SPATIAL AND TEMPORAL CHARACTERISTICS OF PALEOSEISMIC FEATURES IN THE SOUTHERN TERMINUS OF THE NEW MADRID SEISMIC ZONE IN EASTERN ARKANSAS

Haydar J. Al-Shukri and Hanan H. Mahdi

Department of Applied Science, University of Arkansas at Little Rock

alshukri@seismo.ualr.edu

501-569-3086

mahdi@seismo.ualr.edu

and

Martitia Tuttle

M. Tuttle & Associates, Georgetown, ME

mptuttle@earthlink.net

Award 03HQGR0050

May 2006

Three- Dimensional Imaging of Earthquake-induced Liquefaction Features with Ground Penetrating Radar Near Marianna, Arkansas

Haydar J. Al-Shukri, Hanan H. Mahdi, and Martitia Tuttle

ABSTRACT

Ground Penetrating Radar (GPR) is a powerful tool to study earthquake-related features such as sand blows and faults. The study area is near Marianna, Arkansas, and the work involves GPR surveys of large elliptical sand deposits. Our primary goal was to locate feeder dikes of sand blows and to image the contact between sand blows and the buried paleo-surface in order to optimize the location of trenches. A secondary goal was to image the sand blows in three dimensions to define their sizes and morphology. Trenching large sand blows is costly and provides a limited view of the overall structure. GPR helps to identify possible locations for the venting dikes and to visualize the subsurface features. It also helps to map the locations of tree stumps in the sand blows that are useful for dating.

The surveys imaged sharp contacts in near-surface sediments that were confirmed in trenches to represent boundaries between sand blows and buried soils. One survey in particular showed a sharp discontinuity in the boundary related to a large feeder dike. Because sand thickness was no more than 4 meters, a 400-MHz antenna was used. This antenna is designed to provide high-resolution images of the upper 5 meters of soil. Data acquisition was along parallel profiles oriented normal to the long axes of the sand deposits at all sites. Data reduction and analysis procedures included removal of direct and ground surface effects, frequency filtration, gain control, profile migration, and three-dimensional visualization. In future work, we plan to refine field procedures and test additional survey configurations for acquisition of the best result. We will survey additional sites to help with the follow up trenching and sampling work.

INTRODUCTION

Geophysical techniques have proven to be a powerful tool in the study of liquefaction-related sand blows and sand dikes resulting from strong earthquakes (Wolf *et al.*, 1998; Tuttle *et al.*, 1999; Lui and Li, 2001) and faults (Sexton, *et al.*, 1992). Geophysical methods used in near-surface studies include seismic (reflection and refraction), magnetic, gravity, resistivity, and heat flow studies. All of these techniques are based on the same fundamental principle: changes in the physical properties (seismic velocity, magnetism, density, resistivity, etc.) of rocks and sediments. These changes can be used to illustrate stratigraphic and structural setting in the subsurface. Ground Penetrating Radar technology is known to work well in dry, sandy conditions and is widely utilized in environmental and engineering sciences. Recently, several studies have proven GPR to be instrumental in analyzing near surface Earth structures (Veeken, *et al.*, 1999; Yetton, *et al.*, 1998). GPR has the advantages of higher resolution than other geophysical methods, it is non-invasive, and it provides greater aerial and depth coverage than trenching. It allows for less setup/survey time than traditional land-based seismic methods, and it can be carried out by two people. Although penetration depth is

substantially less than that of shallow seismic methods, GPR penetrates deep enough (several meters) to study near-surface liquefaction features.

Recently, GPR has been applied to near surface geological structures and pale-seismological features (Salvi *et al*., 2003) using low-frequency antennas (200, 100, and 50 MHz) to investigate the active Celano–L'Aquila fault system, Abruzzi (central Apennines, Italy). These scientists also used GPR data to guide the selection of appropriate trench sites. Gross *et al.* (1999 and 2000) used 2-D and 3-D GPR data to study the Wellington Fault in New Zealand, and the San Andreas Fault in California, attributing data offsets or abrupt terminations of laterally continuous reflections to faulting. They also indicated that GPR helped in locating trench sites.

GPR transmits electromagnetic radiation that propagates through the ground then returns to the surface. The radar waves travel at speeds that are dependent upon the dielectric constant of the subsurface. Reflections are produced by changes in the dielectric constant due to changes in the subsurface material and/or conditions. The travel time of the electromagnetic waves from transmitting antenna to receiving antenna is a function of the depth of the reflection point and the electric properties of the earth media. Thus, interpretation of reflected energy yields information on subsurface structural variation and condition of the media. As in seismic techniques, there is a trade-off between depth and structural resolution. Data are most often collected along a profile, so that plots of the recorded signals with respect to survey position and travel-time can be associated with images of the subsurface structure. GPR signals can be collected fairly rapidly and initial interpretations can be made with minimal data processing, thereby making the use of GPR in shallow geophysical investigation cost-effective with little technical personnel support (Cardimona *et al*.,2000).

Recently, Al-Shukri *et al*. (2005) and Tuttle *et al.* (2006) found several earthquake-induced sand blows and related linear structures in eastern Arkansas south of Marianna, Arkansas, more than 100 km from the currently active New Madrid seismic zone. Al-Shukri *et al*. (2005) established that sand blows occurred in the area, and suggested that some of them were prehistoric in age. Tuttle *et al.* (2006) determined that some of the sand blows formed during very large earthquakes centered near Marianna between 5,000-7,000 years ago. Some of the sand blows are very large (~600 by 450 meters), resembling those in the immediate vicinity of the New Madrid seismic zone, implying very strong ground shaking. Huge amounts of sand erupted to the surface to form sand blows up to 2.5 meters thick. The sand is medium to fine grain, which makes GPR an ideal tool for imaging the sand blows.

We present the results of 3-D GPR surveys at three sites to determine the location of the feeder dikes and to map the contact between the old surface and the sand blows. We have also conducted GPR profiling to relocate a trench that was excavated and subsequently back-filled in 2001. The high-resolution GPR surveys were exceptionally helpful in imaging tree stumps that were buried in the sand blows.

3-D GPR METHODOLOGY

Ground Penetrating Radar surveys were conducted at three sites 8 km southwest of Marianna, Arkansas. The sites occur close to one another and are named Daytona Beach (DB), Johnson Farm (JF), and Nancy 2 (Figure 1). A fourth survey involving several short (~10 meters) parallel profiles was conducted at the Nancy 2 site to relocate a trench that was excavated four years before. Because thickness of most of the sand blow is no more than 5 meters, a 400 MHz monostatic antenna was used in all four surveys. The antenna is designed to give high-resolution results in near-surface (~5 meters) sandy soil. The data for all surveys were collected using Geophysical Survey Systems, Inc. (GSSI) SIR® 10B data acquisition system. A survey wheel was also used to calibrate the profile length and the number of scans for each profile.

Analogous to 3-D seismic analysis, all profiles of each survey are compiled into a single 3-D file using specially designed software (RADAN, of the GSSI). Before this compilation, an individual profile is processed to correct for the antenna delay time and to remove the predicted direct signal and the signal that reflected back from the surface to the receiver. It is necessary to remove the delay time in order to retain the zero time as the time of signal transmission from the antenna. The high amplitude of the direct and surface reflections usually mask the signal related to subsurface anomalies. Low- and high-pass filtering (800 MHz and 100 MHz) is also used to remove unwanted frequency bands. The processing and imaging software allows the slicing of data in any desired section, as well as viewing from any desired direction and orientation.

Daytona Beach Site (DB)

The DB site is located approximately 8 km southwest of Marianna, Arkansas (Figure 1). This site is part of a complex sand blow field extending over a radius of more than 600 meters. The site is in a farm field that has been repeatedly graded and leveled, affecting the soil profile. Tuttle *et al.* (2006) presented photographic evidence that this sand blow forms a northwest-oriented, large light-colored area that is part of 2km-long lineament (Figure 2). Existence of ponds, similar to the one west of the sand blow, may be related to ground failure at the site. At the surface, the sand is distinguishable by its light brownish color, which makes it easy to map the boundary of the blow (Figure 3). The sand blow fines upward from coarse sand to silty, very fine sand (Tuttle *et al.*, 2006) and has been excavated in some areas for use in highway construction.

The DB site was selected for trenching, logging, and radiocarbon dating, however, siting the trench was difficult. The sand blow is very large, and agricultural grading and leveling of the site has disturbed the surface soils. We searched for feeder dikes to confirm that the large sand deposit was, in fact, a sand blow,. We excavated several soil pits and used a soil probe to determine that the sand blow thickens towards the east and that a possible feeder dike is located towards its eastern margin (Tuttle *et al.*, 2006). We then employed GPR to map the morphology of the sand/silt contact.

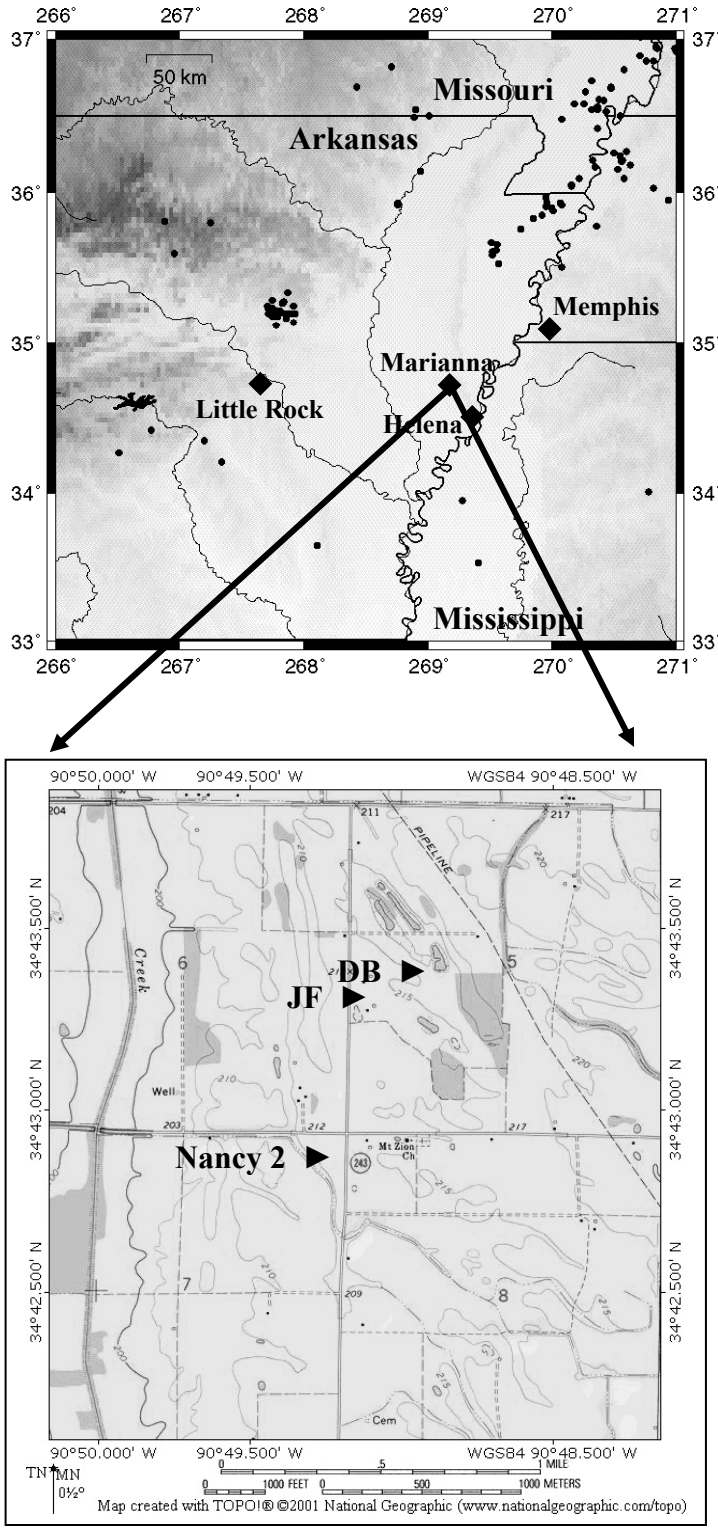

Figure 1. Location map of the study area. Earthquake (Mag > 3.0: 1974-2005) locations shown as black dots in the top map. The sites of Daytona Beach (DB), Johnson Farm (JF) and Nancy 2 sites are shown in the zoomed-in bottom map.

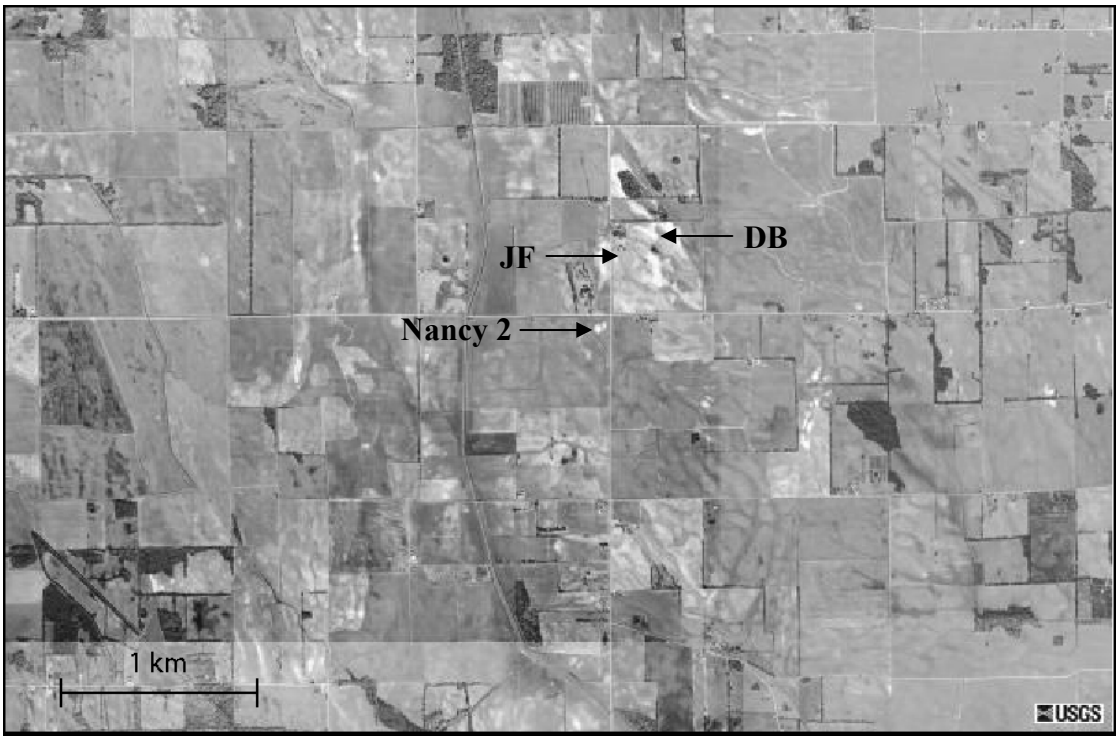

Figure 2. Aerial photograph of sand blows appear as light colored areas. Arrows mark location of the Daytona Beach (DB), Johnson Farm (JF) and Nancy-2 sites.

Data Acquisition. The survey layout is designed to collect data so that high-resolution 3-D images can be developed and studied. An area having dimensions of about 100 meters by 20 meters was selected for the surveys. Data acquisition is conducted along 15 parallel profiles each 80 meters long and oriented in an east-west direction (Figure 3). The spacing between profiles (~1 meter) is controlled by rows of cotton plants. The survey wheel, which is used to measure the length of the profile and the number of scans per unit length, is calibrated to collect 8183 scans per profile. This produced a spacing of about 1 centimeter between scans. With this configuration, it is possible to produce a high-resolution 3-D image of a volume of the earth having dimensions of 80 meters by 15 meters by 5 meters. This volume includes the sand blow and the underlying soil.

Analysis and Results. The 3-D image of the data with an east-west vertical section is shown in Figure 4. The most prominent feature of this image is the continuous east-dipping surface, which is identified as the contact between the sand blow and the underlying silt loam. The dipping or inclination in this contact starts at about 30 meters and continues to about 70 meters distance. From 0 to 30 meters distance, the surface is undisturbed and relatively flat lying. It is also clear that this contact is disturbed or breached at about 70 meters distance from the western end of the profile. This surface exhibits the same structure throughout the 15 meters width of the surveyed area. Continuous slicing of the 3-D image from north to south shows that the distance to the breach point becomes continuously larger. This suggests that the feature that disturbed or breached the contact has a northwest – southeast orientation.

Figure 3. Photographs of the GPR survey sites. Daytona Beach (top photograph) shows the cotton groves (east-west) where the GPR profiles are located. The survey team is shown moving east. The Johnson Farm (middle photograph) survey profiles (white strings) are laid in east west direction. The survey operator is moving toward west. The Nancy-2 sand blow (lower photograph) is shown as dark colored area. The bottom photograph (pointing toward the south) was taken during the winter of 2004, almost 4 years after a trench was excavated in the area.

A trench was excavated at the DB site during the fall of 2004. Details of trenching, dating, and tectonic interpretation are presented in Tuttle *et al.* (2006). The trench was oriented parallel to the GPR profile (west-east). The upper panel of Figure 4 shows the 3-D GPR data and the lower panel shows the log of the trench's northern wall. Comparing the GPR section and the trench log, there is almost a perfect match between the two results. Details of the eastern ends of both the GPR data and the trench log further demonstrate the close match (Figure 5). The termination in the continuity of the sand-silt contact identified in the GPR section clearly fits the location of the feeder dike of the sand blow. The continuity of this contact and its sharp termination helped to determine the trench location and its orientation. These results are a clear demonstration of the effectiveness of GPR in mapping such features, including the contact between the sand blow and the underlying paleo-surface, and the 3-D morphology of the sand blow and feeder dike.

Johnson Farm Site (JF)

This site is located about 300 meters to the west of the Daytona Beach site and about 600 meters from the Nancy 2 site (Figure 1). The sand at the surface, although not as thick as at the DB sand blow, is similar in grain size and color. At this site, it was less clear where and how to site the trench.

Data Acquisition. The survey layout for this site is also designed to collect data such that high-resolution 3-D images can be developed. A rectangular area having dimensions of 27 meters by 16 meters was selected for the survey. The layout consists of 33 parallel profiles each with a length of 27 meters with spacing of 0.5 meter between profiles (Figure 3). The profiles are laid out in an east- west direction. The survey wheel is calibrated to collect 5498 scans per profile, which produce a distance of 0.5 centimeters between scans.

Analysis and Results. The 3-D image of GPR data for the JF site was produced in a similar manner as the DB site. Figure 6 shows the 3-D image having a vertical section through the middle of the survey and parallel to the profiles. The contact between sand and silt loam, which is indicated by the first red line at a depth of about 0.5 meters, is clearly identified and mapped. Across the surveyed area there is no indication that this contact was disturbed or the silt loam was breached. An exception is a feature at a distance of 20 meters from the start and about 8 meters from the first profile. This feature is manifested by a depression in the GPR signal of the sand – silt contact forming a hemispherical shape of radius approximately 1 meter in length (Figure 6). A similar, but less pronounced feature was also found in the middle of the GPR survey (not shown in Figure 6). Because of the continuity of the contact at the bottom of the features, we concluded that these features do not represent a sand dike. Our two possible interpretations of the features were either of holes dug in the last few years or a large tree stumps. We preferred the latter interpretation due to the anomalous GPR signature (Figure 6). The landowner confirmed that there has been no land disturbance at the site for more than 15 years.

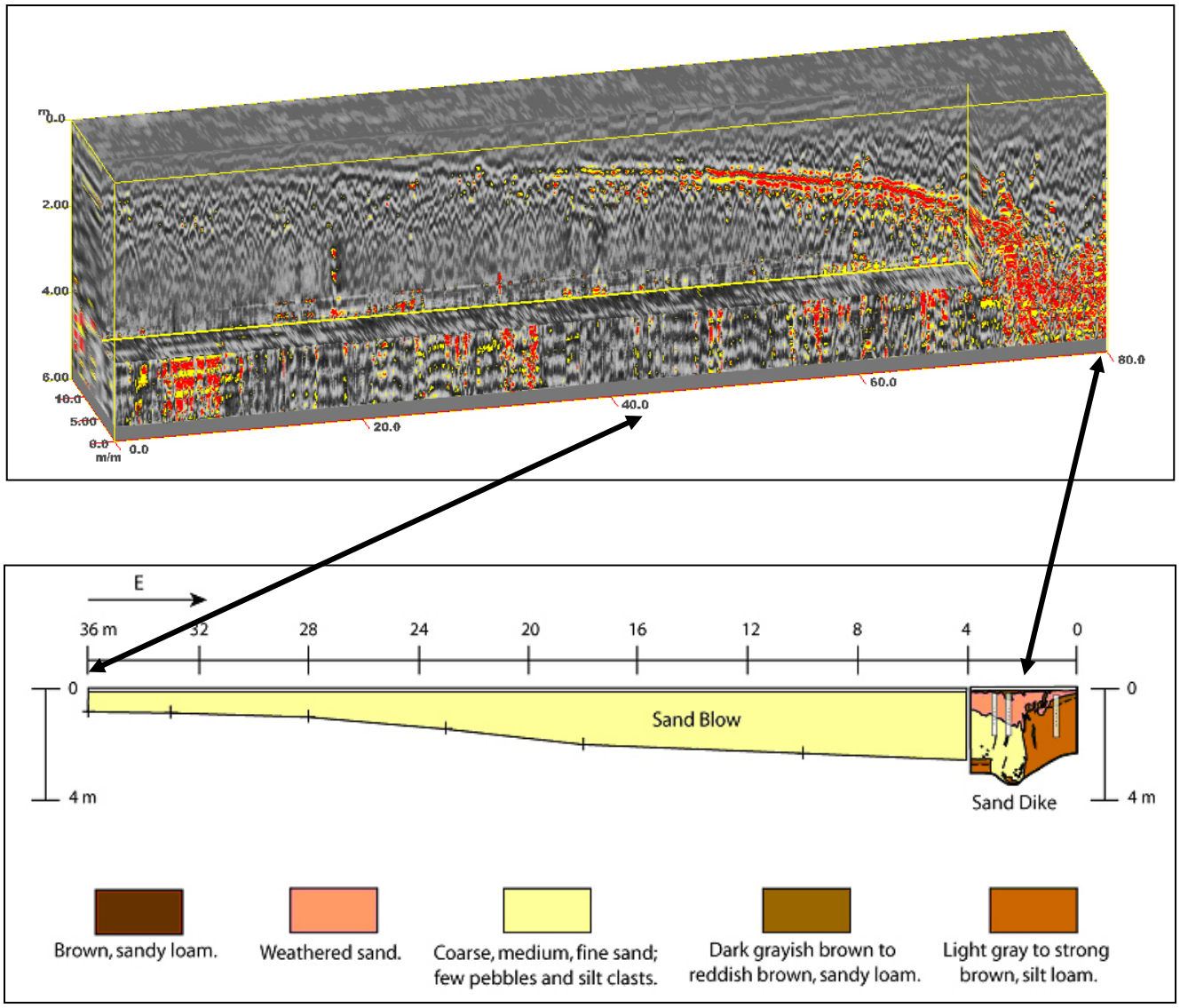

Figure 4. Three-dimensional image of GPR data (top panel) and trench log (bottom panel) at the Daytona Beach sand blow. The sand – silt contact, which appears as red colored line in the profile, dips toward the east and breached at the eastern end of the profiles. The trench at the site was excavated close to the middle of the surveyed area and was extended a few meters beyond the eastern end. Trench log was taken from Tuttle *et al*. (2006).

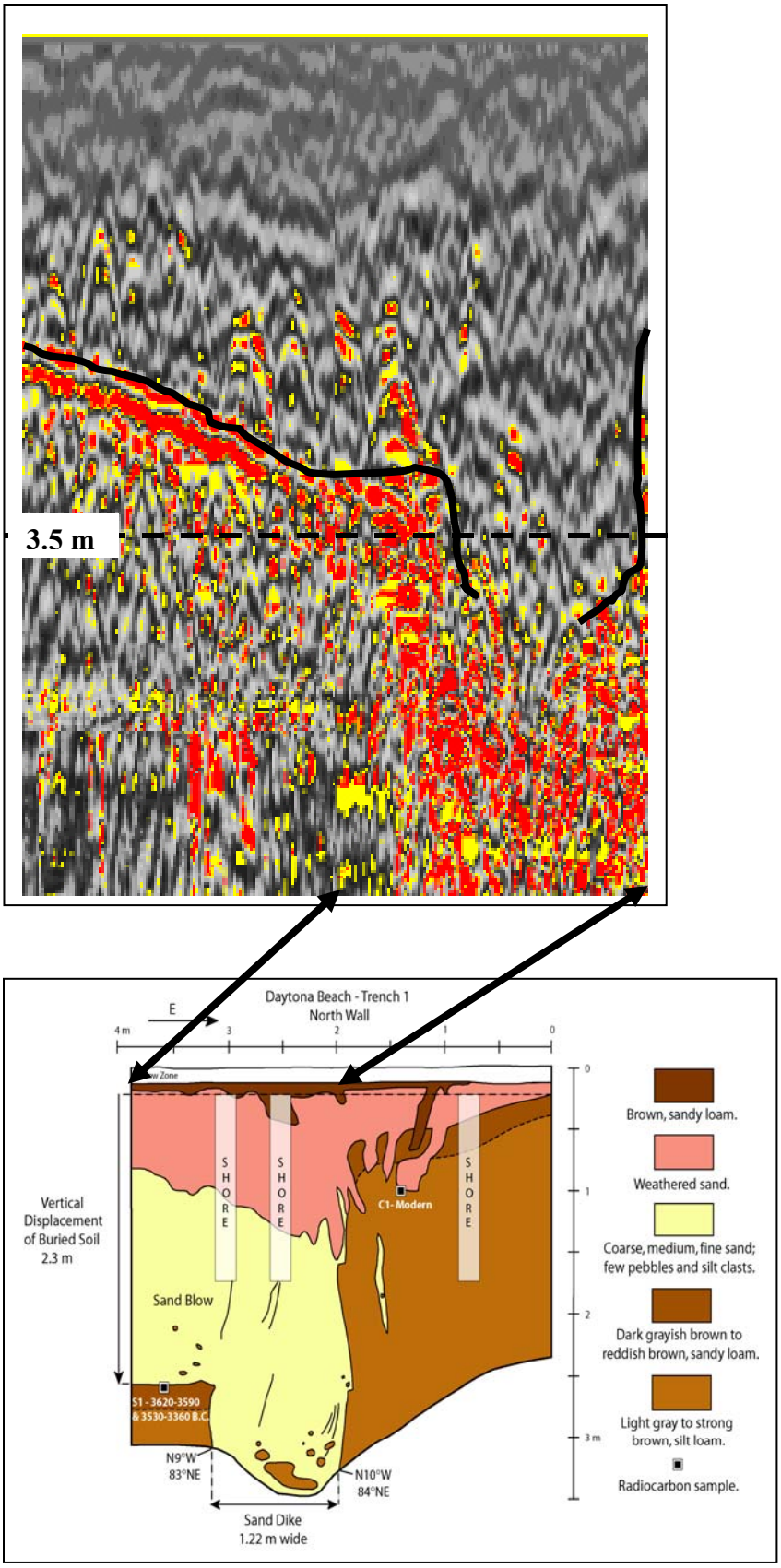

Figure 5. A zoomed image for the last few meters of eastern end of the GPR profile and trench log at the Daytona Beach sand blow (Figure 4). Black heavy line in the GPR image represents the contact between the sand and silt loam. The trench log was taken from Tuttle *et al*. (2006).

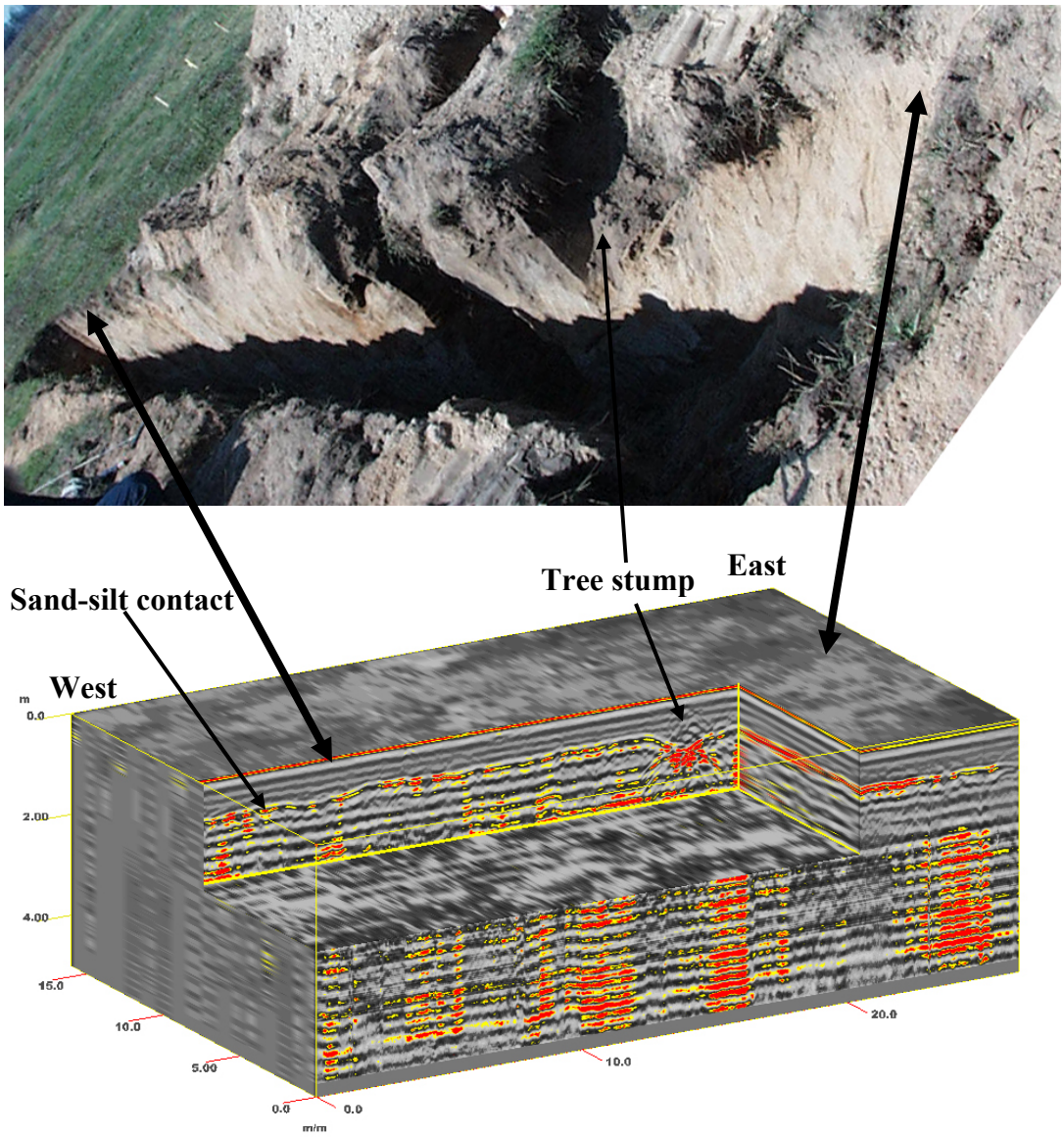

Figure 6. Photograph of the E-W trench and three-dimensional GPR image at the Johnson Farm sand blow. See text for detail.

Two trenches, one 15 m and the other 7 m, were excavated to study the site. We carefully cleaned and inspected the trench walls and found no sand dikes confirming the interpretation of the GPR data (Figure 6). We found two large tree stumps at the locations indicated by the GPR data.

Nancy 2 Site

Two GPR surveys were conducted at this site. The first one was performed 2000 to site a trench for paleoseismological investigation. Results of the 2000 survey given by Al-Shukri *et al.* (2005) are not presented in this paper. However, the trench results confirm the existence of two venting dikes and a buried tree stump that match the locations of the predicted features in the GPR data.

The second survey, presented here, was performed in order to relocate the trench and to collect additional samples for radiocarbon dating. Farming activity had eliminated all indications of the trench (Figure 3). The survey, conducted in the fall of 2004, was designed to help precisely map the boundary of that trench. A number of parallel profiles were collected normal to the general direction (north-south) of the trench with the intention of delineating the northern and southern walls of the old trench. No 3-D image was needed to accomplish the goal of the survey. Fifteen profiles were collected with spacing of about 3 meters. Representative examples of these profiles are shown in Figure 7. These profiles clearly demonstrate the effectiveness of GPR in locating such manmade features. Although the same soil was used to backfill the trench four years before, the disturbance was still distinguishable in these profiles.

CONCLUSIONS

Three high-resolution 3-D GPR surveys and one profiling survey were conducted at three sites to study earthquake related sand blows in east central Arkansas, USA. In all four surveys, GPR was successful in accomplishing the intended goals. At both the DB and Nancy 2 sites, GPR was instrumental in siting trenches for paleoseismological investigations. Trenching of the sand blows at the sites confirmed the existence of sand dikes at the locations suggested by the 3-D GPR data. Data from the JF site indicated that the sand-silt contact was not breached and identified no signature in the data hinting at the existence of dikes or major sand – silt disturbances. However, an anomaly interpreted as a large buried tree stump is clearly visible in the data profiling results. Trenching of this site confirmed the interpretation of the GPR data.

Interpretation of GPR data of sand blows is not as difficult as other GPR applications where soil layers are gradational. Sharp discontinuities between the sand blow and the underlying silt loam and between the feeder dike and host sediment are helpful in mapping important sedimentological and structural boundaries. GPR is also helpful in finding buried tree stumps and manmade soil disturbances.

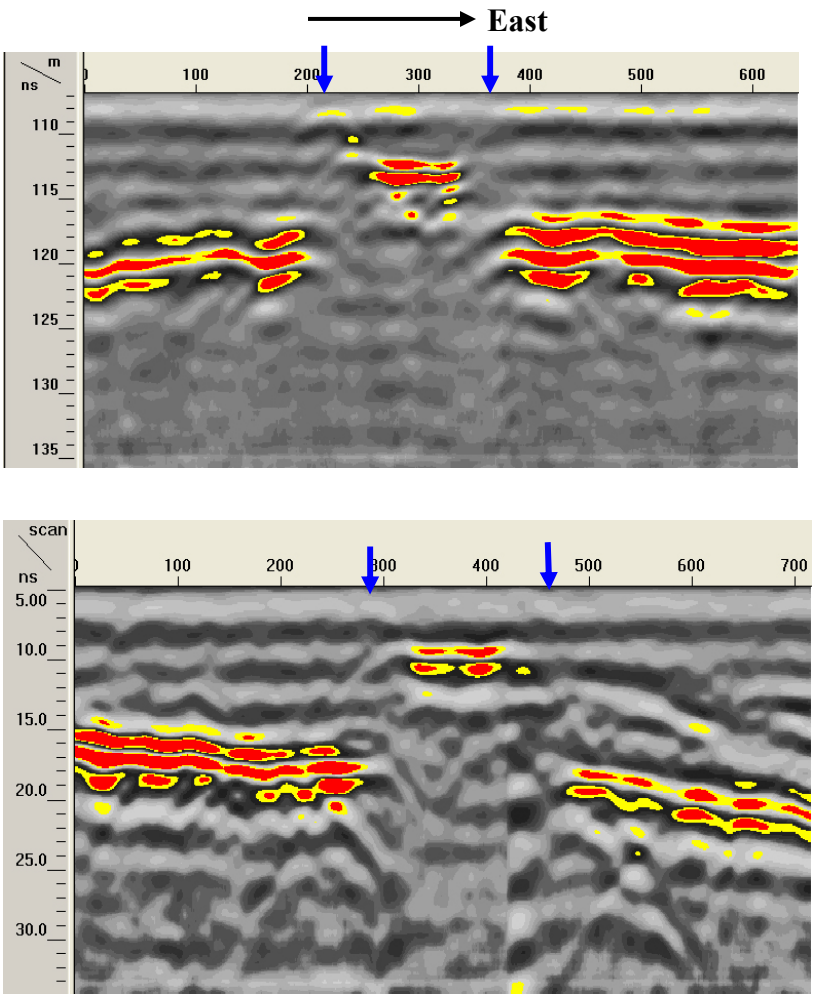

Figure 7. Two GPR profiles at Nancy –2 sand blow (Figure 3). The blue arrows show the location of the north-south trench that was excavated four year before the GPR survey. The profiles lay approximately normal to the trench. See text for details.

ACKNOWLEDGMENTS

We thank M. Egan, S. Eyuboglu, J. Shaw and his father, Mr. Shaw for field assistance; and Mr. Don Johnson and Mr. Terry Toler for allowing us access to their farmland for fieldwork. The research was partially supported by the USGS/NEHRP (Award #00-HQ-GR-0066 and Award #03HQGR0050) and the Arkansas Science and Technology Authority (Award #00-B-38)

REFERENCES

Al-Shukri Haydar J., Robert E. Lemmer, Hanan H. Mahdi, and Jeffrey B. Connelly (2005). Spatial and Temporal Characteristics of Paleoseismic Features in the Southern Terminus of the New Madrid Seismic Zone in Eastern Arkansas, *Seismo. Research Lett.*. **76,** 502-511.

Cardimona, S., Webb, J., and Lippincot T. (2000). Ground Penetrating Radar, Geophysics 2000, Dec 11- 15th, St Louis, Missouri.

Gross, R, K Holliger , A Green, G Seitz, and J Baldwin (1999). 3D Ground Penetrating Radar on the San Andreas Fault: A Complementary Paleoseismological Tool, abstract, 1999 AGU Fall Meeting.

Gross, Ralf, Klaus Holliger, Alan G. Green, and John Begg (2000). 3D ground penetrating radar applied to paleoseismology: examples from the Wellington Fault, New Zealand, Proceedings of SPIE Volume: 4084, p. 478-481, Eighth International Conference on Ground Penetrating Radar, Editor(s): Noon, David A.; Stickley, Glen F.; Longstaff, Dennis Published: 4/2000.

Lui, L., and Y. Li (2001). Identification of liquefaction and deformation features using ground penetrating radar in the New Madrid seismic zone, USA: *J. Appld. Geophys.* **47**, p. 199-215.

Salvi, S., F. R. Cinti, L. Colini, G. D'Addezio, F. Doumaz and E. Pettinelli (2003). Investigation of the active Celano–L'Aquila fault system, Abruzzi (central Apennines, Italy) with combined ground-penetrating radar and palaeoseismic trenching**,** *Geophys. J. Int.,***155,** 805–818.

Sexton, J.L., H. Henson, Jr., P Dial, and K. Shedlock (1992). Mini-sosie high resolution seismic reflection profiles along the bootheel lineament in New Madrid seismic zone, *Seismological Research Letters*, v. 63, n. 3, p. 297-307.

Tuttle, M. P., Collier, J., Wolf, L. W., and Lafferty, R. H. (1999). New evidence for a large earthquake in the New Madrid seismic zone between A.D. 1400 and 1670, Geology, v. 27, n. 9, p. 771-774.

Tuttle, M. P., Al-Shukri, H., Mahdi, H. (2006). Very large earthquakes centered near the New Madrid seismic zone 5,000-7,000 years ago, *Seismo. Res. Letts.* (accepted).

Veeken, P.C.H., Dagallier, G., Malartre, F., Laitinen, A.L., and Van Campenhout, L.P.A.M. (1999). Application of digital ground penetrating radar (GPR) for investigating the geology and structuration of the shallow subsurface, Proceedings of the 13th annual international conference on applied geologic remote sensing: Vancouver, B.C., Canada, p. II-419 - II-429.

Wolf, L. W., J. Collier, M. Tuttle, and P. Bodin (1998). Geophysical reconnaissance of earthquake-induced liquefaction features in the New Madrid seismic zone, *J. Appld. Geophys.* **39**, 121-129.

Yetton, M.D., and Nobes, D.C. (1998). Recent vertical offset and near-surface structure of the Alpine Fault in Westland, New Zealand, from ground penetrating radar profiling: New Zealand Journal of Geology and Geophysics, **41**, 485-492.