FINAL TECHNICAL REPORT

External Grant Ward Number 07HQGR0069

Title

Spatial and Temporal Characteristic of Paleoseismic Features in the Southern Terminus of the New Madrid Seismic Zone in Eastern Arkansas

Principal Investigators:

Haydar Al-Shukri, Hanan Mahdi, and Okba Al Kadi
Arkansas Earthquake Center
University of Arkansas at Little Rock
2801 South University Avenue
Little Rock, AR 72204

Martitia Tuttle
M. Tuttle & Associates
128 Tibbetts Lane
Georgetown, ME 04548

Spatial and Temporal Characteristic of Paleoseismic Features in the Southern Terminus of the New Madrid Seismic Zone in Eastern Arkansas

07HQGR0069

Haydar Al-Shukri, Hanan Mahdi, and Okba Al-Kadi, University of Arkansas, Little Rock, Arkansas;

Martitia Tuttle, M. Tuttle & Associates, 128 Tibbetts Lane, Georgetown, ME 04548

ABSTRACT

A number of high-resolution Ground Penetrating Radar (GPR) and resistivity profiles and three-dimensional surveys were conducted to define the morphology and assist in the interpretation of the origin of large earthquake-induced liquefaction features, including sand blows and sand dikes, along a northwest-southeast oriented lineament in east-central Arkansas. Satellite images, aerial photographs, and field reconnaissance, and paleoseismic investigations indicate that these features are widely distributed across east-central Arkansas, particularly south of Interstate 40. The highest concentration of these features is near Marianna, Arkansas. There is strong and accumulating evidence that the sand blows in the Marianna area formed as a result of strong ground shaking from large local prehistoric earthquakes.

GPR data were collected using 400 MHz central frequency monostatic antennas and a high-speed data acquisition system. Data was collected along profiles ranging in length from several meters to several hundred meters arranged to intersect the sandy features. Resistivity surveys were also conducted along some of those profiles. Several sites were selected to collect high-resolution 3-D data to delineate the morphology of these features and to estimate the volume of sand that erupted. A common feature in most profiles and 3-D data is the sharp discontinuity between vented sand and the buried silt loam (old surface) which can be easily distinguished and correlated between profiles. Large sand dikes were also prominent features in the GPR data. With additional research, this information may be translated into expected levels of ground shaking over various exposure times and could lead to changes in the seismic hazard maps and building codes

Two trenches were excavated across a sand blow at one of the study sites, DB-SE2. The trenches revealed two generations of sand blows and sand dikes. Weathering characteristics of the younger sand blow suggest that it is prehistoric in age and possibly similar in age to the sand blow at the nearby Daytona Beach site studied previously. Radiocarbon dating of an organic sample collected below the sand blow at DB-SE2 provides a maximum constraining age of 10.1 k years. OSL dating of soil collected of the basal contact of both generations of sand bows should help to further constrain their ages. A fracture that cross cuts the sand blows has a strike similar to that of the lineament and may be related to faulting. Its length and morphology as well as parallelism to the nearby White River fault zone suggest that the lineament is fault controlled. However, additional work including geophysical and geological investigations will be needed to verify the presence of a fault below the layer that liquefied.

INTRODUCTION

The study area is near Marianna, Arkansas, which is located in east-central Arkansas, about 75 km southwest of Memphis, Tennessee, and 80 km south of the southwestern end of the New Madrid Seismic Zone (NMSZ) (Figure 1). Paleoliquefaction features attributed to New Madrid seismicity have been found as far north as St. Louis, Missouri, as far west as Pocahontas, Arkansas, as far east as Union City, Tennessee, and as far south as Madison, Arkansas (Figure 1). Analysis of satellite images reveal circular to elliptical light tonal anomalies in east-central Arkansas. Many of these anomalies proved to be sand

blows that formed as a result of earthquake-induced liquefaction features (Al-Shukri et al., 2006; Tuttle et al., 2006). During ground shaking, pore-water pressure builds up in loose, water-saturated, sandy sediment. If the pore-water pressure exceeds the overburden pressure, the sediment has liquefied and can be mobilized, flowing through cracks, fissures, and other zones of weakness towards the ground surface.

During previous studies, we identified sand blows on satellite images and aerial photographs of the area (Al-Shukri, *et. al.*, 2005, 2006, and Tuttle *et. al*., 2006). Sand blows typically show up as patches of light hue within a matrix of darker hue related to silty soil. Numerous large sand blows were seen to occur along a northwest-southeast lineament. GPR was used in defining the morphology of the sand blows and delineating the feeder dikes through which water and sand erupted to the surface. Dating of several sand blows indicated that they formed from 5-7 ka.

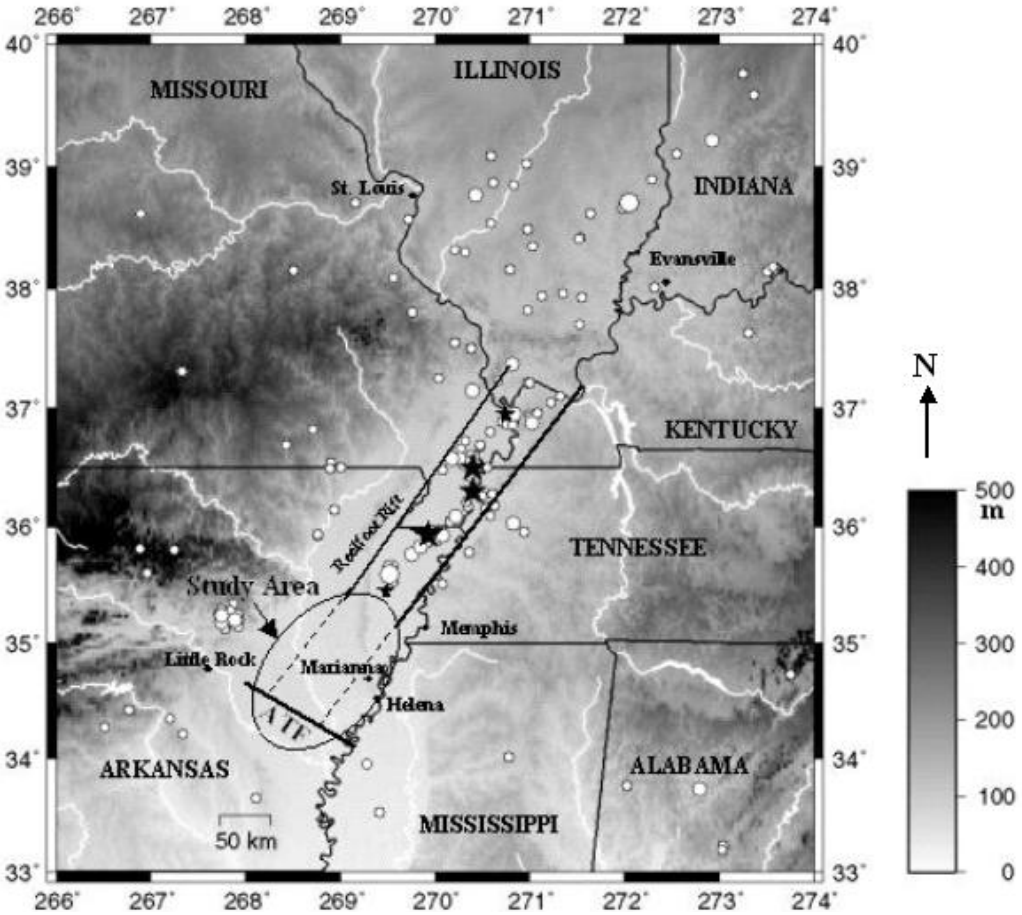

Figure1. Map of the central U.S. showing east-central Arkansas study region (circled) in relation to major structural elements including Reelfoot Rift fault system and Arkansas Transform fault (ATF, black lines) and seismicity between 1974 and 2005 with magnitudes between 3 and 5.0 (white dots). Large (M>6) historical earthquakes of New Madrid seismic zone within the Reelfoot Rift fault system were depict by black stars (Modified from Al-Shukri *et al.*, 2006).

Geophysical methods have proven to be powerful tools in the study of faults (Sexton *et al*. 1992) and of liquefaction-related sand blows and sand dikes resulting from strong earthquakes (Wolf *et al*. 1998; Tuttle *et al*. 1999; Lui and Li 2001; Al-Shukri *et al*., 2006; Maurya *et al*., 2006). Geophysical methods used in near surface studies include seismic (reflection and refraction), magnetic, gravity, resistivity, and ground

penetrating radar (GPR). All of these techniques are based on the same fundamental principles related to changes in the physical properties (seismic velocity, magnetism, density, resistivity, and permittivity) of rocks and sediments. These changes can be used to image stratigraphy and structural features in the subsurface.

GPR is a geophysical prospecting method used to provide high-resolution images of the subsurface. The GPR antenna transmits an electromagnetic wave (EM) pulse that travels from the surface through the soil and rocks. Energy is reflected from boundaries or objects in the subsurface that have contrasting dielectric properties. The reflected energy is received by the monostatic or bistatic antenna on the surface and recorded digitally. All sedimentary layers and other buried materials in the ground have particular physical and chemical properties that affect the velocity of EM energy propagation; the most important of these are electrical conductivity, electric permittivity, and magnetic permeability. Most geologic media are non-magnetic (i.e., their relative magnetic permeability are practically equal to 1 (Telford, et. al., 1976), and so, the electric permittivity and conductivity have, in most cases, greater importance for the GPR technique. The greater the change in velocity at an interface, the higher the energy of the reflected wave. In this research, we used GPR to create 3-D images of earthquake–induced liquefaction features known as sand blows and sand dikes, to track a northwest-oriented lineament delineated by liquefaction features, and to select trench locations for paleoseismic investigation. The paleoseismic investigation involved excavating two trenches across a sandy patch on the surface and well-expressed sand blow and related sand dikes imaged with GPR, logging the stratigraphic and structural relations exposed in the trenches, collecting samples for radiocarbon and optically stimulated luminescence (OSL) dating, and interpreting the results of the fieldwork and dating of selected samples.

GEOPHYSICAL AND PALEOSEISMOLOGICAL INVESTIGATIONS

The area in the Western Lowlands chosen for this study is located about 8 km southwest of Marianna, Arkansas, characterized by sandy patches ranging from 100 m by 150 m to 200 m by 600 m in size in fields that are actively farmed for cotton, rice, and soybeans. We selected sites for geophysical surveys on the basis of interpretation of satellite images and aerial photographs and results of field reconnaissance. We identified light-colored, circular to elliptical features on satellite images and aerial photographs that likely represented sand blows. We inspected those features in the field to determine if they were in fact sandy patches surrounded by finer-grained soils. We hand dug soil pits 1-2 m deep to verify the presence of sand as well as to determine the depth to the buried soil and the general morphology of the sand blows. The thickness of the sand blows was later used to calibrate the GPR profiling. Six sites were selected for GPR study and named Daytona Beach site (DB), Daytona Beach NW1 (DB-NW1), Daytona Beach NW2 (DB-NW2), Daytona Beach NW3 (DB-NW3), Daytona Beach SE1 (DB-SE1), and Daytona Beach SE2 (DB-SE2) (Figure 2). The selection of these sites was not random; but rather designed to test the hypothesis that the lineament noticed in our previous studies is delineated by sand blows and that the emplacement of the feeder dikes may be fault controlled. We conducted geophysical surveys at these selected sites in October 2007, as well as in July and August 2008, and the paleoseismological investigation was carried out in November of 2008.

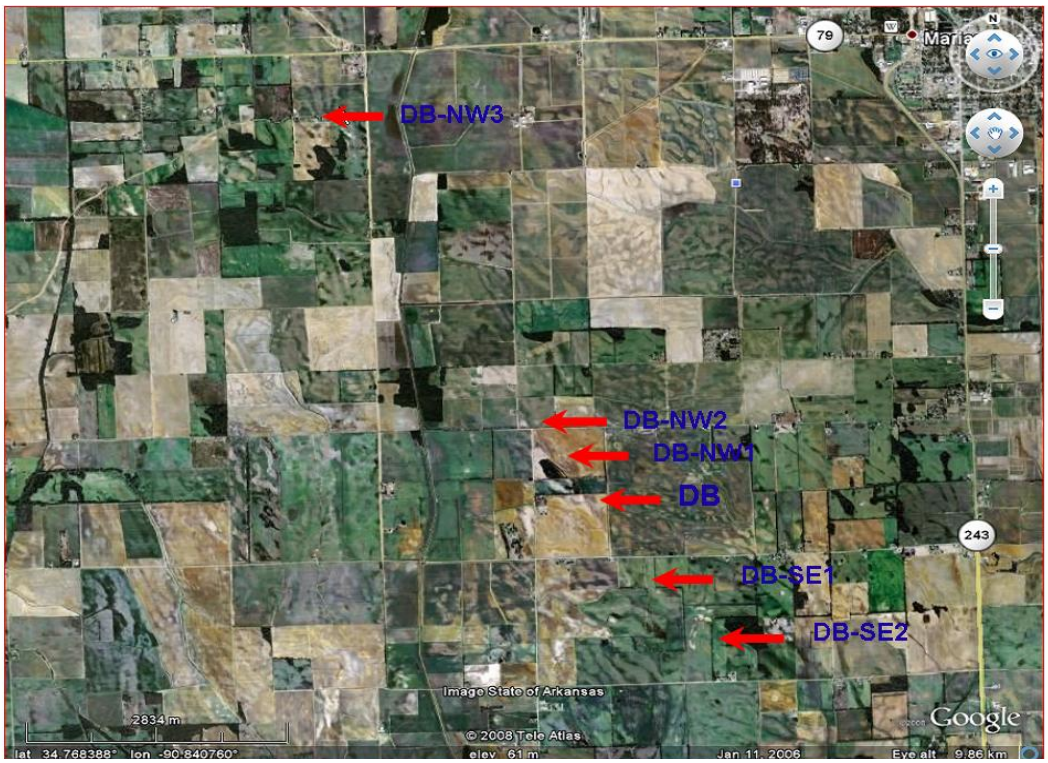

Figure 2. Satellite image of western lowland showing DB site located 8 km southwest of Marianna. The image also shows the locations of sites DB-NW1, DB-NW2, DB-NW3, DB-SE1, and DB-SE2 surveyed

We conducted GPR surveys at the above mentioned six sites, using the Geophysical Survey Systems, Inc. (GSSI) Subsurface Interface Radar (SIR-3000) System equipped with 400 MHz monostatic antenna. A 16-inch diameter survey wheel model 620 was utilized to acquire a fixed number of scans per unit distance providing a constant horizontal scale for the entire survey.

We collected data along profiles that ranged in length from several meters to several hundreds meters with a total of 7,173m profiles length. All these profiles were arranged to intersect the sandy features. Each profile was processed to correct for the antenna delay time, remove the predicted direct signal related to the surface reflections, and band pass filtered (high pass 100 MHz, and low pass 800 MHz). The most common post-processing techniques were applied to the data using RADAN for Windows XP version 6.5-computer software program. Profiles were examined to locate various anomalies or features that are related to subsurface structural changes. To establish confidence levels in the interpretations of each anomaly, categories of probable, possible, and questionable were defined based on the presence of anomalies in a various number of reflections. Correlation of a specific anomalous feature to an actual subsurface structure was the goal of data interpretation.

A few sites were selected to collect high-resolution 3-D GPR data (covered 1,240 square meters) to delineate the morphology of these features and to estimate the volume of erupted sand. The 3-D data was collected at each site by surveying profiles with 1-meter spacing. A common feature in most profiles and the 3-D data was the sharp discontinuity between the sand and the underneath silt loam (old surface) which can be easily distinguished and correlated between profiles. Feeder dikes also were prominent

features in the GPR data. This information was translated into expected levels of ground shaking over various exposure times and could lead to changes in the seismic hazard maps and building codes.

Resistivity method is helpful in locating and mapping liquefaction features. Buried liquefaction features often appear as a high resistivity anomaly. The high gradient in resistivity values reflects a contrast in properties between the unconsolidated sands of liquefaction features and the fine-grained sediments of the host deposits (Wolf and Tuttle, 2003). A few sites were selected to collect Electrical Resistivity profiles. The data for this survey were collected using the OhmMapper system from Geometrics Inc. During the resistivity surveys, profiles were run normal to the long axes of the sandy area at all sites. Each profile is processed using RES2DINV and RES3DINV. Results of these shallow geophysical surveys were used as alternative or complimentary to GPR data to delineate and define the extent of liquefaction features before the excavation and trenching process.

During the paleoseismological investigation, we excavated two trenches at one particular site, where our GPR survey suggested complex ground failure and the presence of one or more large sand dikes and sand blows. We had the trenches excavated with a backhoe and braced the trenches with shoring borrowed from the USGS office in Memphis. We cleaned the trench walls with shovels and hand tools to expose sedimentological contacts and structures and then logged the entire length of the southern wall of both trenches at a scale of 1" = 1 m. We also logged portions of the trench walls that were of particular interest at a scale of 1” = 50 cm. We documented sedimentological, stratigraphical, and pedological characteristics, as well as structural relations, of the liquefaction features. We also documented the sedimentological and pedological characteristics of the surrounding sediments, and collected carbon samples for radiocarbon and soil samples for OSL dating.

RESULTS AND ANALYSIS

Six sites were selected within an area of approximately 4 km in radius located about 7 km south-southwest Marianna, Arkansas (Figure 2). This area seems to have the highest concentration of sand blows south of Interstate 40. Below is a description of the GPR surveys conducted at the six sites, the paleoseismological investigation conducted at one of those sites, and our interpretation of the results. Locating feeder dikes, and possibly other subsurface structures, and imaging the morphology of sand blows along a northwest-southeast oriented lineament were the primary goals of the geophysical surveys. Confirming the presence of sand blows and sand dikes, and possibly fault-related structures, and determining the age of the liquefaction features were the primary goals of the paleoseismological investigation.

Daytona Beach Site (DB)

The DB sand blow covers an area of more than 200m by 600m and extends in the northwest-southeast direction. A paleoseismological investigation at the site, including GPR profiling of the site (Al-Shukri, *et al*, 2006). and trenching, logging, and dating of the sand blow (Tuttle, *et al*, 2006), was conducted several years ago. For this study, additional GPR surveys were conducted at the DB site in July 2008 to investigate the eastern end of the sand blow not surveyed in previous work.

A 127m GPR profile was surveyed using a 400 MHz monostatic antenna. The profile extends in an east-west direction and oriented to intersect the long axis of the sand blow between two trenches previously excavated at the site (Figure 3). The profile exhibits a prominent anomaly that is linear in shape and extends throughout most of the profile. A geophysical anomaly (red-blue colored) starts about 5m from the east end of the profile at a depth of about 1.2m and dips to the west at a constant angle and disappears at a depth of 2.8m at a distant of about 40m from the east. The anomaly appears again at the same depth at

a distant of about 60m from the east. From that point, the anomaly dips in a reverse angle towards the end of the profile to a depth of 1.0m. This anomaly maps the contact between the sand blow and silt loam or the buried surface). As documented during the previous studies (Al-Shukri, *et al*, 2006; Tuttle, *et al*, 2006), the buried surface is breached by a sand dike at the lowest part of the anomaly at a distance of about 50m from the east. The profile in Figure 3 exhibits a sharp change in the morphology of contact between the sand and the silt loam from the one that was collected by Al-Shukri, *et al*. (2006).

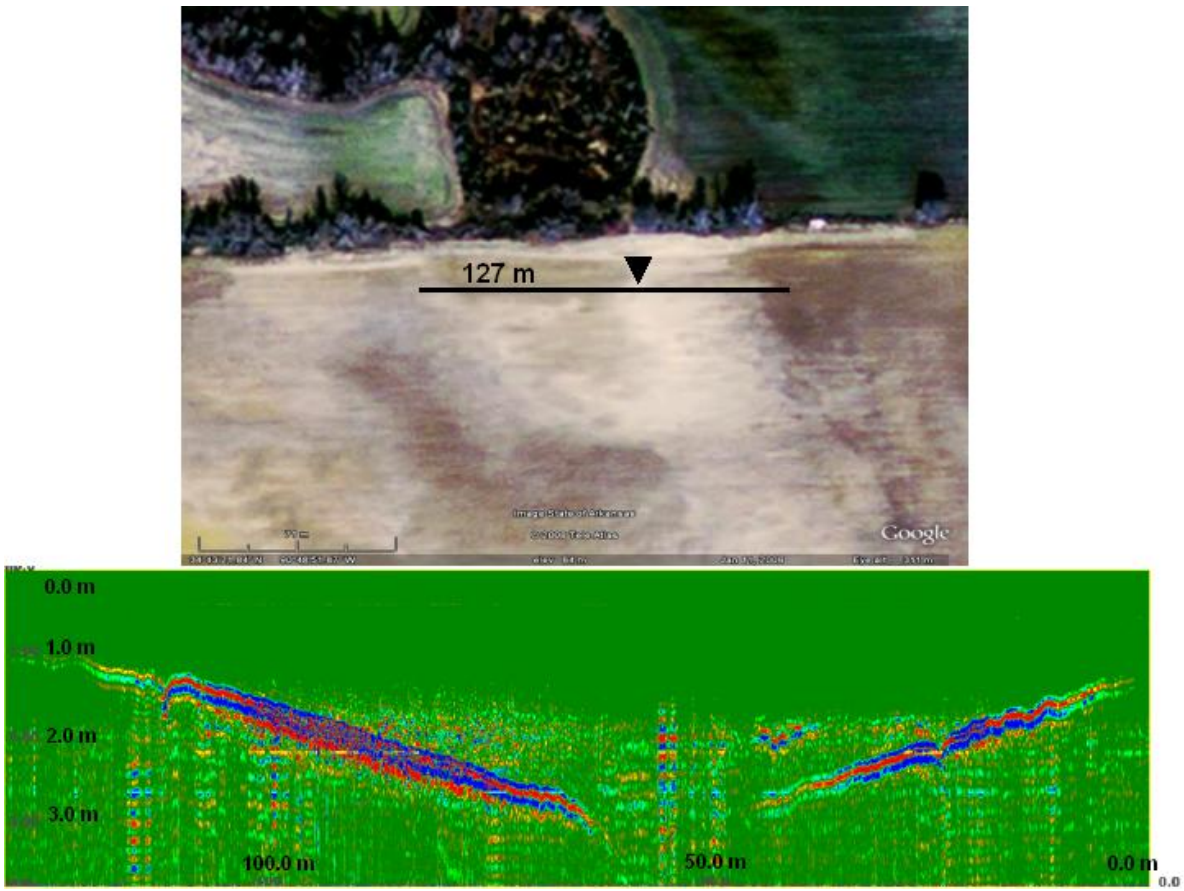

Figure3. GPR survey data at Daytona Beach sand blow. Top panel is the satellite image of Daytona Beach site showing the light color sandy area of the liquefaction feature, sand blows, and GPR profiles (black line) with expected feeder dike (sold triangle) place. Bottom panel is the GPR data showing anomalies of sand blows (see text for interpretation).

During the previous studies, we excavated two trenches 230 m apart across the sand blow (Tuttle, *et al*., 2006). In the more northern trench, the ground subsidence was asymmetrical. The ground surface on the west side of the sand dike subsided 2.45 m, while the ground surface on the east side only subsided 0.55 m. In the more southern trench, the ground subsidence was fairly symmetrical, with the west side down only 0.3 m (1.45 versus 1.15 m) more that the east side. The new GPR profile was collected between the two trenches about 10 m south of the northern trench. It shows symmetrical ground subsidence more similar to that observed in the southern trench. Our observations during the studies at the DB site illustrate that ground subsidence can vary greatly along the strike of the main feeder dike.

Daytona Beach NW1 Site (DB-NW1)

The sand blow at the DB-NW1 site is the northwestern extension of the sand blow at the DB site. The GPR survey at this site (Figure 4) was located approximately 750m to the northwest of the DB site (Figure 2). Three parallel profiles were surveyed in an east-west direction with a total of 417 meters in length. The first profile (121m) is shown in Figure 5. The data in this profile consists of 5,995 scans (GPR reading points), each having a range of 40 ns, which provides approximate depth of 2.0m for investigation.

The top panel of Figure 5 shows the entire profile and the lower panel shows a zoom in on the major anomalous feature. This feature is linear in shape (red-blue colored reflections) and extends throughout the profile at an average depth of 1 meter. These reflections map the contact between the sand and the silt loam (the old surface). At about 80 meters from the west, these reflections start to dip to the east with a downward curvature to about 1.5 meter depth at a distant of 105 meters. The reflections appear again at a distance of 108 meters at the same depth. The sand-silt loam contact is discontinuous between 105 and 108-meter distances. We interpret this discontinuity to be the feeder dike through which the sand-bearing water erupted to the ground surface during the earthquake. The location of the dike coincides with the location of the straight line between the two trenches (Al-Shukri, *et. al.*, 2006, and Tuttle, *et. al.*, 2006) at the DB site. These finding suggest that the DB dike extends to this location where it is approximately 3 m wide. The other two profiles (not shown) were used to derive similar conclusions.

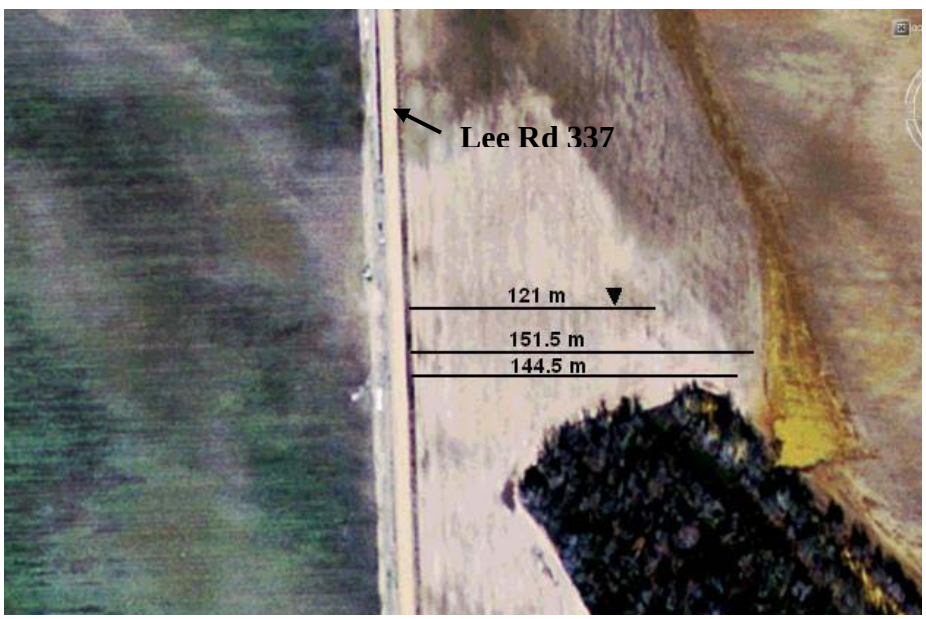

Figure 4. Satellite image of DB-NW1 site showing sand blows (light color area) and GPR profiles (black lines) with expected feeder dike locations (sold triangle).

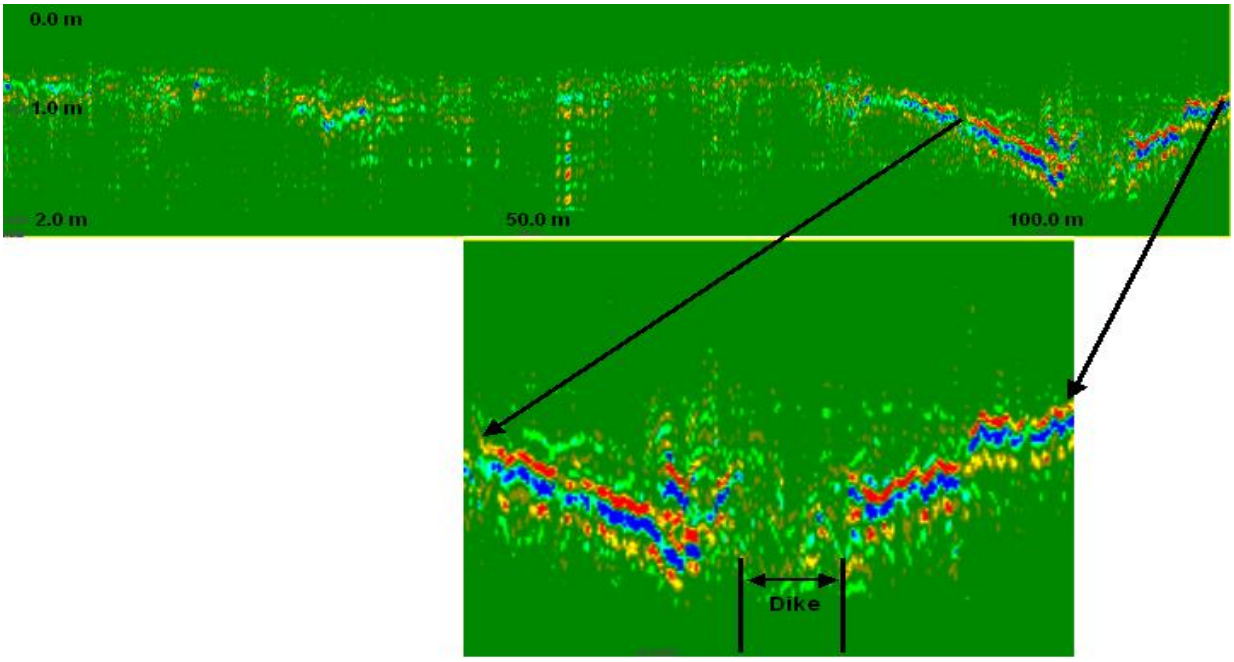

Figure5. GPR data from DB-NW1 site showing anomalies of sand blows. Red and blue color bands represent the contact between the sand blow and silt loam (old surfaces). The dike location is shown in the zoom image (See text for details).

Daytona Beach NW2 Site (DB-NW2)

Further to the northwest, a 100m by 150m sandy area was surveyed with a 3-D scheme (Figure 6). The location of this survey is at a distance of 1,100 meters to the northwest of the DB site (Figure 2). The 3-D survey covers an area of 7m by 80m. Data was collected along eight profiles, each 80m long and oriented in an east-west direction. Spacing between profiles was kept at 1 meter.

Resistivity profiles were also collected for this site in a bi-directional method starting from E-W direction and ending in W-E direction. Survey configuration starts by 2.5 m interval spacing between transmitter (Tx) and receiver (Rx). A constant Tx-Rx spacing of 2.5 m was used for every bi-directional survey until we reached a maximum spacing of 15 m.

Figure 7 shows a GPR profile at the middle of the survey area. Similar to the previous two sites, a linear anomaly that extends throughout the profile is the dominant one. This anomaly ranges in depth between 0.5m and 1m (Figure 7). Using the information from the small hand dug trenches, this anomaly coincides with the contact between the sand blow and the silt loam of the old surface. This contact indicates subsidence in the silt loam by about 1 meter between the distance of 28m and 65m from the beginning of the profile. This profile shows an approximately 4 meter wide breach to silt loam located at the center of the profile. This breach is related to the feeder dike where the sand erupted to the surface. The reduction of the anomaly intensity at both ends of the profile is due to thinning of the sand and the increased water saturation, which caused severe wave attenuation.

Figure 8 shows a comparison between GPR data (top panel) and Resistivity data (lower panel). Results show that high resistivity values are well related to GPR sand blows anomalies.

Figure 6. Satellite image of DB-NW2 site showing sand blow (light color area) and the 7 by 80 meter grid (black lines) of GPR profiles

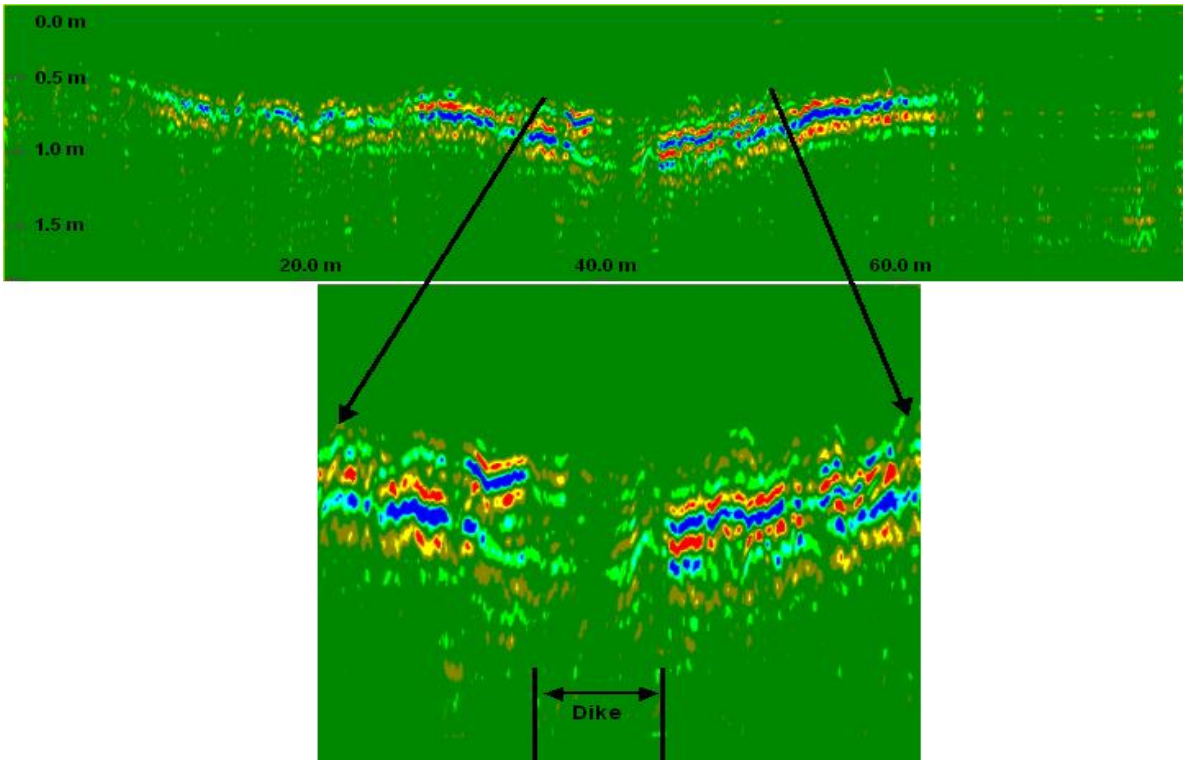

Figure 7. GPR data from DB-NW2 site showing anomalies of sand blows. Red and blue color bands represent the contact between the sand blow and silt loam (old surfaces). The dike location is shown in the zoom image (See text for details).

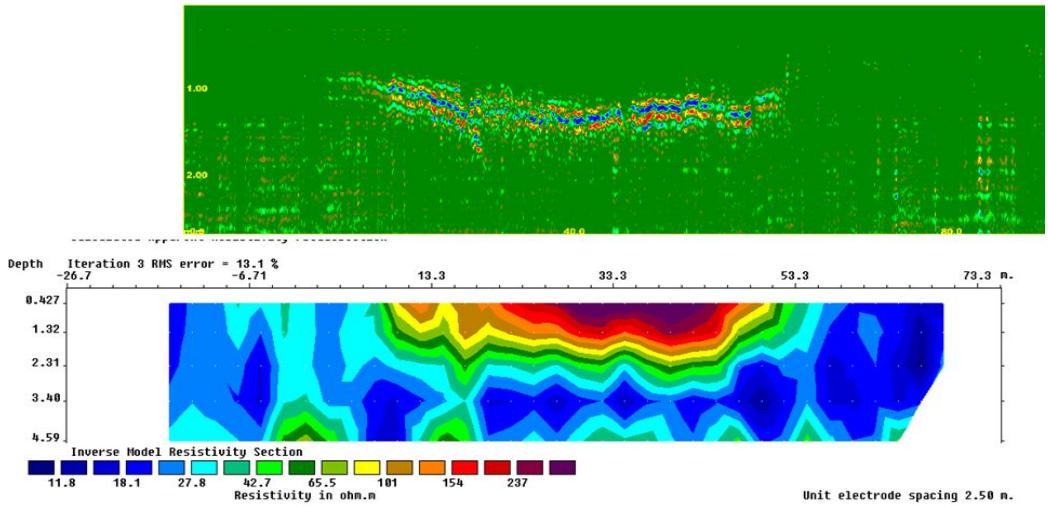

Figure 8: Top panel represent GPR profile from DB-NW2 site and lower panel represents the resistivity survey results. Notice the correlation between the high resistivity values (red) and the GPR sand blows anomaly

Daytona Beach NW3 Site (DB-NW3)

Further to the northwest, a 40m by 80m sandy area was surveyed. The GPR survey on this site (Figure 9) was located approximately 5,850m to the northwest of the DB site (Figure 2). Several parallel profiles were surveyed in an east-west direction with a total of 550 meters in length. Two profiles were chosen shown in figure 9. The northern profile is 52m in length. The data for this profile consists of 2,615 scans (GPR reading points), each having a range of 50 ns, which provides approximate depth of 2.5m for investigation. Top panel of figure 9 represents a satellite image of DB-NW3 site. The two solid black lines represent the location of the two selected GPR profiles, the northern one with 52 m length and the southern one of 69 m length. Solid triangles represent the expected feeder dikes location.

The middle panel of Figure 9 shows the entire 52m profile and the lower panel shows a zoom in on the major anomalous feature. The main feature of the GPR data was a linear anomaly that runs across most of the profiles with depth ranges between 0.75 and 1 meter. We interpret this anomaly as the contact between the sand blow and the silt loam (old surface). This silt loam is obviously breached in at least one location in these profiles. The breach occurs between 28.5 and 33 meters from the start of the survey. All data at this site indicates a subsidence of the old surface by about 0.75m in the middle of the profiles.

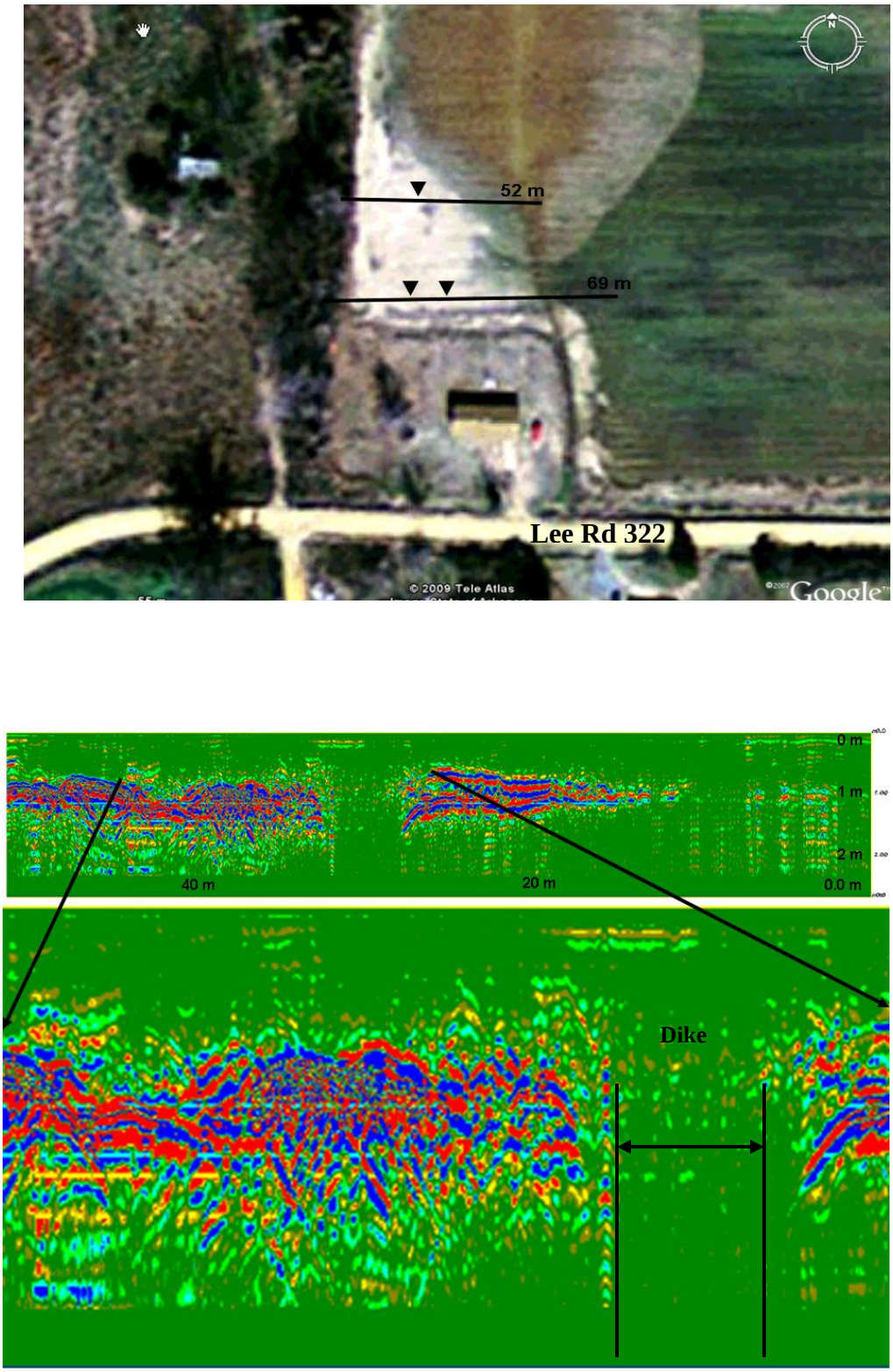

Figure 9: Top panel represents satellite image of DB-NW3 site showing possible sand blows area. (Light colored). Black lines represent the location of the GPR survey with expected feeder dikes (solid triangles). Middle panel represents the GPR data showing sand blows anomalies. Red and blue color bands represent the contact between the sand blow and silt loam (old surface). Lower panel represent a zoom in image showing the location of the sand dike.

Daytona Beach SE1 Site (DB-SE1)

S, surveying was shifted to the southeast to investigate the extension of the feeder dike in that direction. The sand in this site is relatively thick, medium sized, loose sand that is light in color. The sand at this site resembles the DB and the DBNW sand blows. DB-SE1 is located approximately 1,300m southeast of the DB site (Figure 2). The surveys at this site were both 3-D and single profile. All surveys were conducted in an east-west direction (Figure 10). The 3-D survey consists of six parallel profiles each 100 meters long and spaced at 1 meter apart. The first of the two single profiles had a length of 159 meters located about 50 meters to the north of the 3-D survey, and the second was located 80 meters to south of the 3-D area with a length of 235.5 meters.

Similar to the other four sites to the northwest, the main feature of the GPR data was a linear anomaly that runs across most of the profiles with depth ranges between 0.5 and 1.5 meters (Figures 11, 12 and 13). Using data from hand dug trenches; we interpreted this anomaly as the contact between the sand blow and the silt loam (old surface). This silt loam is obviously breached in at least one location in these profiles. In the 3-D data, the breach occurs 80 meters from the start of the survey (Figure 11). In the other two profiles, the breach occurs at about 83 and 155 meters, respectively (Figure 12 and 13). All data at this site indicates a subsidence of the old surface by about 0.5m in the middle of the profiles (Figure 11).

Figure 10. Satellite image of Daytona Beach SE1 site showing sand blows, and GPR profiles (black lines) with expected feeder dikes (solid triangles).

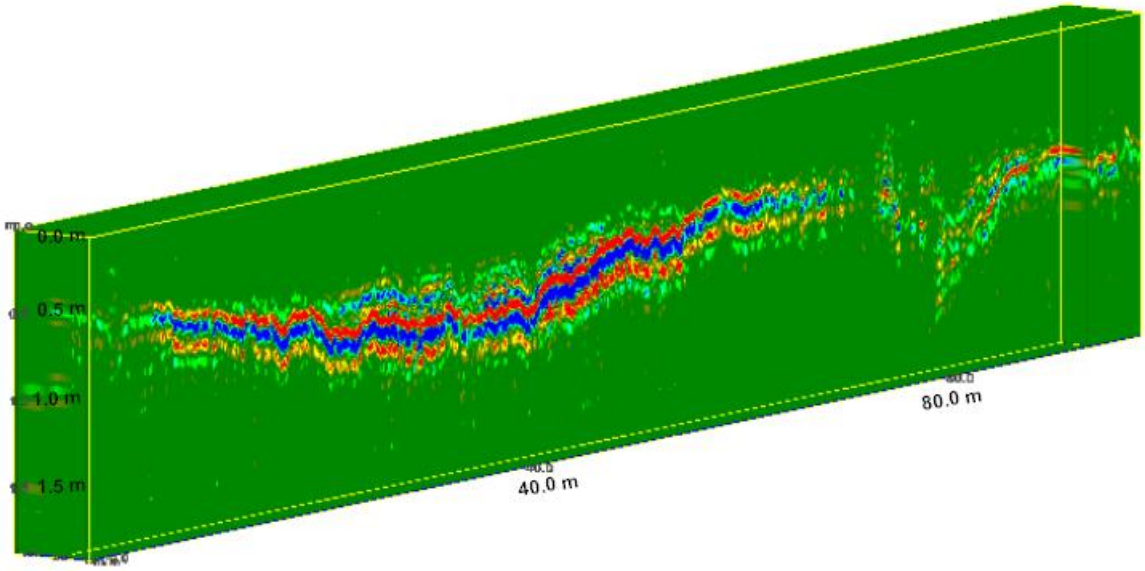

Figure 11. GPR data from Daytona Beach SE1 site showing anomalies of sand blows and feeder dikes in 3-D images. Red and blue color bands represent the contact between the sand blow and silt loam (old surfaces), and the dike location shown at a distance of about 80 meters from the start of the survey (See text for details).

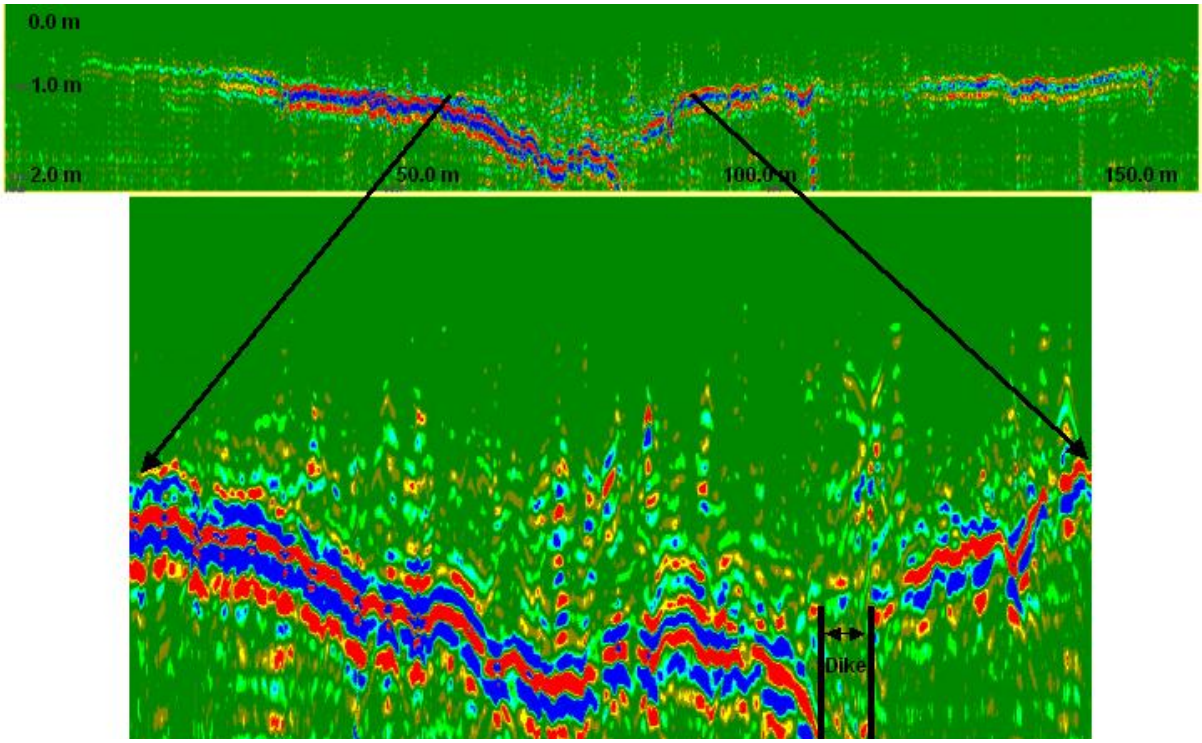

Figure12. GPR data from Daytona Beach SE1 site to the north of the 3-D survey area showing anomalies of sand blows. Red and blue color bands represent the contact between the sand blow and silt loam (old surfaces). The dike location is shown in the zoom in image (See text for details).

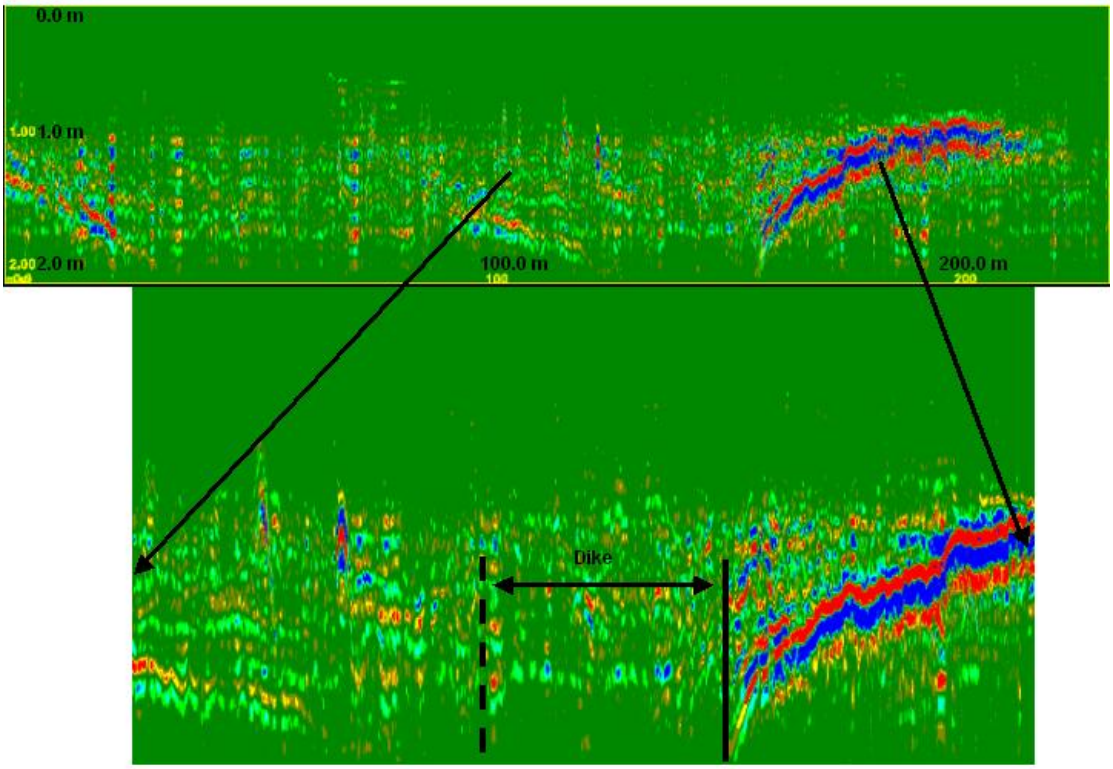

Figure13. GPR data from Daytona Beach SE1 site to the south of the 3-D surveyed area showing anomalies of sand blows. Red and blue color bands represent the contact between the sand blow and silt loam (old surfaces). The dike location is shown in the zoom in image (See text for details).

Daytona Beach SE2 Site (DB-SE2)

The last site that we present in this study is located further to the southeast at a distance of 2,250 meters from the DB site (Figure 2). A single resistivity profile with a length of 100 meters was surveyed (Figure 14). We collected multiple GPR profiles over a 60 m by 24 m area and created a 3-D image. GPR data collected at this site shows a disrupted sand-silt contact within 4 m of the surface similar to that observed at the other sites and suggestive of a soil breached by sand dikes and buried by sand blows. A major discontinuity in the buried soil, representing a large sand dike, is located at a distance of about 68 meters from the start of the profile (Figure 15). Also, subsidence of the soil by more than 1 meter is visible in the data.

Figure14. Satellite image of Daytona Beach SE2 site showing sand blows and location of GPR profiles (black lines) and Resistivity profiles (blue line). Red lines represent the location of two trenches excavated as part of the paleoseismology investigation.

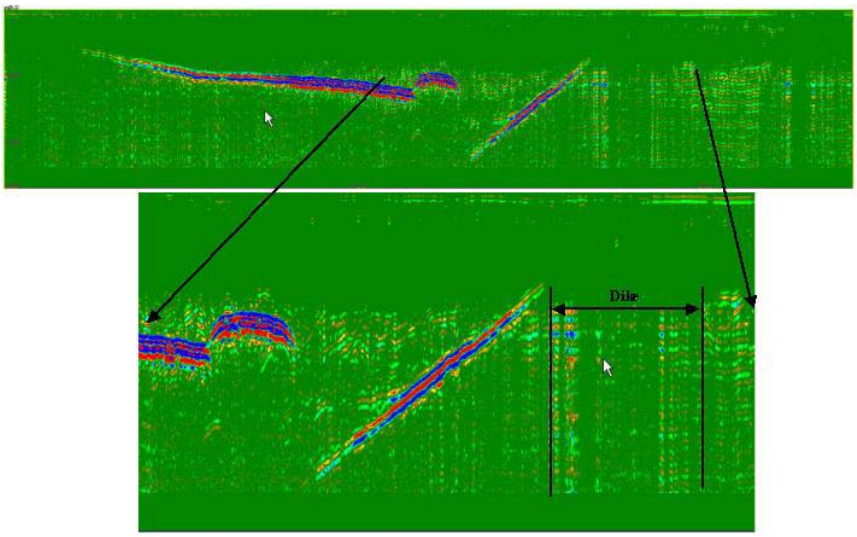

Figure15. GPR data from DB-SE2 site showing anomalies in the contact between the sand blow and underlying silt loam indicated by red and blue color bands. Discontinuities in the contact are related to subsidence and dike intrusions. A major dike location is labeled in the zoomed in image (See text for details).

The 3-D survey covers an area of 24m by 60m. Data was collected along thirteen profiles, each 60m long and oriented in an east-west direction. Spacing between profiles was kept at 2 meter.

Figure 16 shows the 3D image of the GPR data at depth of 175 cm. The anomalies range in depth between 1.25m and 3.5m. This anomaly represents the contact between the sand blow and the silt loam of the old surface. This contact is vertically offset by about 1.8 meter between the distance of 43.5m and 44.75m from the beginning of the profile. The 3D image shows an approximately 5.25 meter wide breach in the silt loam and trends across the survey area. This breach is a major feeder dike of the sand blow.

Resistivity data was also collected for this site along a 100m long profile. We used the same survey configuration as at site DB-NW2. Comparing the resistivity data to the GPR data, high resistivity values relate well to the sand blow (Figure 17). The most prominent anomalies in both GPR and resistivity data correlate with the breach of the silt loam layer indicative of the locations of the dikes. The results support using resistivity as an alternative to, or in addition to, GPR. In some cases, resistivity is superior to GPR for imaging sand blows and sand dikes, especially when the sediment is wet. Due to the deeper penetration of electric current, resistivity method can reveal deeper information than the GPR technique.

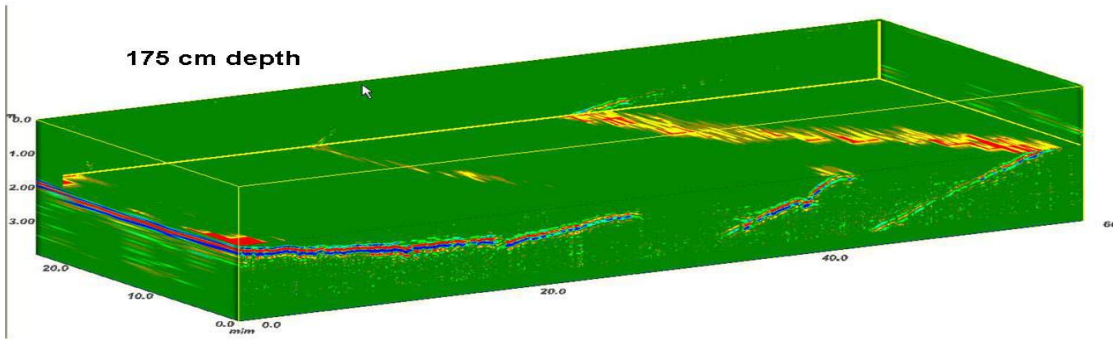

Figure16. GPR data from Daytona Beach SE2 site showing anomalies of sand blows and feeder dikes in 3-D images at 175 cm depth. Red and blue color bands represent the contact between the sand blow and silt loam below (old surface), and the dike location shown at a distance of about 30 meters from the start (0,0) of the survey (See text for details).

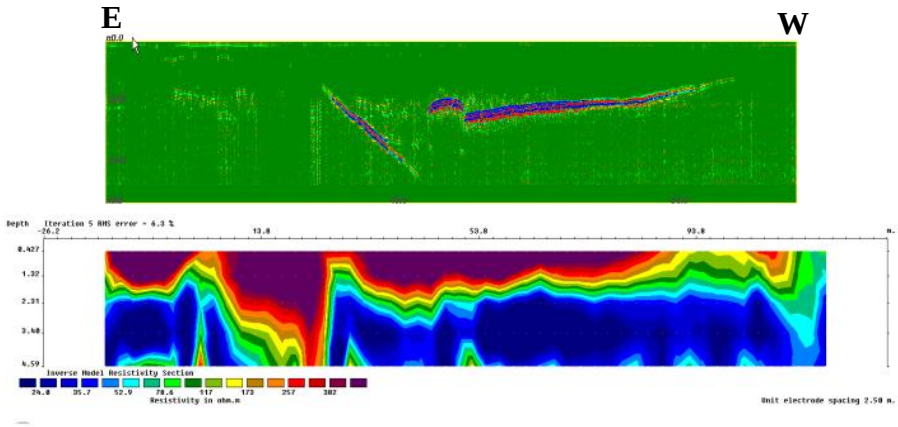

Figure 17: Top panel represents the GPR profile from DB-SE2 site and lower panel represents the resistivity survey results. Comparing the two results shows that high resistivity values are well related to the sand blow and sand dikes. Notice the anomaly that correlates very well with the major sand dike in both profiles.

On the basis of the distribution of sandy soils on the ground surface, findings in soil pits, and the location of large sand dikes as imaged in the geophysical surveys, we selected locations of two trenches that would revealed sand blows and sand dikes for paleoseismic study (Figure 14). The southernmost trench, named Triple Crown, was 55.5 m long and the northernmost trench, named Double Crown, was 42.5 m long. Both trenches were oriented roughly east-west in order to cross the northwest-southeast trending sand dikes (Figures 18 and 19).

In the Triple Crown trench, we found three large sand dikes (about 1.3 m, 2+ m, and 12 m wide) and two small sand dikes (7 cm and 10 cm wide) and an overlying sand blow that is up to 2.2 m thick in the vicinity of the sand dikes and in some places thicker than the trench was deep (Figure 18). The large sand dikes have strikes of N20-50°W and dips of 72-80° NE and NW. As illustrated on the trench log between the 43-m and 49.5-m marks, the easternmost large sand dike is reddish brown in color. Sand of a similar nature extends towards the east, forming a thin (8 cm) sand blow overlying mottled silt and occurs along the western margin of the large sand dike at about the 27-m mark and extends towards the west to the 26-m mark, again forming a thin (10 cm) sand blow overlying mottled silt. West of 26-m mark, the thin reddish brown sand blow dips below the floor of the trench and is absent below the less weathered sand blow shown between the 17-m mark and western end of the trench. Here, the large sand blow buries a brown silt loam. In between the 28-m and 43-m marks, the sand dike is much less weathered and related to a large sand blow typically 1.5-2 m thick that extends the full length of the trench. The upper 1 m of the large sand blow is very iron-stained.

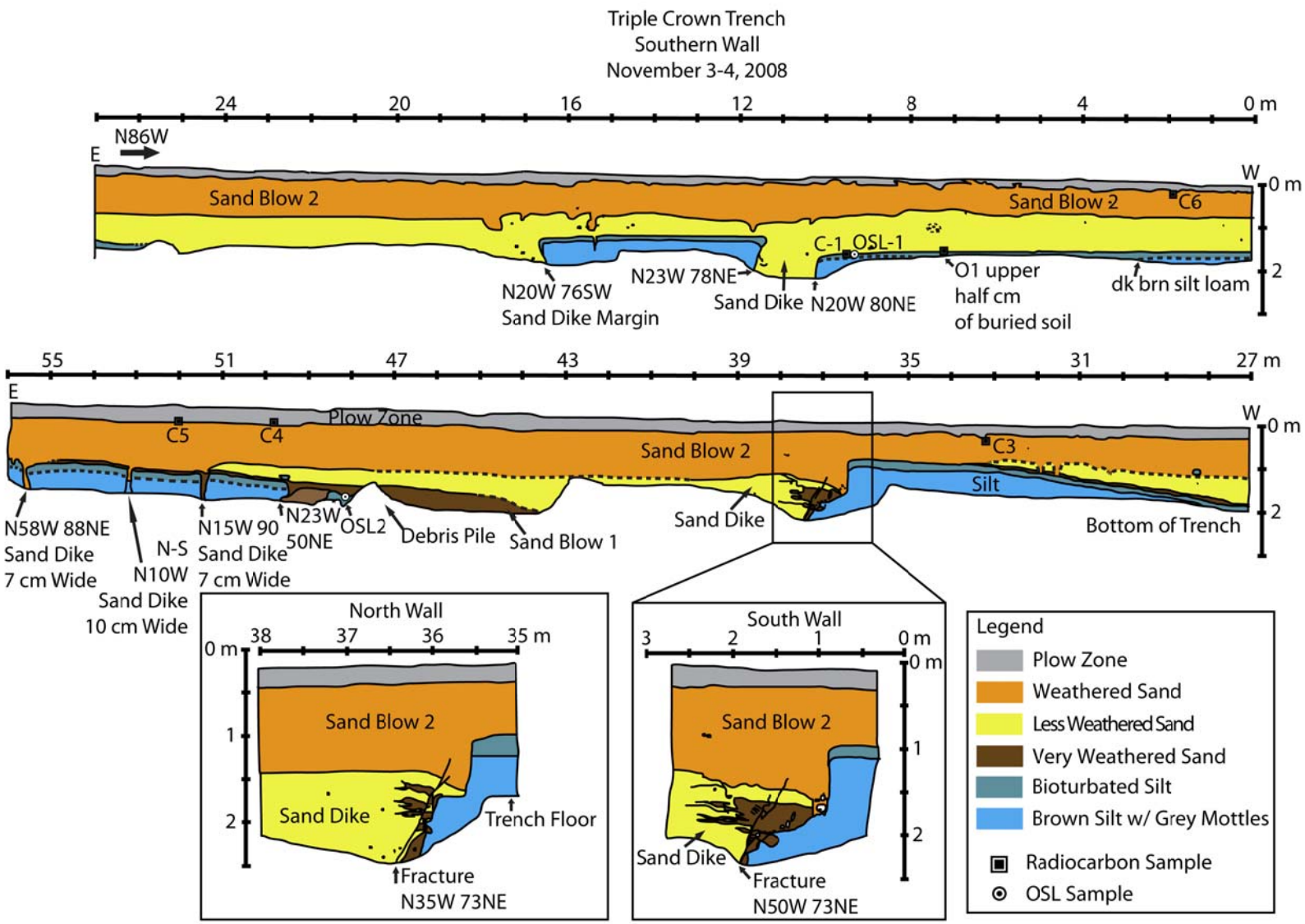

Figure 18. Log of south wall of Triple Crown trench at Daytona Beach site DB-SE2, showing two generations of sand blows. Older sand blow is labeled 1 and younger sand blow is label 2. Radiocarbon dating of sample C-1 indicates that suggests that sand blow 1 formed before 10.1 ka and that sand blow 2 formed after 10.1 ka.

The weathering characteristics and structural and stratigraphic relations of the sand dikes and sand blows exposed in the trench indicate that they formed during two different events. Weathering of the large sand blow is similar to that observed in the sand blows at the Daytona Beach site, indicating that the Triple Crown sand blows are prehistoric in age and possible as much as 5.5 k years old. Only a few organic samples were recovered from the buried soil. One of those samples (C1) collected near the 9-m mark from the silt loam below the large sand blow yielded a two-sigma calibrated date of 9560-9960 and 9990-10150 yr B.P. (Figure 18). This date provides maximum age constraint for the younger sand blow, indicating that it formed less than 10.1 ka. If this is a close maximum age, the large sand blow predates the sand blow at the Daytona Beach site. OSL dating is being performed on soil samples collected below both generations of sand blows. The results of the OSL dating are not yet available but hopefully will help to constrain the ages of the sand blows.

In the Triple Crown trench at the 37-m mark, the sand adjacent to the margin of the large dike is cut by a fracture that strikes N50°W and dips 73°NE (Figure 18). The fracture cuts across reddish brown sand and into the overlying less weathered sand. Layering and layer thickness within the sand varies in some places across the fracture suggesting some lateral displacement along the structure. Unlike many of the sand dikes, the fracture is similar to the strike of the lineament. This sort of fracturing is unusual in sand dikes and sand blows and may be related to faulting.

In the Double Crown trench, we found four sand dikes ranging from 5-40 cm wide and a fifth sand dike that was at least 1 m wide (Figure 19). We were not able to measure the full width of the larger sand dike because the buried soil had subsided to a depth greater than the bottom of the trench. Three of the sand dikes strike between N25-34°E and dip between 76-80° SE. The smallest dike has a strike and dip of N5°W and 83°NE. The western margin of the largest dike has a strike and dip of N24°W and 65°NE. The sand dike at the 25-m mark is filled with brown sand. Similar brown sand extends towards both the east and west, forming a thin (8 cm) sand blow overlying mottled silt. West of the 20-m mark, the thin reddish brown sand blow dips below the floor of the trench and is absent below the less weathered sand blow between the 4-m mark and western end of the trench. Stringers of brown sand within less weathered sand occur in the largest sand dike between the 4-m and 5-m marks. Except for the stringers of brown sand, this sand dike is clearly related to the large sand blow 0.8-1.7 m thick that extends the full length of the trench. The upper 1 m of the large sand blow is very iron-stained.

Similar to the Triple Crown trench, there are two generations of sand dikes and sand blows exposed in the Double Crown trench. Weathering of the two generations of features is similar to those in the other trench suggesting that they formed during the same events. Despite careful examination, no organic samples were found in the buried soil to help date the sand blows and thus the events. A soil sample of the contact between the older sand blow and buried silt loam was collected at the 25-m mark and submitted for OSL dating (Figure 19). Once the result of the OSL dating is available, it should help to constrain the ages of the sand blows.

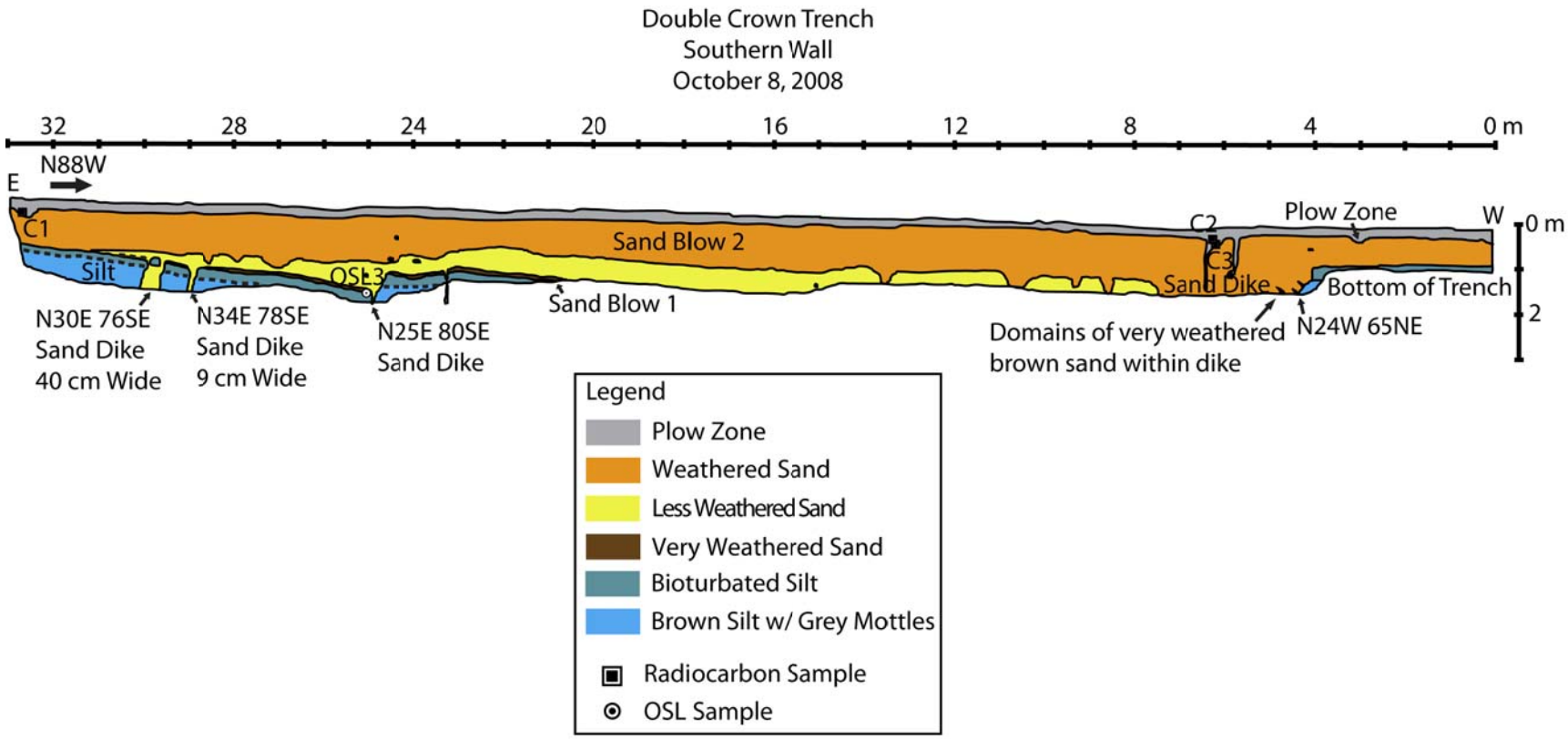

Figure 19. Log of south wall of Double Crown trench at Daytona Beach site DB-SE2, showing two generations of sand blows. Older sand blow is labeled 1 and younger sand blow is label 2. Radiocarbon dating of buried silty soil below sand blow 1 in Triple Crown trench provides age constraint for same sand blows observed in Double Crown trench..

DISCUSSION AND CONCLUSIONS

It has become increasingly evident that the Marianna area experienced major earthquakes from 5.5-10.1 ka. The evidence is presented by Al-Shukri *et al.* (2005), Al-Shukri *et al*. (2006) and Tuttle *et al.* (2006), as well as in this report, representing a continuation of our previous studies. The main goals of this project are to verify that the northwest-southeast oriented lineament identified during our previous study (Tuttle *et al.*, 2006) is delineated by sand blows and to test the hypothesis that the lineament is fault controlled. In this study, we define the location of the lineament with greater clarity and trace it farther to the northwest (Figure 2). The 10-km long lineament is marked by many large sand blows similar to the one at the Daytona Beach (DB). Sand blows at six sites were studied during this project.

GPR data collected at the six sites indicate that severe ground disturbance took place along the northwest-southeast oriented lineament in the past. This disturbance included earthquake-induced liquefaction, surface subsidence, sand dike emplacement, and venting of sand blows on the ground surface. At all the study sites sand dikes, representing the conduit through which water and sand erupted to the surface to form sand blows, range in width from 1-4 m. The sand blows cover larger areas from 100 m by 150 m to 200 m by 600 m and range to more than 3 m thick. This indicates that a huge amount of sand was vented to the surface during strong ground shaking. With additional research, it may be possible to relate the size of sand blows to the magnitude of the causative earthquake.

At Daytona Beach SE2 site, trench observations confirm the interpretations of the geophysical data of at least one major sand dike and a large sand blow at this site. Not imaged by GPR, the trenches revealed additional smaller sand dikes and an older sand blow. Both generations of liquefaction features are very weathered, like the sand blow at the Daytona Beach site, suggesting that they may be as much as 5.5 k yr old. Radiocarbon dating of the buried silt loam soil provides maximum age constraint of 10.1 ka for the younger of the two sand blows and minimum age constraint for the older sand blow. OSL dating is underway and should help to further constrain the ages of the sand blows. In one of the trenches, an unusual fracture cross cuts layering in the sand dike, has a strike very similar to the lineament, and may be related to faulting.

Lateral spreading can occur during earthquake-induced liquefaction and produce asymmetrical ground failure similar to what we've observed at the Daytona Beach study sites. However, the fissures associated with lateral spreads are usually arcuate in plan-view and parallel to a stream channel or other free face towards which the lateral spread moves. Its great length, linear morphology, and parallelism to the nearby White River fault zone support the interpretation that the lineament may be fault controlled rather than related to lateral spreading (Figure 20). This interpretation, however, must be verified by geological and/or geophysical studies that show fault displacement of strata below the sand layer that liquefied.

There appears to be at least a 5-10 k yr long history of strong ground shaking along the Daytona Beach lineament and possibly across the Marianna area. The sand blows in the Marianna area are much more weathered than and pre-date those in the New Madrid seismic zone. No sand blows have yet been found in the Marianna area that is less than 5 ka and could have formed during the 1811-1812, 1450 A.D., or 900 A.D. New Madrid earthquakes. Therefore, the Marianna sand blows do not represent distant effects of earthquakes generated by the New Madrid seismic zone. Instead, their large size and spatial relations to local faults suggest that the causative earthquakes were centered in Marianna. Furthermore, the compound nature of some of the Marianna sand blows are indicative of sequences of large earthquake resulting from complex fault interaction similar to the behavior of the New Madrid fault zone (Tuttle et al., 2002 and 2005). Additional study is necessary to determine the history of faulting along both the Eastern Reelfoot Rift Margin fault zone and the White River fault zone during the past 20 k years, to compare the chronology of events along the Eastern Reelfoot Rift Margin fault in the Marianna area and western

Tennessee, and to assess the potential threat of these fault zones to Memphis, Little Rock, and other communities in the region.

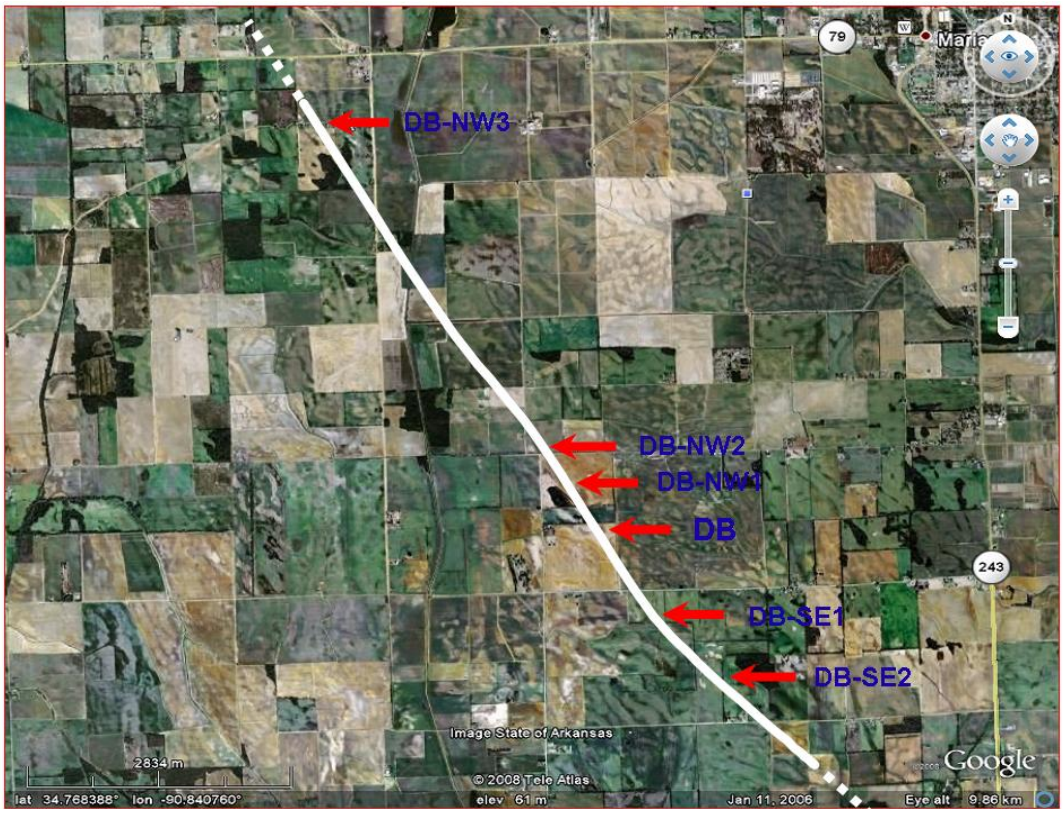

Figure 20: Satellite image showing the 10 km long NW-SE oriented lineament marked by sand blows that may represent a fault at depth.

ACKNOWLEDGEMENTS

The USGS/NEHRP National Earthquake Hazard Reduction Program partially funded (07HQGR0069) this study and covered additional costs for radiocarbon dating. OSL dating was performed by Shannon Mahana of the US Geological Survey. The authors are grateful to GIT, University of Arkansas at Little Rock for using the GPR system and their vehicle and the USGS for use of a field vehicle and trench shoring. The authors particularly thank Aycan Catakli, Mert Su, Najah Abd, for field assistance; Natasha McCallister for field assistance and drafting of the trench logs; and Mr. Johnson and Mr. John McClendon for allowing access to their farmland for fieldwork.

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.

Al-Shukri, H., H. Mahdi, and M. Tuttle, 2006, Three-Dimensional Imaging of Earthquake-induced Liquefaction Features with Ground Penetrating Radar near Marianna, Arkansas, *Seismo. Res. Lett*., 77, 505-513.

Geophysical Survey Systems, Inc., 2005, Radan 6.5 User's manual, Geophysical Systems Survey, Inc., North Salem, New Hampshire, 213pp.

Lui, L., and Y. Li, 2001, Identification of liquefaction and deformation features using ground penetrating radar in the New Madrid seismic zone, USA. *Journal of Applied Geophysics* 47, 199–215.

Maurya, D.M., N., Goyal, Patidar, A.K., Mulchandani, N., Thakkar, M.G., Chamyal, L.S., 2006. Ground Penetrating Radar imaging of two large sand blow craters related to the 2001 Bhuj earthquake, Kachchh, Western India, *Journal of Applied Geophysics*, 60, 142–152.

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.

Telford, W. M., Geldart, L. P., Sheriff, R. E. and Keys, D. A., 1976, Applied Geophysics: Cambridge University Press, Cambridge.

Tuttle, M. P**.**, Al-Shukri, H, and Mahdi, H., 2006, Very large earthquakes centered southwest of the New Madrid seismic zo ne 5,000-7,000 years ago, Seismological Research Letters, v. 77, n. 6, p. 664-678.

Tuttle, M. P., Schweig, E., III, Campbell, J., Thomas, P. M., Sims, J. D., and Lafferty, R. H., III, 2005, Evidence for New Madrid earthquakes in A.D. 300 and 2350 B.C., Seismological Research Letters, v. 76, n. 4, p. 489-501.

Tuttle, M. P., Schweig, E. S., Sims, J. D., Lafferty, R. H., Wolf, L. W., Haynes, M. L., 2002, The earthquake potential of the New Madrid seismic zone, Bulletin of the Seismological Society of America, v. 92, n. 6, p. 2080-2089.

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.

Wolf, L. W., J. Collier, M. Tuttle, and P. Bodin, 1998, Geophysical reconnaissance of earthquake-induced liquefaction features in the New Madrid seismic zone. *Journal of Applied Geophysics* 39, 121–129.

Wolf, L. W., P. M. Tuttle, 2003, Geophysical of earthquake-induced liquefaction at cultural sites in the New Madrid seismic zone, *USGS external project*, No. 1434-01HQGR0003, 36 P.