Ground-penetrating radar survey at the pyramid complex of Senwosret III at Dahshur, Egypt, 2008: search for the lost boat of a Pharaoh

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ABSTRACT

A survey at Dahshur, Egypt, employed 3-D ground-penetrating radar (GPR) in an attempt to locate pharaonic boat burials at the pyramid complex of King Senwosret III. In AD 1894, the original excavator reported finding five or six boats; however, only four “Dahshur boats” are known in museum collections today. The suspected site of the lost boat burial(s) lay beneath the large 1894 excavation backfill pile. The steep topography of the backfill required nonstandard GPR processing methods to accurately image the subsurface of the site. Although revealing no definitive traces of any remaining boats, imaging results did indicate discernible strata associated with the original naturally deposited surface, an excavated boat pit, debris and fill associated with either its original creation or its excavation, and deeper, presently unidentified archaeological remains.

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1. Introduction

In 1894, J. de Morgan (1895) spent two field seasons excavating at the pyramid complex of Khakaure Senwosret III (c. 1870–1831 BC) at Dahshur, Egypt. The complex included within its perimeter wall the mud-brick pyramid of this Twelfth-Dynasty king, subsidiary pyramids, a temple, and other structures (Arnold, 2002). The northern end of the complex overlies shaft tombs of the Third Dynasty (c. 2687–2649 BC) (Arnold, 2002: pp. 107–108; de Morgan, 1895: pp. 75–76). North of the perimeter wall are Middle Kingdom pyramid complex wall was a 7/C2 (Arnold, 1992: 52–53), it was empty at the time of discovery.

Also in the vicinity of the southwestern corner, de Morgan discovered two groups of 10 m long wooden boats, as well as sledges (de Morgan, 1895: fig. 105, pp. 81–83, pl. XXIX–XXXI). These water and land transports probably participated in the funeral of Senwosret III; interment would have made them available for the king’s continued use after death and would have sequestered these “magically charged” objects from the realm of the living (Arnold, 2002: pp. 106–107; Lehner, 1997: pp. 118–119; Taylor, 2000: p. 105).

De Morgan (1895: p. 82) described the hulls as buried directly in the ground, shored up along their sides by unfired mud bricks. Half a century later, Hassan (1946: p. 157) described two distinct types of burials: boats in the southern group “had been placed upon the gravel, their sides supported by piers of mud bricks, and the whole buried under a mound of sand and debris”; the northern boats “were buried in a tunnel-like construction of bricks” (see also Porter and Moss, 1981: p. 885).

The number of boats de Morgan found varies among his reports and even within the same report. Four are known with certainty and have been well studied: CG 4925 and CG 4926 (Fig. 1) in the Egyptian Museum in Cairo (Creasman, 2005; Reisner, 1913: pp. 83–87; Ward, 2000: pp. 83–102); FMNH 1842 at the Field Museum of Natural History in Chicago, Illinois (Ward, 2000: pp. 83–102); and CMNH 1842-1 at the Carnegie Museum of Natural History in Pittsburgh, Pennsylvania (Patch and Haldane, 1990; Ward, 2000: pp. 83–102). However, at various times de Morgan claims to have
If the fifth boat has remained in situ at Dahshur, it is anticipated to be in more or less its original state. After excavation, the four known Dahshur boats underwent processes of repair and restoration that might have significantly altered certain aspects of the ancient joinery. This has led to modern controversy surrounding basic Egyptian boatbuilding techniques of this period. The ancient boatbuilders used mortise-and-tenon joinery (Creasman, 2005; Steffy, 1998: p. 36 Fig. 2fig. 3-14a, p. 276; Ward, 2000: pp. 90–92) throughout the hull and supplemented this in critical areas of stress with a different technique. No later than 1895, a type of joinery known as “dovetails” (small bowtie-shaped tenons of wood set into inboard plank faces) was noted on the Dahshur boats (Frothingham and AuthorAnonymous, 1895; Reisner, 1913: p. xxii n. 1, p. 84), and at least some of these dovetails were known to be modern. Whether these replaced ancient dovetails (Creasman, 2005) or are entirely modern adaptations of a completely different joinery technique, in which cordage latches planks together through channels cut into the planks (Haldane, 1984, 98–101; Ward, 2000: pp. 93–95, 97), remains an open debate.

Desire to clarify this fundamental question prompted two seasons of non-invasive remote-sensing surveys to search for the missing Dahshur boat(s), which, being unrestored, could provide new data. In 2007, an initial exploratory geophysical survey in the area of de Morgan’s boat excavations, undertaken with the cooperation of the Metropolitan Museum of Art’s Egyptian Expedition to Dahshur headed by Dieter Arnold, demonstrated the viability of both magnetometry and conductivity for detecting features of not only stone but also fired mud brick and unfired mud brick at the site (Creasman et al., 2009). Hesse (1970) attributed such success to the magnetic properties of the Nile River mud harvested for bricks, which has been repeatedly confirmed by Herbich (2003) and Herbich et al. (2007). However, the results of the 2007 survey underscored the necessity of a more highly detailed non-invasive investigation of the area. The sensitivity of ground-penetrating radar (GPR) to subtle contrasts in materials and its high-resolution imaging capacity suggested that it would be the ideal tool for the task.

Given de Morgan’s descriptions, it was thought that GPR would register the mud bricks and debris used to support or bury the boats; this layer of material, whether thoroughly disturbed by excavation or partly or wholly intact, would contrast well with the loose surrounding strata of sand. GPR has been used successfully at numerous other archaeological sites within Egypt (e.g. Abbas et al., 2005; Hafez et al., 2008) and elsewhere (e.g. Goodman et al., 2007; Sternberg and McGill, 1995; Tohge et al., 1998). A basic review of GPR theory and practice for archaeological applications is given by Conyers and Goodman (1997).

For the survey undertaken in October of 2008, which employed a Sensors and Software Pulse Ekko 100 ground-penetrating radar, historical accounts and photographs and the results of the 2007 survey led us to select a 31 × 27 m area (GPR area 1) as the location most likely to harbor the missing Middle Kingdom boat, hypothesized to be beneath the backfill pile adjacent to one of de Morgan’s excavated boat pits. The team also performed a brief GPR survey at the northeastern corner of the pyramid complex (GPR area 2) and surveyed the secondary enclosure between the outer and inner enclosure walls (i.e. the southwestern corner of the pyramid complex) with a Geometrics G-858 cesium vapor magnetometer; these last two surveys will be subjects of separate reports, as they are not directly related to the search for the boats.

2. Theory

Ground-penetrating radar is a subsurface remote-sensing tool that utilizes electromagnetic propagation to detect subsurface targets. A typical GPR system consists of a signal analyzer for...
generating and recording radio frequency signals and antennas for transmitting and receiving the electromagnetic (EM) signal (Fig. 3).

GPR is traditionally used for reflection or “echo-sounding” surveys, in which electromagnetic waves are propagated from an antenna through the subsurface (medium 1). Upon being impeded by a target of contrasting EM properties (medium 2), the waves are reflected to a receiving antenna, where the intensity and travel time of the signal are recorded. The intensity of the reflected wave \( R \), at normal incidence, is proportional to contrasts in electromagnetic impedance \( Z \) of the upper \( Z_1 \) and lower \( Z_2 \) media:

\[
R = \frac{Z_2 - Z_1}{Z_2 + Z_1}
\]

\[
Z_j = \frac{\omega}{\mu_j \sqrt{\epsilon_j \mu_j \sigma_j + i \omega \sigma_j}}
\]

where the subscript \( j \) is either medium 1 or medium 2, \( \epsilon \) is the dielectric permittivity, \( \mu \) is the magnetic permeability, \( \omega \) is the angular frequency, \( \sigma \) is the electrical conductivity, and \( i \) denotes that the term is an imaginary component. At typical GPR frequencies, \( \mu \) is effectively the same as that of a vacuum (Demarest, 1998). Both \( \sigma \) and \( \epsilon \) varies with material type. Table 1 provides values of \( \sigma \) and \( \epsilon \) for some common earth and archeological materials.

Greater contrast in EM properties produces a relatively greater intensity of reflected wave. The total travel time that the reflected wave takes to reach the receiving antenna depends on the distance...
\(D\) of the reflector from the antennas and the speed \(c\) at which the electromagnetic waves propagate through the background. For collocated GPR antennas, the travel time is given by:

\[
T = \frac{2D}{c}
\]

\[
c = \frac{1}{\sqrt{\mu \varepsilon}}
\]

In the interpretation of GPR reflection survey data, one would desire to use the data to determine the location and EM contrast of subsurface targets. However, the reflected signal from a target arriving at travel time \(T\) can come from any point within the subsurface that is distance \(D\) from the antenna. Furthermore, the intensity of the signal also depends on the distance of the target and the radiation pattern of the antennas (Fig. 4).

In imaging, the objective is to compensate for the effects of the wave propagation and the radiation patterns of the antenna in order to correctly represent the location and the effects of the relative contrast of subsurface targets, a process known as “migration.” Most GPR-specific imaging techniques have some means of weighting the raw data to remove the effects of the antennas from the data, and they utilize constructive and destructive interference to properly place targets. More explicit descriptions of GPR imaging techniques are given in Moran et al. (2000), Streich and van der Kruk (2007), and van der Kruk et al. (2003).

The considerable technical challenges presented by the steep slopes of de Morgan’s excavation pit and backfill pile in GPR area 1 (Fig. 5) necessitated advanced GPR techniques. Large changes in elevation over a survey area create problems for correctly compensating for the effects of propagation and the antenna pattern with standard imaging techniques (Lehmann and Green, 2000). To deal with topography, Lehmann and Green (2000) adapted an imaging technique from seismic exploration to GPR, and this proved suitable for GPR area 1. An outline of their method, described in more detail in the next section, is as follows:

1. Forward modeling to determine the migration template;
2. Calculating the appropriate weighting factors;
Summing the weighted observed data along the curve defined by the migration template and assigning this value to the specified subsurface point in the migration image.

3. Methodology

The GPR data were acquired with a Pulse Ekko 100 time-domain system over a two-dimensional grid. We utilized broadband dipole antennas with a center frequency of 200 MHz. The data were acquired in the reflection mode, with a constant offset of 0.5 m. Common midpoint (CMP) velocity analysis determined the average velocity of the radar waves in the subsurface to be 0.125 m/ns. Spectral analysis of the data showed that the highest intensity of the signal centered at 140 MHz. Using this information, we designed the survey spacing to maximize coverage area while minimizing aliasing (Grasmueck et al., 2005). The horizontal spacing between measurement points was 0.4 m in both the north–south and east–west directions. Each measurement recorded 200 ns of data at a sampling interval of 0.4 ns to generate the vertical component of the data. The acquired data were then filtered and imaged using software written by Douglas Sassen. These data were filtered to remove the low-frequency signal (a process known as “dewowing”) and then low-pass filtered to remove interfering signals above 200 MHz. Corrupted traces were muted and then interpolated. Following this basic processing, the data were then imaged using an adaptation of Kirchoff migration for GPR data on steep topography, based the aforementioned technique first described by Lehmann and Green (2000).

In this method of imaging, one first determines for each acquisition point of the survey the total travel time from the transmitter to a specified point in the subsurface and back to the receiver; this is referred to as the migration template. Because this step requires accurate estimation of the location of both the transmitter and receiver for each acquisition point in three dimensions, the GPR survey area was first surveyed on a 1 m grid to generate a topographic map of the area (Fig. 5).

Using this map, the 3-D coordinate of each of the over 5000 transmitter and receiver pairs were estimated using bilateral interpolation. According to sampling theory (Jerri, 1977), the accurate interpolation of the topography from the 1 m grid is limited to surface topography with a periodicity of 2 m or greater, meaning smaller features such as runnels and stones are not accurately represented. With the 3-D coordinate of each transmitter \((tx,ty,tz)\) and receiver \((rx,ry,rz)\) location and velocity \(c\) known, the two-way travel time \(T\) to any specified subsurface point \((x,y,z)\) is:

\[
Rd = \sqrt{(tx-x)^2+(ty-y)^2+(tz-z)^2}
\]
Using this travel time $T$, the amplitude from the raw data is determined from the data using a windowed version of Shannon’s interpolation formula (Jerri, 1977). In the second step, appropriate weighting factors are determined for every point used in the final image. This weighting factor for a specified point depends on the distance from the antennas, the combined radiation pattern of the antennas, and the number of points that fall on the migration template for the point. To compensate for the distance from the antennas, a SEC gain was applied to the data (Yilmaz and Doherty, 1987). Calculating the combined radiation pattern of the antennas requires that the slope of the land surface be taken into account when calculating angles. Therefore the surface normal (a line perpendicular to the land surface) for each antenna point was calculated using the curl of the slopes estimated from the topographic map. The angles and radius from the surface normal to the specified point were input into a heuristic model of the GPR antenna radiation pattern. At a radius greater than three wavelengths from the antennas, the data were weighted with the far-field radiation pattern of a dipole over a half space (Engheta et al., 1982). In the near-field ($<1$ wavelength from the antennas) the pattern was approximated as spherical, and in the transition zone (1–3 wavelengths) the pattern was linearly interpolated between the near-field and far-field patterns. Points in the strongest portions of the radiation pattern are given the smallest weights (0.1); points within the weakest portions of the pattern are given the largest weights (1.0). This effectively reduces the influence of the antenna radiation pattern.

In the final step of the imaging, the weighted data along the template is summed and this value is assigned to the specified point. This is repeated for every point specified for the final image. During this summation process, signals that returned from a particular point within the subsurface will constructively interfere at that point in the image, while elsewhere the signal will destructively interfere. Thus, following the summation, the final image will represent the subsurface with the correct geometry and contrast.

![Fig. 9. A north–south oriented fence diagram, at 15.2 m from the west end of the area, outlining the textural difference between the excavated boat pit, the debris and host sediments.](image1)

![Fig. 10. An east–west oriented fence diagram, through the center of the pit, indicating some of the major features seen in and around the boat pit. Feature A is also shown in Figs. 11 and 12.](image2)
Following imaging, coherency and instantaneous amplitude attributes were extracted to aid in the interpretation. Coherency is a measure of the difference between a small window of the GPR signal compared by shape to its immediate neighbors. It is useful for detecting edges and for differentiating chaotic and regular areas. The instantaneous amplitude is the amplitude for a particular frequency centered on an analysis point within the data. It is useful for interpretation because it simplifies the data by removing the oscillations associated with the GPR signal. Coherency was calculated using the eigenstructure coherency algorithm (Gersztenkorn and Marfurt, 1996), and the instantaneous amplitude was calculated using the discrete wavelet transform.

**Fig. 11.** An aerial perspective of the instantaneous amplitude (156 MHz) depth slices at 0.5 m below the surface (a), 2.75 m below the surface (b), and 5.0 m below the surface (c). In (d) all amplitudes for the 3-D volume that are in the top 90% of intensity scale appear.

**Fig. 12.** An aerial perspective of showing the areas of highest coherency (90%) within the 3-D volume.
transform (DWT) using the Morlet wavelet (Chopra and Marfurt, 2007).

4. Results

4.1. Interpretation of GPR area 1: the search for the boat

For GPR area 1 (Fig. 6), provide 3-D diagrams of the GPR data. Textures of the imaged data reveal three distinct zones: (1) the original naturally deposited sediments, (2) the debris and backfill associated with either the original creation of the boat pit in the Twelfth Dynasty and/or the refuse of de Morgan’s excavation of the boat, and (3) the excavated pit for the boat(s) and possibly additional, unidentified structures.

The originally deposited sediments have very low differences in EM contrasts, with a small-scale and irregular texture (Fig. 6). A relatively continuous reflector demarks the surface between the debris and backfill and the original sediments across the entire site at approximately 0.5 m below the current site surface (Fig. 8). The debris and backfill typically show higher EM contrast than the original sediments. High-contrast features vary from laterally continuous surfaces to a hummocky texture characterize de Morgan’s excavated boat pit (Fig. 9).

An east–west profile through the center of the excavated boat pit (Fig. 10). Figs. 7–12 shows some other features apparent in the data, including two distinct surfaces within or below the boat pit (at depths of 2.75 m and 5.0 m) and a wall presumed to be the eastern wall of the vaulted brickwork structure. At the site, the decomposed mud brick of this wall remains visible at the surface.

Extracting the instantaneous amplitude attributes from the data provides a more simplified view of the imaged data (Fig. 11). In the 0.5 m depth slice (Fig. 11a), slice edges of the excavated boat pit are clearly outlined by lower amplitudes. In the 2.75 m depth slice (Fig. 11b), the surface seen in Fig. 10 appears to have an elliptical shape, similar to that of a boat. This is believed to be the remnants of the mud-brick support structure for one of the boats excavated in 1894 by de Morgan. In the 5.0 m depth slice (Fig. 11c), the strongest contrasting features are seen, with the peak amplitude corresponding to the feature labeled A in Fig. 10. The volume display (Fig. 11d) of the >90% amplitude shows that the largest contrasting feature is at the 5.0 m level. The coherency attributes extracted from the imaged data show the strongest similarity levels (>90%) at the same 5.0 m level (Fig. 12).

5. Discussion and conclusions

Careful examination of the current GPR images detects no direct evidence of boat remains in the area of our survey. One boat pit can be confirmed; however, two pits were expected, or else one pit large enough to have contained two boats. The low contrast and small-scale irregular texture, interpreted as the original sediment deposit, is intact below de Morgan’s backfill pile, providing no evidence for a boat pit dug into the subsurface there. There are small changes in texture and amplitude on the edges of the survey area, but these are likely due to bias in the images caused by the smaller number of acquisition points near the edges, which resulted in lower signal-to-noise ratios. Improving the image quality and interpretation is possible through more refined imaging techniques and the extraction of more attributes; however, most of the potential of the data has already been realized. The questions of the location and existence of the fifth Dahshur boat remain outstanding.

If a fifth boat was removed from the site, there should be evidence of its removal, presumably in the form of a boat pit; but where is the pit? Ground-penetrating radar clearly imaged only one boat pit, although based on de Morgan’s excavation notes (1895), at least two should be present in the search area. Given the history of archaeological revisitation at the site, specifically circa 1900 (see Patch and Haldane, 1990), it is possible that previous searches for items of intrinsic value in this area have been thorough enough to have completely destroyed any evidence of the missing boat, its support structure, and its pit.

The survey proved useful in many respects: delineating the depth and extent of the presumably empty boat pit excavated by de Morgan, structural features, and the strata of previous excavations. Being able to determine the depth of the interfaces between the original sediment deposit and the backfill and debris is significant. In regions of the world such as Egypt, heavily excavated during periods when modern archaeological methods and recordkeeping were undergoing development, localized application of GPR could be very useful for determining the status of areas of interest for reexcavation; the remote-sensing methods used at Dahshur in 2007 and 2008 can provide for reflexive investigations.

The imaging has also provided information regarding the locations of walls and surfaces in and around the boat pit. Most interesting is the high-contrast, highly coherent area below the boat pit at a subsurface depth of 5 m (see Figs. 10–12), approximately 2.25 m deeper than our interpretation of the boat-pit depths. Such high contrast and high coherency indicate an artificial feature consisting of materials that differ from the local sediments. It is questionable that de Morgan’s excavation reached this. Included at this 5 m deep surface is a small (2 × 2 × 3 m) highly reflective feature labeled A in the aforementioned figures. Archaeological verification of this unknown feature is recommended, as no structures other than the boat pits and vaulted chamber are known to neighbor the southwestern corner of Senwasret III’s pyramid complex and it is not possible to interpret with certainty what the high-contrast, highly coherent area obtained from the GPR data represents.

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Table 1

<table>
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<th>Material type</th>
<th>Relative dielectric permittivity</th>
<th>Electrical conductivity S/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand/gravel</td>
<td>[4–10]</td>
<td>[1E–7 to 1E–3]</td>
</tr>
<tr>
<td>Wet sand/gravel</td>
<td>[10–20]</td>
<td>[1E–3 to 1E–2]</td>
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<tr>
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<td>[2–6]</td>
<td>[0.1 to 1.0]</td>
</tr>
<tr>
<td>Wet clay/silt</td>
<td>[7–40]</td>
<td>[0.1 to 1.0]</td>
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<td>Granite</td>
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<tr>
<td>Limestone</td>
<td>[4–8]</td>
<td>[1E–9 to 0.1]</td>
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<tr>
<td>Air</td>
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<td>[0]</td>
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<tr>
<td>Fresh water</td>
<td>[81]</td>
<td>[1E–6 to 0.01]</td>
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* Permittivity constant is 8.85E–12 F/m.
Appendix A. Supplemental material

Supplementary information for this manuscript can be downloaded at doi: 10.1016/j.jas.2009.10.013.

References


