Pleistocene	Convoluted beds

This project was conducted to investigate the limits of three southeast Arkansas sand blow fields and the continuity of these fields by excavating Holocene stream bank alluvium in areas obscured on aerial photography by forest cover and recording the presence or absence of sand dikes and related liquefaction features. Figure 2 shows the mapped limits of the three sand blow fields in southeast Arkansas and the limits of the largely non-forested agricultural lands of the Ashley County and Desha County sand blow fields and a small agriculturally-cleared area within the forested uplands that comprises the Bradley County sand blow field. Our previous trenching of sand blows in these sand blow fields revealed stratigraphic and cross-cutting relationships that show a minimum of three sand-venting earthquakes in the last 7000 years in the Ashley County field, three in the last 8000 years in the Desha County field, and at least one in the Bradley County field (Fig. 3)(Cox et al., 2004, 2007, 2010).

The USGS CPT (Cone Penetration Test) truck collected data to a depth of 20 m in the Ashley County and Desha County 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. Together, the CPT data and the shear-wave velocities indicate that ground accelerations > 0.5 g are needed to liquefy susceptible sediments and vent them to the surface through surficial clay that is >5 m thick in both sand blow fields. These accelerations suggest near source shaking and an earthquake of ~M 7.0 (Cox et al, 2007). Following Ambraseys' (1988) empirical relationship of earthquake magnitude and greatest distance to liquefaction, the radii of the fields suggest earthquake magnitudes of M 5.3 (Bradley County field), M 6.0 (Desha County field), M 6.1 (Ashley County field), or M 6.7 (Bradley County field continuous with either Ashley or Desha County fields). Our new results bear upon these estimates because they add field data that permit the reassessment of the limits and continuity of these fields.

PREVIOUS INVESTIGATIONS

Cox et al. (2000) previously documented paleoseismicity in Drew County, AR by excavating six surface faults within the Saline River fault zone: all faults displace marine Eocene units and fluvial Pleistocene units; five show post-Wisconsin loess movement (luminescence age = 23,600$\pm$3000 yr B.P.); and three deform middle to late Holocene silt (luminescence age = 5100$\pm$600 yr B.P.) as fault-tip flexures. Therefore, the youngest movement post-dates 5100 yr B.P. Trenches and road-cut exposures revealed 30 meters of left-lateral strike-slip offset along the principal Saline River fault zone shear plane since Wisconsin loess deposition, indicating an average slip rate of 1.13 to 1.46 mm/y.

In Cleveland County, AR, fifty kilometers northwest of the Cox et al. (2000) Drew County trench study, a faulted anticline exposed in a Saline River bank displaces an organic-rich alluvial horizon with a ^{14}C age of 720 to 550 yr B.P. (Cox et al., 2012). The anticline is topographically expressed as a prominent 1.3 km-long highly linear ridge in Holocene alluvium that is collinear and continuous with a 1.5-km scarp that displaces Holocene and late Wisconsin Deweyville alluvial terraces.

Trenching of sand blows at five sites in the Ashley County and Desha County fields near this fault zone revealed stratigraphic and cross-cutting relationships that show at least three sand-venting earthquakes of magnitude 6+ in the last 8000 years (Cox et al., 2004, 2007, 2010). At one site in Ashley County, 40 km southeast of the Drew County fault trenching site and 90 km southeast of the fault

exposure in Cleveland County, ^{14}C dating of organic material filling a vent crater indicates the most recent sand venting episode was ~700 yr B.P. (Cox et al., 2004), similar in age to the faulting event in Cleveland County.

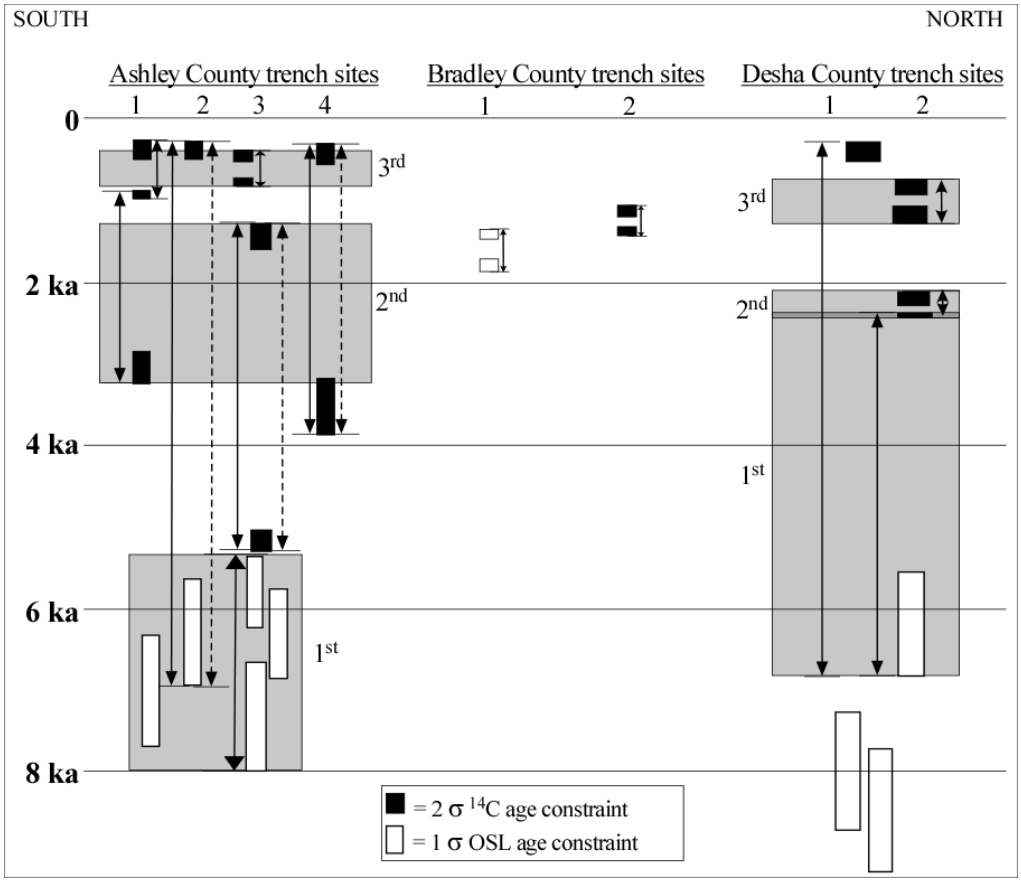

FIGURE 3. Sand blow chronology of the study area (Cox et al., 2004, 2007, 2010). Arrows denote the time range for sand blow events as defined by maximum and minimum ^{14}C and luminescence age constraints (a dashed arrow denotes a second sand blow event occurred between the same age constraints). Gray boxes designated "1st," "2nd," and "3rd" denote age ranges for interpreted earthquake sequences that minimize the number of earthquakes required to account for a given sand blow field. See Figure 2 for locations of sand blow fields.

GEOLOGIC AND TECTONIC SETTING

The study area is on the northern Gulf of Mexico coastal plain, an Atlantic-type passive margin that began forming with Triassic rifting during Pangean breakup. Within the proposed study area, 2 km of Mesozoic/ Cenozoic sediment overlie rifted Paleozoic basement (Murray, 1961; Cushing et al., 1964; Salvador, 1991; Hosman, 1996). Initial rifting and graben development during Mesozoic was aligned with a zone of lower-crustal weakness along the late Proterozoic Alabama-Oklahoma transform fault on the southern edge of the craton (Fig. 1)(Sawyer et al., 1991; Thomas, 2006; Cox et al., 2013). Geophysical modeling of this deep Proterozoic cratonic margin shows it to be a sharp discontinuity (not typical of an

extended transitional crust) and supports a transform fault interpretation (Mickus and Keller, 1992; Harry and Londono, 2004). Preceding Triassic rifting, thrust sheets were emplaced obliquely over the late Alabama-Oklahoma transform margin during the late Paleozoic Ouachita orogeny (Thomas, 2006). Some rift faults were reactivated as strike-slip faults following Late Cretaceous uplift in south Arkansas accompanied by igneous activity (Cox et al., 2013).

The Cenozoic sequence (Fig. 4) crops out in the study area. Rates of deposition were high during Paleocene and Eocene (65 to 35 Ma)(Onellion, 1956; Murray, 1961; Cushing et al., 1964; Hosman, 1996). Marine Midway Shale deposition during Paleocene was followed by the fluvio-deltaic Wilcox Fm. containing regionally significant lignite beds. Maximum subsidence rates obtained during Wilcox time, providing accommodation space for lignite deposition. The Middle Eocene Claiborne Group consists of an alternating proximal and distal deltaic sequence: Cane River Fm.; Sparta Sand; Cook Mountain Fm.; and Cockfield Fm. Marine conditions returned during Late Eocene with deposition of Jackson Fm. clay and calcareous sand (Wilbert, 1953). Eocene strata are unconformably overlain by Quaternary sediments.

Quaternary sediments in the study area that may contain liquefaction features include alluvium of the Ouachita and Saline rivers and their tributaries and tributaries of Bayou Bartholomew (youngest abandoned course of the Arkansas River). Active floodplains are flanked by older Holocene terraces on rivers and major tributaries, and there are at least three Pleistocene terrace complexes (Deweyville, Prairie, and Intermediate Complex) on these rivers (Saucier and Fleetwood, 1970; Saucier and Smith, 1986; Saucier and Snead, 1989; Saucier, 1994). The Deweyville terraces are Wisconsinan (35 to 12 ka), and Prairie terraces are Sangamon (80 to 120 ka). Intermediate Complex terraces are pre-Sangamon, but their ages are poorly constrained. A veneer of Late Pleistocene eolian silt (Peoria Loess) is discontinuously present in the eastern study area, and a thin mid-Holocene eolian silt may be present on some ridges (Follmer, 1996; Cox et al., 2000). Quaternary and ongoing uplift and ground tilting in the region are indicated by geodetic surveys (Meade, 1975; Officer and Drake, 1981; Calais et al., 2006) and geomorphology (Schumm et al., 1982; Burnett and Schumm, 1983; Cox, 1994). These movements appear to be related to activity of the Saline River fault system along the northeast flank of the Monroe uplift (Fig. 1).

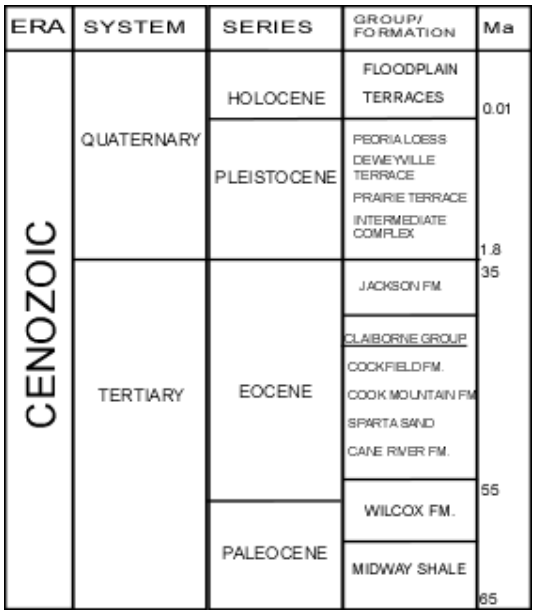

FIGURE 4. Stratigraphic chart for units that crop out or are near the surface in the study area.

INVESTIGATIONS UNDERTAKEN

We conducted a field search for liquefaction features to further assess the occurrence of strong paleoseismicity in southeastern Arkansas. Our field procedure involved visiting streams located between the Bradley County sand blow field and the Ashley County or the Desha County sand blow field, observing natural outcrops (rare) or excavating vertical 1 m x 1 m faces into Holocene alluvium at selected sites, and describing/ sampling/ photographing the stratigraphy and any liquefaction features in the excavation or outcrop at each site. We looked for small-scale structures formed by liquefaction of unconsolidated sediments (e.g., Nichols et al., 1994; Owen, 1996; Ross et al., 2011; Counts and Obermeier, 2012; Sims, 2012). Holocene and Pleistocene alluvium were discriminated in the field on the basis of degree of weathering and induration (both are significantly greater in Pleistocene alluvium). As stated in our proposal, our research questions are:

1) What are the geographic extents of the Ashley County, Bradley County, and Desha County liquefaction fields, and is the Bradley County field continuous with the Ashley County and/or the Desha County fields?
2) What are the geographic extents of liquefaction features associated with individual paleoearthquakes in southeast Arkansas (what were their magnitudes)?
3) What are the ages of these earthquakes, and what is the recurrence interval of large earthquakes in the region?

Our current results (observations of mostly small-scale liquefaction features at field sites shown on Figure 2) contribute greatly to answering Question #1. However, at the time of this writing, dates from the analysis of our age-control carbon samples have not been reported to us by the NSF-Arizona AMS Laboratory (Table 2 lists the field site number and the grid location of all carbon samples collected and designates those that have been submitted to the NSF-Arizona AMS Laboratory), and regretfully we cannot answer Questions # 2 and 3, yet.

In our initial field visits, we learned that Holocene alluvium deposits of streams draining the Pleistocene (Sangamon) Prairie terrace in the south and southeast of the study area (Sites A-1 through A-6 and F-3 and F-4, Fig. 2 and Table 1) are composed of poorly stratified silt and clay that has been reworked from the 4 to 5 m-thick silt/clay loess cap on the terrace. In addition, downstream reaches of tributaries that receive backwater flow from rivers during flooding are also characterized by poorly stratified silt and clay alluvium, presumably deposited during backwater flooding (Site B-3 and B-6, Fig. 2 and Table 1). Due to the low liquefaction potential of silt/clay and the absence of stratification at these sites, we cannot interpret our lack of observation of liquefaction features as evidence of lack of ground shaking, and we designate these sites as “Reworked loess” rather than “Holocene – no liquefaction” on Figure 2. Our field sites designated “Modern alluvium” on Figure 2 contained historic artifacts.

At our field sites in the central and upstream reaches of streams that drain sand/ gravel-bearing Eocene and Pleistocene substrates, Holocene alluvium is composed of stratified gravel, sand, silt, and clay of high liquefaction potential. Features we observed at some sites that we interpret as strong evidence for liquefaction include sand dikes and intrusions, convoluted or disrupted beds, blocks of one horizon suspended within another horizon that liquefied, foundered blocks, and water-escape “dish” structures (Table 1). We also interpret swelling and pinching of the thickness of sand horizons as possible evidence of liquefaction. The geographic relationship of our field sites containing liquefaction features to the three previously documented sand blow fields is shown on Figure 2. Below in “Results”, we describe those

sites shown on figure 2 that display Holocene or Pleistocene liquefaction features as well as sites that display stratified Holocene sand/gravel alluvium without evidence of liquefaction.

RESULTS

Site B-1) We observed well stratified gravel, sand, and clay Holocene alluvium without liquefaction features in our stream bank excavation on Flat Creek (Figure 5). Although Unit 2 pinches out to the right of our grid, we interpret this as the margin of a small filled paleo-channel rather than a pinch-and-swell liquefaction feature because its internal stratigraphy is not deformed. We interpret several small clay bodies within Unit 2 as rip-up clasts of Unit 1 that were incorporated during scour of the paleo-channel rather than as blocks suspended in sand that liquefied. We presume that the thin-bedded fine sands of Unit 2 would have readily deformed if this site had been subjected to strong ground shaking after their deposition.

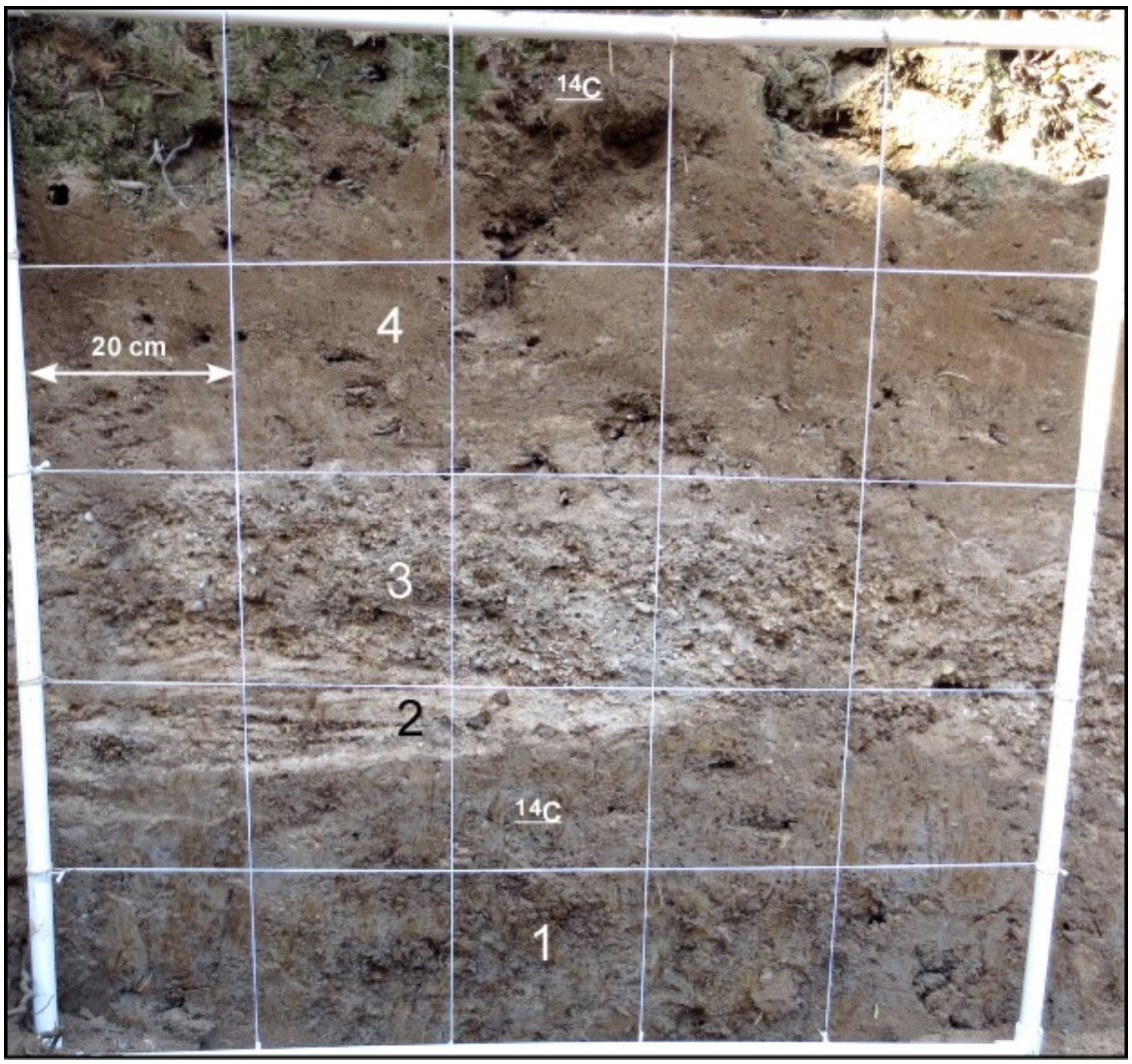

FIGURE 5. Site B-1 (Flat Creek) – Our excavation in Holocene alluvium. No liquefaction observed . Top is up. 1 = Massive silty clay; 2 = Thin-bedded fine sand; 3 = Medium-bedded sandy gravel; 4 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab).

Site B-2) We observed stratified gravel Holocene alluvium in a natural stream bank outcrop on Panther Creek (Figure 6). Cylindrical burrows filled with sandy, gravelly silt cross-cut the stratigraphy, but we interpret no liquefaction features at this site.

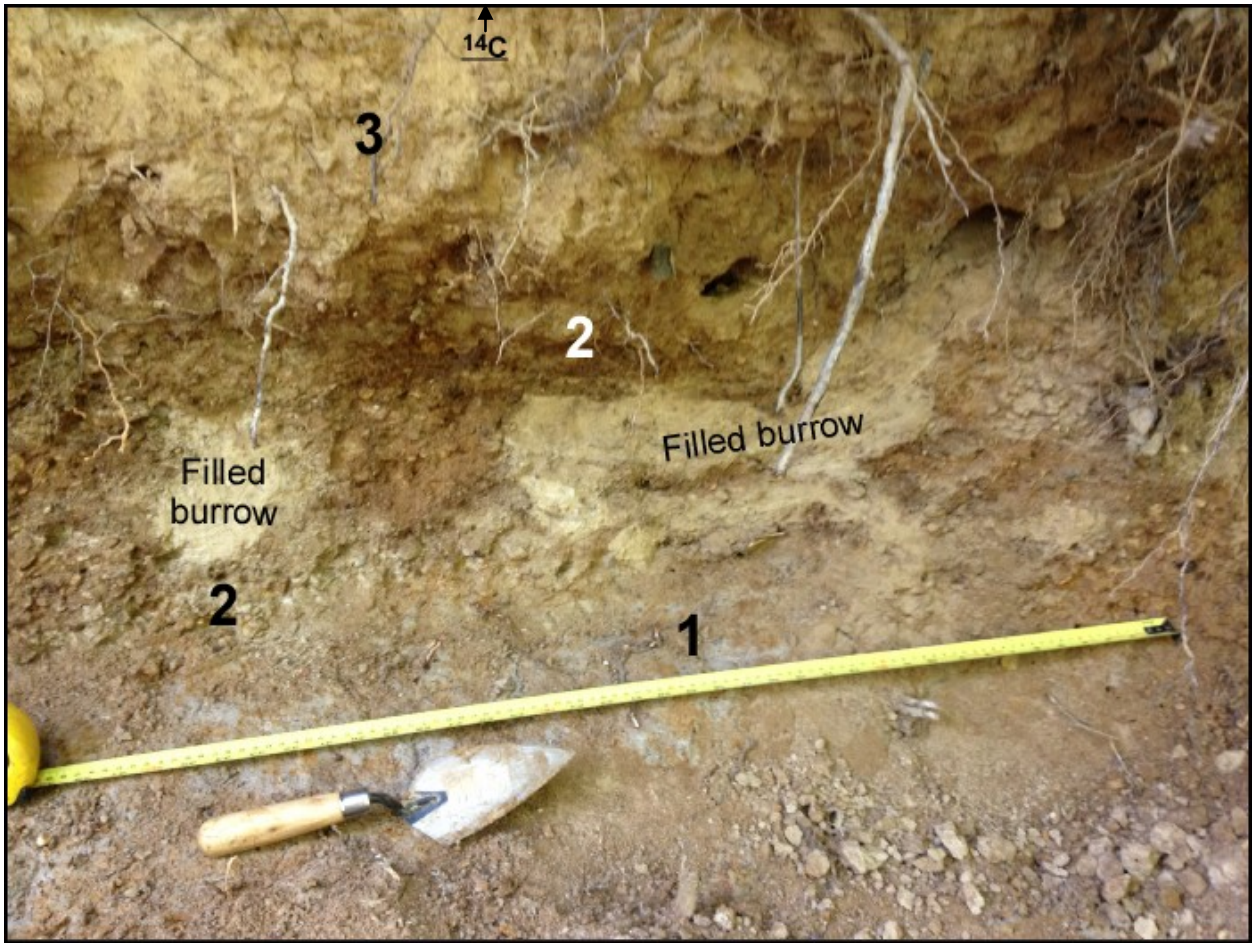

FIGURE 6. Site B-2 (Panther Creek) – Vertical outcrop of Holocene alluvium in stream bank with no observed liquefaction. 1 = Massive clay; 2 = Medium-bedded gravel; 3 = Massive silt loam. Tape is extended 1 m. ^{14}C denotes carbon sample (underlined = submitted to lab).

Site B-4) At a natural outcrop of moderately indurated Middle Pleistocene (Intermediate Complex of Saucier and Snead, 1989) on the South Fork of Clear Creek we observed sand dikes, convoluted beds, suspended blocks, and pinch and swell of beds (Fig. 7). These features are indicative of liquefaction in response to strong seismicity that occurred during Pleistocene before these sediments became indurated. The ENE strike of the sand dikes is consistent with mode I jointing in response to the ENE-WSW Quaternary compressive stress field of the eastern United States (Zoback, 1992).

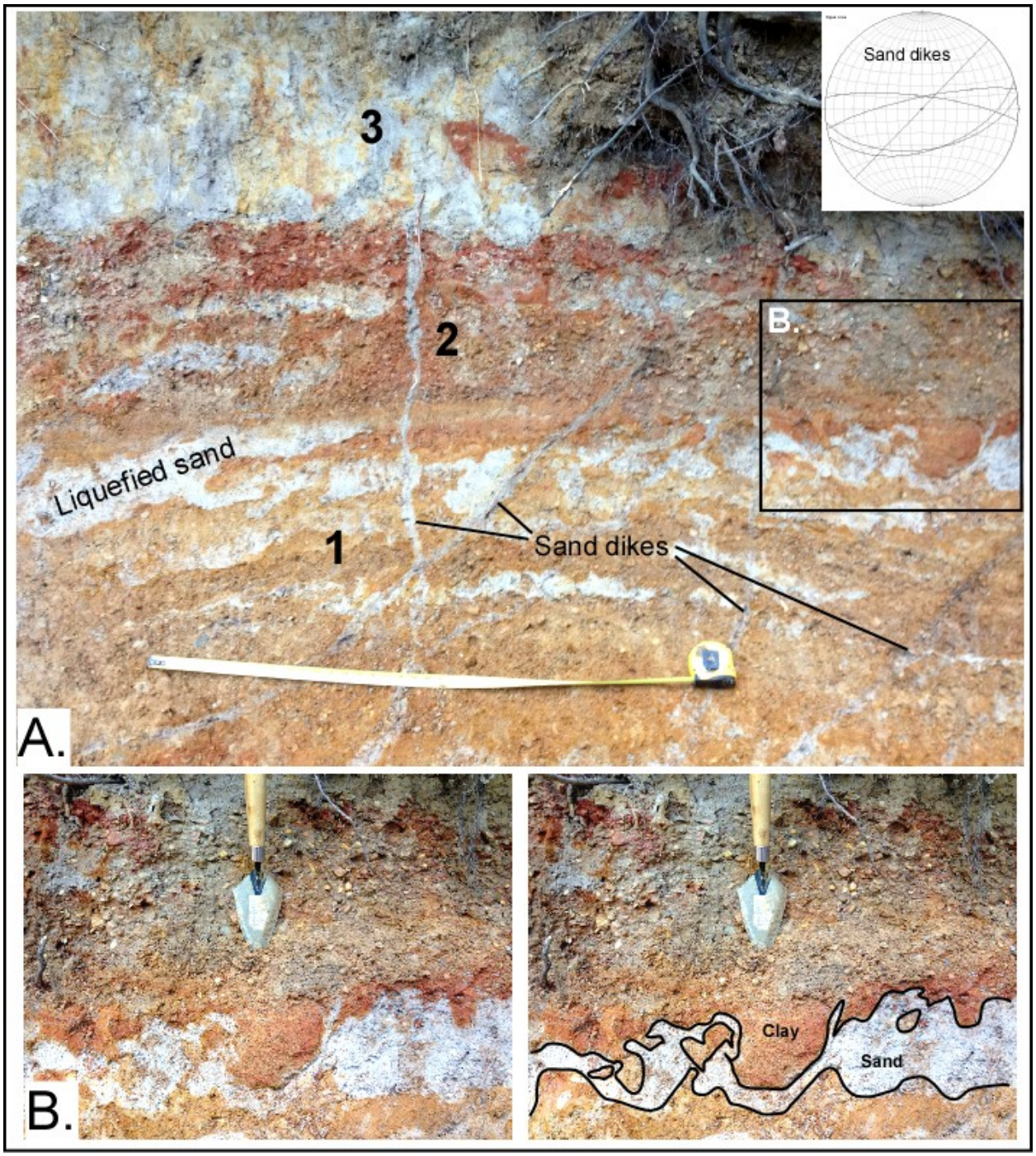

FIGURE 7. Site B-4 (South Fork of Clear Creek) - A) Subvertical outcrop of Middle Pleistocene alluvium showing clastic dikes, convoluted bedding, pinch and swell features, and detached blocks. 1 = Medium interbeds of clay and fine/medium sand; 2 = Medium-bedded gravel; 3 = Massive clay. Tape is extended 1 m. Inset shows lower hemisphere stereogram of great circles plots of sand dikes at this site. B) Detail showing convoluted bedding.

Site B-5) In our excavation on Clear Creek, we observed well stratified Holocene sand disrupted by planar clastic dikes up to 20 cm wide and a clastic intrusion 60 cm wide (Fig. 8). We also observed suspended blocks transported upward within the intrusion, a foundered block of Units 4 and 5, small-scale convoluted bedding, and pinch and swell of Units 2 and 3. We interpret these features as liquefaction evidence of strong Holocene seismicity. This site may record lateral spreading. The dip of the strata is in a downstream direction and may reflect depositional dip.

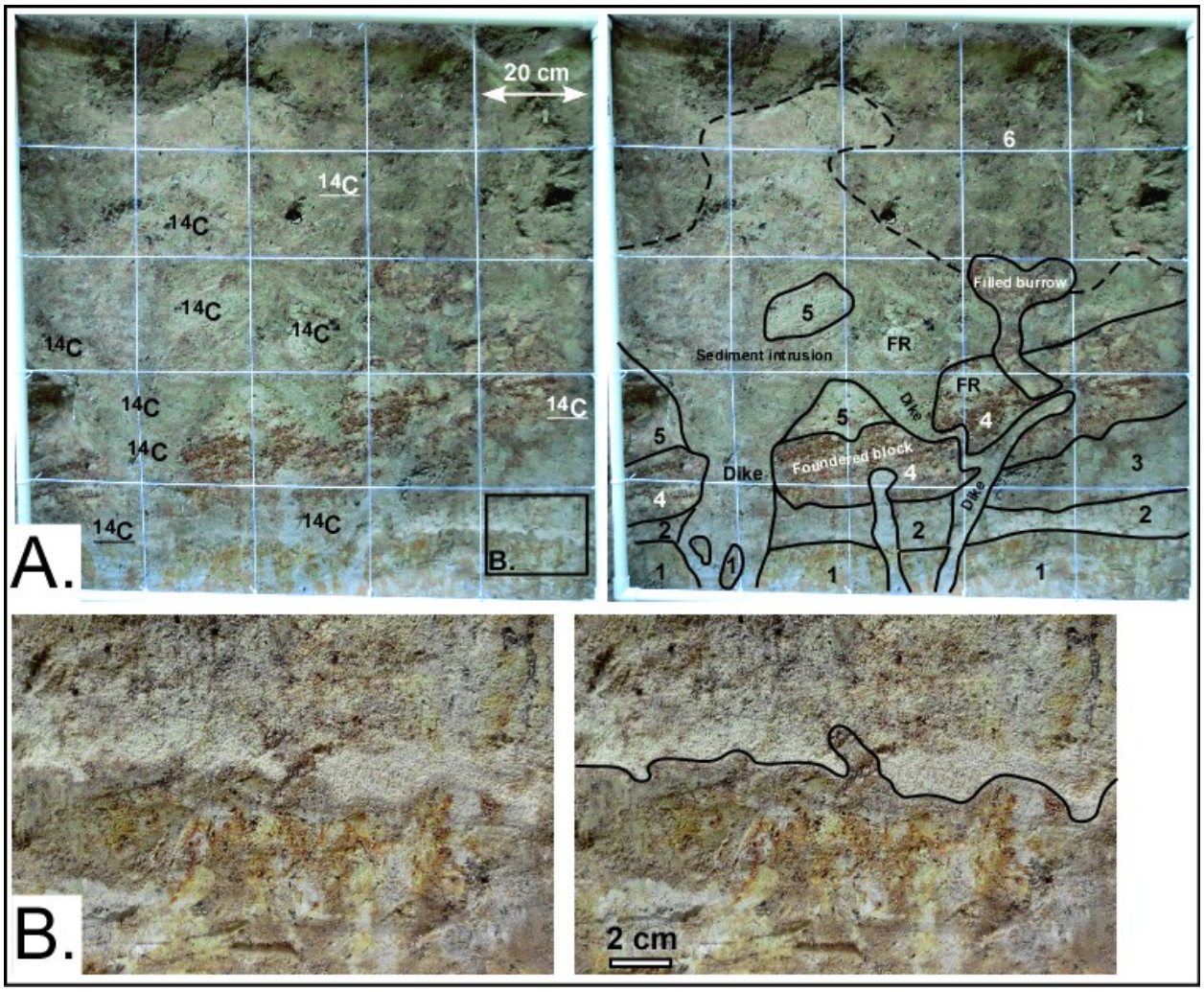

FIGURE 8. Site B-5 (Clear Creek) – Our excavation in Holocene alluvium. A) Uninterpreted (left) and interpreted (right) 1x1 m grid. Top is up. 1 = Massive silty clay; 2 = Medium-bedded structureless fine sand; 3 = Structureless fine sand with clay inclusions; 4 = Thin-bedded oxidized medium/fine sand; 5 = Medium-bedded fine sand; 6 = Massive fine sandy loam; FR = Filled root cast. ^{14}C denotes carbon sample (underlined = submitted to lab). B) Detail showing small-scale liquefaction.

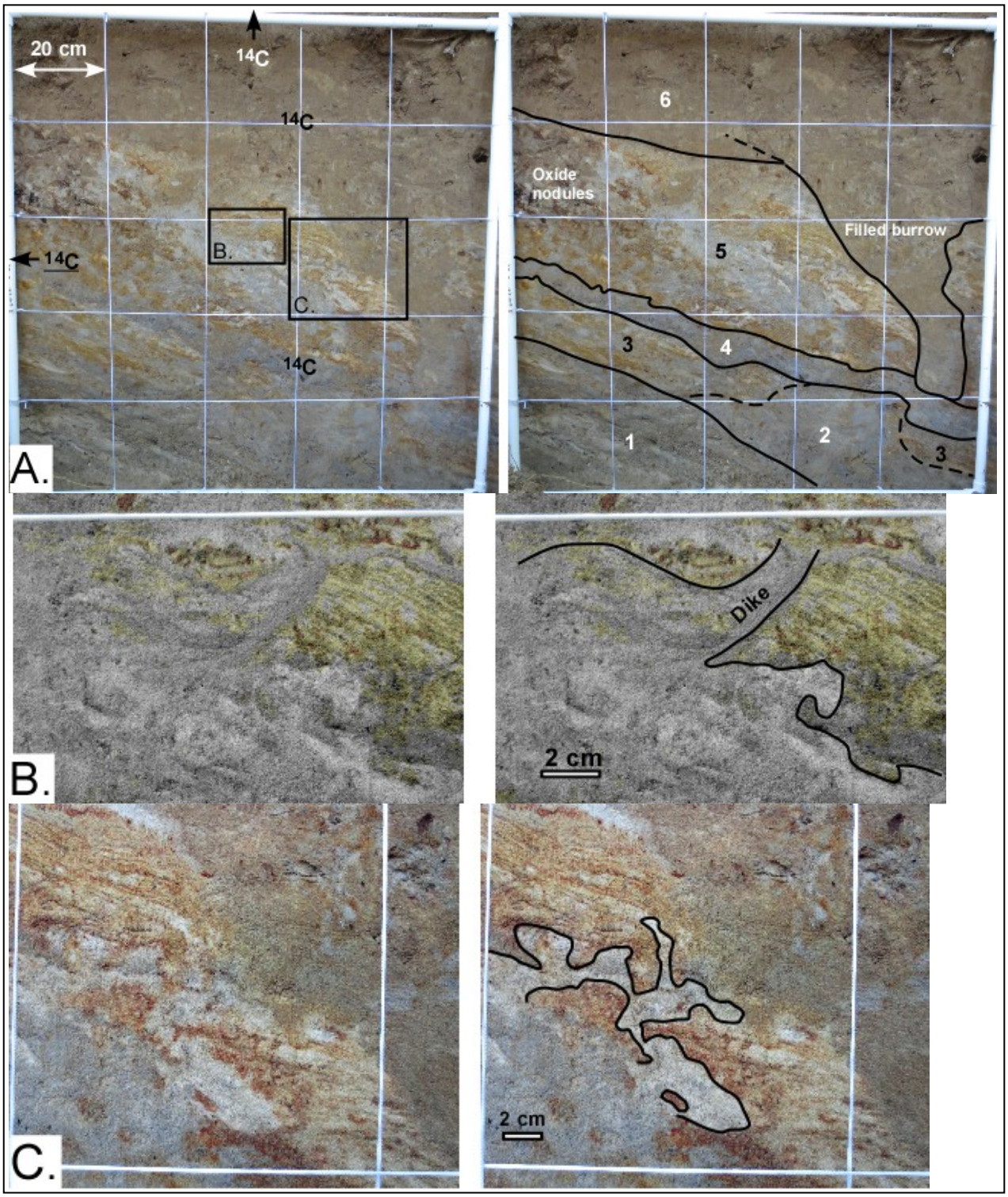

FIGURE 9. Site C-1 (Hungerrun Creek) - Our excavation in Holocene alluvium. A) Uninterpreted (left) and interpreted (right) 1x1 m grid. Top is up. 1 = Medium-bedded coarse sand and gravel; 2 = Structureless fine/medium sand; 3 = Medium-bedded fine sands; 4 = Massive clay-rich fine sand; 5 = Thin-bedded fine sand; 6 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab). B and C) Detail showing small-scale clastic intrusions.

Site C-1) In our excavation on Hungerrun Creek, we observed well stratified Holocene sand disrupted by sand intrusions, convoluted beds, and pinch and swell of bedding (Fig. 9). We interpret these features as liquefaction evidence of strong Holocene seismicity. A burrow filled with sandy loam was also observed. The dip of the strata is in a downstream direction and may reflect depositional dip.

Site D-1) We observed well stratified gravel and sand Holocene alluvium in our stream bank excavation on Wood Creek (Figure 10). Burrows filled with silt loam cross-cut the stratigraphy, but we interpret no liquefaction features at this site.

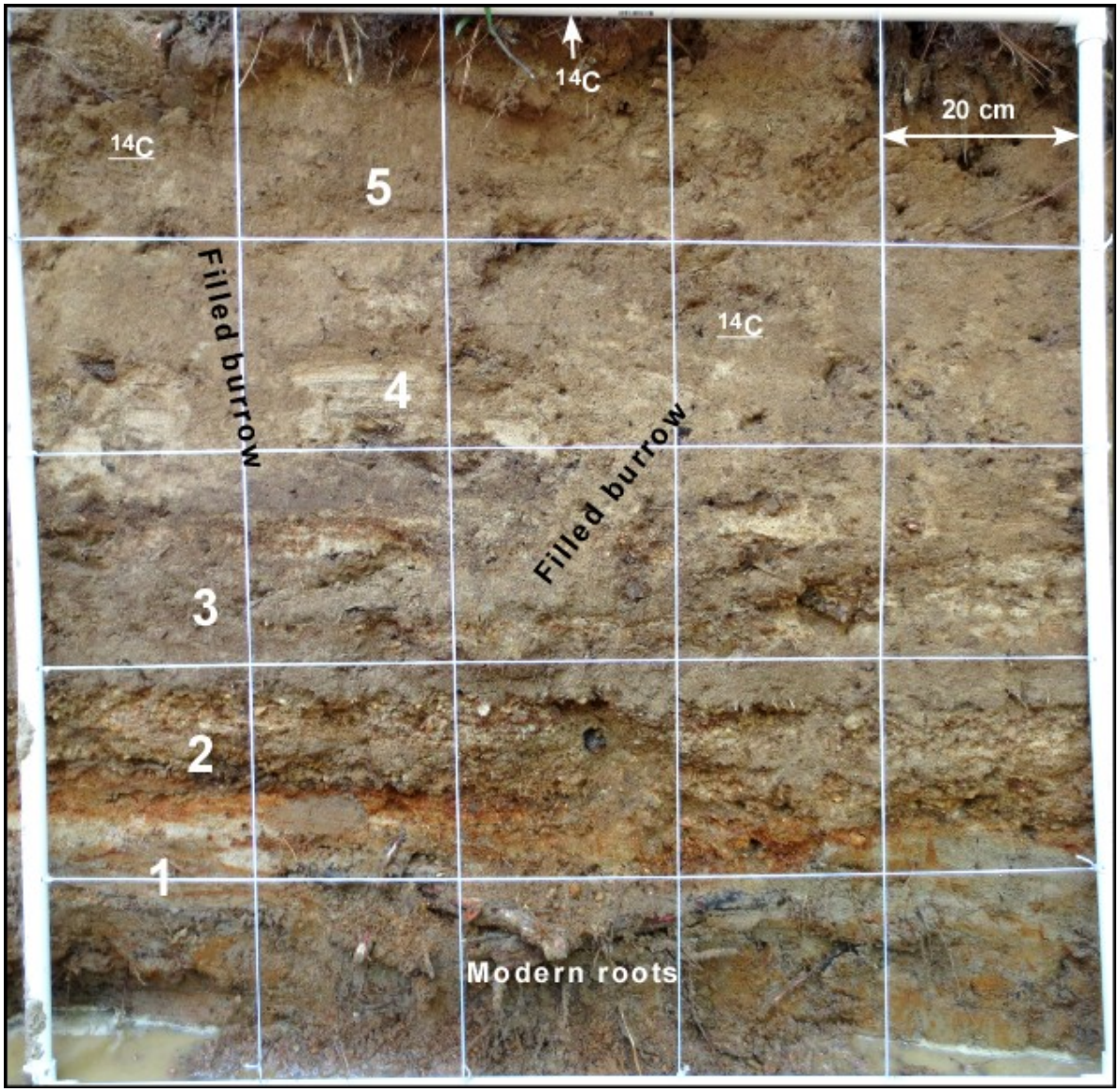

FIGURE 10. Site D-1 (Wood Creek) - Our excavation in Holocene alluvium. No liquefaction observed. 1 = Medium-bedded fine sand; 2 = Medium-bedded gravel; 3 = Interfingering medium beds of fine/medium sand and gravel; 4 = Thin-bedded fine sand; 5 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab).

FIGURE 11. Site D-4 (Langford Creek) - Our excavation in Holocene alluvium. Possible minor liquefaction of Holocene sediment. Top is up. A) Gridded excavation. 1 = Medium-bedded gravel; 2 = Medium interbeds of fine sand and clay; 3 = Medium-bedded fine sands with minor clay lenses; 4 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab). B) Detail showing minor pinch-swell features.

Site D-4) We observed stratified gravel, sand, and clay Holocene alluvium in our stream bank excavation on Langford Creek (Figure 11). Down-warping and small-scale pinch and swell of beds in the lower right-hand part of our grid suggest possible minor liquefaction due to ground shaking at this site.

Site D-5) We observed stratified gravel, sand, and clay Holocene alluvium in our stream bank excavation on Sandy Creek (Figure 12). These beds are convoluted and exhibit pinch and swell. We interpret these features as liquefaction evidence of Holocene seismicity and ground shaking.

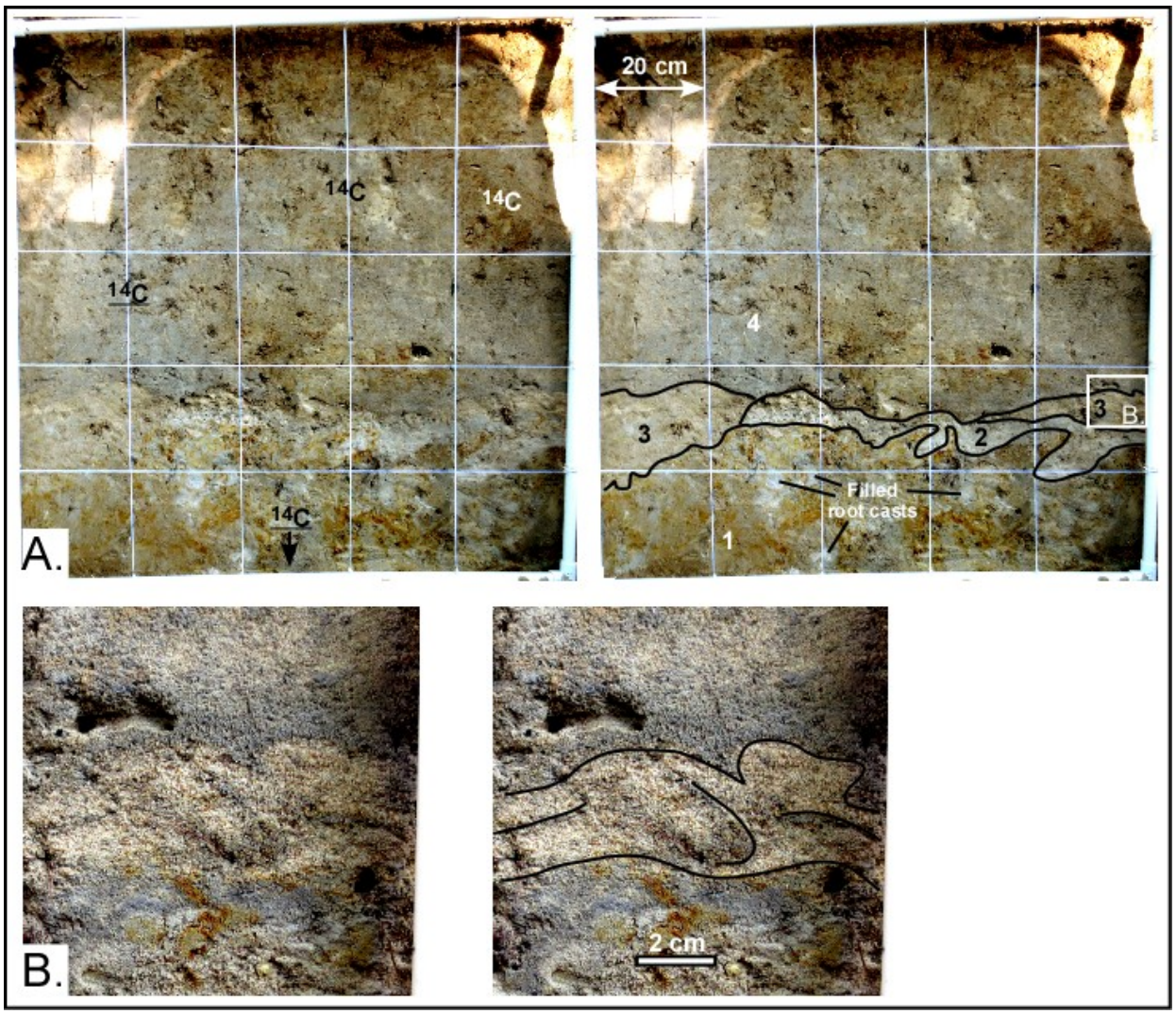

FIGURE 12. Site D-5 (Sandy Creek) - Our excavation in Holocene alluvium. A) Uninterpreted photograph of gridded excavation (left) and interpreted photograph (right). 1 = Massive sandy clay; 2 = Medium-bedded gravel; 3 = Medium/thin interbedded clay and sand; 4 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab). B) Detail showing small-scale contorted beds.

Site D-6) In our excavation on Wolf Creek, we observed well stratified Holocene sand and clay disrupted by dish structures indicative of water escape and by clay blocks suspended in sand (Fig. 13). We interpret these features as liquefaction evidence of strong Holocene seismicity.

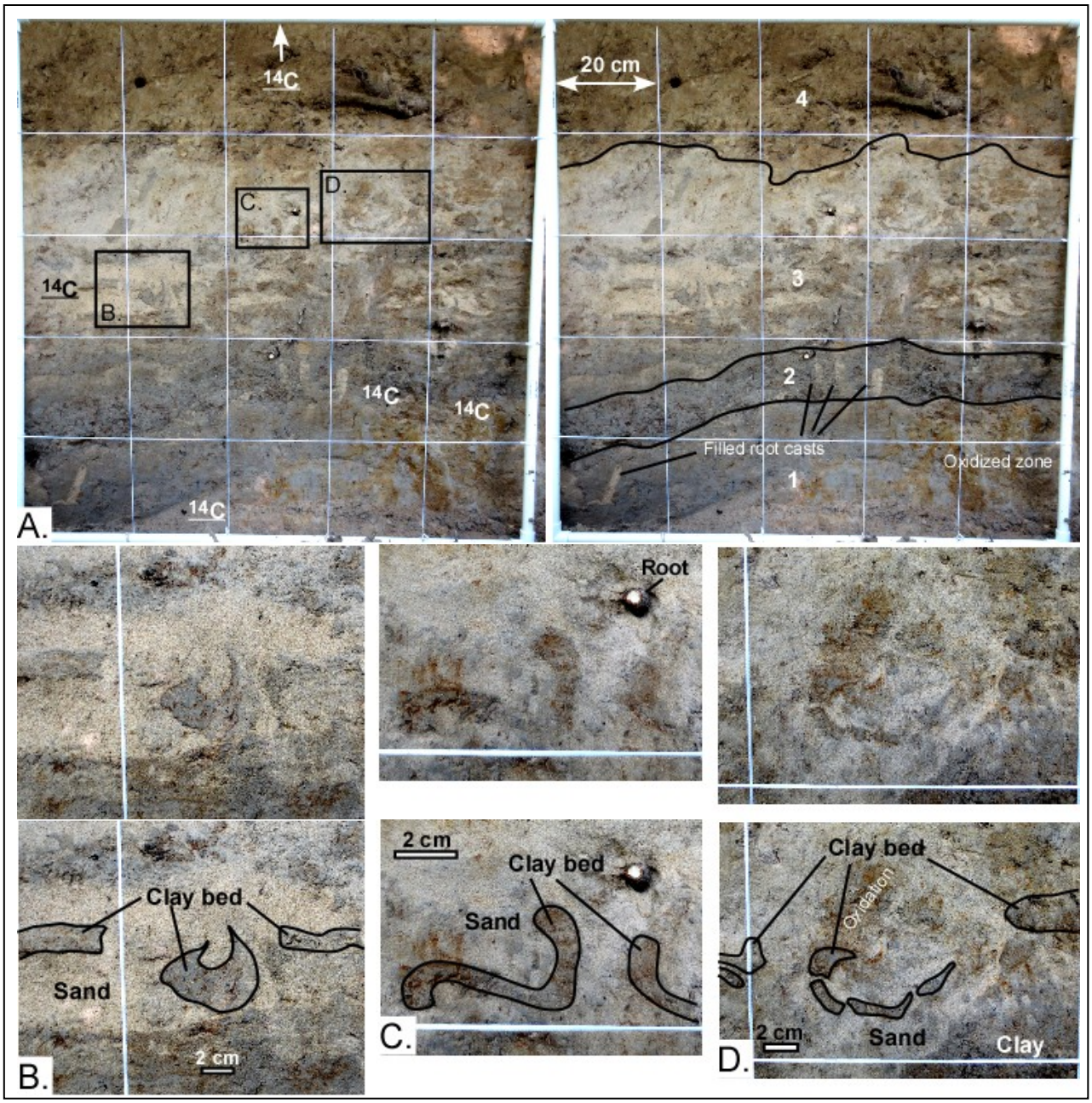

FIGURE 13. Site D-6 (Wolf Creek) - Our excavation in Holocene alluvium. A) Uninterpreted photograph of gridded excavation (left) and interpreted photograph (right). 1 = Massive clay; 2 = Medium-bedded sandy clay; 3 = Medium interbeds of fine sand and clay; 4 = Massive loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab). B, C, and D) Details showing individual clay beds deformed by fluid-escape “dish” structures.

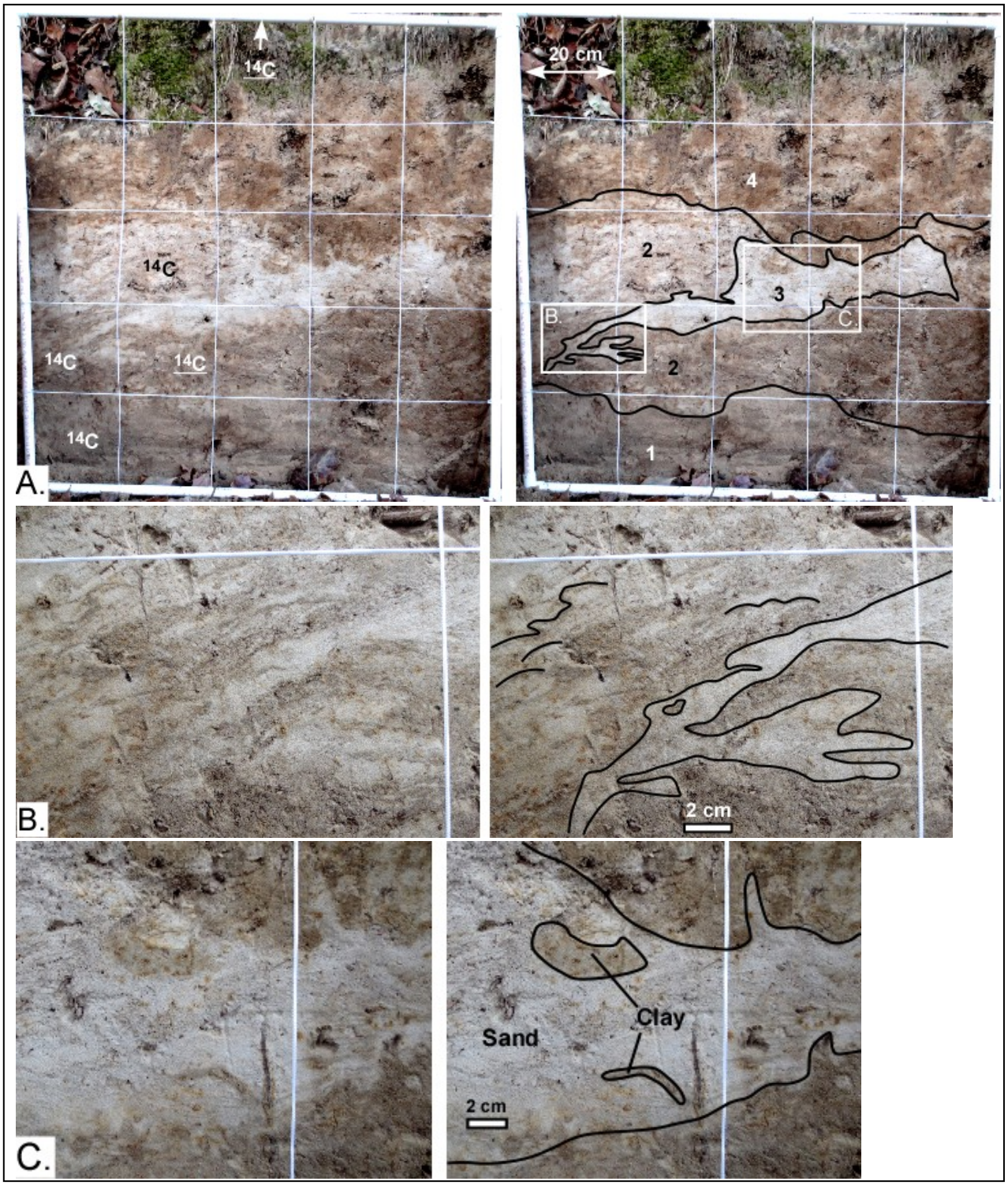

FIGURE 14. Site E-1 (Upper Cutoff Creek) - Our excavation in Holocene alluvium. A) Uninterpreted photograph of gridded excavation (left) and interpreted photograph (right). Top is up. 1 = Massive fine/medium sand; 2 = Medium interbeds of sandy clay and fine/medium sand; 3 = structureless body of fine sand; 4 = Massive to poorly bedded sandy loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab). B and C) Details showing small-scale sand intrusions, contorted beds, and detached blocks.

Site E-1) In our excavation on Upper Cutoff Creek, we observed well stratified Holocene sand and clay disrupted by a sand intrusion (Unit 3), convoluted beds, and clay blocks suspended in sand (Fig. 14). The geometry of the Unit 3 sand intrusion suggests that its source was Unit 1, but we did not observe a clear connection. We interpret these features as liquefaction evidence of strong Holocene seismicity.

Site G-1) We observed poorly stratified clay and sand Holocene alluvium in our stream bank excavation on Beech Creek (Figure 15). Burrows and root casts filled with sandy loam cross-cut the stratigraphy, but we interpret no liquefaction features at this site.

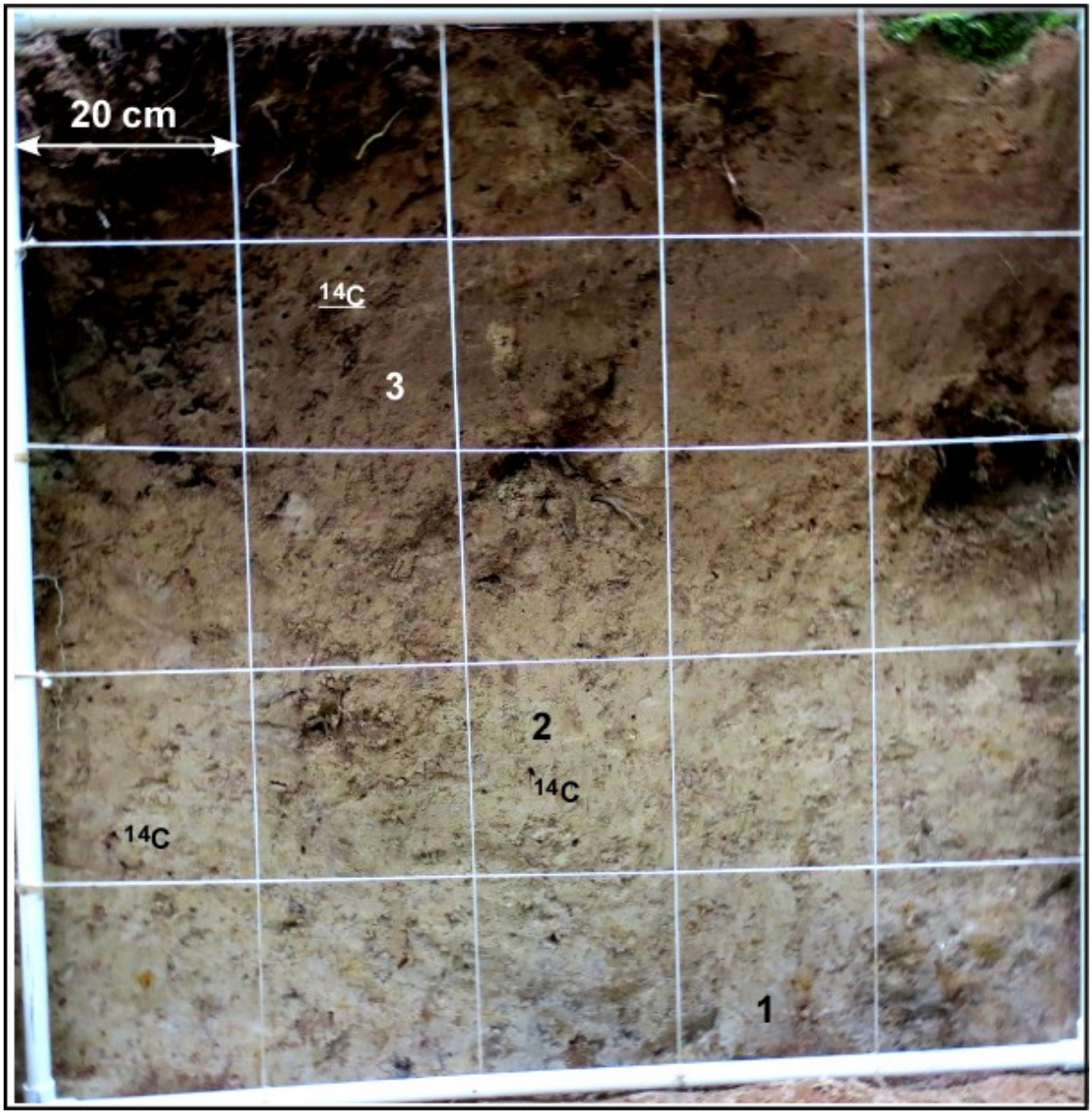

FIGURE 15. Site G-1 (Beech Creek) - Our excavation in Holocene alluvium. No liquefaction observed. 1 = Massive gravel-bearing clay; 2 = Massive medium/fine sand; 3 = Massive sandy loam (aggraded A soil horizon). ^{14}C denotes carbon sample (underlined = submitted to lab).

Site G-2) We observed poorly stratified clay and sand Holocene alluvium in our stream bank excavation on Steepbank L'Aigle Creek (Figure 16). Root casts filled with sandy loam cross-cut the stratigraphy, but we interpret no liquefaction features at this site.

FIGURE 16. Site G-2 (Steepbank L'Aigle Creek) - Our excavation in Holocene alluvium. No liquefaction observed. 1 = Medium/thin-bedded, fine/medium sand; 2 = Massive sandy loam (aggraded A soil horizon).

Site H-1) On a vertical wall of a sand mine in the late Pleistocene (Sangamon) Prairie terrace (Fig. 17) we observed convoluted bedding in well stratified, weakly indurated fluvial sand beneath 4 m of silty clay (weathered latest Pleistocene Peoria loess). We interpret these convoluted beds as liquefaction in response to strong seismicity, and we argue that liquefaction occurred during Pleistocene because these weakly indurated sediments now have a low to moderate liquefaction potential and because we observed

no sand intrusion into the Peoria loess. Root casts filled with reworked loess cross-cut the stratigraphy but are unrelated to the convoluted bedding.

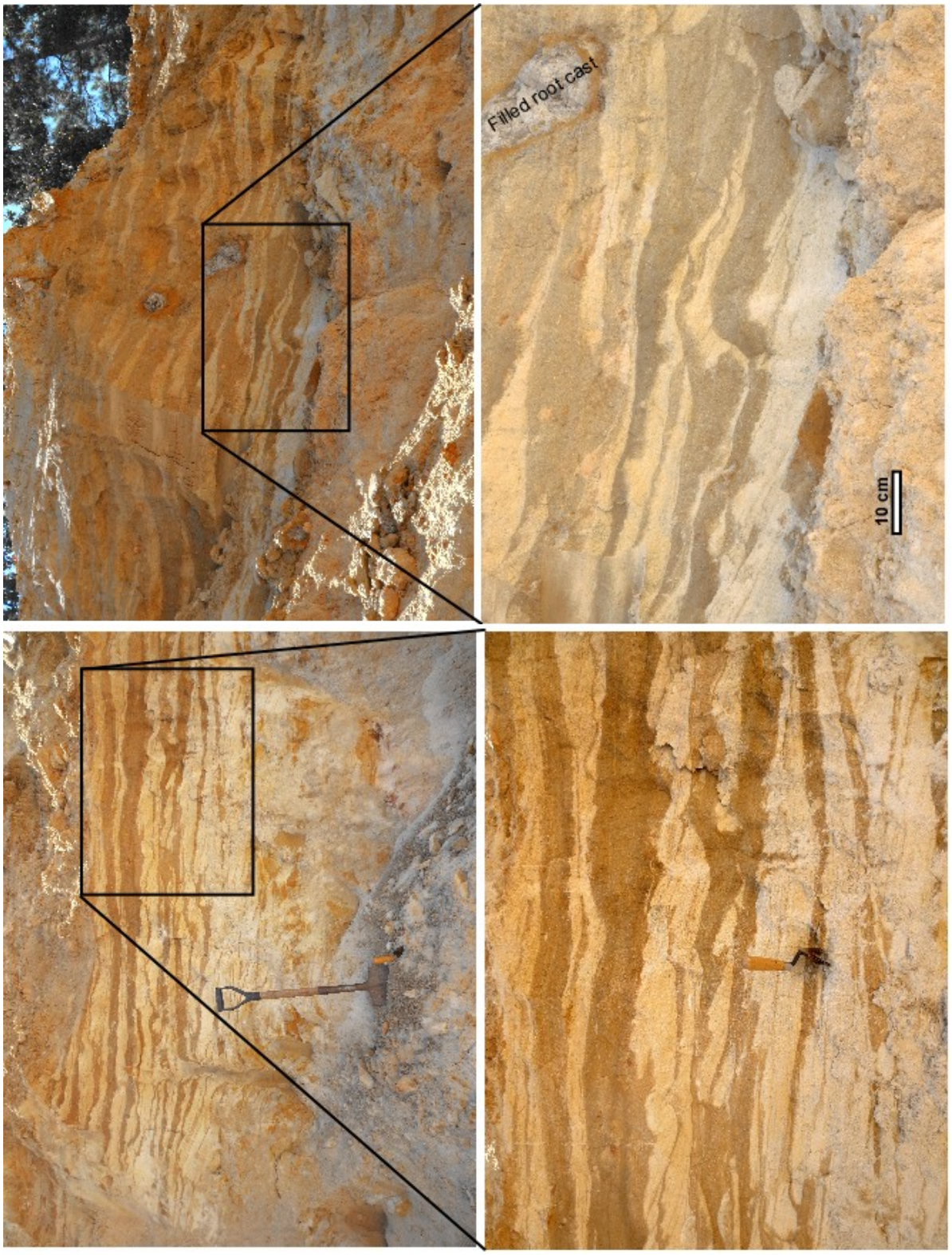

FIGURE 17. Site H-1 - Sand mine exposures of late Pleistocene alluvium displaying convoluted bedding.

DISCUSSION AND CONCLUSIONS

We found evidence for Holocene liquefaction that we interpret as resulting from strong ground shaking at five field sites (B-5, C-1, D-5, D-6, and E-1; Table 1 and Fig. 2) and possibly at field site D-3. In addition, we observed evidence for Pleistocene liquefaction at field sites B-4 and H-1. All these sites are clustered near Pleistocene and Holocene surface ruptures of the Saline River fault zone described in Cox et al. (2000), and we tentatively assign paleo-earthquakes related to this liquefaction to movements on that fault zone. However, our forthcoming radiocarbon age data are required to make temporal correlations between these liquefactions events and faulting events. At five field sites, we observed Holocene alluvium that showed no evidence of liquefaction (B-1, B-2, D-1, G-1, and G-2), and at one field site Pleistocene alluvium showed no evidence of liquefaction. The locations of field sites B-1 and B-2 suggests that the Bradley County sand blow field is NOT continuous with either the Desha County or Ashley County sand blow fields, thus bearing on our Research Question #1 and supporting a paleo-earthquake magnitude LESS THAN a M 6.7 estimate for a continuous field based on Ambraseys (1988). However, our field sites that show Holocene liquefaction may be part of a greater Desha County sand blow field. If this is the case, the distance from the center of the field to the farthest liquefaction is ~35 km, corresponding to M 6.4 by the Ambraseys (1988) empirical relationship of magnitude and distance to farthest liquefaction. However, our forthcoming radiocarbon age data are required to make temporal correlations between liquefactions events in this study and in the Desha County sand blow field. Finally, we conclude that the Bradley County sand blow field is limited in extent and related to local surface faulting within the liquefaction field that are reported in Cox et al. (2012). Thus, the magnitudes of paleo-earthquakes related to the Bradley County sand blow field are probably in the low part of the range known to cause sand venting (M 5 to 5.5).

Table 2. All carbon samples collected for potential age determination at NSF-Arizona AMS Laboratory.

SITE #/ SAMPLE #	X GRID CELL	Y GRID CELL	SUBMITTED	MATERIAL	mg	age(yrBP)	COMMENT
B-1/1	3	2	yes	CHARCOAL	14	no gas	
B-1/2	3	5	yes	BULK SOIL	10000		
B-2/1	top	top	yes	BULK SOIL	10000		NO GRID
B-5/1	3	1		CHARCOAL			
B-5/10	2	3		CHARCOAL			
B-5/2	3	4	yes	CHARCOAL	28		
B-5/3	5	2	yes	CHARCOAL	46		SUBMITTED ALL CHARCOAL
B-5/4	1,2	2		CHARCOAL			
B-5/5	2	4		CHARCOAL			
B-5/6	3	3		CHARCOAL			
B-5/7	1,2	2		OXIDE?			
B-5/8	1	1	yes	CHARCOAL	58		
B-5/9	3	1		CHARCOAL			
C-1A/1	3	1,2		CHARCOAL			
C-1A/2	5	1		CHARCOAL			
C-1A/3	3	-1	yes	WOOD	83		
C-1A/4	2	4	yes	ABRADED CHARCOAL? FECAL PELLETS?	71		
C-1B/1	-1	3	yes	CHARCOAL	76		
C-1B/2	3,4	2		CHARCOAL			
C-1B/3	3,4	5,6		FECAL PELLET? GLOBULAR MASSES			
C-1B/4	3	6,7	*	BULK SOIL			not enough $
D-1/1	4	4	yes	PLANT FIBER	87	no gas	
D-1/2	1	5	yes	CHARCOAL	61		
D-1/3	top	top	*	BULK SOIL			REPRESENTATIVE OF SITE, not enough $
D-4/1	3	2	yes	CHARCOAL	40		
D-4/2	5	1	yes	CHARCOAL	52		
D-4/3	3	6,7	*	BULK SOIL			not enough $
D-5/1	1,2	3	yes	CHARCOAL	33		
D-5/2	3,4	4		CHARCOAL			
D-5/3	5	4		CHARCOAL			
D-5/4	3	-1	yes	CHARCOAL	63		replacement for 1-1/1
D-6/1	2	1	yes	WOOD	64		
D-6/2	4	2		CHARCOAL			
D-6/3	1	3	yes	BURNT SEED?	22	no gas	SUBMITTED ALMOST ALL CARBON
D-6/4	5	2		CHARCOAL			
D-6/5	3	10	yes	BULK SOIL	10000		replacement for 3-1/1
E-1/1	1	2		ROOT BARK			
E-1/2	1	1		ROOT BARK			
E-1/3	2	2	yes	PLANT FIBER & FECAL PELLET?	8		SUBMITTED ALL CARBON
E-1/4	2	3		OXIDE? V TINY FRAGMENTS			
E-1/5	3	9	yes	BULK SOIL	10000		replacement for 3-6/3
F-1/1	1	2		CHARCOAL			MODERN SEDIMENT? VINAL STRIP
G-1/1	1	2		CHARCOAL			
G-1/2	2	4	yes	BULK SOIL	10000		
G-1/3	3	2		CHARCOAL			
G-2/1	3	1	yes	CHARCOAL	70		
G-2/2	2	4	yes	CHARCOAL	330		

* Alternate samples for submission if replacements are requested by the NSF-Arizona AMS Laboratory.

NON-TECHNICAL SUMMARY

Previous studies of south Arkansas soils have shown prehistoric earthquakes caused sand in soils to liquefy and erupt and the ground to collapse. How widespread these disturbances are relates to the strength (magnitude) of prehistoric earthquakes, and good estimates of the strength of past ground shaking are necessary for planning future earthquake mitigation strategies. Therefore, this study examined soils for evidence that sands had liquefied in forested areas of south Arkansas where sand eruptions cannot be seen on aerial photographs. These results suggest at least three locations of prehistoric earthquakes and one may have experienced a magnitude 6.4 earthquake.

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