Imaging Paleo-Landscapes with Downhole Susceptibility

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Abstract

Noteworthy among the emerging spectrum of imaging tools available for use in archaeological geophysics are software packages for imaging and animating amplitude time slices of ground-penetrating radar (GPR) data. Such software has been adapted for use with magnetic susceptibility data gained using a newly developed downhole instrument, the Bartington MS2H sensor. The potential of this approach for providing information useful in understanding archaeological landscapes is illustrated by work at a prehistoric multi-component site located at the confluence of the Red and Sheyenne Rivers in North Dakota, USA. Measurements of volume magnetic susceptibility recorded at 2 cm depth intervals over a grid of downhole locations were imported into GPR-SLICE software. Resulting images allowed the identification of multiple buried paleosols extending across the site as well as areas of focused human activities on these stable surfaces, providing visualization of landscape change and use over time.

1 Introduction

Distinctive trends characteristic of North American archaeological geophysics include a strong focus on ground-penetrating radar (GPR) applications and an emerging but significant interest in applications of magnetic susceptibility methods. State-of-the-art software for GPR signal processing and data presentation (e.g., Goodman, Nishimura, et al. 2006; Goodman, Steinberg, et al. 2006; Grasmueck et al. 2004, 2005) and new options for the field measurement of fine-scale depth variations in magnetic susceptibility (Dalan 2006a, 2006b) are two significant contributions that have resulted from these interests. The research described in this paper combines these trends in a pioneering approach for visualizing buried landscapes using magnetic susceptibility data and GPR processing software. This approach was tested at a prehistoric multi-component site known as the Dahnke-Reinke site (32CS29) located in the Red River Valley, North Dakota, USA. Investigations at this site provided a pilot data set for manipulation using GPR software and allowed exploration of the potential of this combination of magnetic susceptibility data and imaging software for understanding the morphology, formation, and use of archaeological landforms.

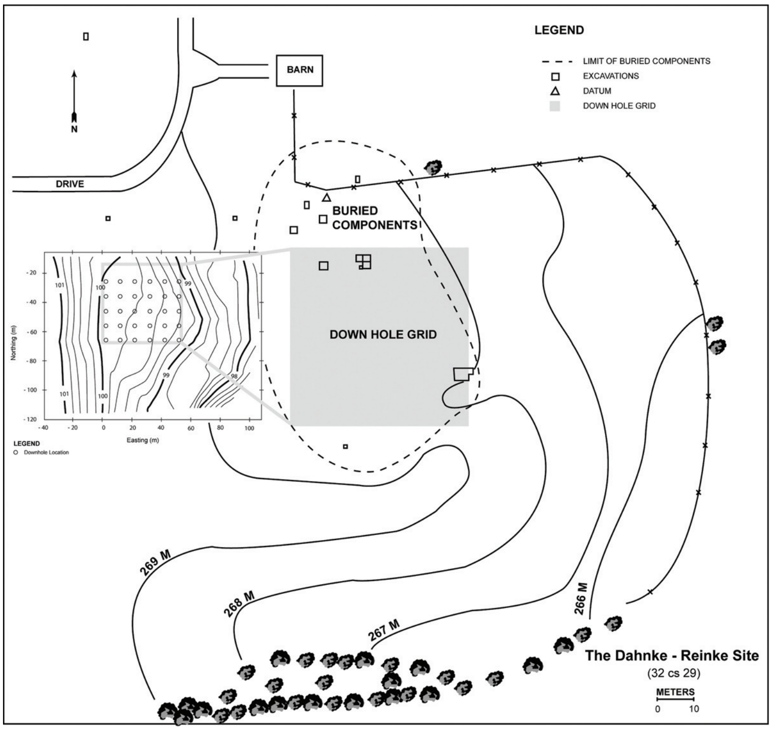

Figure 1. Map of the Dahnke-Reinke site showing the locations of previous test excavations, buried components, and the grid of downhole locations. Detailed insert of the grid of downhole tests does not depict the row of 6 tests at S15 that were not completed due to flooding. Fine-scale topographic changes are shown in relation to an arbitrary elevation of 100 m assigned to a local datum at S15E0.

The Dahnke-Reinke site (32CS29) is located in an active floodplain at the confluence of the Red and Sheyenne Rivers in North Dakota, USA (Figure 1). The site was first identified in the 1980s on the basis of surficial Late Woodland period artifacts observed across a series of three terraces. Subsequent test excavations over a three-year period documented that prehistoric occupation was concentrated on the middle of these three terraces where at least two Woodland period layers and possibly a deeper Archaic period occupation were revealed (Thompson 1990). (Plains Archaic dates from approximately 8000-2500 years BP and the Woodland period spans the period from 2500-450 BP)

Figure 2 illustrates how downhole susceptibility studies can be employed to identify buried soils and cultural layers. The soil profile in this figure comes from one of Thompson's test excavation units in the southeastern portion of the middle terrace (Figure 1). The volume susceptibility measurements were collected using a prototype version of the recently released Bartington Instruments MS2H downhole sensor. This instrument was employed at two locations within a few meters of these excavations. Peaks in susceptibility (enhanced susceptibility values) coincide with the two paleosols (2AB and 3AB). These buried soils were enhanced from 1.4 to over 3 times subsoil values. The 2AB horizon is more prominent at the Core 3 location and the 3AB horizon is more prominent at the Core 5 location, and this correlated with the density of cultural materials.

Downhole data shown in Figure 2 were collected by the senior author as part of a larger study involving a number of archaeological sites and non-archaeological, dated paleosols within the Red River Valley region. The goal of that study was to develop a combined downhole susceptibility and soil magnetic approach to buried site detection. That research demonstrated that it was possible to locate buried soils across various contexts within the region using downhole susceptibility investigations. A contrast in the magnitude of the signal between paleosols associated with human occupation and those palesols without a cultural association was apparent although the level of this contrast varied among test sites and thus would need to be recalibrated in each new archaeological and natural environment. Laboratory soil magnetic techniques allowed the identification of a distinctive signature for archaeological soils that was more broadly applicable. An increase in remanence-carrying grains residing in the coarse fraction (>0.053 mm, fine sand and larger) of the archaeological soils, identified through a distinctive increase in the ratio of coarse to whole soil remanence, allowed cultural soils to be separated from non-cultural soils (Dalan 2006b).

For the present study, we knew that contrasts in susceptibility could be used to identify the paleosols at the Dahnke-Reinke site. We also knew that within this local environment the degree of magnetic enhancement related to the presence of cultural materials and thus could be used as a rough proxy for areas of prehistoric cultural activities. The development of a downhole magnetic susceptibility instrument together with database software made possible rapid and relatively non-invasive data collection. A grid of downhole tests over a large portion of the middle terrace at the Dahnke-Reinke site, processed using appropriate software for visualization and presentation, would thus allow us to see the topography of stable surfaces and intervening flood deposits as well as areas of human occupation. GPR software provided direction and support in imaging this complex three dimensional (3D) data set, allowing us to reexamine conclusions reached by previous investigators about the relationship of layers identified in widely spaced excavation units and, thus, about the formation of the middle terrace and the distribution of humans across it at various periods of time.

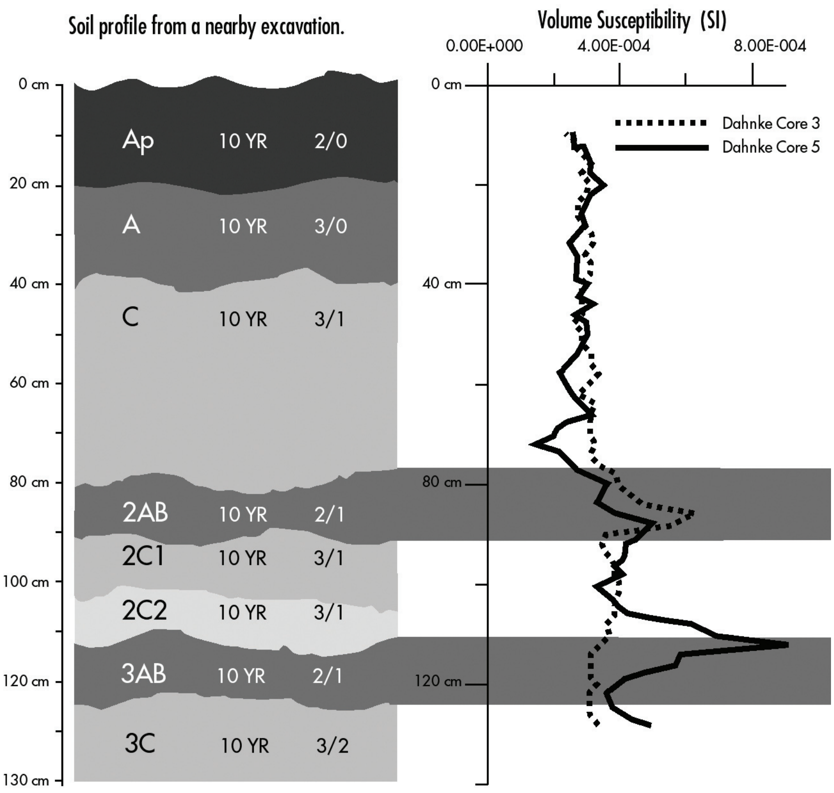

Figure 2. Stratigraphic and soil magnetic data from selected locations at the Dahnke-Reinke sites. Stratigraphic data is derived from a 1987 excavation block located in the southeast portion of the middle terrace (Figure 1). Cultural materials were encountered in the two buried soils (2AB and 3AB). Peaks in susceptibility are apparent in two downhole susceptibility tests conducted a few meters to the north and south of this excavation block. The 2AB horizon is more prominent at the Core 3 location and the 3AB horizon is more prominent at the Core 5 location.

2 Methods

2.1 Downhole Susceptibility

Downhole susceptibility tests were conducted over a 50 m square area covering a large section of the middle terrace (Figure 1). A Bartington Instruments MS2 susceptibility meter and MS2H downhole susceptibility sensor (http://www.bartington.com/ms2h.htm) were used to collect volume susceptibility measurements at 2 cm increments down 22 mm-diameter core holes made with a hand-held push tube soil sampler. The Multisus FieldPro (v1.0.1) database program loaded on a pc tablet computer was used to view data in graph and tabular form during capture and to record all measurements and field and sampling information.

Downhole tests were conducted at

locations positioned at 10 m intervals. Original plans had been for 36 locations but tests were abandoned along the northernmost row of six cores (at S15) when it became apparent that field activities were harming crops already compromised by flooding. Therefore, downhole studies were halted after completing tests at only 30 locations. Tests during flooded conditions did demonstrate that the MS2H sensor performed well even when submerged in standing water. Susceptibility measurements were recorded to a depth of 130 cm below the ground surface (bs). All measurements commenced at 10 cm bs to avoid edge effects. Values were recorded in SI units (i.e., International System of Units, abbreviated from the French "Le Système International d'Unités") and the sensitivity setting was 1.0. The downhole studies were completed over a period of three days.

Two separate tests were accomplished at each location. An initial rapid reconnaissance test (timed test) was accomplished by first zeroing the MS2H sensor in air, taking readings automatically at approximately one-second intervals as the sensor was lowered at 2 cm increments down the core hole, and concluding with a final reading in air at the end of the test. The difference between the initial zero reading in air and the final air reading measures sensor drift. Using the Multisus FieldPro software, this drift was distributed linearly along the readings down the core hole. In the second test (manual test), measurements were taken manually as the sensor was positioned at each 2 cm increment down the core hole, allowing more precise depth control. Drift was checked and corrected for at 40 cm intervals. Manual measurement and more frequent drift correction requires more time and in some cases resulted in greater overall drift although this technique ensured that instrument drift was more accurately distributed. As mentioned above, the manual test also provided the advantage of better depth control.

2.2 Data Processing and Imaging

Initial data treatment involved deleting extra readings at the end of the timed tests resulting from the delay between reaching the bottom of the core hole and stopping the measurement sequence at the computer (this can now be accomplished during data collection using version 1.01 of Multisus Fieldpro). Single plots of the two drift-corrected downhole tests at each location were then prepared using the Golden Software Grapher program (v. 4) (Figure 3). A common vertical and horizontal scale was used for all figures. Values were presented in uncalibrated units. SI volume magnetic susceptibility values can be approximated by multiplying the measurements by 1E-5. The timed and manual tests at each location were first compared to ensure that replicable results had been produced from test to test at each core location. Minor differences in vertical positioning of the sensor accounted for almost all differences between tests.

As part of a traditional approach to interpretation, these individual graphs were visually compared and anomalous zones of susceptibility representing the buried soils and cultural deposits were followed as they extended across adjacent records. The 30 downhole plots were arranged in rows representing their relative placement across the middle terrace, and a pencil and ruler were employed to trace enhanced zones (peaks) in susceptibility as they continued across tests to the east and west and also across tests to the north and south. This approach was time-consuming and it was difficult to visualize how discontinuous layers related across the widely-spaced core holes.

In contrast, an alternative approach pioneered in this study integrated the grid of downhole susceptibility data gathered at the Dahnke-Reinke site using GPR-SLICE software. The grid of downhole logs served as a database for constructing and animating a series of images at multiple depths (depth slices) akin to the amplitude time slices produced with GPR surveys. Raw (unsmoothed) data from the manual tests were used as inputs in these efforts due to the increased precision of their Z (depth) coordinates. The data from the manual tests across the entire grid were first assembled into Microsoft Excel files by 2 cm levels to produce 61 depth-slice datasets starting at 10 cm and ending at 130 cm bs.

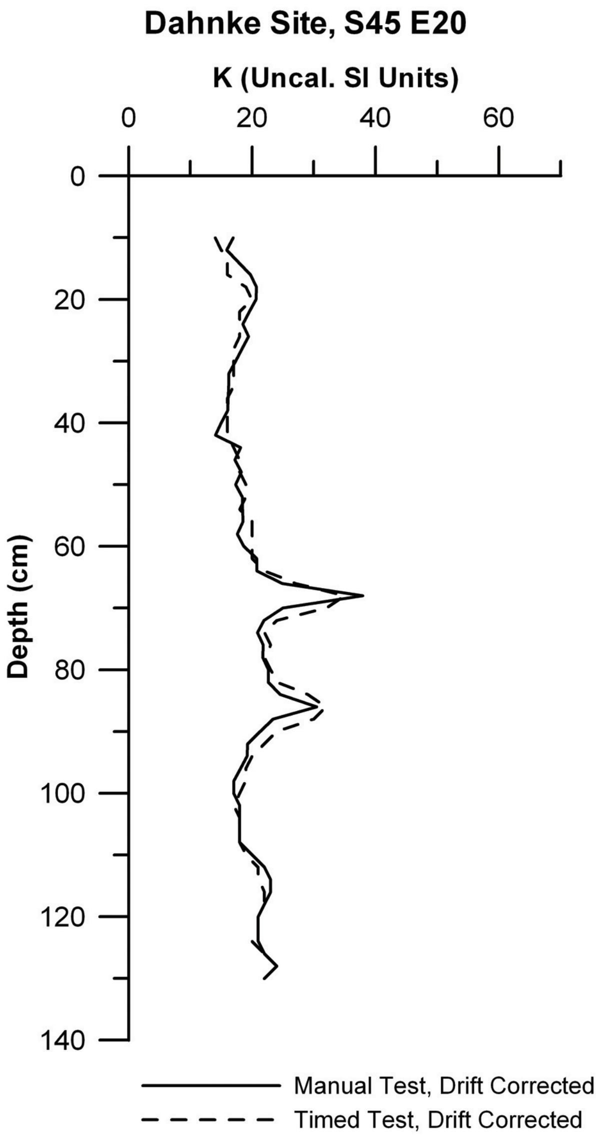

Figure 3. Example plot of the two tests completed at each location on the downhole grid. Volume susceptibility measurements are presented in uncalibrated Bartington units.

For importation of the data into GPR-SLICE software, a number of processing steps were then followed to generate 61 separate susceptibility depth files. The susceptibility measurements at each depth were first vertically smoothed using susceptibility values that were 2 and 4 cm away from the susceptibility readings at that depth. Weights of 5% were assigned to measurements 4 cm above and below the depth level, measurements 2 cm above and below the depth level were assigned weights of 20%, and the depth level measurement was weighted at 50%. Using weighted averages of these 5 depths smoothed out both measurement noise and positioning errors in the vertical direction, and accommodated slight topographic changes in paleosol surfaces across the terrace.

As the horizontal downhole spacing was quite coarse, there were few data to constrain higher resolution Kriging solutions for interpolating the susceptibility depth slices. For this reason, simple inverse distance gridding was employed using a distance weighting that was proportional to the inverse squared distance to any measurement that was included within the search radius. The search radius was set to 1.5 times the borehole spacing or 15 m. The sparsely sampled two-dimensional (2D) susceptibility measurements were then interpolated to 10 cm pixels to generate high density 2D gridded depth slices (e.g., Figure 4).

With the development of the individual 2D depth slices, the next step was to compile all the individual 2D susceptibility depth slices into a single (binary) file. With a single 3D volume of susceptibility measurements, a host of imaging displays using GPR-SLICE software were available. GPR-SLICE software allows for interpolating between any consecutive 2D depth horizons to generate finer scale depth intervals that can be imported into a compiled 3D volume. Initially, no interpolation was implemented between the Dahnke-Reinke depth horizons, and a single volume with just 61 vertical horizons was developed. In order to smooth the appearance of the volume in the vertical direction, a second volume was also created with three interpolations between the 2 cm depth slices.

In GPR-SLICE, data may be presented using either relative or absolute normalization. Absolute normalization represents in color the absolute or true value of susceptibility at any location in a volume. This method of data presentation allows one to see exactly the relationship of highs and lows in susceptibility measured across a site. An example display using absolute normalization developed for the 2D susceptibility depth slices at the Dahnke-Reinke site is given in Figure 4.

Using relative normalization, any depth level within a volume is given the full range of colors. To generate a 3D volume with relative normalization, the 2D susceptibility slices are first displayed on the computer screen where lo-cut and hi-cut settings across the data histogram can be automatically set to three standard deviations away from mean susceptibility readings. The histogram thresholds are set for each 2D map. The number of standard deviations to apply the lo-cut and hi-cut thresholds for displaying colors across the histogram can be locally adjusted, as can the individual data transforms at any level. Once these settings are made, vertical interpolation between the 61 depth horizons can be implemented. The interpolation process for a relative normalization volume is to interpolate between the colors shown at each level, rather than the actual absolute value of the susceptibilities at those data locations.

In the generation of a relative normalization volume, contrasts at any given level are given the full dynamic range for display. With GPR data in GPR-SLICE imaging, this is the common practice (although this may not be the case with other GPR software packages). In an absolute display, the contrasts which one is mapping may require enhancement

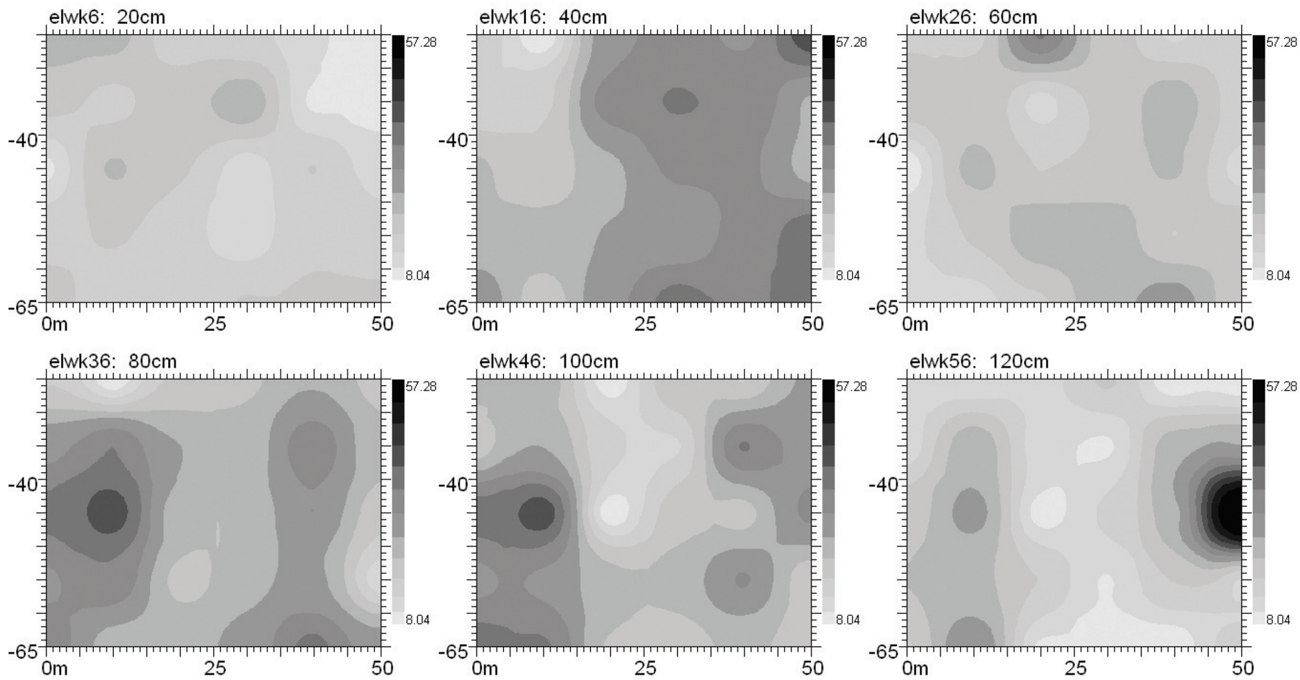

Figure 4. Six of the 61 2D susceptibility depth slices computed for the Dahnke-Reinke site. Depths (in cm) are indicated at the top of each figure. Data are displayed with absolute normalization.

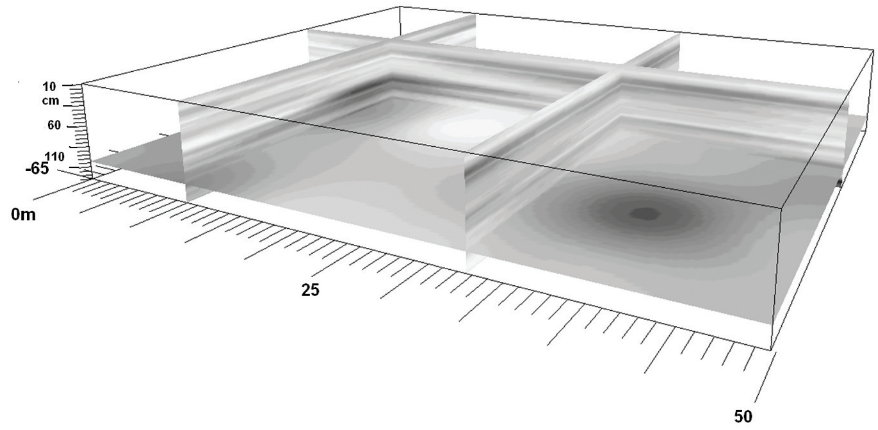

Figure 5. 3D fence diagram of susceptibility readings developed from a volume generated using relative normalization between the individual 2D depth slices.

to amplify small changes within a given level. For this reason, as one would wish to display weak to strong reflections, relative normalization is considered more useful for radar displays. Whether absolute or relative normalization is most appropriate for mapping susceptibility changes warrants further investigation. Both types of volumes provided useful information in this study.

3 Results

Three questions were asked at the Dahnke-Reinke site that are of general interest in many archaeological investigations. These questions concerned the existence of buried surfaces (paleosols), the topography of these surfaces as they extended across the landform, and the identification of locations where cultural occupation was concentrated. The images and animations produced using GPR-SLICE software proved extremely helpful in answering these questions.

Shown in Figure 4 is a portion of the 2D susceptibility depth slices generated for the site. Mid-range colors indicate the presence of buried soils, with the darkest colors indicating cultural activity. Images of the 3D volume can be used to help show the continuity of horizontal susceptibility layering across the site. An example 3D fence diagram, showing multiple X, Y, and Z planes in the volume, is presented in Figure 5. An example of a borehole view, allowing susceptibility layers to be traced across a line of boreholes, appears in Figure 6. The 3D shapes of specific susceptibility values within the volume are shown for two orientations and two different isosurface thresholds of 50% and 30% away from the maximum reading (Figure 7).

Although the individual images can be analyzed for this information, animations of these images were very helpful in visualizing the entire landscape. Dynamic presentation of the data provides a means for seeing the continuity and 3D shapes of susceptibility horizons in a real-time presentation that cannot be easily described in simple, static, 2D, anomaly images (e.g., Figure 4). Three dimensional fence plots (e.g., Figure 5) can be used to look at simultaneous vertical sections, which can be likened to stratigraphic profiles measured from narrow excavation trenches.

The GPR-SLICE imaging software provides for real-time displays that can allow the user to instantly rotate, tilt, and place any combination of slices in X, Y, or Z planes to visualize subsurface structures within the susceptibility volume. The application of isosurface rendering and real time rotation allows one to visualize 3D shapes of susceptibility which may correlate with geomorphic, soil, or anthropogenic origins. In contrast to static 2D maps, the interpreter now has tools useful for understanding the complex nature of a 3D dataset. The software also allows for data flythrough into the volume, which provides another means of interacting with and understanding the data.

The results gained to date at the Dahnke-Reinke site cannot be considered definitive as downhole tests are still widely spaced relative to resolution in the vertical dimension. This data, however, has provided much useful information and has

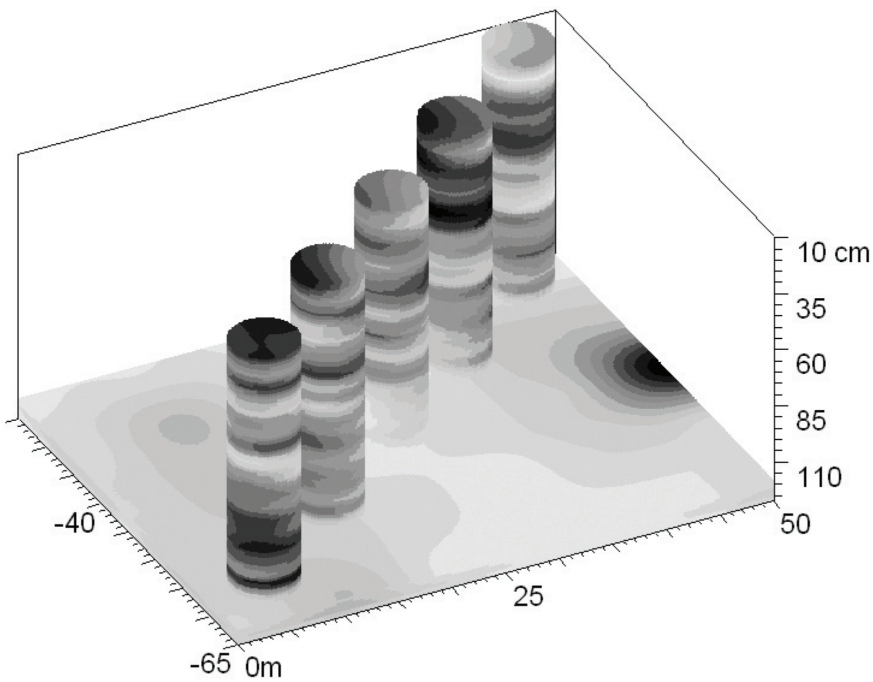

Figure 6. Borehole display of the 3D susceptibility volume (relative normalization).

allowed a reexamination of conclusions reached by investigators based on the widely-spaced test excavations. For example, we are able to identify more than two buried soils at the site that can be followed across the middle terrace. The two buried soils shown in Figure 2 had been equated with a relatively shallow buried soil in the northern portion of the terrace. Thinner flood deposits between the two stabilization periods in the north made the discrimination of two separate buried soils difficult in that region. The susceptibility data indicate that the buried soils do not slope rapidly to the south but, rather, slope gently to the east, and that the shallow buried soil noted in test excavation units to the north is not continuous with deeply-buried soils in southern portions of the terrace (Figures 5 and 7a). A number of relatively high susceptibility regions have been targeted on each of the buried surfaces that are likely foci of prehistoric occupation (Figure 7b).

4 Conclusion

This study has explored the potential of downhole susceptibility data and GPR imaging software for application in research on archaeological landscapes. Such an approach can be used to broadly characterize a landscape providing knowledge relevant to a site and its context, including information regarding landscape development, stabilization, and use.

Downhole susceptibility studies resemble radar surveys in that both may be used to gather high-resolution data on the variation of physical properties with depth. Thus, these two methods provide an opportunity that is not possible with many other geophysical methods. Unlike the abrupt interfaces recorded by radar data, susceptibility methods are able to document minor and gradual changes that may relate to soil formation or human influence and, thus, can be very useful in the study of archaeological terrains.

Newly developed downhole susceptibility sensors and software allow the collection of robust 3D data sets useful for understanding archaeological landscapes. These data sets, however, present challenges in presentation and interpretation that have not yet been met with developments in magnetic susceptibility software. Although other options exist for imaging 3D geophysical data, in this study these challenges were met using software developed for use in GPR processing. Limitations in resolution are, of course, related to the density of downhole tests across the site.

The formalization of appropriate procedures for creating 3D susceptibility volumes, useful for interpreting stratigraphic and anthropogenic contexts, is still in process. There are numerous processing options that can be investigated and comparisons with excavation and/or coring data will aid in their evaluation. In our current implementation, we did not try 3D gridding. This is not practiced in GPR imaging since overlapped slices of radargrams can be created which effectively gives us control in the third dimension. Should GPR software be the imaging choice for susceptibility volumes, it may be useful to extend the current gridding to simultaneous 3D gridding. Developments are

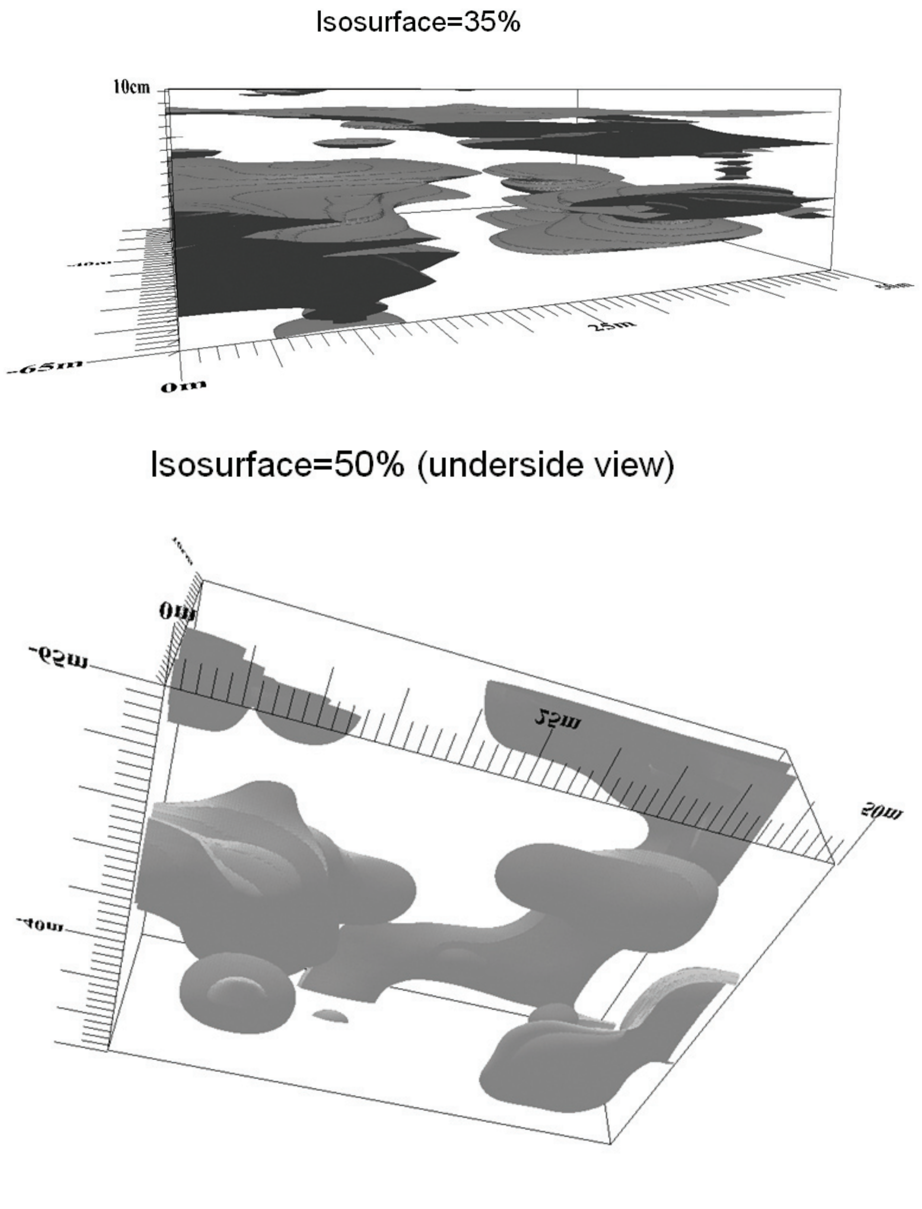

Figure 7. Isosurface rendering of susceptibility measurements that are 50% (bottom diagram, view from underneath) and 35% (top diagram, view from the south) of the maximum susceptibility readings in the dataset. (7a above, 7b below)

planned for GPR-SLICE to provide for 3D migration that will eventually read a 3D velocity volume constructed from sparse measurements of the velocity (hyperbola) measured across the site. Thus, developing 3D gridding for susceptibility imaging is actually an important step that will be dually useful for imaging and migrating radar data. This is but another example of the beneficial interaction between the two methods.

At the Dahnke-Reinke site, enhanced susceptibility values relating to buried surfaces and cultural deposits, as documented by down-hole tests conducted adjacent to excavation units at this and other sites within the Red River Valley, provided an avenue for mapping paleosols and areas of cultural activity. Imaging capabilities of GPR-Slice were used to integrate a grid of discrete downhole susceptibility records into a 3D picture of the Dahnke-Reinke landscape. A spatially broad and more accurate understanding of human occupation and landform development resulted.

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