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Electromagnetic Conductivity Mapping for Site Prediction in Meandering River Floodplains

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ABSTRACT Spatial mapping using electromagnetic (EM) conductivity can quickly define past sedimentary environments within meandering river floodplain settings and, most important, those most likely to include archaeological materials. Natural levee and uplifted fluvial terrace environments would have been the most likely areas for people to place permanent settlements, as these topographically high areas would have remained dry during most annual floods. The spatial patterning of high and low electrical conductivity regions, when combined with geological core and auger information, can define a number of depositional environments in floodplains including channels, point bars, natural levees and oxbow lakes. Conductivity maps can then be used to predict the locations of prehistoric floodplain environments, and therefore the most likely locations for archaeological remains. Suitable areas can then be further tested for archaeological features using detailed geophysical surveys and other archaeological survey methods. Case studies are presented from California, Texas and Mississippi that integrate these methods for depositional environment mapping as a way of accessing the archaeological potential in meandering river floodplains. Copyright © 2008 John Wiley & Sons, Ltd.

Key words: conductivity; electromagnetic induction; EM; meandering river floodplains; predictive models

Introduction

Buried archaeological sites are notoriously difficult to evaluate in floodplain settings. Cultural materials are often deeply buried and any existing features contained within the fluvial depositional units have either no surface expression or there are few, if any, surface artefacts that might hint at their presence. Random trenching, coring, or shovel testing can sometimes provide information on sediments, soil types and ancient environmental conditions but they rarely encounter the cultural materials of interest contained within. In some cases topographic maps and aerial photographs give clues to ancient environments, but often agricultural activities obscure these patterns through repeated ploughing or land levelling. One approach to mapping past floodplain environments and predicting the location of buried archaeological sites is electromagnetic (EM) conductivity mapping integrated with strategically placed sediment cores or auger holes. Conductivity maps often clearly depict flood-

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plain depositional environments, which can then be used as a predictive model for archaeological site suitability based on knowledge of how people built on or exploited past environments.

Electromagnetic induction applications in archaeology developed in Europe in the 1960s (Scollar, 1962; Howell, 1968; Tite and Mullins, 1970; Parchas and Tabbagh, 1978; Tabbagh, 1986), and began to be used by North American scholars in the 1980s (Bevan, 1983; Frohlich and Lancaster, 1986; Dalan, 1989). The EM method includes a broad range of instruments and configurations, but the majority of current archaeological work utilizes low-frequency Slingram instruments, most notably the EM31 and EM38 manufactured by Geonics Limited (Ontario, Canada). This series of instruments has proven very useful for discovery and mapping of buried archaeological features using both conductivity and magnetic susceptibility readings, which are complementary to other commonly used geophysical methods such as magnetometry and ground-penetrating radar (Clay, 2001, 2006). The EM38 penetrates to a maximum depth of about 1.5 m and is used for detailed mapping of archaeological features, while the EM31 penetrates to about 6 m and is better suited to mapping broad landscape patterns. Conductivity measured with the EM31 and similar instruments have been used to characterize soils and sediments on a broad scale, and are particularly useful for mapping large fortifications and earthworks (Bevan, 1983; Dalan, 1989). It is this ability of the EM31 to quickly map and characterize changes in sediments over large areas at depths varying from 2 to 6 m (depending on the orientation of the instrument and the mode of collection) that lends it to the task of floodplain mapping.

Electromagnetic conductivity is ideally suited for the task of depositional environment mapping because floodplain units have recognizable geometric patterns and are composed of distinctly different sedimentary facies (i.e. different ratios of sand, silt, clay, and organic matter). Meandering river floodplain settings contain a relatively predictable set of sedimentary units (Reineck and Singh, 1973; Collinson, 1978) deposited in environments such as active channels, point bars, natural levees, lakes, marshes, floodplains and abandoned channels (Figure 1). Expected sedimentary constituents found in these environments range from sand (in point bars and active channels) to clay and associated organic matter (in marshes and abandoned channels). These differences are clearly manifested in EM conductivity data, where high conductivity is indicative of those sediments high in clay, organic matter and moisture, whereas low conductivity indicates a greater proportion of sand or gravel and less moisture retention (McNeill, 1980a). In plan view ancient point bars,

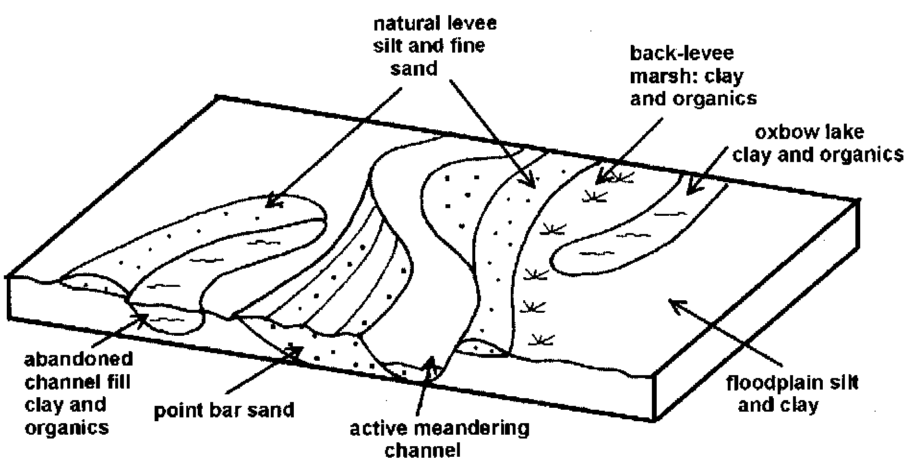

Figure 1. Schematic cross-section showing some of the common depositional environments in meandering river systems, which can be identified in conductivity maps based on their size, shape and sedimentary constituents.

for example, appear as cusp-shaped low-conductivity anomalies due to a high proportion of sand and gravel, whereas adjacent oxbow lake anomalies are recognized by their channel-shape and relatively high conductivity due to their predominant constituents of clay and organic matter. Natural levees, typically composed of silt and fine-grained sand, are curvilinear, moderately conductive, and often bounded by oxbow lakes and abandoned, filled channels of the ancient river (Figure 1).

Within vast and diverse active floodplain settings, natural levees would have been the most suitable land for long-term prehistoric habitation and use because they were topographically elevated and therefore have a lower risk of flooding (Guccione *et al.*, 1988). Even subtle differences in topography would have been significant, with lower areas often inundated for several months each year, while the higher natural levees often remained dry during annual floods. In addition, natural levees often have the most arable land and are located close to streams or oxbow lakes, which are rich in other animal and plant resources (Guccione *et al.*, 1988; Kidder, 1996). Using this basic model of human settlement within meandering river floodplains, EM conductivity maps can be used to identify the most probable locations of archaeological sites.

We have used EM conductivity for depositional environment mapping in three USA river systems: the Sacramento (California), Mississippi (Mississippi) and Red Rivers (Texas). In all cases a Geonics EM31 instrument was used and conductivity maps were interpreted based on pattern recognition, knowledge of floodplain geomorphology and sediment information obtained from strategically placed cores or auger probes. The goal in all these studies was to identify past floodplain environments, which could be tested for cultural remains using other more detailed geophysical surveys or standard archaeological excavations. These studies illustrate the power of these methods for ancient environment mapping and archaeological site prediction. The method was first tested in an orchard in the Sacramento Valley, where a historic map indicated that a subtle depression in the shape of an oxbow lake had been present prior to agricultural levelling. The conductivity data and auger tests confirmed the presence of the oxbow lake and discovered additional floodplain features, and this case served as a model for future work. In Mississippi and Texas, conductivity maps were used to guide subsequent detailed geophysical survey which led to discoveries of prehistoric habitations. We found that the EM conductivity method is ideally suited for this task because it characterizes sediments in approximately the upper 5–6 m (McNeill, 1980b), and large areas on the order of 4–5 ha can be surveyed in 1 day. More importantly, survey is rapid because EM instruments do not require direct contact with the ground (as opposed to electrical resistance which requires insertion of electrodes), and coarse sampling on the order of several metres is adequate to define the large buried sediment bodies (Figure 2).

Materials and methods

The EM31 was used to measure conductivity over areas ranging from 38 to 300 hectares, with measurements taken every 3–10 m along transects spaced 12–50 m apart. Measurements were recorded by digital data loggers and then interpolated and gridded to make conductivity maps. The EM31 has a fixed coil spacing of 3.66 m and uses a frequency of 9.8 kHz for maximum depth penetration of about 6 m (McNeill, 1980b; Bevan, 1983). Both conductivity (quadrature phase component) and magnetic susceptibility (in-phase component) can be measured with the EM31, but not simultaneously. In the studies presented here only conductivity was used, as magnetic susceptibility would have required duplicate surveys with the instrument set to record the in-phase component. Conductivity is also much better suited to characterizing floodplain environment clastic constituents.

Electromagnetic instruments measure conductivity by quantifying how materials respond to an applied electromagnetic field. The applied (primary) field induces a secondary EM field in proportion to the overall ground conductivity, which is then measured by the instrument's receiver (Bevan, 1983; McNeill, 1980b; Reynolds, 1997; Mussett and Khan, 2000). The method can be used for exploring a range of depths by

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Figure 2. A Geonics EM-31 instrument with Polycorder 720 data logger.

varying the coil separation, coil orientation and possibly the induced frequency (Mussett and Khan, 2000). Assertions that varying induced frequency while maintaining a fixed coil separation can produce independent readings from multiple depths (Won *et al.*, 1996) for the most part have been poorly substantiated by field testing (McNeill, 1996; Ernenwein, 2002). The EM31 was chosen for floodplain mapping because the fixed frequency and coil separation allows energy penetration to about 5–6 m in the ground when operated in the vertical dipole mode for greatest depth penetration. In this mode the EM field penetrates to the greatest depth in the ground. With the instrument carried at hip height, the instrument's sensitivity to ground materials steadily increases down to roughly 1.5 m, and then decreases until it is no longer within the instruments depth range, about 5–6 m (McNeill, 1980b; Bevan, 1983). The measured conductivity values are therefore a weighted function of the conductivity of all the layers in the ground, but most influenced by materials from about 3 to 5 m depth.

The factors that most affect the electrical conductivity readings are soil moisture, depth and the thickness of sediment and soil layers, variations in chemistry and bed thickness, and the geometry of the units that have these measurable properties (McNeill, 1980a). Subtle changes in the amount of organic material, clay content and type, and sediment constituent changes such as sand, gravel, or clay will also affect electrical conductivity readings. In general moist, organic-rich, or clay-rich sedimentary units such as oxbow lake deposits are more conductive than dry, sandy bodies such as point bars.

Case studies

Sacramento Valley, California

This survey was part of a larger effort to locate buried oxbow lake deposits in the Sacramento Valley (Ernenwein, 2002). The survey discovered relict oxbow lake deposits and associated floodplain units using a combination of aerial photographs, topographic maps and conductivity surveys (Ernenwein, 2002). Here we present one of these surveys because it clearly demonstrates the ability to characterize floodplain depositional environments using EM conductivity. The 950 × 800 m survey area was located within a large orchard about 150 m west of the modern Sacramento River. A 1945 United States Geological Survey (USGS) topographic map shows a shallow depression in the shape of an oxbow lake that is almost completely within the survey area (Figure 3), however, today the land surface is completely flat owing to agricultural levelling. Conductivity data were collected using transects spaced 12–15 m apart depending on the spacing of the trees in different parts of the orchard, and readings were taken every 7 m along those transects. Transect spacing was dependent on the tree spacing in the orchard, and grid parameters were measured using a tape measure.

Data points collected within the transects for this case study, and all others discussed below, were gridded using *Surfer 8* and contoured to produce the images of variations in conductivity. As expected, the conductivity map revealed the buried oxbow lake deposits and adjacent fluvial features (Figure 4). The filled oxbow lake suggested by the topographic map (Figure 3) is indicated by higher conductivity, whereas an adjacent point bar shows lower conductivity. An additional channel, perhaps a chute cutoff or smaller oxbow lake is also indicated by high conductivity and topographic depressions in the

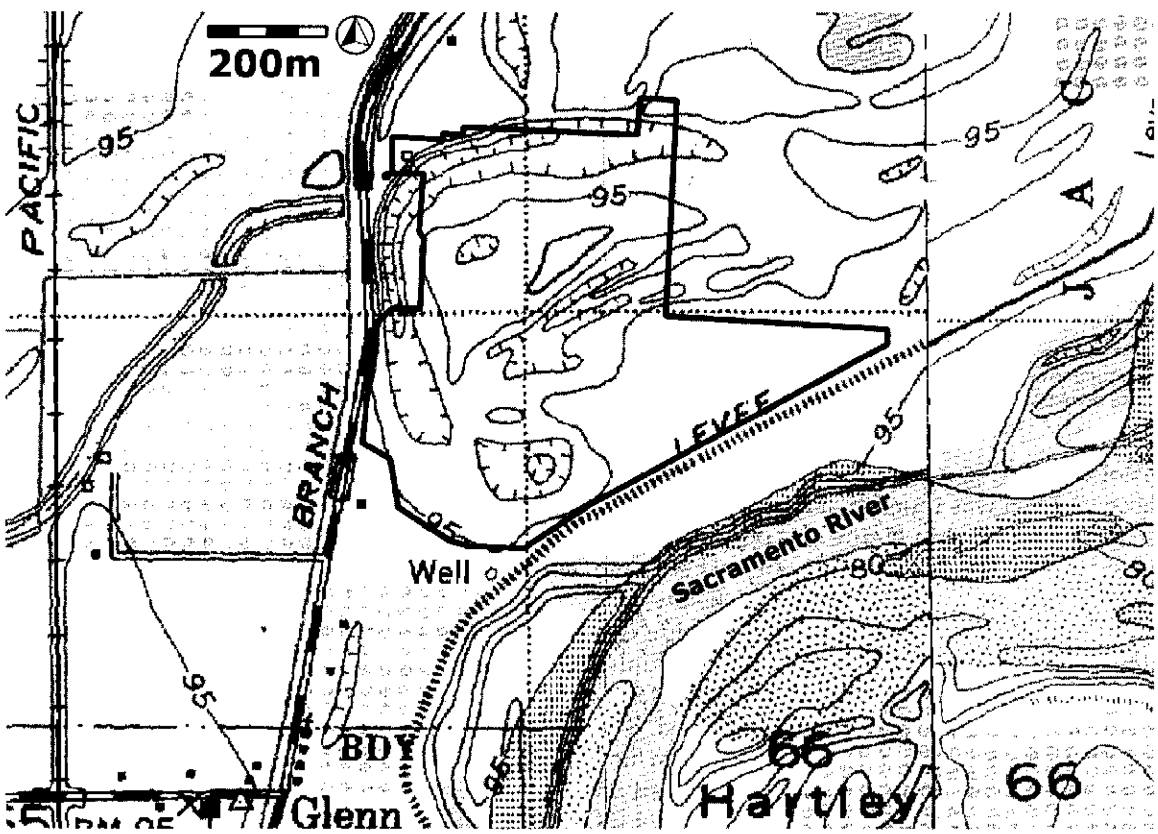

Figure 3. A 1949 United States Geological Survey topographic map showing location of survey and landforms prior to agricultural levelling. Contour interval 5 ft.

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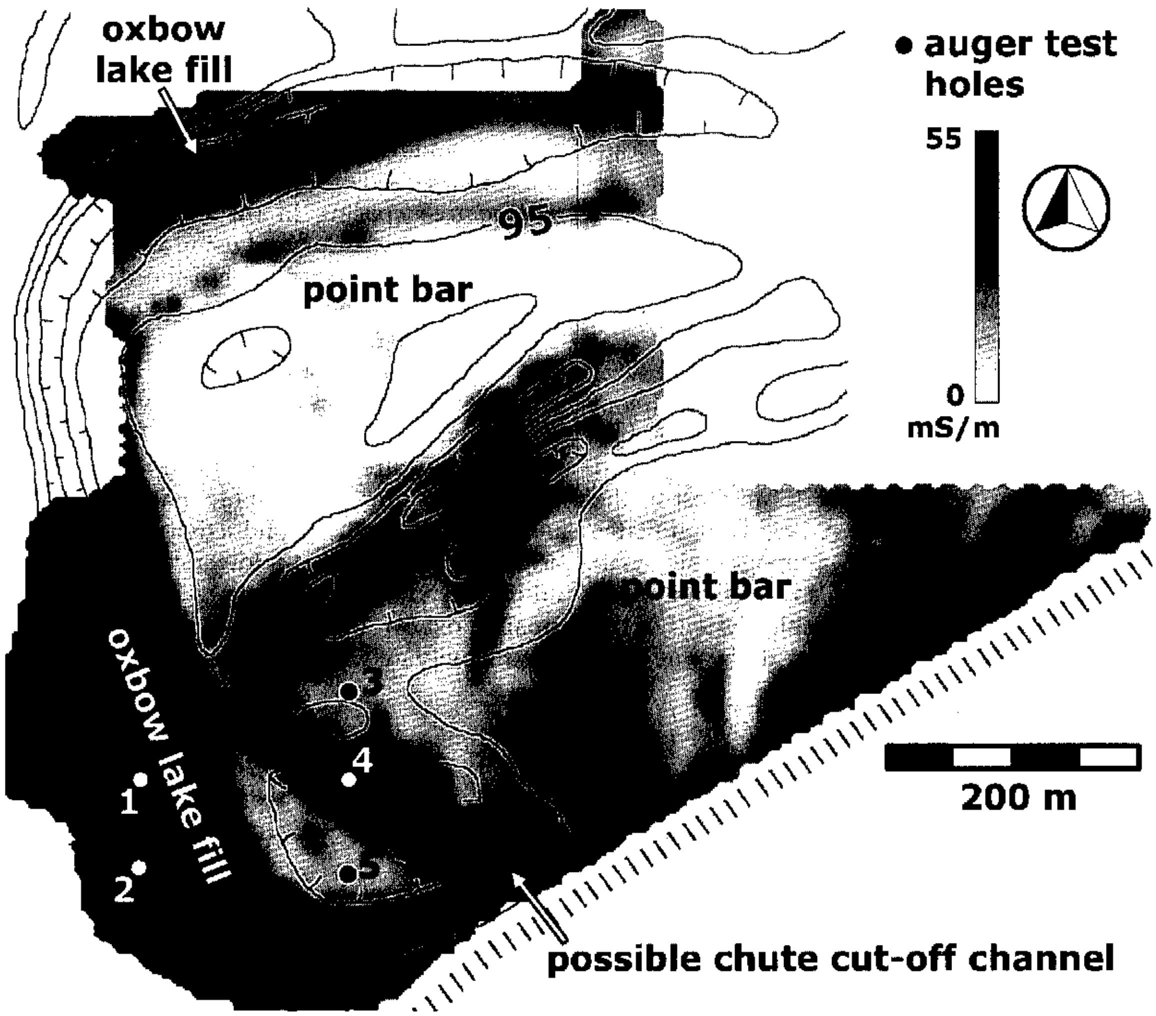

Figure 4. Electrical conductivity map of an area in the Sacramento Valley, California, floodplain system showing a large sandy point bar bounded by fine grained channel-fill and oxbow-lake sediments. Contour lines from the 1949 topographic map (Figure 3) indicate where an oxbow lake was once located, but the surface is flat today due to agricultural levelling.

historic map (Figure 4). Additional evidence for these features was found by augering in the five locations indicated in Figure 4. Auger 1 encountered organic-rich clay and silt from just below the plough zone to about 3.5 m depth. Below that depth, coarse sand was encountered. Within this same high conductivity area, Auger 2 found similar fine-grained sediments to a depth of 4.9 m, below which coarse sand was encountered. The organic-rich clay units in these two holes, which were analysed for grain size and organic carbon content, are interpreted as abandoned channel-fill sediments at the base grading upward to oxbow lake units at the top (Ernenwein, 2002).

Auger holes 3 and 5 recovered silt and sand from the surface to about 2.5 m, underlain by coarse sand to a depth of about 4.5 m. These sediment types are consistent with fining-upward sandy point-bar units. Auger 4 encountered organic-rich clay and silt from the surface to a total depth of 4.5 m, with coarse sand at the base. This narrow unit is probably the remains of a chute cutoff channel that was deposited during the accretion of the point bar. Units of this sort are often visible as subtle topographic swales in actively forming point bars (Reineck and Singh, 1973; Collinson, 1978).

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This survey shows that EM conductivity data are well suited to mapping floodplain deposits, even if the land surface has been levelled for agriculture. These environmental maps can then be used to predict where archaeological sites might be located. The most likely areas for finding the remains of prehistoric habitation in the survey area are the low-conductivity point bars, which would have been the highest topographic points. The abandoned channel and oxbow lake areas might have seen ephemeral human use, but are unlikely to have seen any kind of permanent settlement due to periodic flooding. Those areas, which make up roughly half the survey area, can be effectively discounted as containing significant buried cultural features.

Mississippi River, Mississippi

The purpose of this EM survey was to place the site of Parchman Place Mounds into its environmental context by mapping depositional environments that might have been present during prehistoric occupation. It was also used to explore for additional sites associated with this ceremonial centre consisting of one large platform mound surrounded by several smaller mounds. This site is situated in the Upper Yazoo Basin, an area of the Mississippi floodplain. It is late Mississippian in age with radiocarbon dates ranging from AD 1400 to 1450 (Phillips *et al.*, 1951). It appears that the areas of known occupation were built on a natural levee (Weinstein, 1981). Conductivity data were collected with an EM31 within a 1000 × 750 m area, with transects spaced 50 m apart and readings taken every 10 m (Lowe, 2005). Although never artificially levelled, this land has been cultivated for more than 100 years, effectively muting the prehistoric topography. At the time of the survey the ground was a fallow cotton field, and dry except for some standing water in low areas from recent rains.

The conductivity data, collected in the vertical dipole mode, were gridded and mapped producing the map in Figure 5. The linear bands of low and high conductivity trending northeast-southwest in the northern portion of the survey area were interpreted as point-bar sands bounded by an oxbow lake and swale sediments. These interpretations were tested with four cores drilled by a hydraulic corer (Lowe, 2005). Core A-1 encountered clayey deposits with abundant iron concretions, typical of floodplain overbank deposits, underlain by additional clay units. These clay deposits are interpreted by their sedimentary structures as oxbow lake or swale deposits, which were encountered to a depth of 3 m. Cores A-2, A-3 and A-4 encountered sandy sediment, with some interbedded silt layers and possible buried soil horizons, which appear to be floodplain sediments. These were encountered from 2.5 to 5 m below the ground surface. The narrow low conductivity area between the oxbow lake and floodplain units is probably a natural levee, based on its location between these two depositional environments (Figure 5). The conductivity data suggest that the Mississippi River shifted northwest, probably prior to the construction of the prehistoric settlement, leaving behind the levee where the site is located.

These interpretations help put Parchman Place Mounds into its environmental context, and also suggest other areas that would have been suitable for long-term human habitation. One suitable area is the natural levee delineated by low conductivity areas to the north of the site (Figure 5). It is likely that there was also an oxbow lake in the vicinity, indicated by the high conductivity near core A-1. Archaeological excavations were carried out on the buried natural levee mapped by EM just to the north of the site in 2004 and 2005. These discovered a borrow pit probably used in construction of the nearby mound. A magnetometry survey (Johnson *et al.*, 2002) conducted south of the site (Figure 5), revealed a number of house structures clustered in groups around a central plaza (Figure 5, inset map).

Red River, Texas

In preparation for the construction of a new flood control levee on the Red River in northern Texas, an EM survey was performed in an area where there were nearby known archaeological features consisting of mounds and scattered pottery. The ground was very wet during the survey and the land was being used as a cattle pasture. Nearby sites, excavated in the late 1970s, consist of circular houses and burial mounds in the higher

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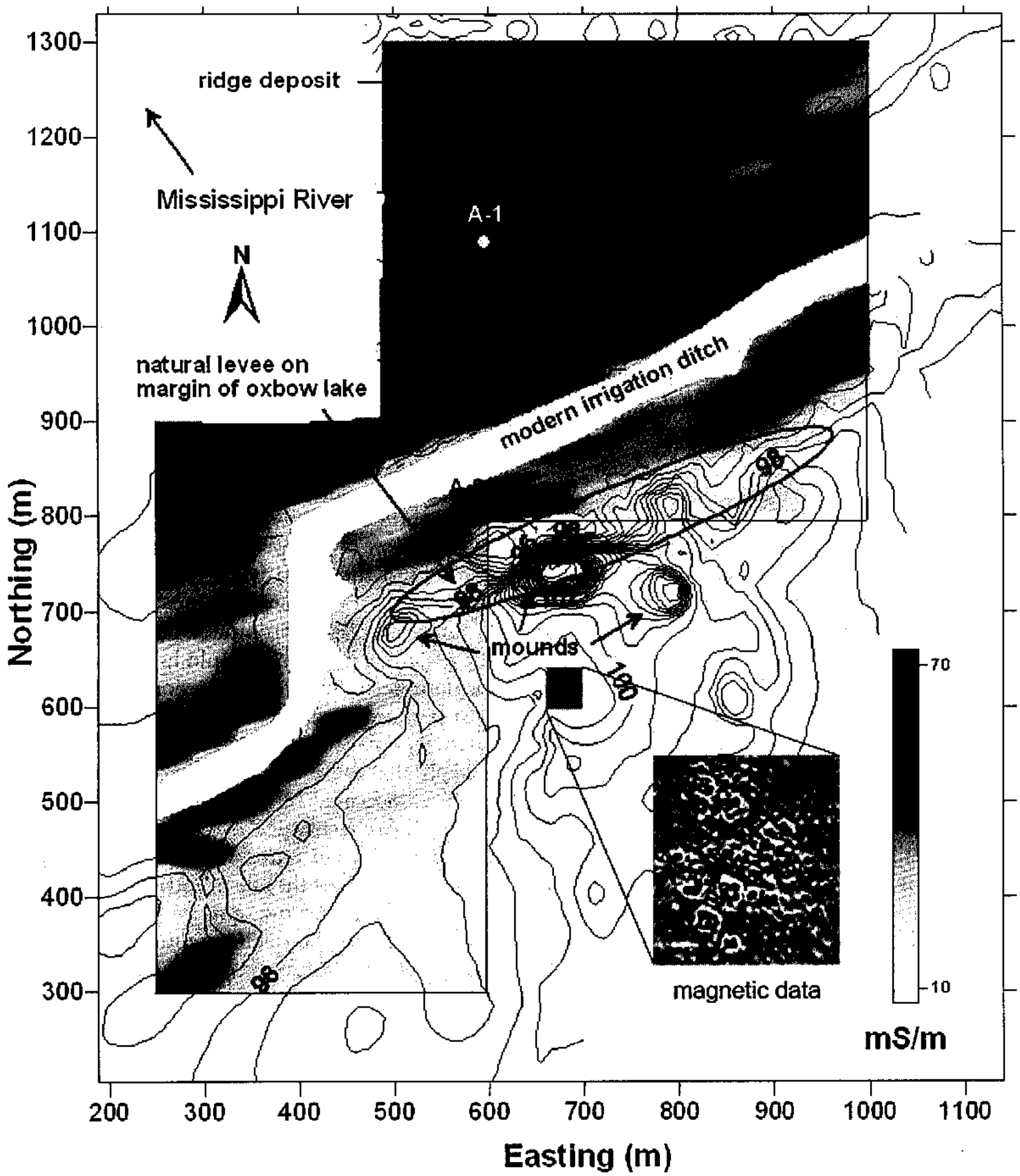

Figure 5. Electrical conductivity map of an area in the Mississippi River floodplain showing natural levee and adjoining oxbow-lake sediment units, with present-day topographic contours superimposed. The inset map is a magnetic gradiometer map (scale: black = 5 nT, white = −5 nT) showing the house features in the Parchman Place Mounds settlement.

topographic areas of the floodplain (Schambach, 1982). A 2500 × 1200 m area was surveyed with the EM31, with transects spaced 50 m apart. Data points were collected every 2.25 seconds and fiducial marks were manually inserted every 10 m with the aid of a pedometer. Start time, end time, and pace count data were also recorded to aid in spatial correction of each line.

A narrow band of high conductivity trends roughly north-south (Figure 6), bounded by a low conductivity region to the east and a moderate conductivity area to the west. The high conductivity area is interpreted as an abandoned channel fill and possible oxbow lake deposits, while the low and moderate conductivity areas are interpreted as natural levee and floodplain sediments respectively. The interpretation of these environments is supported by Margaret Guccione of the University of Arkansas, who drilled a number of cores in and surrounding the high conductivity area (personal communication, 2005). Her interpretation of depositional units within the upper 6 m was based on sedimentary structures, grain size and the types and distribution of organic matter in each unit.

Most notable are cores TX-4 and TX-5, which penetrated alternating units of organic clay and thin sand beds to a depth of 5 m. These units were interpreted by Guccione as abandoned channel-fill sediments in close proximity or on the edge of a natural levee. Cores TX-2 and TX-3 recovered fine-grained sand and clay units with abundant organic matter, probably deposited in an abandoned channel. Sediments in Core TX-1 were composed of alternating sand and silt, interpreted as a natural levee deposit. When these depositional environment interpretations are integrated with the EM conductivity map it is clear that the narrow linear high conductivity area, which trends northward, is an abandoned channel of the river that was filled with oxbow lake or marsh sediments (Figure 6).

To the west and north of this channel, floodplain sediments were deposited, which saw periodic deposition of coarser overbank sediments. As has been demonstrated elsewhere in the Red River floodplain (Pearson, 1982) these topographically low areas were unsuitable for

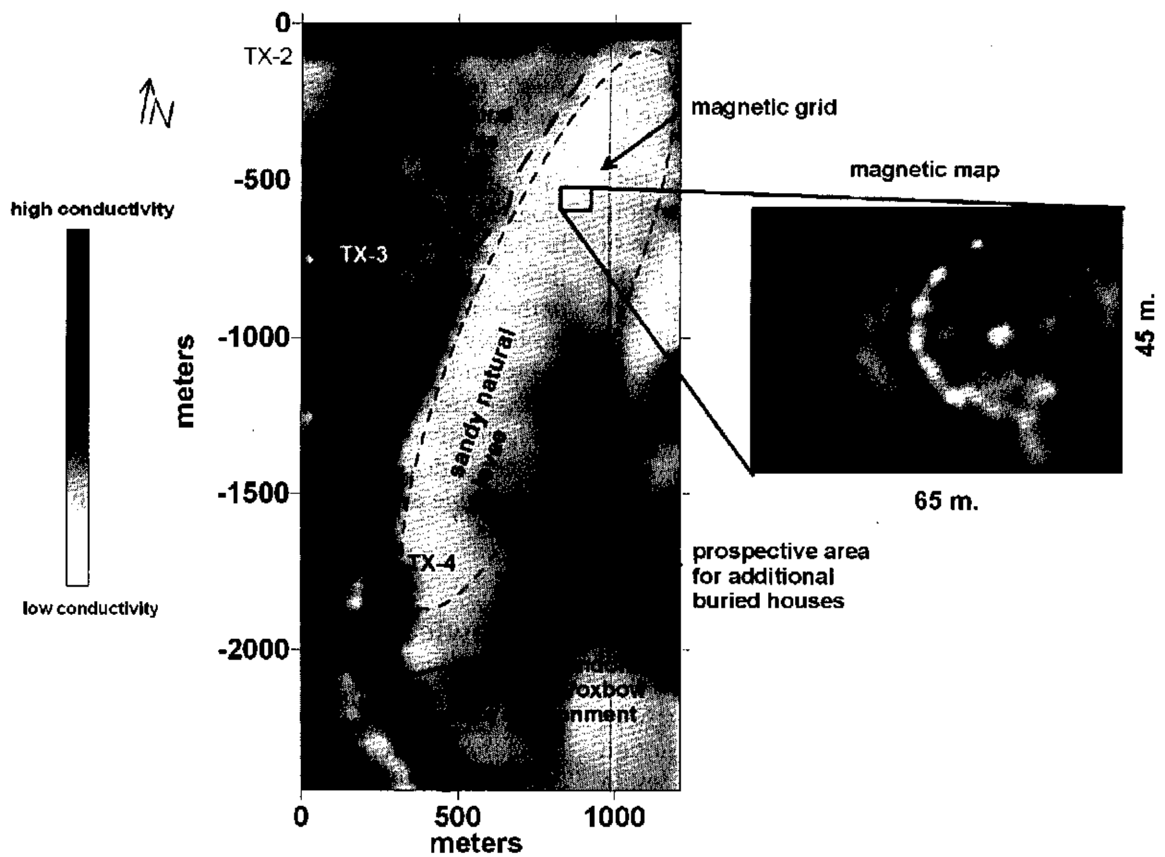

Figure 6. Electrical conductivity and magnetic maps of the Red River floodplain, Texas. The inset is the magnetic gradient map (scale: white = 5 nT, black = −5 nT) showing the round outline of a Caddoan house preserved on the natural levee.

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long-term human habitation because of the wet ground and periodic flooding. In contrast, sediments in the eastern part of the survey area have lower conductivity, and are therefore sandier, indicating an associated natural levee (Figure 6). This area probably became suitable for habitation after the active channel was abandoned and the river moved some distance to the north. The natural levee then remained a topographic high area within what was still an active floodplain.

It is along similar natural levees that a number of important village sites have been discovered in the Red River floodplain (Pearson, 1982). The Caddoan people who inhabited this portion of the Red River were both farmers and hunter-gatherers (Schambach, 1982). This ancient natural levee, which today is essentially flat due to agricultural levelling, would have been high enough to have avoided inundation from annual floods, but still close to resource-rich marshes and fertile floodplain soils. The EM conductivity map also shows another high conductivity area to the east of the levee, which is perhaps another abandoned channel or marsh deposit (Figure 6).

Based on the geographical extent of the hypothesized environments from the EM conductivity map and the core information, random shovel testing was performed along the edge of the hypothesized natural levee. A few ceramic artefacts were found clustered in one region of this low conductivity area, and that region was selected for a detailed magnetometry survey (Figure 6, inset). The survey was conducted with a Geometrics 858 caesium magnetometer with an 856 proton magnetometer used as a base station for diurnal correction. The resulting magnetic map shows a circular Caddoan house probably dating from between about AD 1200 and 1600 with a central hearth and burned exterior walls (Pearson, 1982). Although only a small area of the natural levee was surveyed magnetically, the presence of one Caddoan structure suggests that additional houses may be distributed throughout the interpreted natural levee (Figure 6). Although the remainder of the natural levee was not tested further, it was protected from levee construction by the U.S. Army Corp of Engineers in order to avoid disturbing the possible archaeological features buried along this ancient landscape.

Conclusion

Archaeological sites in floodplain environments are often difficult to locate due to agricultural levelling and ploughing and also because they are quickly covered by flood sediments. Electromagnetic conductivity maps allow specific floodplain depositional environments, such as oxbow lakes, point bars and natural levees to be delineated. Strategically placed cores can be used to calibrate the conductivity readings and help in interpretation of buried depositional environments. When this is done those environments that were most suitable for prehistoric habitation can be identified and used as a predictive model for site suitability. Knowing the locations of past depositional environments can also put known archaeological sites into their ancient environmental context.

This method was applied at three locations in the USA, showing that relatively large areas of meandering river floodplain can be mapped quickly and effectively with EM conductivity. As the targeted geological features are very large, widely spaced transects can be used with a much lower data density than typical archaeogeophysical surveys aimed at detecting smaller archaeological features. This allows as much as 4–5 ha to be surveyed per day. Our results in these three studies demonstrated that large portions of the survey areas (in the order of 60 to 90%) were probably not suitable for long-term prehistoric habitation, and could therefore be excluded from further archaeological testing. At both the Mississippi River and Red River sites subsequent archaeological testing and geophysical surveys in the suitable areas revealed buried archaeological features.

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