GEOPHYSICAL INVESTIGATIONS OF EARTHQUAKE-INDUCED LIQUEFACTION AT CULTURAL SITES IN THE NEW MADRID SEISMIC ZONE

Final Report
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TOWARDS A PALEOEARTHQUAKE CHRONOLOGY FOR THE NEW MADRID SEISMIC ZONE

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Technical Abstract

Award Number: 1434-01HQGR0003

Title: Geophysical Investigations of Earthquake-Induced Liquefaction at Cultural Sites in the New Madrid Seismic Zone

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Geophysical and paleoseismological investigations were conducted at four culturally sensitive Native American sites in the New Madrid seismic zone (NMSZ). The goals of these studies were to (1) expand regionally the database of known prehistoric liquefaction features, (2) improve age constraints of earthquake-induced liquefaction events prior to A. D. 1450, (3) reduce uncertainties related to timing, source areas, magnitudes and recurrence intervals of large NMSZ earthquakes, and (4) understand better the geologic and hydrologic factors that contribute to liquefaction and ground failure. Age constraints for the timing of the liquefaction events were provided by a combination of radiocarbon dating of charcoal, wood and plant remains, along with artifacts of distinctive cultural periods. Results of the study indicate that liquefaction features at two of the sites probably formed during the NMSZ A.D. 900 +/- 100 yr event. Liquefaction features at the other two were most likely associated with the NMSZ A.D. 1450 +/- 100 yr event (see Tuttle et al., 2002, for a compilation of sites and events).

In addition to collecting information about the liquefaction features located at each of the sites, geophysical surveys and trench excavations were used to study the stratigraphic relations at sites to determine how these relations might influence the development and maintenance of overpressures during strong ground shaking. Information on sediment compositions, unit thicknesses, and geometric relations of the sand blows and sand dikes relative to host deposits were used construct small-scale models for studying the development of overpressures using a range of permeabilities for different sedimentary units. Results show how interbedded and interfingered sediments with differing permeabilities can lead to sustained overpressures in alluvial sites. Areas with low permeabilities can redirected flow upwards and produce regions of high overpressures. The model explains how overpressures can develop beneath fine-grained deposits or adjacent to fine-grained deposits, where liquefaction features are often observed.

Non-Technical Abstract

Collaborative paleoseismological and geophysical investigations of earthquake-induced liquefaction have been conducted at selected sites in the New Madrid seismic zone to reduce uncertainties related to timing, source areas, magnitudes, and recurrence intervals of large New Madrid earthquakes. Most of these investigations focus on archeological sites, which contain abundant material for dating liquefaction features and therefore causative earthquakes. Geophysical surveys serve to define the extent of features and to minimize disturbance of the archeological sites during trenching. Evaluations have been carried out at thirteen sites, with detailed paleoseismological and geophysical investigations conducted at four of those sites.

Investigations Undertaken

Investigations conducted under this U.S. Geological Survey award has focused on the study of liquefaction caused by prehistoric earthquakes at archeological sites in the New Madrid seismic zone (NMSZ). Specifically, the research objectives were (1) to expand regionally the database of liquefaction features (see Tuttle et al., 2002 for comprehensive summary); (2) to improve age constraints of liquefaction events prior to A.D. 1450; (3) to reduce uncertainties related to estimates of timing, source areas, magnitudes, and recurrence intervals of large New Madrid earthquakes; and (4) to understand better the geologic factors that contribute to liquefaction and ground failure. To achieve these objectives, the principal investigators and collaborators pursued the following activities:

(1) reconnaissance surveys to determine the presence of sand blows at cultural sites in the New Madrid region and to estimate the approximate age of the liquefaction features;

(2) surface geophysical surveys at selected sites to delineate liquefaction and cultural features prior to excavation and to gain information on the stratigraphy and sediment properties of the site;

(3) surface collection of artifacts and removal of the plow zone in targeted areas, mapping of sand blows and cultural features and horizons in plan view, collection of artifacts and organic materials from cultural features intruding sand blows and from cultural horizons buried by sand blows;

(4) excavation of sand blows to study and document their sedimentological and structural characteristics and to expose the pre-event surfaces of buried cultural horizons, and collection of samples for grain-size analysis and radiocarbon dating;

(5) excavation of archeological test units, usually 1 m x 1 m in area and 30 cm to 60 cm in depth, in cultural horizons buried by sand blows, screening of excavated material and recovery of artifacts from 10-cm-thick levels, mapping of level surfaces in plan view, and collection of flotation samples from 20 cm x 20 cm control columns located in one corner of each test unit;

(6) processing of samples from cultural horizons and features, artifact analysis, and radiocarbon dating of selected charcoal, wood, and plant samples.

The investigations were carried out collaboratively by Dr. Lorraine W. Wolf of Auburn University (AU), Dr. Martitia Tuttle of M. Tuttle & Associates (under USGS award number 1434-01HQGR0164, *Towards a Paleoearthquake Chronology for the NMSZ*), Dr. Robert Lafferty of Mid-Continental Research Associates (MCRA), and Dr. Eugene Schweig of the U.S. Geological Survey and represent a continuation of past joint efforts (e.g., Tuttle and Schweig, 1995; Tuttle et al., 1996; Collier et al., 1997; Collier, 1998; Wolf et al., 1998; Tuttle et al., 1998; Tuttle, 1999; Wolf, 1999; Barnes et al., 1999; Tuttle et al., 1999; Schweig et al., 1999; Barnes, 2000; Tuttle, 2001; Wolf et al., 2001; Browning et al., 2002; Tuttle et al., 2002; Wolf et al., 2002; Browning, 2003). Other participants in these and past studies include Jonathan Collier, April Barnes, Sharon Browning and Stephanie Parks (A.U. graduate students), Dr. Russell Weisman of Missouri Department of Transportation, Dr. James Price of the National Parks Service, Dr. Larry Grantham of Missouri Department of Natural Resources, Dr. John Sims of John Sims and Associates, and Marion Haynes and Dr. Claudine Payne of the Arkansas Archeological Survey. This report was prepared by L. Wolf and M. Tuttle, with significant contributions from R. Lafferty and M-K Lee (AU).

Results

Based on reconnaissance surveys conducted in 2000 and 2001 (described in Tuttle et al., 2000; Tuttle, 2002; Wolf, 2002), we selected several sites for detailed investigations. Field investigations are completed for five sites, namely Archway, Dillahunty, Cagle Lake, Obion River 216, and Towosahgy (Figure 1). Analyses of data and samples collected at the sites are described below.

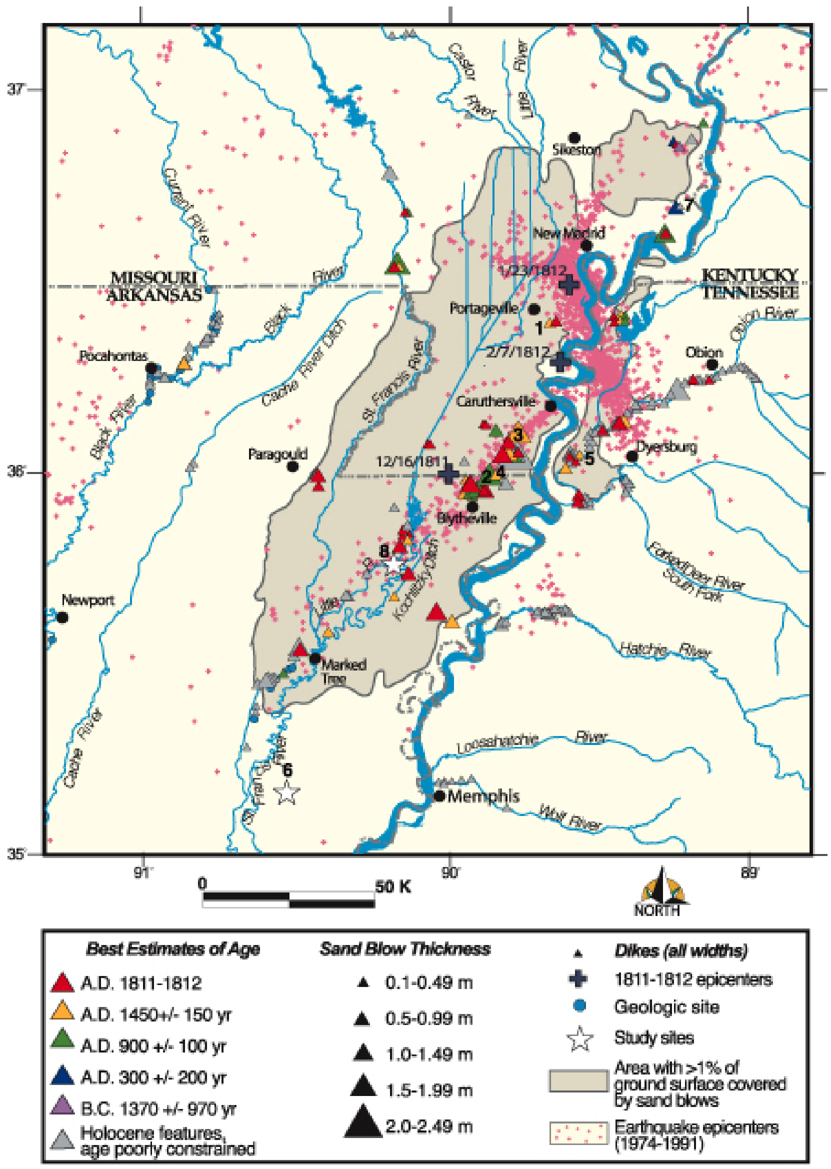

Figure 1. Map of NMSZ showing estimated ages and measured sizes of liquefaction features. Study sites discussed in this report include 2-Archway; 3-Cagle Lake; 4-Dillahunty; 5-Obion 216; 7-Towosahgy. Area of surficial sand-blow deposits is from Saucier (1977) and Obermeier (1989).

Archway (3MS620): During a previous investigation, Tuttle and collaborators logged a large compound sand blow and associated sand dikes exposed in a drainage ditch and collected artifacts and organic samples for dating at this archeological site, located northeast of Blytheville, Arkansas (Figure 1; Tuttle et al., 2000). The compound sand blow is composed of three, possibly four major sedimentary units thought to have formed as a result of several closely timed episodes of liquefaction at the site. The sand blow buries a soil horizon containing a few Native American artifacts of the Woodland cultural period, including a large Withers fabric-marked potsherd diagnostic of the terminal Early Woodland (Ca. 200 B.C.). Radiocarbon dating of a large root collected along the contact between the sand blow and underlying soil yielded a calibrated date of A.D. 1670-1960. There was some concern, however, that the root might have recently grown into the deposits from the ditch bank. A charcoal sample collected from the top of the sand blow yielded a date of A.D. 1680-1960. These dates suggest that the compound sand blow may have formed during the historic period. Therefore, the liquefaction features were tentatively attributed to the 1811-1812 earthquakes but additional study seemed warranted given the presence of Woodland artifacts in the soil below the sand blow and the uncertainty regarding the root.

As part of this project, we conducted additional study of the same large, compound sand blow but in an area just west of the drainage ditch, where artifacts are abundant on the ground surface and a Woodland pot was recovered below the plow zone and above a sandy layer (M. Haynes, pers. comm., 2000). We carried out geophysical surveys over a grid covering ~ 2100 m^2. Resistivity/conductivity surveys allowed us to map the extent of the sand blow, and the magnetic survey helped to locate buried cultural features (e.g., pits) (Figure 2). On the basis of observations made in the ditch cutbank, geophysical surveys, surface density of artifacts, and soil properties, two areas were selected for further investigation. In these areas, we removed the plow zone and excavated two trenches and one archeological test unit (Figures 3 and 4).

Stripped area 1 was located about 20 meters west of the drainage ditch. Numerous cultural features, including a large bowl-shaped pit, other pits, post molds, two possible hearths, and house floors, that coincided with magnetic highs were exposed just below the plow zone (Figures 3 and 5). Trench 1 was excavated in the northeast corner of the stripped area where there were no cultural features. Trench 1, oriented roughly N-S across the smaller resistivity anomaly,
revealed a fining-upward fluvial deposit in which no liquefaction features were found. Browning collected sediment samples from various places in the wall of Trench 1 and performed grain-size analysis in order to compare the grain-size distribution of the fluvial deposit and that of the nearby sand blow.

Stripped area 2 was located about 5 meters west of the drainage ditch (Figure 4). Trench 2, oriented across the larger resistivity anomaly, exposed a cross-section of the sand blow, underlying cultural horizon, two small sand dikes, and several sand-filled animal burrows (Figure 6 and 7). A sand dike exposed in the floor of the trench is approximately 5 cm wide and oriented N40-44°E. Another sand dike exposed in Test Unit 1 is up to 14 cm wide striking N43°W and dipping steeply to the northeast. The sand dikes crosscut a black, silt loam soil horizon containing numerous pottery sherds and other artifacts. In fact, several sherds occurred at the contact between the cultural horizon and overlying sand blow. In this location, the sand blow is

Table 1. Results of radiocarbon analysis of samples collected at Archway, Cagle Lake, and Dillahunty archeological sites.

Site Sample Lab Sample	13C/12C Ratio	Radiocarbon Age Years BP (1-sigma)[1]	Calendar Years AD/BC (2-sigma)[2]	Sample Description
Archway-C1 Beta-166245	-24.3	200 ± 40	AD 1640-1690 AD 1730-1810 AD 1920-1950	Charcoal from root cast within sand blow
Archway-C5/FSN18 Beta-166246	-26.2	920 ± 40	AD 1020-1210	Charcoal from cultural horizon 60 cm below sand blow
Archway-FSN6 Beta-171219	-24.6	1310 ± 40	AD 660-780	Hickory nutshell from flotation sample collected 0-10 cm below sand blow
Cagle Lake-F101 Beta-160377	-26.3	240 ± 60	AD 1500-1690 AD 1730-1810 AD 1920-1950	Wood from aboriginal post mold in top of sand blow
Cagle Lake-C106 Beta-166251	-25.6	170 ± 40	AD 1650-1890 AD 1910-1950	Charcoal from aboriginal post mold in top of sand blow
Cagle Lake-FSN116 Beta-171217	-24.7	440 ± 40	AD 1420-1500	Hickory nutshell from flotation sample collected 0-5 cm below sand blow
Cagle Lake-C104 Beta-166250	-25.7	580 ± 40	AD 1300-1420	Charcoal from cultural horizon 5-15 cm below sand blow
Cagle Lake-C100 Beta-166249	-25.9	460 ± 40	AD 1410-1480	Charcoal from cultural horizon 47 cm below sand blow
Dillahunty-C4 Beta-166247	-26.3	70 ± 70	Modern	Charcoal from top of soil above sand-blow crater
Dillahunty-C5 Beta-166248	-25.6	470 ± 50	AD 1400-1490	Charcoal from base of soil above sand-blow crater
Dillahunty-FSN4 Beta-171218	-9.7	980 ± 70	AD 910-920 AD 960-1210	Maize kernel fragment from flotation sample collected 0-10 cm below sand blow

[1] Conventional radiocarbon ages in years BP or before present (1950) determined by Beta Analytic, Inc.

[2] Calibrated age ranges in calendar years determined by Beta Analytic, Inc. (Talma and Vogel, 1993; and Stuiver et al., 1998; Stuiver and van der Plicht, 1998).

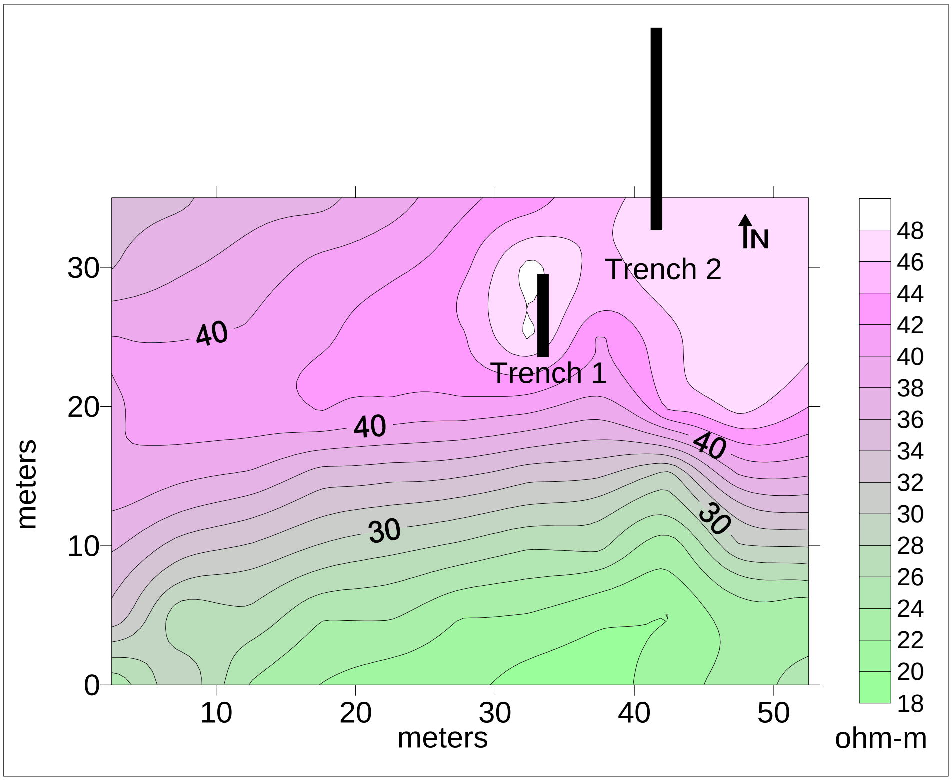

Figure 2. Resistivity survey at Archway site. Black rectangles show position of trenches. Buried liquefaction features often appear as high resistivity anomalies. High values in northeastern portion of grid reflect large buried sand blow that was excavated and logged (Trench 2).

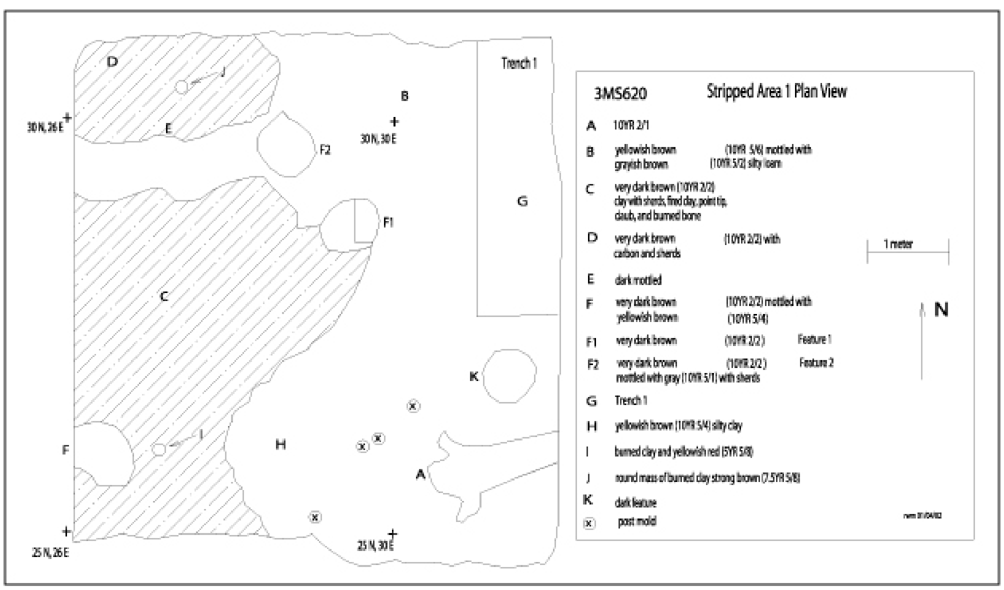

Figure 3. Plan view of area 1 with plow zone removed. Most of stripped area was underlain by Native American occupation horizon. Trench 1 (G) was excavated along eastern part of area where no cultural features occur. Feature 1 was partially excavated (see Figure 5). (Provided byMCRA.)

more than 11 m wide and about 90 cm thick and composed of four, major sedimentary units. In the nearby drainage ditch the sand blow was about 25 m wide and up to 1.5 m thick.

As exposed in Trench 2, the lowermost unit (Unit 4) of the sand blow is the thickest, exhibits flame structures, contains lenses of lignite, and fines upward from fine sand to silty, fine sand (Figure 7). The next-to-lowermost unit (Unit 3) also fines upward from fine sand to very fine sand and includes clasts of underlying soil units. Some of the sand in this unit was vented through an animal burrow near the 10-meter mark of the log and possibly another near the 3-meter mark. The next higher deposit (Unit 2) has three subunits and the most complex stratigraphic relations. The lowermost subunit (Unit 2c) is dominantly fine sand with domains of clasts and organics that apparently vented locally through animal burrows between the 8- and 10-meter marks. This subunit fines upward from fine sand to silty, very fine sand and interfingers with the overlying subunit (Unit 2b) between the 6- and 7-meter marks. The uppermost subunit (Unit 2a) is the finest (silt) and thinnest of the three members and pinches out towards the south. The overall gradation of Unit 2 is from fine sand to clayey silt. The uppermost sandy unit (Unit 1) also fines upward from silty, very fine sand to very fine sandy, silt and contains lenses of lignite especially in the finer portion of the deposit. No feeder dike or vent area for this unit was exposed in the trench. All four sedimentary units, but especially Unit 1, are disturbed by bioturbation. Root casts are more prevalent in this section than in any other previously studied by us in the NMSZ.

The four sedimentary units described above can be correlated with units previously logged in the drainage ditch and interpreted as sand blow deposits. The earlier study suggested that Unit 4 might be a fluvial deposit. We now think that interpretation is unlikely due to the position of the site on an interfluve and the tonal patterns on aerial photographs indicative of sand blows and not recent fluvial deposits. Observations made in Trench 2, and previously in the nearby drainage ditch, indicate that four closely timed liquefaction events occurred at the site. The high degree of bioturbation of the sand blow and the burial of a Native American occupation horizon, with some artifacts on the surface at the time of burial, strongly suggest that the compound sand blow is prehistoric in age.

A 0.9 m x 0.9 m archeological test unit was excavated at the south end of the trench to sample the Native American occupation horizon below the sand blow. The cultural horizon was approximately 60 cm thick and had a high density of artifacts ranging up to 800 per cubic meter. Ceramic artifacts collected below the sand blow include cord-marked grog, sand, and grog-and-sand-tempered pottery (Figure 8). Table 2 presents the distribution, by temper, of the pottery sherds in Test Unit 1. Sand-tempered pottery dominates the lowest level (6). There is an abrupt appearance of grog-tempered cordmarked pottery in level 5. In the two overlying levels (3 and 4), grog-tempered pottery increases to 25% of the assemblage, and most of these sherds are larger than 1.2 cm in diameter.

We selected five sand-tempered and six grog-tempered sherds, primarily from Test Unit 1, for microscopic examination of pastes (Table 3). This is not a random sample of either the test unit or the whole site; however, the results are suggestive of some long-term developments in pottery making. The sand-tempered sherds from Level 1 have small (0.1 mm) cord marking on the

surface. All the sherds have reduced, black (5YR1/0) cores with whitish (5Y8/2) to light yellowish brown (10YR6/2) exteriors and interior surfaces. Such an affect is obtained by heating the pot and then smothering it in something like damp leaves or pine needles long enough for the carbon to fully penetrate the interior of the vessel. The vessel is then turned rightside up and is
subjected to a hot oxidizing fire. This process produces a hard surface, but maintains the impermeability imparted by the carbon. In contrast, some of the earlier sand-tempered sherds exhibit signs of poor control of the firing process (Table 3). Sand-tempered sherd 12-2 was fired all of the way through to a moderate yellow brown, but there is a lighter, fine yellow line in the center that could possibly have been the fold for a lip. Grog-tempered sherd 9-7C has light-colored, rectangular grogs with black carbon clouds swirled around the grogs. Sherd 9-7B had an interior of very pale orange (10YR8/2) with 0.3 mm-wide black wavy stripes sparsely distributed throughout. The exterior was fired to a yellow brown. The post-reduction, oxidation firing apparently had not totally oxidized either of these pots. Sherd 9-7A is light grayish orange (10YR7/4) throughout its paste, including a few 1.2-mm-sized grogs. The firing of most of these grog-tempered sherds is different from the sand-tempered sherds, in that the final result is totally oxidation, whereas the sand-tempered sherds still have a reduced interior.

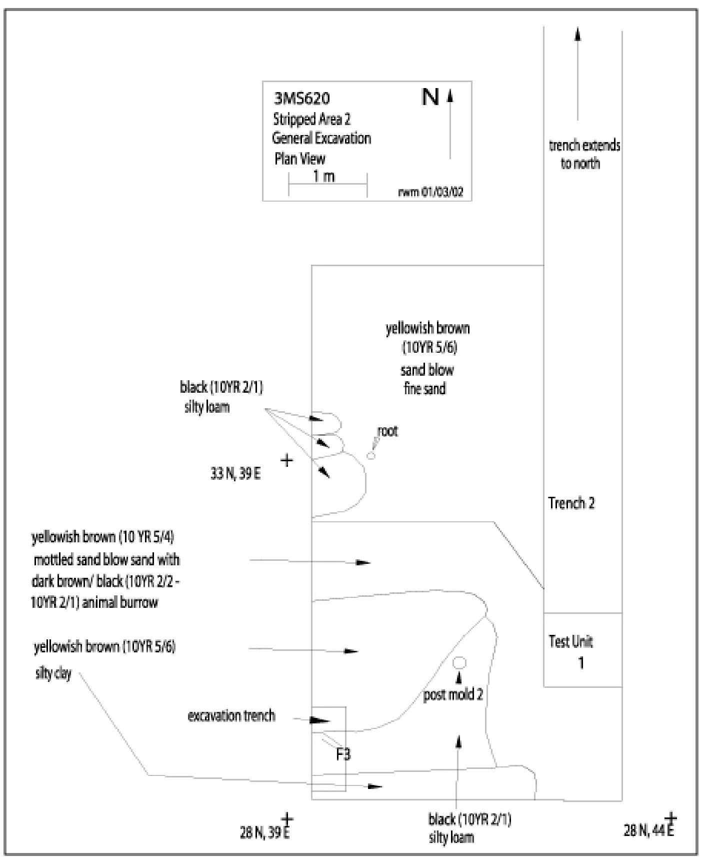

Figure 4. Plan view of area 2 with plow zone removed. Portion of large sand blow was exposed at north end of stripped area. Trench 2 was positioned to expose sand blow and its relation to buried Native American occupation horizon. Test Unit 1 was excavated in buried occupation horizon at southern end of Trench 2 where cultural features and many sand-filled animal burrows occur. (Provided by MCRA.)

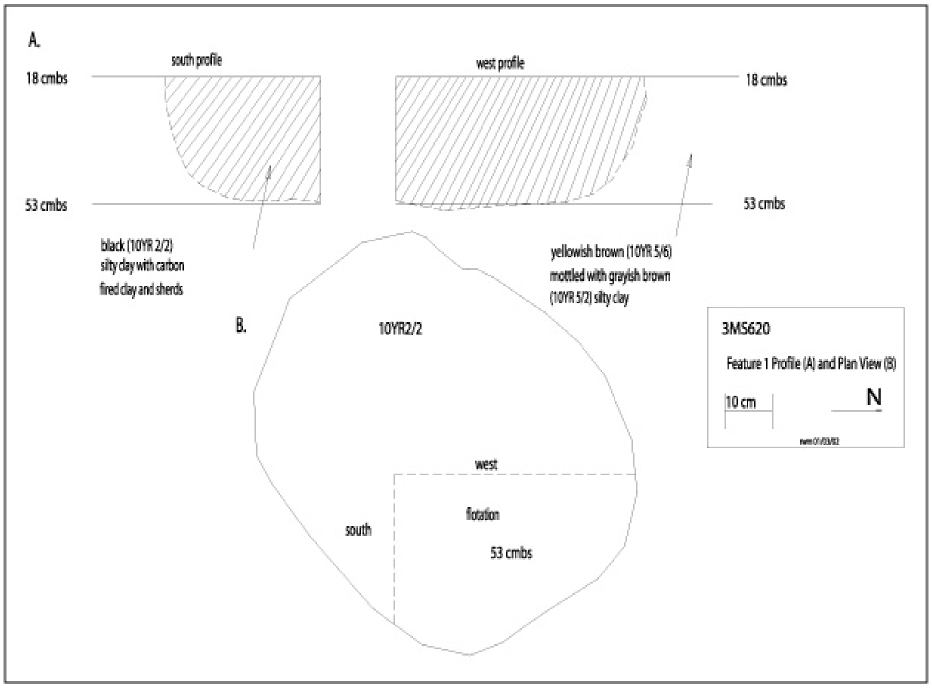

Figure 5. Plan view and profile of Feature 1, a large bowl-shaped pit. (Provided by MCRA.)

Figure 6. Photograph of Trench 2 and Test Unit 1 at Archway archeological site north of Blytheville, Arkansas, showing sand blow with many root casts. Photograph by M. Tuttle.

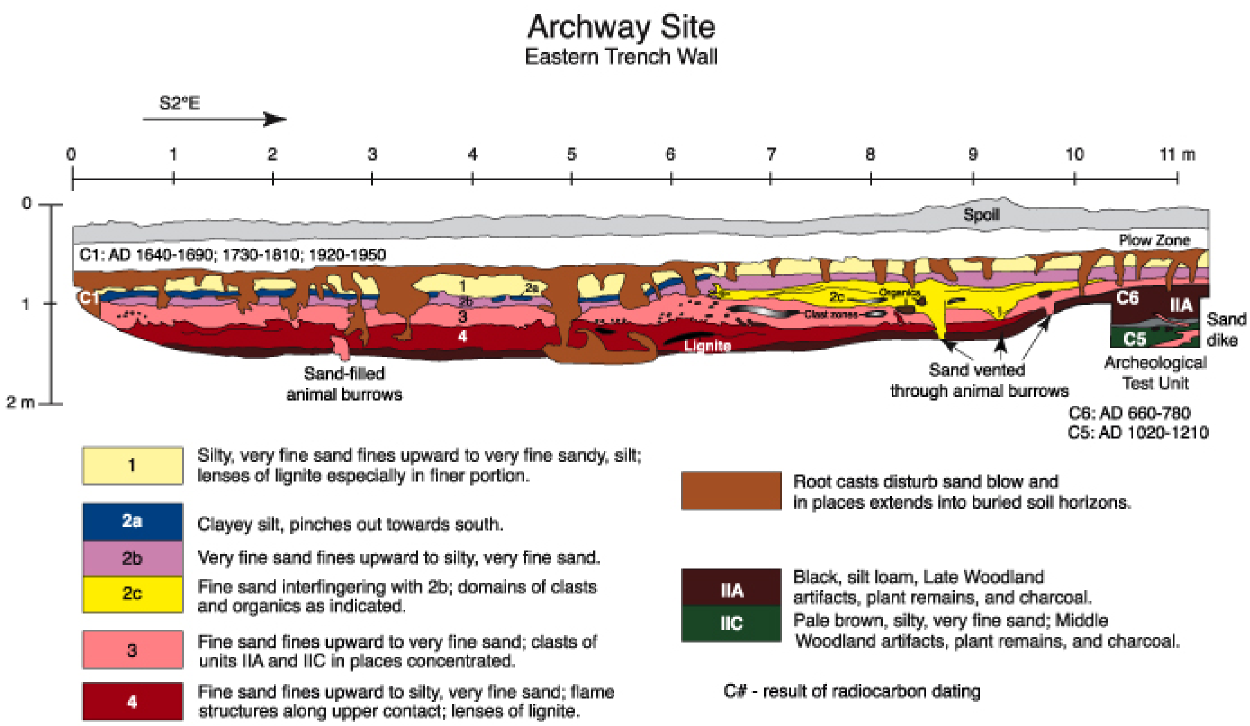

Figure 7. Log of Trench 2 at Archway archeological site. Sand blow is composed of four major units and is disturbed by high degree of bioturbation. Sand vented through small dikes and animal burrows; main vent in nearby drainage ditch was described previously. Sand blow buries cultural horizon containing Middle to Late Woodland artifacts. Several Late Woodland artifacts occur at the sand blow/cultural horizon contact. Liquefaction features probably formed during the A.D. 900, +/- 100 years, event. Log by M. Tuttle and S. Browning.

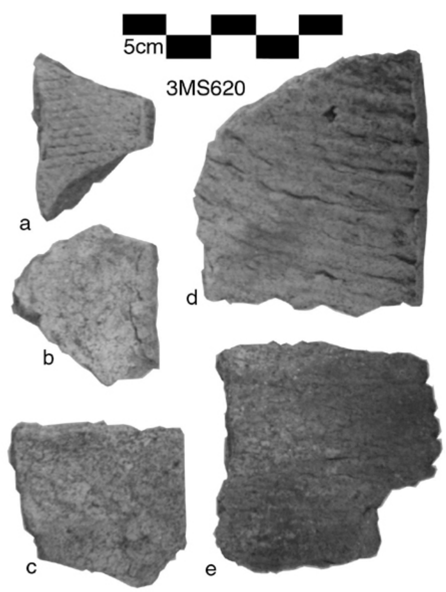

Figure 8. Pottery sherds from Archway site. a. fine cordmarking, b. & c. smoothed surface, d & e. coarse cordmarking. Photograph by MCRA.

Table 2. Types and weights of ceramic artifacts recovered from Archway Test Unit 1.

	Sand Tempered				Grog Tempered				Total	
Level	Sherds (g)	%	Total (g)	%	Sherds (g)	%	Total (g)	%	grams	%
Top	56.1	62	90.7	84	3.5	21	16.8	16	107.5	9.38
1	38.7	23	168.7	87	25.3	100	25.3	13	194.0	16.94
2	49.6	37	134.1	82	23.9	80	30.0	18	164.1	14.33
3	8.7	5	162.4	75	4.0	8	53.2	25	215.6	18.82
4	4.6	3	146.3	82	0	0	31.9	18	178.2	15.56
5	47.5	29	165.2	92	15.0	100	15.0	8	180.2	15.73
6	17.2	16	105.9	100					105.9	9.25
Total									1145.5	100.0

Table 3. Oxidation and reduction band thickness and paste Munsell colors of sand- and grog- tempered ceramics from Archway site.

Temper	Interior Surface		Middle Core		Exterior Surface	
Level/Cat/# 2001-798-	mm	Munsell	mm	Munsell	mm	Munsell
Sand						
L-1/ 3-2A	0.3	10YR8/2	4.0	5YR1/0	1.5	
3-2B			4.3	5YR1/0	2.3	
3-4A	0.3	10YR6/2	5.0	5YR1/0	0.5	
L-4/ 12-2			8.0	10YR5/4		
SA-1, 1-11	1.4	10YR5/6	4.0	5YR1/0	1.0	
Grog						
L-1/3-3			5.0	5YR1/0	0.5	5YR5/6
L-3/ 9-7A						
9-7B			4.0	10YR8/2	2.0	10YR5/6
9-7C				10YR7/4	1.0	10YR8/2
F-1, 2-2A		10YR5/4	3.0	5YR1/0	0.5	10YR5/4
SA-1, 1-14				10YR8/2		

The early sand-tempered pottery seems also to have larger cords and poorer control of the firing process. The cordmarking on the grog-tempered pottery is of very large cords, the largest being 8 mm in diameter (Figure 8, d and e), and the cords are almost always perpendicular to the lip. The few rims have slightly folded, almost smoothed-over lips. The only types that are similar are the Baumer ceramics from southern Illinois (Cole et al., 1951). Although there are grog-tempered sherds in level 3, our sample is so small that it is hard to ascertain their significance.

The ceramics suggest that Level 3 corresponds with the Middle Woodland cultural period and the overlying levels correspond to the early part of the Late Woodland Barnes phase, estimated to be ca. A. D. 400-600. Analyzing them level by level, the sherds in this one test unit suggest that the Late Woodland components have fine, cordmarked ceramics with small cords (Figure 8, a) and reduced cores. Most often the interior surface of these sherd will also be reduced. The exteriors are oxidized, often to white. The earlier pottery is often smoothed over and has larger cords, approaching 3 mm. Although the sample is not large enough to lend statistical credence to these observations, they are suggestive of potentially useful analyses to differentiate earlier from later Woodland components.

Lithics artifacts recovered from Test Unit 1 also help to estimate the age of the cultural horizon buried by the compound sand blow. Table 4 presents measurements of the projectile points that have been recovered from the Archway Site. Dickson (1991) argued that Rice Side-Notched points (Figure 9 a, c, and d) are actually Steuben points (Figure 9, b) that have been worn down and had their ears on either side of the notch broken off. These barbs are a crucial part of the weapon. The two points with ears as the widest part of the artifact are classified as Steubens and the others are classified as Rice Side-Notched (Table 4). There appears to have been ears on the Rice side notched points, because they exhibit small snap fractures. The haft widths of the four Rice Side-Notched points are similar to that of the Steuben. The widths of the Rice points, which were measured on the blade, are smaller than the Steuben widths, because the Rice points have been used and resharpened. The presumed preforms are large enough to have ended up as the Rice Side-Notched and Steuben points. The other two points, a Gary and a Big Creek, may be Late Archaic; although Dickson (1991) found very similar Gary points from the Late Woodland stratum at Albertson.

Some lithic tools recovered from the surface are consistent with occupation of the site during the Middle to Late Woodland periods. Dr. Payne reported two complete basalt adzes recovered from the site. These adzes have rounded edges and have been dated elsewhere to the Woodland period. Also, two Cobden chert prismatic blades and one hoe were recovered. Blades of Cobden chert is known to have been produced in the Late Archaic and Middle Woodland periods. The hoe (Figure 10, b) was narrow and made of mottled gray and dark maroon chert, possibly Kornthal (Parry 1992). The tool has undergone three stages of re-sharpening, based on the amount of polished on the flake scars. Another possible adze bit end made of sandstone was recovered. The tool is about the same dimensions, but the polishing striations run across the bit. Similar artifacts have been recovered from the Middle Woodland period Baumer site in southern Illinois (Cole et al. 1952). In addition, one brown gravel haft end (proximal) of an adze was found at the site. It has a trianguloid cross-section and is 31 mm wide (Figure 10, e). Adzes apparently were in use for a long time span including the Woodland and Mississippian periods (Williams and Brain

Table 4. Measurements of flaked lithics from Archway.

Type/ Catalogue #	Thickness (mm)	Haft Width (mm)	Maximum Width (mm)	Length (mm)	Comments
Steuben/Rice					
99-560-37	5.5	17.4	24.0	54.0	Ears widest
2001-798-7-7	9.9	13.8	21.2	61.2	Blade widest
2000-641-1	9.4	11.2	17.9	42.8	Blade widest
99-560-36	6.0	18.5	23.7		Ears widest
99-560-38	7.3	18.8	21.5	36.2	Blade widest, Novaculite
Total	38.1	79.7	108.3	36.2	
Average	7.6	15.9	21.7	48.6	
Preform					
2000-774-1	10.0	(21.5)	23.2	47.8	Orthoquartzite
2001-787-2-1	8.3	20-5	24.8	54.0	3MS619, partially heat treated
Big Creek					
2000-601-13-3	7.0	19.0	27.0	40.0	Blade
Gary					
2001-798-27-1	11.7	19.5	26.6	67.5	Blade
Hoe					
2000-774-2	14.4		54.2		Cobden

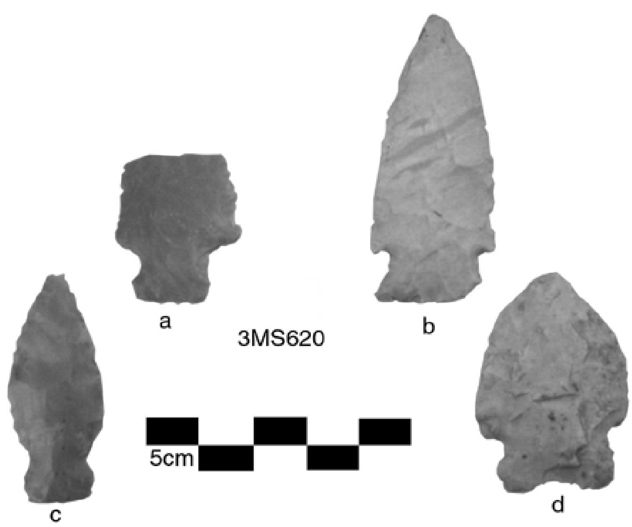

Figure 9. Rice Side Notched: a, c, d. Steuben: b. Photograph by MCRA.

1988; Ray 1995; and Lafferty and Sierzchula, 2002). Two celts with rounded cross sections (Figure 10, c and d) also from the site are characteristic of the Woodland period.

In summary, the archeological data indicate a change in the ceramics from coarsely corded, sand-tempered pottery with fairly poor control of the firing atmosphere, to the typical finely corded, sherds with reduced interiors and a well-oxidized exterior. The early ceramics, level 3 and below, also have a substantial grog-tempered component that was fired very differently from the later sand-tempered pottery, and is similar to the pottery at the Burkett site (23MI20) in southeast

Missouri, and the Baumer site in the lower Ohio River valley. Partially folded notched rims are characteristic of these assemblages. This pottery type, plus the points, blades, hoe, and celts suggest that early occupation begins during the Middle Woodland period and continues into the Late Woodland ca. A.D. 400-800. The large Steuben/Rice point in level 2 argues for the later end of this range, because data from nearby sites, such as 3MS306, suggest that small similarly-shaped arrow points were being made about A.D. 800-900. Most of the artifacts from the Archway site indicate occupation during the Middle to Late Woodland periods. Given its stratigraphic position immediately above the cultural horizon, the sand blow formed after A.D. 400-800.

Beta Analytic, Inc. performed radiocarbon dating of two charcoal samples (C1 and C5/FSN18) and a thin hickory nutshell (FSN6). We had collected sample C1 from a root cast extending into the top of the sand blow and sample C5/FSN18 from the cultural horizon exposed in the test unit about 60 cm below the sand blow (Figure 7). Gina Powell identified plant remains, including sample FSN6, in the 10-cm-thick flotation sample of level 1 collected immediately below the sand blow. Taken from a root cast, C1 was not an ideal sample but was dated only because no better samples was found above the sand blow. Unfortunately, C1 yielded several ranges of calibrated dates including A.D. 1640 to 1690, 1730-1810, and 1920 to 1950 (Table 1). This result is not helpful in constraining the age of the sand blow. Samples C5/FSN18 and FSN6 yielded dates of A.D. 1020 to 1210 and A.D. 660-780, respectively. The date for FSN6 is consistent with the artifact assemblage of the cultural horizon and provides maximum age constraint for the overlying sand blow. The date for C5/FSN18 is not consistent with the artifact assemblage and is about four hundred years younger than that of sample FSN6 collected 50-60 cm higher in the section. Sample C5/FSN18 appears to have been out of stratigraphic position. Perhaps C5/FSN18 comes from a root grown into the cultural horizon some 800-1000 years ago and subsequently burned. This seems a plausible explanation given the prevalence of root casts at the site. If this were the case, the date might actually provide minimum age constraint of A.D. 1020 to 1210 for the sand blow.

The stratigraphic position of the sand blow immediately above the Native American occupation horizon, the Late Woodland artifacts in the upper levels of the horizon, and the radiocarbon date of the hickory nutshell collected within 10 cm of the base of the sand blow indicate that the sand blow formed not more than a couple hundred years after A.D. 660-780. Therefore, the large compound sand blow probably formed during the A.D. 900, ± 100 years, New Madrid event.

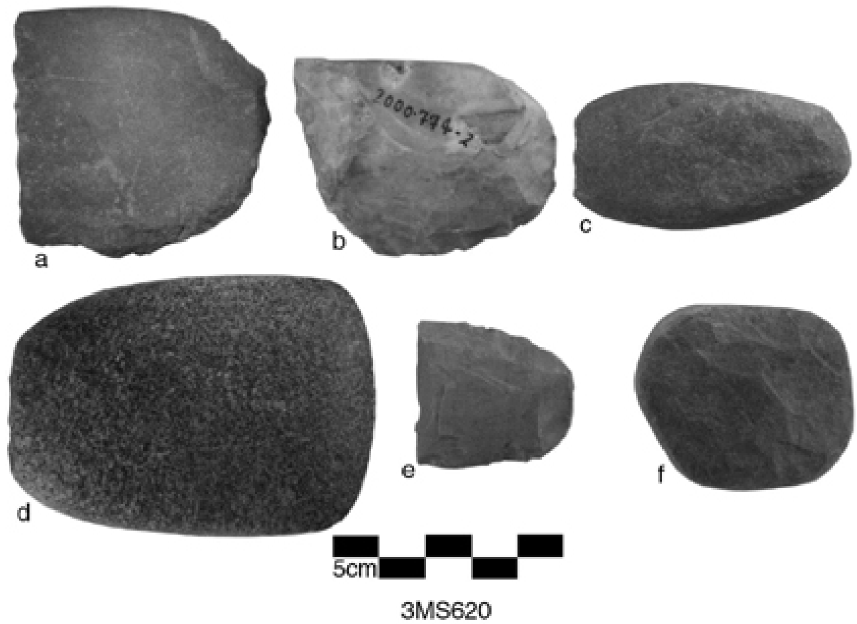

Figure 10. a. hoe preform,. b. hoe; c and d. celts, e. brown gravel adze, f. hammer. Photograph by MCRA.

Cagle Lake (23PM568): The Cagle Lake site is located north of Steele, Missouri, adjacent to an abandoned weigh station on Interstate 55 (Figure 1). Dr. Russell Weisman, an archeologist with the Missouri Department of Transportation, discovered a sand blow and related sand dike above a Middle to Late Mississippian occupation horizon in trenches at the weigh station. A large aboriginal pit and inset post mold dug into the top of the sand blow indicated that it was prehistoric in age (R. Weisman, pers. comm., 2001). Radiocarbon dating of wood (sample F101) from the post mold yielded a calibrated date of A.D. 1500-1690, 1730-1810, 1920-1950 (Table 1).

Weisman and Tuttle excavated a new trench (10) in the adjacent field where the geologic and archeological records would be less disturbed. The trench was located along strike of the large feeder dike observed at the weigh station and where sandy soils were suggestive of the sand blow. Prior to excavation we removed the plow zone over a 5 m x 7 m area to look for other cultural features that may have been dug into the sand blow. The upper part of the sand blow had been disturbed by plowing. However, we found three post molds and one decayed tree stump (Figure 11). Weisman and Lafferty sectioned the post molds. Material collected from F6 was processed by the flotation method (Figure 12). A few scattered fragments of fired clay and lignite were recovered from the material. We excavated Trench 10 through the sand blow and related feeder dikes until we reached the buried Native American occupation horizon below (Figure 13). We logged one wall of the trench and collected sediment samples for grain-size analysis and organic samples for radiocarbon dating. In addition, Lafferty excavated three archeological test units, collecting flotation samples and screening all other material and collecting artifacts by level.

As exposed in Trench 10, the sand blow is about 7 m wide and up to 170 cm thick. As measured from the weigh station to Trench 10, the sand blow is more than 60 m in length. The width of the sand blow appears to be limited by the downward displacement of the pre-event surface. The main dike is approximately 1 m wide, while a subparallel dike is approximately 75 cm wide (Figure 14). The western margin of the dike strikes N30°W and dips 84°SW. The sand blow is composed of 2 major sedimentary units. The lowermost unit (Unit 2) is the most complex and includes three members. The lower two members (Units 2b and 2c) are of medium to very fine sand and include clasts of silt. The upper member (Unit 2a) is slightly finer-grained and has a deformed upper boundary including load casts. The uppermost unit (Unit 1) includes two members associated with the vent and characterized by flow structure. Subunit 1b is a medium to silty, fine sand, contains clasts of silt and the Native American cultural horizon (Unit IIA). Subunit 1a is fine to very fine sand. The two sedimentary units described above are interpreted as sand blow deposits resulting from closely timed earthquakes. The burial of the Native American occupation horizon by the sand blow and the presence of aboriginal post molds in the top of the sand blow indicate that the compound sand blow is prehistoric in age.

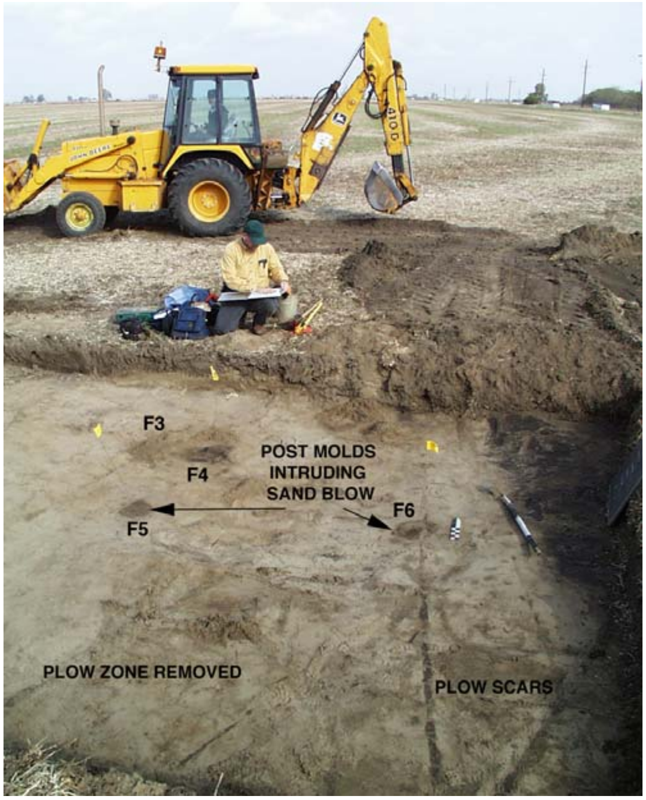

Figure 11. Photograph of area stripped of plow zone to look for cultural features above sand blow. We found three aboriginal post molds (F3, F5, and F6) and one tree stump intruding the top of the sand blow (F4). Radiocarbon dating of charcoal from post mold F5 has helped to constrain minimum age of sand blow. Photograph by M. Tuttle.

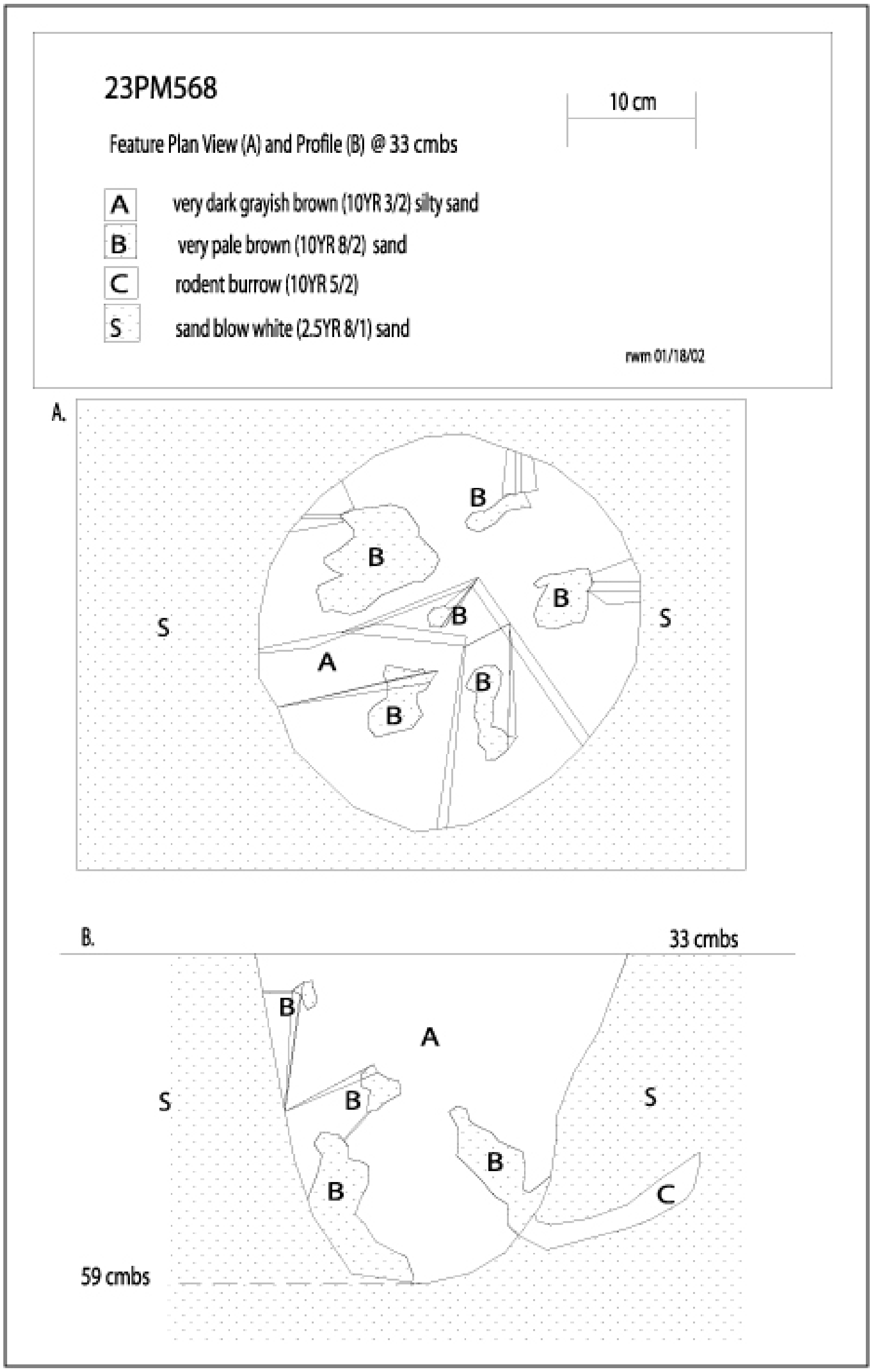

Figure 12. Plan (upper) and cross-sectional (lower) views of aboriginal post mold and hole (F6). The feature had tapered sides and a rounded bottom that intruded 26 cm into the sand. A rodent burrow disturbed the north side of the pit. (Provided by MCRA).

Figure 13. Photograph of trench excavated through sand blow and large feeder dike to buried Native American occupation horizon below. Artifact density is high in the upper 30 cm of the cultural horizon. Photograph by M. Tuttle.

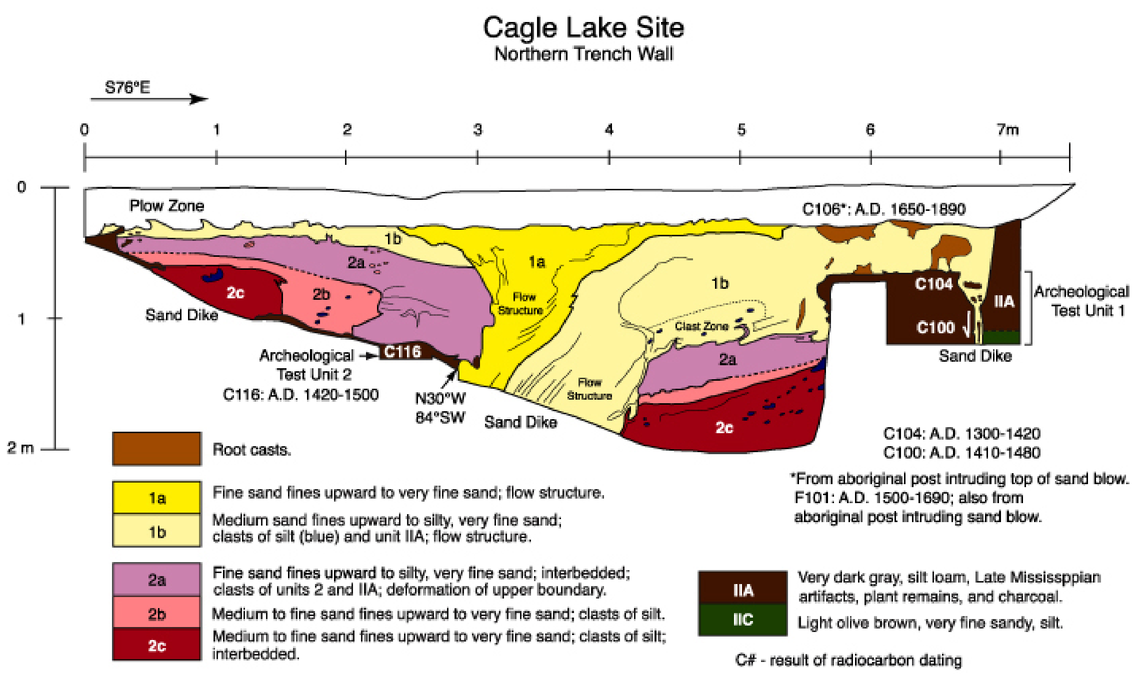

Figure 14. Log of Trench 10 at Cagle Lake archeological site north of Steele, Missouri. Sand blow is composed of major units. Vertical displacement of the ground surface was greatest between the 4 and 6 m marks of the log and is reflected in thickness of the sand blow units 1b and 4. On basis of radiocarbon dating and archeological analysis, sand blow probably formed during A.D. 1450, +/- 100 years, event. Log by M. Tuttle.

Lafferty excavated Test Unit 1 below the eastern end of the trench where the surface of the buried occupation horizon was nearly horizontal (Figure 14). The test unit was 1 m x 0.5 m in area and 0.55 m deep. The top level was 5-cm thick and subsequent levels were 10-cm thick. A small sand dike, roughly parallel to the main dike, was exposed in the test unit. We recovered many artifacts of several ceramic types characteristics of the Late Mississippian period including Parkin Punctate, Campbell Applique, Barton Incised, and beveled Memphis rim mode (Figure 15). In addition, animal bone was well preserved.

Test Unit 2, only 40 cm x 20 cm in area and 5 cm deep, was excavated adjacent to the main dike (Figure 14). One flotation sample was collected and that material was processed by the flotation method. Gina Powell identified plant remains in the processed sample. A hickory nutshell (FSN116) was selected for radiocarbon dating.

Test Unit 3 was excavated in the cultural horizon immediately below the sand blow in the bottom of weigh station Trench 1. Lafferty collected flotation samples in 3-cm or 4-cm levels from the test unit. The remainder of the unit was excavated in 10-cm levels down to 40 cm below the sand blow. All levels contained high densities of artifacts. Ceramic types were late Nodena phase with a great profusion of decorated sherds, including Parkin Punctate, Campbell Applique, fine Bell paste wares, most with beveled Memphis mode rims. Three very thin strap handles were recovered. These strap handles are also Late Mississippian types. Also, we found two Madison arrow points (Figure 16) in levels 1 and 3 and a basalt hammer in level 3. Bone preservation was excellent throughout the cultural horizon, and one half of a bird-bone bead was recovered from level 1. The artifact assemblage from the three test units is quite similar to that recovered at the Dodd site (Tuttle et al., 1999) and the Campbell site and indicate that the cultural horizon directly below the sand blow was occupied during the Late Mississippian period, or about A.D. 1400-1500.

Beta Analytic, Inc. carried out radiocarbon dating of three charcoal samples (C100, C104, and C106) one wood sample (F101), and a hickory nutshell (FSN116). Weisman had collected F101 from a post mold intruding the sand blow where it was exposed at the nearby weigh station. Sample C106 came from post mold F5, FSN 116 from the flotation sample collected from 0-5 cm below the sand blow, C104 from 5-15 cm below the sand blow, and C100 from 47 cm below the sand blow (Figure 14). F101 and C106 yielded multiple ranges of calibrated dates. However, because the samples came from aboriginal post molds, the dates after about A.D. 1700 can be excluded. The earliest range for F101, A.D. 1500-1690, provides an upper bound on the age of the sand blow. FSN 116 yielded a calibrated date of A.D. 1420-1500 and provides a lower bound on the age of the sand blow. C104 and C100 yielded dates of A.D. 1300-1420 and A.D. 1410-1480, respectively. They are similar to the date for FSN 116 and in general support the age estimate of the cultural horizon based on the artifact assemblage.

On the basis of radiocarbon dating, the age of the sand blow can be constrained between A.D. 1420 and 1690. The stratigraphic position of the sand blow immediately above Native American occupation horizon indicates that the Cagle Lake site was occupied at the time the sand blow formed. The artifact assemblage suggests that the sand blow formed circa A.D. 1400-1500. The aboriginal post molds dug into the top of the sand blow suggest that Native Americans continued to occupy the site after the event. Therefore, the large compound sand blow and related dike probably formed during the A.D. 1450, ± 100 years, New Madrid event.

Figure 15. Examples of variety of potsherds recovered from Test Unit 1. Photograph by MCRA.

Figure 16. Madison points recovered from levels 1 and 3 of the test unit excavated below the sand blow. Photograph by MCRA.

Geophysical surveys (electromagnetic, electrical resistivity, and magnetometer) were conducted after trenching was complete to determine the extent of the liquefaction features and to locate the approximate boundaries of a nearby Native American mound. A contour plot of the resistivity survey shows high resistivity values in the southeastern portion of the grid, and low resistivity values in the western portion of the grid (Figure 17). The high resistivity values trend northwest in a roughly linear shape, indicating that the large sand fissure and related sand blow extend for another 30 m, making it about 90 m in length. The high gradient in values reflects a contrast in properties between the unconsolidated sands of liquefaction features and the fine-grained sediments of the host deposits. The low resistivity values in the western portion of the survey grid are thought to indicate the location of the mound, which has been nearly leveled by agricultural grading. The roughly circular pattern of the contours reflects the shape and possible dimensions of the mound.

Dillahunty (3MS619): Dillahunty archeological site is located about 200 m northeast of the Archway site (Figure 1), and like Archway, was probably occupied during the Woodland cultural period. The Dillahunty site was drawn to our attention by M. Haynes, who had found Woodland type sherds on patches of sandy ground that adversely affects crop growth. During reconnaissance, we located a sandy patch with sand- and grog-tempered potsherds on the surface. Following our work at the adjacent Archway site, we conducted geophysical surface surveys at Dillahunty. Measurements were collected every 5-m along a grid covering ~3000m^2. Results of the surface surveys, however, were ambiguous and suggested at least two possible trends for buried liquefaction features. We repeated the resistivity survey using a 2.5-m a-spacing with much better results (Figure 18). The results of the surveys suggest that sand fissures trend northwest and are smaller than those at the Archway site.

On the basis of reconnaissance and resistivity surveys, we targeted two areas for trenching. We removed the plow zone in these two areas. In one area, only several small sand dikes were exposed. In the other area, we uncovered a sand blow that is about 40 m wide. We found no cultural features above the sand blow. The sand appears to have vented primarily through a large sand pipe, about 1.2 meters in diameter. The sand pipe and several small dikes, about 5 cm wide, crosscut a black, silty loam soil horizon containing pottery sherds and other artifacts (Figure 19). The sand blow, up to 35 cm thick, was thinner than the sand blow at Archway, and this difference in thickness was reflected in the resistivity measurements. We logged one wall of that trench and collected organic samples for radiocarbon dating and sediment samples for grain-size analysis. The sand blow is composed of three, major sedimentary units (Figure 20). The lowermost unit (Unit 3) is thin and fine-grained. The next-to-lowermost unit (Unit 2) is composed of three subunits, all of which are fine sand in the vent area and fine upward and away from the vent. Subunit 2b contains a lense of silt clasts near the vent. The uppermost unit (Unit 1) includes two members associated with the vent and occurs above the large sand pipe. Subunit 1b is a dark grayish brown silty, fine sand to silty, very fine sand and appears to be a late-phase, vented sand that has been subjected slightly to soil forming processes. Subunit 1a is a silty, clay loam and probably represents a soil developed in fine-grained material that filled a shallow sand-blow crater. Unfortunately, the upper part of the sand blow had been disturbed by plowing. All three sedimentary units described above are interpreted as sand blow deposits resulting from closely timed earthquakes. The amount of soil development within the sand-blow crater and

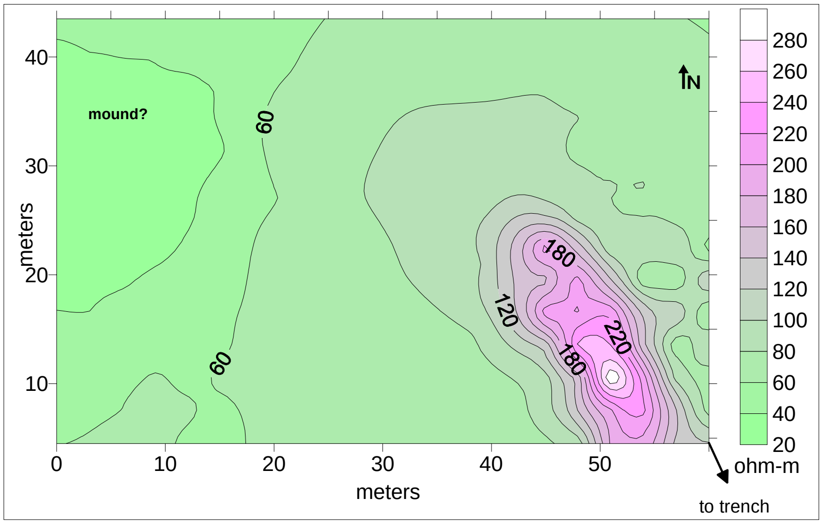

Figure 17. Resistivity survey of the portion of the Cagle Lake site northwest of Trench 10. Northwest-trending anomaly is interpreted as the extension of a large sand blow observed in trench. Circular low-resistivity area in western portion of the survey grid is attributed to a Native American mound that has been leveled by agricultural grading.

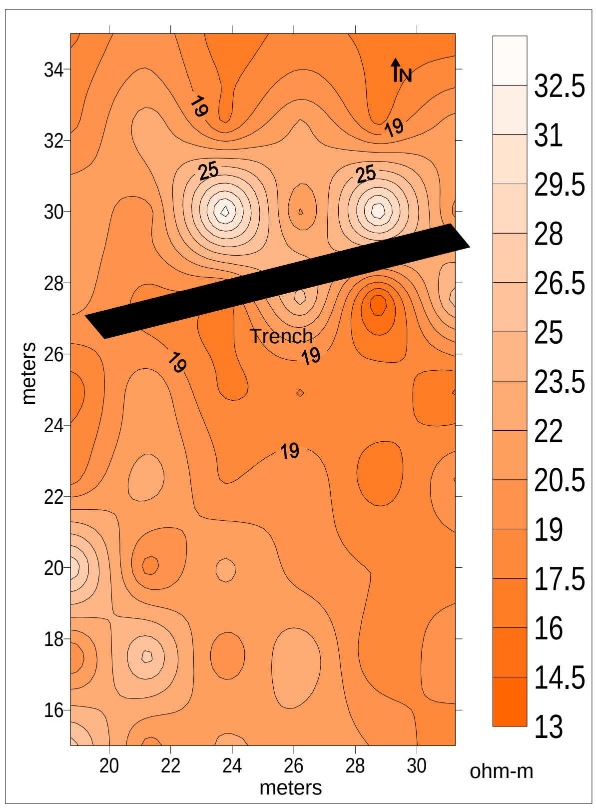

Figure 18. Resistivity survey at Dillahunty showing northwest-trending liquefaction features. Measurements were collected at 2.5-m spacing.

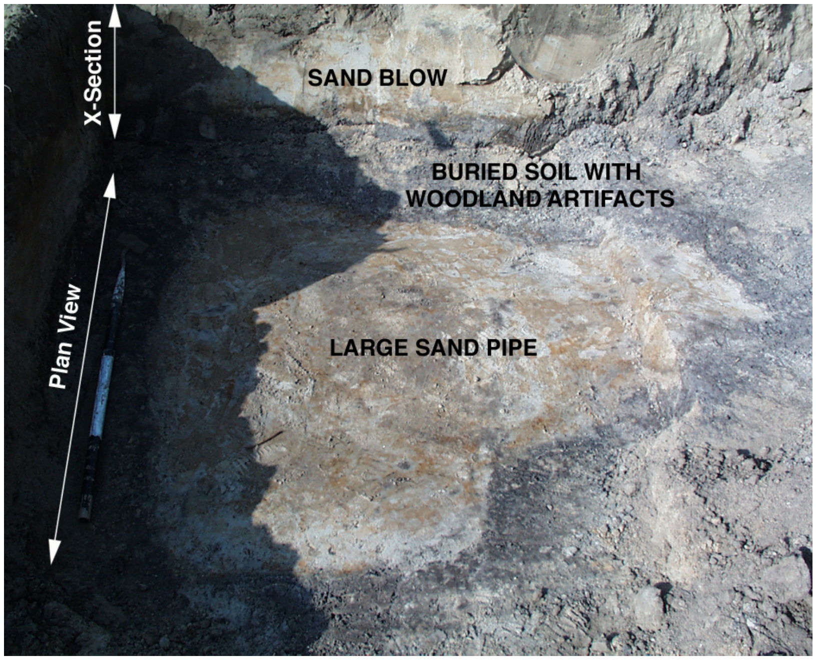

Figure 19. Photograph of excavation below sand-blow crater at Dillahunty archeological site north of Blytheville, Arkansas, showing large sand pipe in cultural horizon through which sand vented. Hoe at left is 1 m in length. Photograph by M. Tuttle.

burial of a Native American occupation horizon suggest that the compound sand blow is prehistoric in age.

We collected artifacts from the surface of the site, the stripped plow zone, and a test unit excavated immediately below the sand blow. One point preform was recovered from the site. The size and shape of this artifact suggests it is a Steuben preform (Figure 21). One sherd collected from the surface has rectangular punctations on the interior and exterior of the thickened lip (Figure 22). The sand temper is very fine, almost invisible at 10X magnification. The sherd has a reduced core and oxidized surfaces. The sherd's compact paste and notched rim are similar to Middle Woodland ceramics elsewhere in the Midwest, but have not been previously described in the study area.

The archeological test unit was excavated in the buried Native American cultural horizon about 2.5 meters from the sand pipe (Figure 20). Forty-one artifacts were recovered in the upper 30 centimeters of the test unit. This is a very low density of artifacts. Almost all the pottery came from level 2 and is coarsely cordmarked and relatively thick. Conspicuously absent is the harder, finely cordmarked pottery characteristic of the Late Woodland period that was present at Archway. It appears that the Dillahunty site was occupied during the Middle Woodland period, coincident with the earlier phase of occupation at Archway. The concentration of potsherds from 10-20 cm below the sand blow suggests that about 200 years passed between occupation and deposition of the sand blow.

Beta Analytic, Inc. performed radiocarbon dating on two charcoal samples (C4 and C5) and a fragment of a maize kernel (FSN4) from the Dillahunty site. We collected both C4 and C5 from the soil developed in a shallow crater in the top of the sand blow and preserved below the plow zone. C4 came from the top of the soil. C5 came from the base of the soil about 10 cm below the plow zone (Figure 19). Sample FSN4 was found in the 10-cm-thick, level 1 flotation sample collected immediately below the sand blow. C4 appears to be modern, but C5 yielded a calibrated date of A.D. 1400-1490 (Table 1). This result provides close minimum age constraint for the sand blow. FSN4 gave a calibrated date of A.D. 910-920 and 960-1210 and suggests that the sand blow formed after A.D. 910-1210. Radiocarbon dating of charcoal from the base of the soil developed in the sand-blow crater indicates that the sand blow formed not long before A.D. 1490. Dating of a maize kernel within 10 cm of the base of the sand blow suggests that the sand blow formed within a couple hundred years after A.D. 910-1210. Therefore, the large compound sand blow probably formed during the A.D. 1450, ± 100 years, New Madrid event.

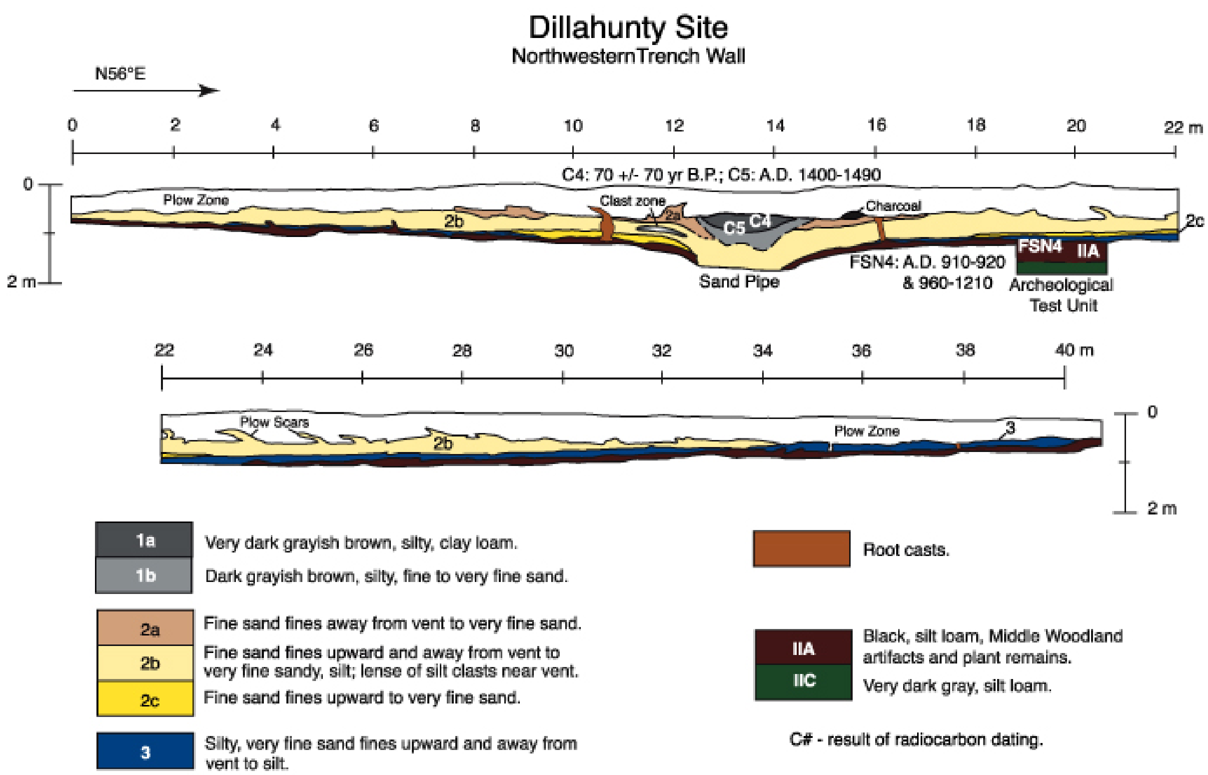

Figure 20. Log of trench wall at Dillahunty site north of Blytheville, Arkansas. Sand blow is composed of 3 units all of which fine away from the vent and most of which fine upward. Sand vented through large pipe over which sand-blow crater formed. These liquefaction features formed between A.D. 910 and A.D. 1490, and probably during the A.D. 1450 event. Log by M. Tuttle and S. Browning.

Figure 21. Photograph of a Steuben preform characteristic of the Late Woodland period found at the site. Photograph by MCRA.

Figure 22. Photograph of sherd with both interior and exterior rim notching. Interior of sherd displayed. Photograph by MCRA.

Obion River 216: A large sand dike and related sand blow was discovered by Tuttle during reconnaissance along the bank of the Obion River (see USGS report for grant 99HQGR0022, 2000). The dike, approximately 1.6-meter wide, feeds a partially reworked sand blow. The dike trends northeast, and sedimentary layers on the east side of the dike appear to be down-dropped. The trend of the dike is similar to the trend of mapped faults in the area, suggesting that this deformation structure may be an expression of near-surface faulting. The exposure was logged and *in situ* tree stumps yielded dates that suggest the liquefaction event occurred soon after A.D. 1300, probably during the A.D. 1450, ± 100 years, event. To investigate the possibility the offset of strata across the dike is related to faulting at depth, we conducted a seismic reflection survey along a profile that should cross the projected position of the dike on the floodplain. Data from the reflection line is currently being processed.

Towosahgy (23NM12): This Native American archeological site is located about 30 km northeast of the Reelfoot scarp in Tennessee (Figure 1), and is preserved and managed as a State Park by Missouri Department of Natural Resources (MDNR). Several mounds are preserved at the site and an interpretative exhibit describes archeological investigations and the history of Native American occupation of the site.

During a prior archeological excavation of Mound A, sandy units described in several test units were interpreted as two sand blows (Price et al., 1990; Saucier, 1991). The lower sand blow was found overlying a clay unit interpreted as a natural levee deposit on which habitation during the Woodland period was established. Cultural material was incorporated into the upper 30 cm of the sand blow, aboriginal pits dug into the top of the sand blow, and cultural horizon developed above the sand blow. A second sand blow was apparently deposited on this cultural horizon. The lower sand blow was estimated to have formed within 100 years prior to A.D. 539 based on radiocarbon dating of charcoal collected from the sand blow itself. The upper sand blow was estimated to have formed between A.D. 539 and A.D. 991. This age estimate is constrained by the sample collected from the lower sand blow and from another sample collected above the upper sand blow.

Because the Towosahgy site presents an opportunity to further constrain the age of an earthquake that induced liquefaction prior to A.D. 800, we wanted to reopen several test units (1, 3, 4, and 10) to examine the liquefaction features and to collect additional material for radiocarbon dating and artifact analysis. Larry Grantham and Denise Dowling of MDNR facilitated our investigations at Towosahgy in November 2002. James Price and Larry Grantham, who were involved in the original excavation in 1989, relocated the test units, and they, along with Robert Lafferty, reopened the test units. We deepened Test Unit 10, collecting flotation samples and screening all other material and collecting artifacts by level, until we had excavated through the sand blow (Figure 23). In addition, we logged almost all the walls and floors of the test units and collected numerous organic samples for radiocarbon dating. Surprisingly, we found only one sand blow, rather than two, exposed in the test units. Field observations suggest that the sand blow is overlain by a Late Woodland to Early Mississippian occupation horizon. In addition, we found a very small (2 mm wide) sand dike crosscutting the sand blow and extending 0.5 m upward into the overlying cultural horizon. Artifact analysis, radiocarbon dating, and drafting of logs are currently under way.

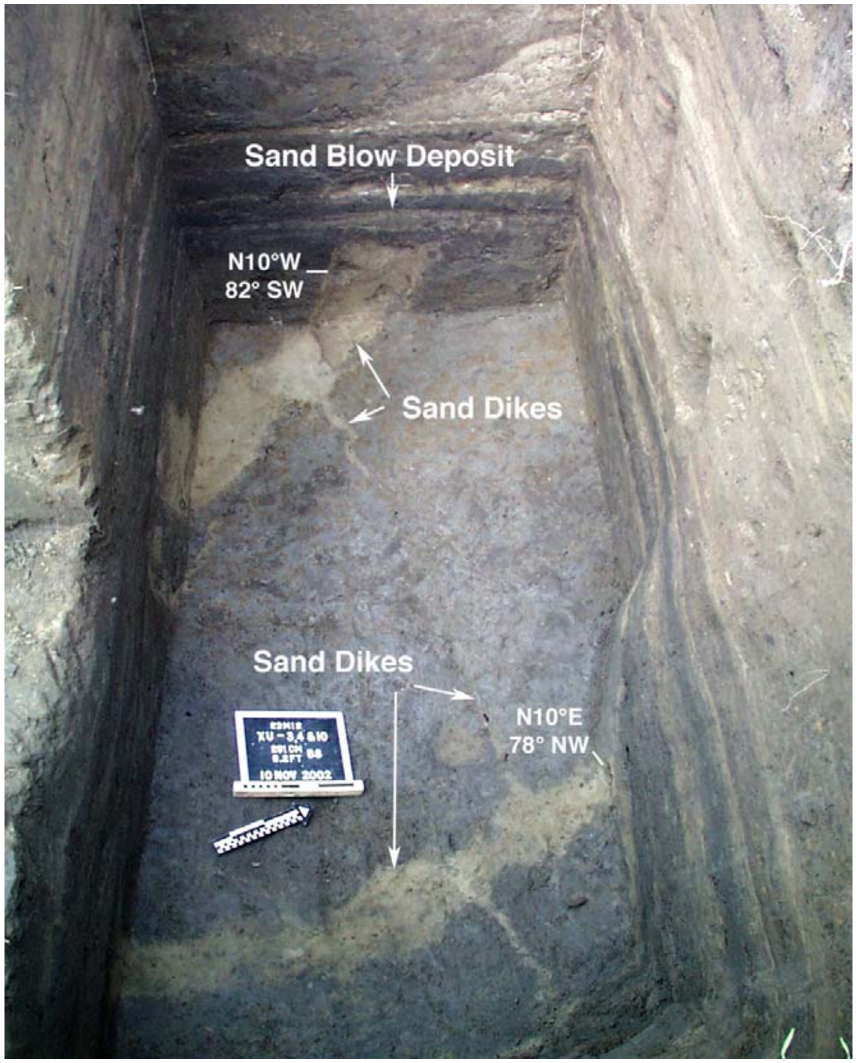

Figure 23. Trench excavation at Towasahgy site. Trench logs are currently under preparation. Preliminary results suggest that the upper sand blow is related to the A.D. 900 NMSZ event. Photograph by M. Tuttle.

We conducted geophysical surveys at the site to map the extent of the sand blow. The geophysical grid was tied to the site grid previously established by Price and Grantham. We collected resistivity data using a Wenner array with 3-m spacing. Despite the fact that it occurs about 1.5-2 m below the surface, the sand blow could be traced across the site (Figure 24). The main body of the sand blow appears to be located southeast of the test units. This is supported by the observation in the test units that the sand blow thickening in this direction. On the basis of the resistivity survey, the sand blow and related feeder dike appear to be oriented N35°E and to be at least 23 m wide and 50 m long. The same or possibly different sand blow appear(s) to extend at least another 40 m towards the north. In addition, a dipole-dipole survey was conducted roughly perpendicular to the main sand fissure inferred from the resistivity data in order to construct a vertical section (Figure 25). The results of this survey suggest a second sand blow/fissure may exist to the east of the one described above.

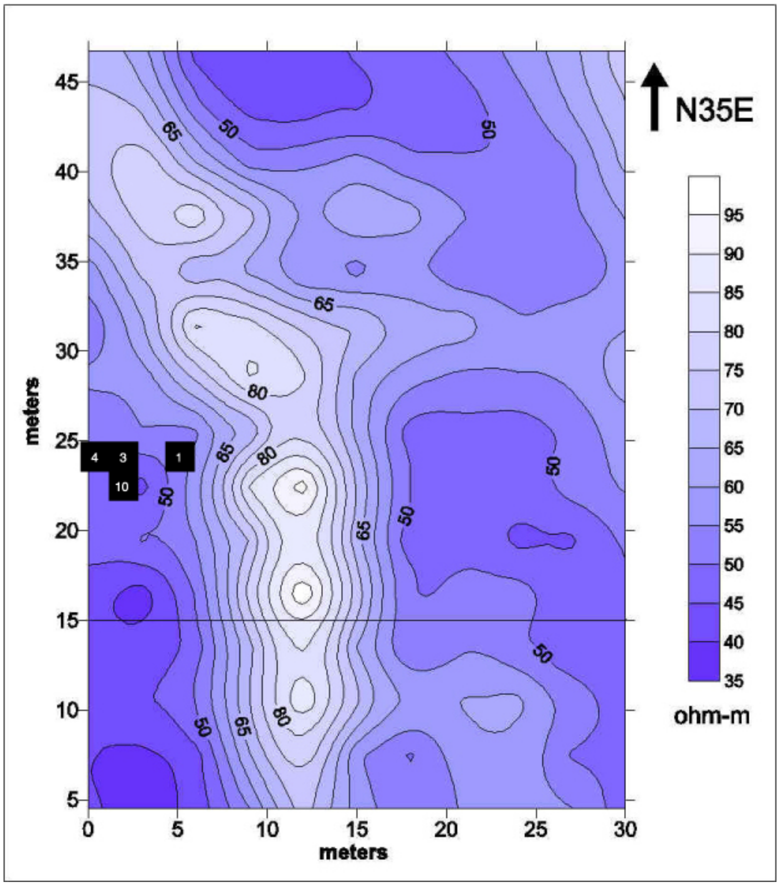

Figure 24. Resistivity survey of Towosahgy site. Linear trend of high resistivity values probably corresponds to main body of sand blow and related feeder dike. Therefore, only northwest margin of sand blow was seen in test units, indicated by black squares. Heavy line shows location of dipole-dipole array discussed in text.

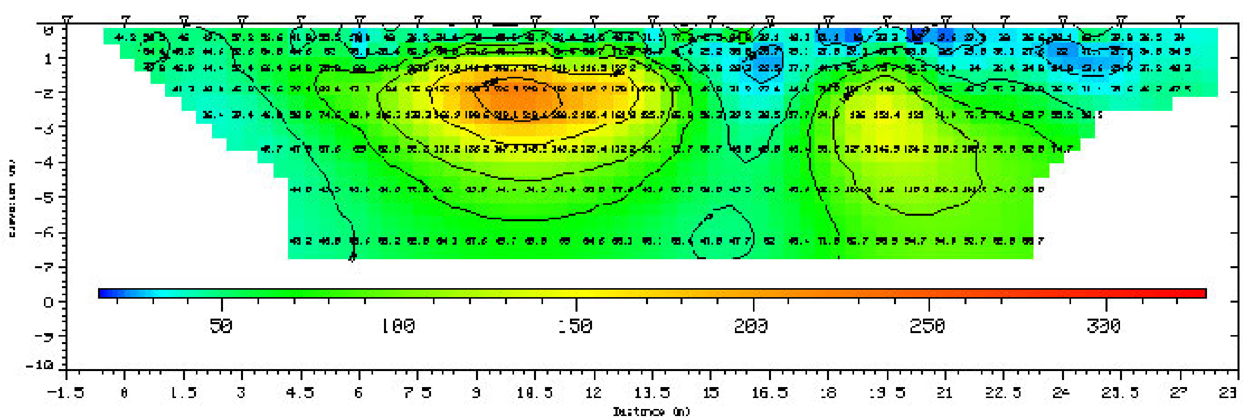

Figure 25. Results of dipole-dipole survey at Towosaghy (see Fig. 24 for position of cross-section on site grid.). Main sand fissure occurs to southeast of the excavated test units. Smaller anomaly, possibly another related sand fissure, appears to east of fissure observed in excavations. Inverted triangles indicate measurement positions.

Hydrogeologic Modeling: To explore the influence of geologic heterogeneity on the development and distribution of overpressures on a site scale, we constructed a small-scale flow model based on geotechnical and geological field observations of liquefaction sites in the NMSZ (Tuttle and Barstow, 1996). Liquefaction features, such as sand blows and sand fissures, have been frequently observed to occur along the margins of clayey, channel-fill deposits above a fine- to medium-grained sand layer. The hydrogeology of this type of liquefaction site can be described as a three-layer system (Fig. 26a): (1) a lower sandy, permeable layer (k = 100 darcy), (2) a low-permeability overbank clay (k= 10^{-6} darcy), and (3) a low-permeability channel-fill deposit (k = 10^{-8} darcy). Permeability of typical alluvial aquifers in the study area ranges from 85 to 175 darcy (Czarnecki et al., 2003).

Modeling results for this simple system show that groundwater recharges along the topographic high and migrates from left to right in the model, in response to the hydraulic gradient created by topographic relief (Fig. 26b). Below the confining channel-fill deposit, the groundwater flow is redirected upwards as it encounters a no-flow boundary on the right hand side of the model. The model predicts abnormal pressure (up to 1.7 atm developed in the discharge area beneath the channel-fill clay (Fig. 26b) as a result of gravity flow. When the overlying confining clays are breached by a permeable sand dike, the model predicts the development of relatively smaller excess pore pressures in the same area (Fig. 26c). Moreover, overpressures do not develop if the right side boundary below the channel-fill is open to groundwater flow.

The various simulations using the small-scale model indicate that the magnitude of overpressure is highly influenced by local sealing efficiency and flow boundary conditions. This observation is in agreement with centrifuge models of liquefaction that show how excess pore pressures develop rapidly in layered soils, where a permeable sand layer is overlain by a less permeable silt layer. The laboratory experiments suggest that during liquefaction, a water interlayer forms between the base of the overlying silt layer and the sand unit, where the upward flow of water through the sand unit is restricted by the relatively impermeable silt layer (Fiegel and Kutter, 1994). In our small-scale model, the areas of maximum overpressure are predicted to occur at the base of the clayey overbank deposit and beneath the clayey channel-fill deposit, where vertical or lateral flow is restricted. Fissures filled with vented sand have been observed along the interface between these depositional units (Tuttle and Barstow, 1996). Geotechnical data indicate that the lowest blow counts (Standard Penetration Tests) occur below the channel-fill deposit, where the small-scale model predicts the highest overpressures to be sustained by gravity flow. Although the geotechnical results may reflect inherent sediment characteristics, the result suggests that this setting may be particularly susceptible to ground failure due to local sealing efficiency.

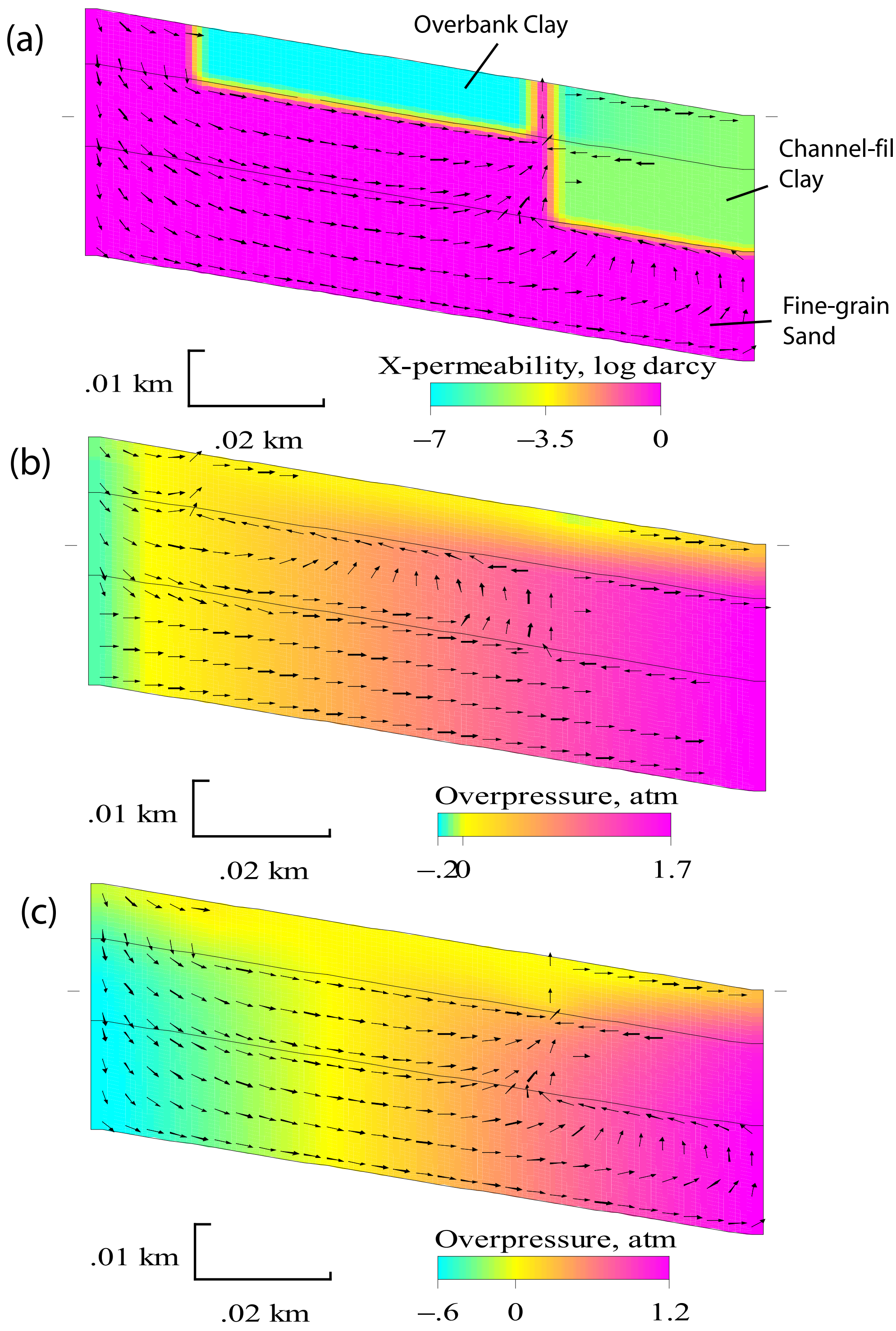

Figure 25. (a) Permeability distribution for geologic model described in Tuttle and Barstow (1996). Calculated fluid flow and abnormal pressure shown for (b) model with sand dike and (c) model without sand dike. Note that in (b) and (c), highest overpressures develop beneath channel-fill deposit and it margin with overbank deposits. Magnitude of overpressures is slightly higher in (c) than (b).

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