The International Journal of Nautical Archaeology (2009) **38**.2: 386–399
doi: 10.1111/j.1095-9270.2008.00214.x

An Exploratory Geophysical Survey at the Pyramid Complex of Senwosret III at Dahshur, Egypt, in Search of Boats

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A geophysical survey at the pyramid complex of Senwosret III at Dahshur sought to determine the suitability of magnetometry and electromagnetic induction (EMI, or conductivity) for mapping the area where several ancient boat-burials were found in the 1890s. At least one boat reported at the time of excavation remains unaccounted for. Tests demonstrated that magnetometry does detect subsurface structures of stone, fired brick, and unfired brick under current site conditions. Data indicated areas of geological activity as well as unexcavated archaeological remains, though no definitive traces of boat burials. No excavation was undertaken but another survey season is planned.

Key words: Dahshur boats, Dashur, Egypt, Middle Kingdom, remote sensing, Senwosret III.

Boats and boat-models are well-known, if not universal, features of Egyptian funerary practices. Tomb reliefs and paintings show the coffin and mourners transported across the Nile River aboard boats, and some tomb owners included boat-models of varying degrees of elaboration among their grave goods (Reisner, 1913; Winlock, 1955; Göttlicher and Werner, 1971; Glanville, 1972; Jones, 1990). In contrast to the abundance of boat-models from tombs, interments of actual vessels are comparatively rare and recovered examples are confined to royal contexts.[1] A working boat was a valuable asset and such disposal, which removed it from use by the living, would not have been undertaken lightly. Participation in the royal funeral could make the boat magically dangerous (Lehner, 1997: 118–19; Arnold, 2002: 107),[2] necessitating at least in some instances its burial, and therefore removal from use by the living. Even if buried outside the architectural limits of the king's funerary complex, the boats became available for the king's continued use in the netherworld (Taylor, 2000: 105; Arnold, 2002: 106).

In 1894, while excavating at the pyramid complex of King Khakaure Senwosret III at Dahshur, Jean-Jacques De Morgan unearthed several boats which probably took part in this king's funeral procession (Fig. 1) (De Morgan, 1895: 81–3, pl. XXIX–XXXI; Ward, 2000: 101–02; Arnold, 2002: 106–07). At the time of his death, Senwosret, who came to the throne in about 1878 BC as the fifth king of the Twelfth Dynasty, had enjoyed a reign of at least 19 and possibly as many as 39 years (Delia, 1980: 284–91). Domestically, under his rule the last of the powerful hereditary local governors ('great chieftains' or 'nomarchs') disappeared as political rivals to the king. Senwosret acquired new territory in the Levant and, more notably, expanded the reach of Egypt farther into Nubia than his predecessors had, completing or establishing fortresses along the way. After his death, or possibly even before it, he was honoured as a patron deity of Nubia at

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Figure 1. Location of sites, specifically Dahshur, Egypt. (authors)

least until the reign of King Taharqa (690–664 BC) (Simpson, 1984: 903–06; Delia, 1980; 1995; 2000: 268; Grajetzki, 2006: 51–8).

The pyramid intended for Senwosret's burial at Dahshur was mudbrick encased with limestone. The complex included seven smaller pyramids, a temple, and courts, the entirety surrounded by an outer wall that was expanded northward and southward during a second building phase (Arnold and Oppenheim, 1995: 46, fig. 3, 48; Arnold, 2002: 89). The wooden boats found by De Morgan, each about 10 m long, were buried beyond this outer wall, at the southwest corner.[3] A pair, GC 4925 and GC 4926 (Fig. 2), can be seen on display in the Egyptian Museum, Cairo (Reisner, 1913: 83–7; Creasman, 2005). Two others found their way into American collections: in Pittsburgh, the Carnegie Museum of Natural History 31760 (Patch and Haldane, 1990) and in Chicago, FMNH 1842 in the Field Museum of Natural History (Ward, 2000: 83–102). Older collections of contemporaneous watercraft in Egypt are known from the Khufu pyramid complex at Giza (Lipke, 1984) and the Early Dynastic cemetery at Abydos (Ward, 2003; 2006), but these have not yet been fully excavated.

Despite the existence of at least four Dahshur boats and their availability to scholars for more than a century, certain basic questions regarding aspects of their construction methods remain unanswered. Although contemporaries, the boats display several differences in construction technique (Creasman, 2005: 25–131). Furthermore, a basic joinery component has long been a matter of contention. In each of the four hulls, dovetails set into the inboard faces of the planks provide transverse strengthening. However, Cheryl Ward proposes that the dovetails are modern additions: she argues that the original fastenings were lashings, but that after excavation the lashing channels were modified for dovetails to add transverse stability to the ancient hulls (Ward, 2000: 93–5, 97). There are other possible interpretations of the dovetail or lashing channels (Dell'Amico, 2005), but in any event, the four available hulls have not provided the data to address this issue adequately.

In his excavation report, De Morgan mentions the presence of not four boats but six, in two caches of three each (1895: 81–2), although he mapped only five of them (Fig. 3). His subsequent reports place the exact number at five (1896: 600; 1897: 11).[4] It is likely that De Morgan added the discovery of a wooden transport sledge to his initial tally which resulted in a miscount of six vessels (1895: 83, fig. 204) and amended his count in subsequent publications. Just seven years after the initial publication of the boats' discovery,

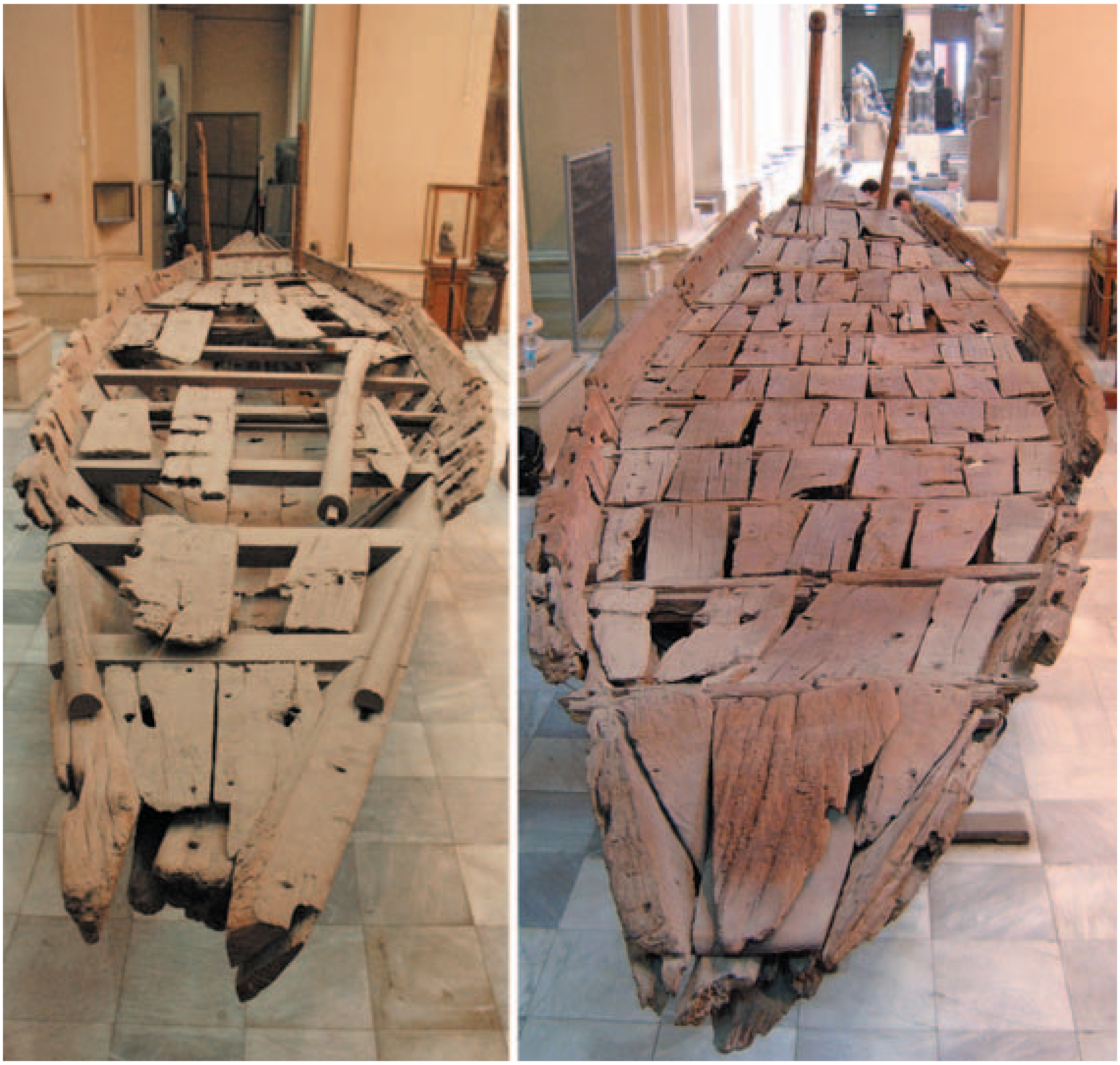

Figure 2. A) GC 4925; B) GC 4926, on display in the Cairo Museum. (authors and J. Levin)

Peet reported that at least one had been exported to a museum in Europe (1902: 187–8), but no museum or private collection is known to include it, leaving the present whereabouts of the fifth Dahshur boat unknown. Although the presence of charring on GC 4925 raises the possibility that the missing fifth boat might have been used as firewood (Creasman, 2005: 56), some opinions suggest that it could remain in the sands at Dahshur (Cron and Johnson, 1995: 43; Arnold, 2002, 106–07; Hawass, 2004). If so, its joinery is likely to have escaped alteration, preserving evidence for the original state of the dovetail or lashing channels.

Lacking clear evidence that the fifth boat was ever removed from the site or destroyed, we decided to address the long-standing question of its location by conducting a non-invasive geophysical survey at Dahshur in co-operation with the Metropolitan Museum of Art's Egyptian Expedition to Dahshur, headed by Dieter Arnold. Our project primarily aimed to conduct a survey with remote-sensing equipment in an area south of the outer or secondary enclosure walls of the pyramid complex in search of the unaccounted vessel, and to map any additional finds. We decided to begin the survey in the area where De Morgan had mapped the boats, the west, and move east and south as time would permit. The secondary goal of the project was to establish the location of the original boat-burials and to clarify whether five or six vessels were originally present (see Creasman, 2005: 8–10). The final goal was to map the dimensions and positions of any other

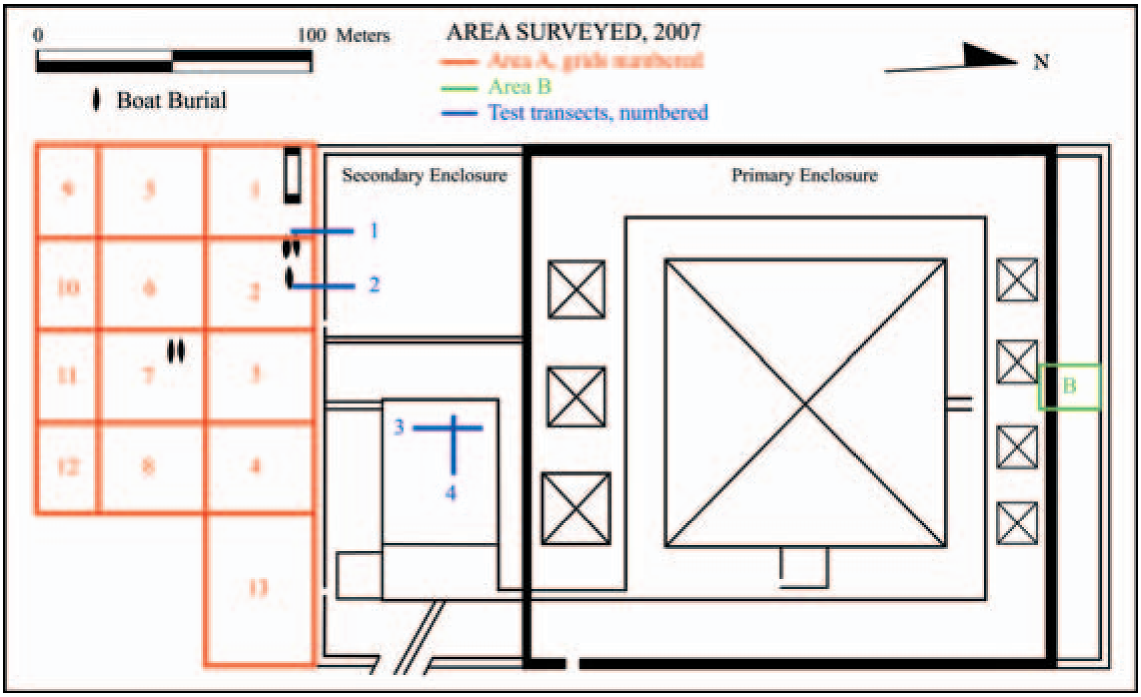

Figure 3. Site map of the pyramid complex of Senwosret III. Boat-burials adjusted to actual location and 2007 survey areas indicated. (after De Morgan, 1895: VII, fig. 105)

structures that our equipment detected within the search area. The survey took place between 25 October and 3 November 2007.

Methods

The 2007 geophysical survey at Dahshur employed two instruments: a Geometrics G-858 caesium vapour magnetometer, operated in gradiometer configuration, and a Geonics EM31 electromagnetic induction meter (also described as a conductivity meter). Elsewhere in Egypt, these instruments have successfully identified Middle Kingdom archaeological features based on thermo-remnant magnetism and enhanced ferromagnetic mineral content resulting from cultural and natural activities (Vining, 2007: 78–89). Based on De Morgan's excavation photographs of the vessels, it was thought that these instruments could register debris beneath or in the boats; this would be densely packed compared to the loose surrounding strata of sand. The debris was probably intended to prevent the hull and deck of each boat from collapsing under the weight of the sand after burial (see De Morgan, 1895: pl. XXIX–XXXI). In his description of De Morgan's excavations, Selim Hassan stated that three boats were 'buried in a tunnel-like construction of bricks' and that the other boats to the south 'had been placed upon the gravel, their sides supported by piers of mudbricks, and the whole buried under a mound of sand and debris' (1946: 157). The Geometrics G-858 caesium-vapour magnetometer would readily detect the presence of such structures.

Recent excavations at the Red Sea site of Mersa/Wadi Gawasis presented an additional possibility for the detection of Middle Kingdom boats (Bard and Fattovich, 2007). The discovery of metallic fasteners in association with ship timbers at Wadi Gawasis appeared to confirm the suspicions voiced by scholars and enthusiasts alike throughout the 20th century that metal fastenings must have been present on period boats in some form to ensure their stability. The extant Dahshur boats show no definitive signs of ancient metallic fastenings, but, the condition of the hulls, including modern repairs, has obscured much of the evidence of the technologies employed in their construction. After discussions with Mark Everett, professor of geology and geophysics at Texas A&M University, it was thought likely that both a conductivity meter and magnetometer could register the presence of similar metallic artefacts, based on the quantities suggested by the excavations at Wadi Gawasis (Childs, 2007: 196). The composition of the fastenings would be critical to the response of each of the instruments. Some ferric content is required for the fastenings to be detectable by the magnetometer; if copper fastenings were employed, it is not likely that they would register unless the quantity was sufficient to substantially change ground conductivity.

Analysis

Ten days of geophysical testing were carried out at the Senwosret III pyramid complex at Dahshur during the 2007 field season. Two geophysical methods were tested: magnetometry and electromagnetic induction (EMI). This testing had two objectives. The principal object was to map an approximately 1.2 ha area immediately south of the complex's exterior compound wall, in the area where excavations by De Morgan recovered the remains of Middle Kingdom period wooden boats (Fig. 3, Area A). The geophysical survey attempted to locate subsurface features in this area which would indicate more precisely the original location of the boats prior to their excavation and also undisturbed areas of interest that potentially may indicate additional boat-burials. Data were collected in 30 × 40 m grids.

The second objective was to test the applicability of multiple geophysical methods to the archaeological features and site conditions at Dahshur and to determine whether additional survey would be warranted. Test data were collected as isolated transects within the outermost compound wall and in a single 15 × 25 m grid on the northern side of Senwosret IIIs pyramid (Fig. 3). This report briefly introduces the two methods employed at Dahshur, presents and summarizes the collected data in graphic and narrative forms, and provides preliminary recommendations based on these results for future research.

Magnetometry

Magnetometry measures variations in the Earth's overall magnetic field. Small-magnitude and localized magnetic anomalies are measured as values in nano-Tesla per metre (nT/m). In addition to geological features and electromagnetic noise, cultural features such as walls, burned areas, or concentrations of certain artefacts can create magnetic anomalies by concentrating or depleting magnetic, ferric mineral relative to the amount found in the surrounding soil. The magnetometer was set to measure values every 0.1 seconds, and transects were walked at a pace of approximately 1 m per second, equating to a recording approximately every 10 cm. In areas that were surveyed as gridded blocks (that is, south of compound wall and north of the pyramid), data were collected along transects spaced 1 m apart. In total, approximately 1.23 ha were surveyed with the magnetometer in Area A and 375 m^2 in Area B.

Different types of material found at Dahshur had magnetic responses. Large quantities of unfired mudbrick, such as those used in construction, had a low magnetic response, with associated anomalies ranging between ±20–30 nT/m when the walls were exposed at the surface. By way of comparison, this is a considerably lower magnetic response than modern garbage on the site (steel cans or wire) had. When these walls were buried by non-magnetic overburden, such as sand, the sensor response was considerably lower but often still recordable. Isolated blocks of granite found at the site also had a magnetic response. These responses are due to minute amounts of ferric mineral, primarily iron oxides, present in soils used in the mudbrick and in the granite. It is important to note that the Dahshur boats, constructed of wood, would themselves have no magnetic response, given that there were probably no ferric materials involved in their construction. Excavation notes and photographs, however, suggest that the boats were interred with mudbrick superstructures. Even though the overall volume of mudbrick used was probably less than that of the compound walls (detectable in magnetometer tests), such structures would also be detectable, but with a more subtle sensor response. This presumes that this signal is not overpowered by more recent sources of noise. Most magnetic anomalies recorded in Area A were very subtle, averaging on the magnitude of ±10–12 nT/m.

Conductivity

The EM31 conductivity meter measures near-surface conductivity between transmitting and receiving sensors, with an effective depth of approximately less than 4 m beneath the instrument. Ground conductivity can be affected by several different variables, including moisture content, porosity, salinity and other chemical changes, and the presence of metallic objects. At Dahshur, compound walls, prior excavations and disturbed areas, geological channels, and probable burial features caused changes in ground conductivity. The direct detection of buried boats at Dahshur with EMI methods is contingent upon significant amounts of metal having been

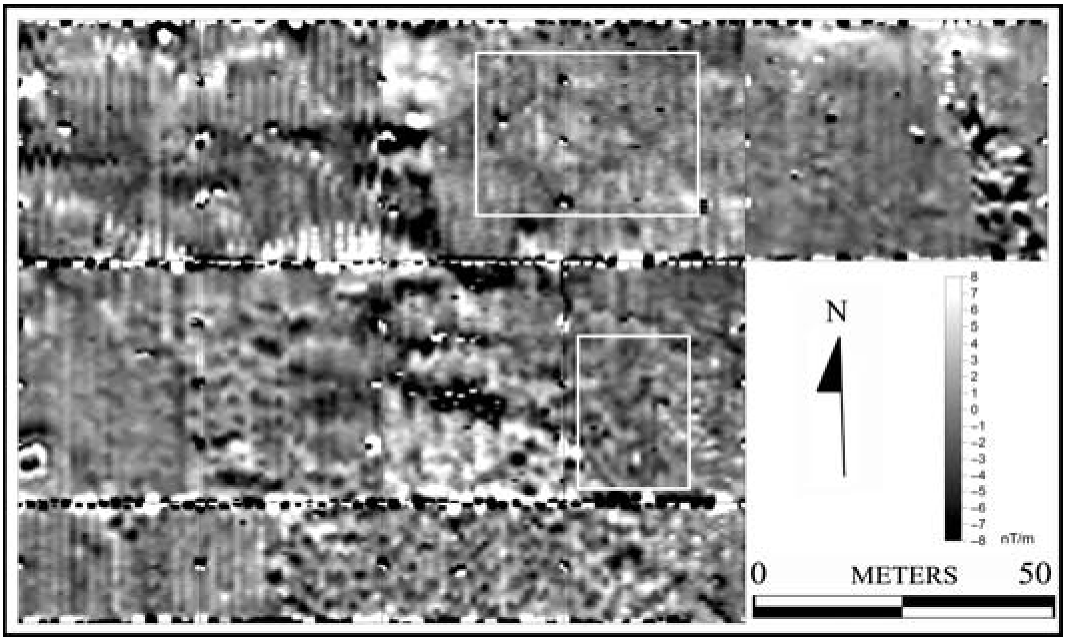

Figure 4. Magnetometer results from survey Area A. Disturbance from De Morgan's excavations is apparent in most of the grids; grids 4 and 13 are the only areas which are largely undisturbed. Areas of anomalies referred to in the text are indicated by the white frames. (authors)

used in the boats' construction; otherwise, buried structures encasing the boats should create detectable features.

During the survey at Dahshur, ground conductivity was measured in milli-siemens per m (mS/m). The analogue meter used is considerably slower to operate than the magnetometer, and with the EM31 there is little gained by spacing data points closer together. Consequently, ground conductivity was measured every metre along transects spaced 2 m apart in Area A in nine grids, for a total of 8400 m^2, while in Area B measurements were recorded every metre along 1 m transects covering a total of 375 m^2. Similar to the magnetometer results, there was a low dynamic conductivity range at Dahshur, with measured values between 1.4–8 mS/m.

Results

For both the magnetic and conductivity surveys, grids were oriented towards cardinal directions, and transects were oriented north-south. Grids were numbered as indicated in Fig. 3. The total magnetic field at Dahshur was modelled based on the International Geomagnetic Reference Field (IGRF) model for the date at which the survey started, and geometry of the magnetic field was used to determine the best grid set-up for collecting data with a minimum of noise. Notwithstanding this, there were several sources of external noise which impacted on the data. There was at the surface a minimum of modern material or trash which introduced noise or unwanted effects into the final data. Most of these objects (such as cans or wires) were readily identified and removed prior to surveying. An additional complication was the use of steel-wire pin flags to mark out the survey grids. For such surveys, it is necessary to use non-conductive materials for marking out survey areas. As these were not available at Dahshur, the wire flags used introduced magnetic anomalies into the data. These are regularly distributed, however, along the grid margins and can be discounted from the final data. Other objects that were missed can be readily identified and discounted based on the anomalies' geometry.

An additional source of 'noise' was from prior excavations and the related backfill piles, most notably from the De Morgan excavations. This disturbed significant portions of the site surveyed in Area A, particularly in grids 1 to 3 and 5 to 8. The end result is that geophysical survey in this area largely records the disturbed near-surface, down to approximately 2 m deep. There do not appear, however, to be significant archaeological features in this area even with removal/minimization of these effects in the data processing, and it is

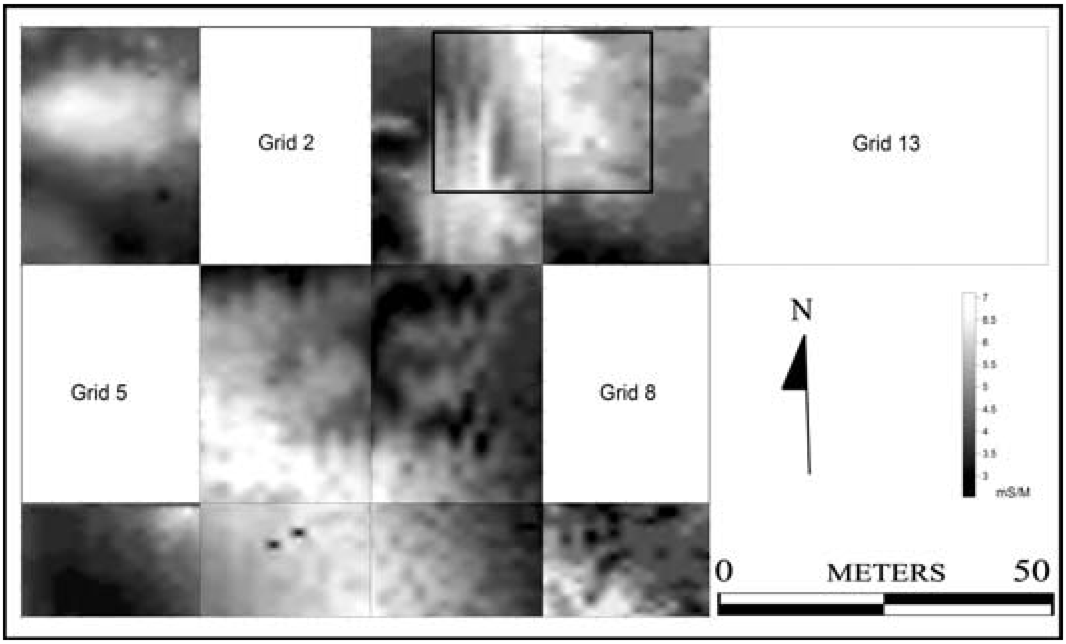

Figure 5. Conductivity results from survey Area A. Empty grids (2, 5, 8, and 13) were not surveyed with the conductivity meter. The area of orthogonal anomalies referred to in the text is indicated by the black frame. (authors)

likely that they do not obscure or overshadow any such features.

It is important to note that magnetic and conductive objects, as well as disturbed areas, appear in the magnetic and conductivity data as real anomalies—they are not data artefacts but rather represent real, physical phenomena and are considered 'noise' only in so far as they complicate the imaging of potential archaeological features. The final source of noise noted at Dahshur was direction-dependent instrument noise that created consistent difference, on average, of ±5–8 nT/m between adjacent transects. Similar effects have been described at the nearby pyramid complex at Saqqara (Mathieson *et al.*, 1999). Yet these had to do with magnetic interference caused by a specific problem with the instrument used in the survey, which was significant only because of the overall low-magnetic contrast at Dahshur. This noise resulted in heavy data striping, as can be seen in principally in grids 1, 2, 9, and 10. This systematic noise was minimized with data processing, and also by modifying the data-collection strategy in other grids.

Area A: magnetic data

Area A is located south of the largest, outermost compound wall surrounding the pyramid of Senwosret III. It runs for 170 m east-west along the compound wall, and extends 100 m south from the wall. Within the surveyed area are at least two large depressions and associated backfill piles from De Morgan's excavations. The surface of this area is also pitted from systematic testing that De Morgan carried out, leaving behind depressions and lag deposits of alluvial cobbles from the deflated backfill piles. The south-central portion of the survey area overlies a natural geological channel that may or may not have been an original access to the pyramid complex. Additionally, the south-east corner of the survey grid also overlies the northernmost edge of an Old Kingdom mastaba field south of the pyramid complex (Arnold, 2002: plan V). These features were recorded by the magnetic survey and to a lesser extent by the conductivity survey, and there are few other features of note in Area A (Fig. 4). Magnetic anomalies are shown in this greyscale image as values between ± 8 nT/m, with negative values shown as black and positive as white; grey areas show little magnetic contrast, at or near 0 nT/m (effectively, non-magnetic areas such as clean sand).

Within the magnetic data, there are several very slight anomalies that trend north-west to south-east, with even slighter anomalies which run approximately at right angles, highlighted in Fig. 4. These features are worth note for a few reasons; they run across transects and were recorded in multiple transects, they are linear, and they have orthogonal or near-orthogonal elements. Finally, the consistent orientation is notable. In the conductivity data these features can be seen as edges between general areas of higher versus lower conductivity. These characteristics indicate that these are not data artefacts. It is not certain what these features may be, but their orientation, location, and magnitude argue against them being caused by archaeological features that are Middle Kingdom in origin. They are rotated approximately 45° out of orientation with other Middle Kingdom features at Dahshur, and have a very weak magnetic contrast. These features, in fact, measure around 0 nT/m—meaning that they are magnetically neutral—but they are apparent as neutral areas within a slightly magnetized background. Additionally, these features are concentrated within the course of the known *wadi*. Given their shape, location, their magnetic characteristics, and the fact that they do not align with known Middle Kingdom features, it is likely that these features are not archaeological but are potentially geological in origin (such as infilled fractures).

The high magnitude anomalies (equal or greater to ±10 nT/m) can be seen in grids 1, 2, 7, and 13. In the case of grids 1 and 2, these are caused by the depressions and backfill piles from De Morgan's excavations. In grid 13, these anomalies are caused by the edge of the mastaba field to the south-east of the Senwosret III pyramid compound. The anomalies in grid 7 are probably caused by De Morgan's excavations which either left backfill piles (which are aligned, creating a magnetic anomaly that appears more organized in the data) or which created a cut in the natural alluvial strata, exposing deposits of magnetized sediments.

Area A: conductivity data

As indicated above, many of the anomalies recorded by the conductivity meter are sharp changes in conductivity values, many of which coincide with the magnetic results. These reflect areas of conductivity changes, rather than discrete anomalies, which are caused by disturbances, sedimentological changes, or anthropogenic features. Known cultural features such as walls created changes in conductivity in Area B. In Area A, however, the conductivity survey did not overlap with similar features (for example, it did not cover the edge of the mastaba field or the exterior compound wall). Other features are apparent, namely depressions resulting from De Morgan's excavations of the boats, and the *wadi* channel.

Summary

The anomalies in Area A, both in the magnetic and the conductivity data, are very low-magnitude and subtle. Most fall within the normal range of variability that can be anticipated for most geological environments. Furthermore, most of these anomalies do not correlate with the known archaeological features found at the Senwosret III complex, with the exception of the edge of the mastaba field, which was mapped by the magnetometer in the south-east corner of grid 13. Anomalies that were mapped by both the magnetometer and conductivity meter indicate physical changes in the subsurface. Many of these may be changes or modifications to the natural strata made in the past; without excavation it is impossible to determine whether these modifications date to the Middle Kingdom or not. Given the known recent history and clear surface geomorphology, it is probable that most, if not all, of these anomalies are due to geological features and/or disturbance from De Morgan's excavations.

A possible exception to this is the rectilinear anomaly in grids 3 and 4, indicated in Figs 4 and 5. It is noteworthy that this anomaly appears both as a change in conductivity values and an area of no magnetism (0 nT/m), and that the shape and location of the anomaly in both datasets roughly coincide. Without excavation, it is impossible to know precisely what features cause this anomaly. It is also important to note that neither the shape nor the orientation of this anomaly matches the known Middle Kingdom features at this site. Other contextual data suggest that it possibly is not archaeological. It is the only feature recorded in the geophysical survey of Area A that is not obviously visible at the surface. Portions of the feature do coincide with cuts in the slope and the location of conductive pin flags used to mark the grids. As the anomaly itself is very weak, it may be a figment created by data artefacts rather than a physical feature.

The magnetic survey did map the edge of the mastaba field and recorded a feature with considerable detail. This feature is oriented north-south and measures approximately 10 m wide by 25 m long. There are several magnetic dipoles within this feature, indicating that it is not a homogeneous structure. Additional work may be able to resolve particular details of the structure, such as interior walls or other indications of its construction.

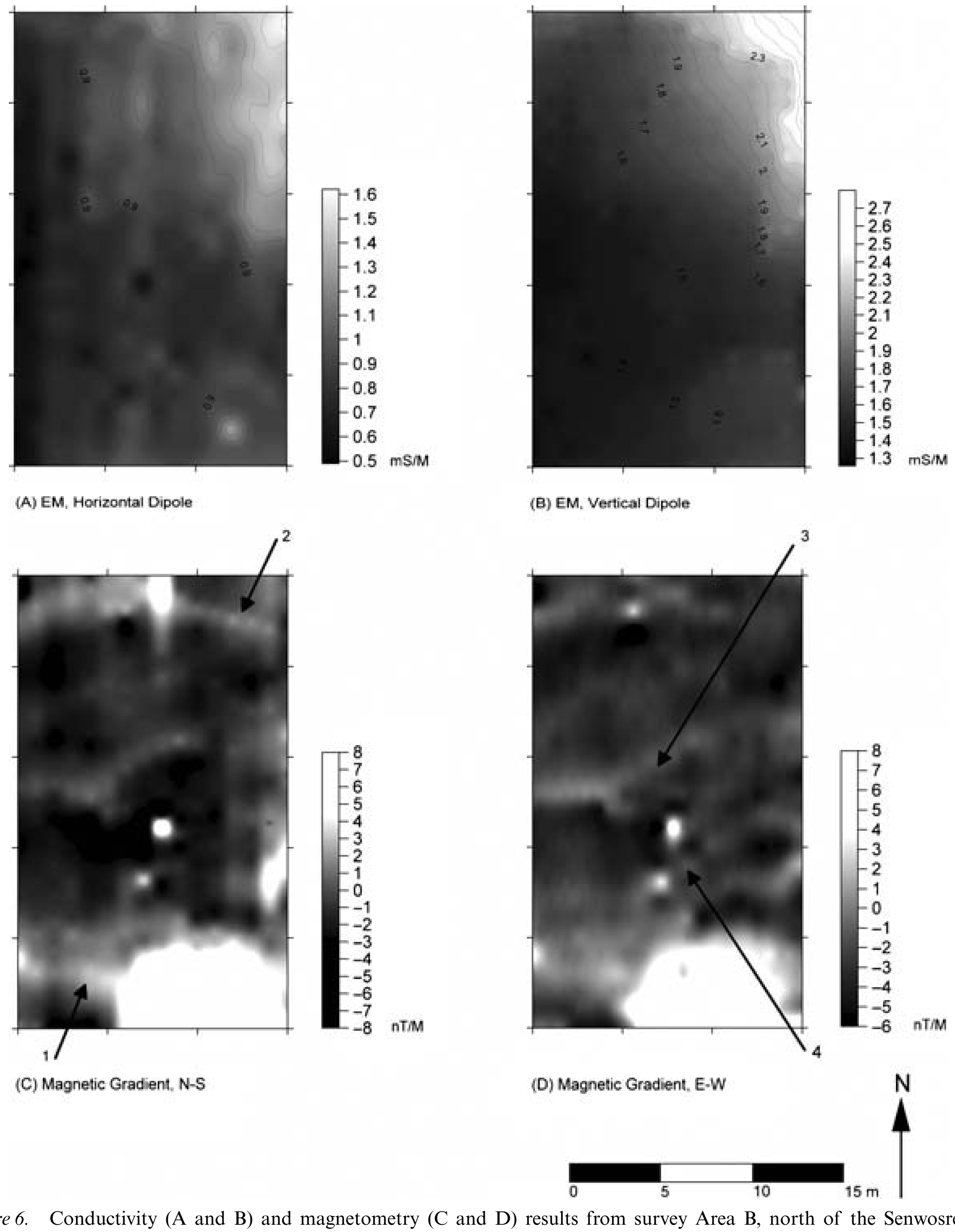

Figure 6. Conductivity (A and B) and magnetometry (C and D) results from survey Area B, north of the Senwosret III pyramid. Anomalies referred to in the text are indicated by arrows 1–4. (authors)

Area B

The geophysical pilot study included a test grid over known architecture and suspected features within the northern portion of the secondary compound walls, referred to here as Area B. The results from this survey are given as four images in Fig. 6. The results of the conductivity survey are given in A and B, while the results of the magnetometer survey are given in C and D. Figures 6A and 6B show the mapped conductivity values for the EM31 operated in horizontal and vertical dipole modes respectively. The data presented in Figures 6C and 6D were collected by the G-858 operated in the same configuration, but with transects run in a north-south direction in the former and in an east-west direction in the latter. For the sake of clarity, only datasets C and D are annotated, although many of the same features are apparent in all images.

All four datasets demonstrate complementary results, with some variation due to instrument orientation and depth of measurement. They share a single large anomaly in the south-east corner of the grid. This is close to an area of a known mastaba, and we assume that this anomaly is due to disturbance from prior excavation. Other known features, both running east-west, are the second phase, outer compound wall in the northern portion of the surveyed area and an interior compound wall, found in the southern portion. These walls were both detected in the magnetic survey and are indicated in Fig. 6C by arrows 1 and 2. They appear as linear anomalies. These walls also seem to appear in A as alignments of generally higher conductivity anomalies. There is an additional linear anomaly detectable in the magnetic data, approximately half-way between these two walls and running roughly parallel to both arrows 1 and 2. This is indicated by arrow 3.

South of this linear anomaly and between it and the interior wall, there are several features of note in both the magnetic and conductivity data. Contoured conductivity values in Fig. 6A and B show several right-angle breaks in the contours. In settings such as this, angular and orthogonal features most often indicate architecture or other anthropogenic modifications to the subsurface. These breaks also correspond to a general area of negative magnetism in C, shown in black. In C and D, the centre of this magnetically-negative area is occupied by a concentration of small, point anomalies such as would be caused by several individual magnetized objects. Given the materials found elsewhere at the site, these could be mudbricks, or possibly fragments of igneous stone. It is important to note that these anomalies are weak (only *c.* ±8 nT/m) and may be caused by weakly magnetic or small fragments of material, or by material buried at depth. Similar anomalies appear in the conductivity data (see especially A). There are three conductivity anomalies in this area, one of low and two of higher conductivity. The location of these conductive and magnetic anomalies is indicated in D by arrow 4. Similar conductive anomalies continue towards the south.

The area of greatest subsurface activity lies between m 5–10 (west-east) and 8–14 (south-north). The orthogonal anomalies surrounding this area suggest that these features may be contained within architecture or some other formal modification of the subsurface. There is additional geophysical activity outside of this region, such as conductivity anomalies and a complex magnetic anomaly. Perhaps significantly, most of this activity occurs well south of the second-phase compound wall, that is, towards the interior of the compound, with fewer anomalies in the northern portion of the grid.

With the current information, it is difficult to identify the precise type of features that cause these anomalies. General characterizations can be made: overall, these anomalies are small, localized, and densely clustered, suggesting several features with none larger than a few metres in extent. They have a low magnetic contrast, and there is little indication of thermal-remnant magnetism or other iron rich deposits. Based on the materials seen elsewhere at the site, it is likely that these are caused by clusters of brick or possibly stone near the surface, such as were used to line intrusive burials from subsequent periods at Dahshur. Depth-dependent measurements suggest that most of these features are at or shallower than 2 m.

Instrument testing

In addition to area surveys south and north of the pyramid, the geophysical work included brief instrument testing to measure the magnetic response of select and known targets. These included the large exterior compound wall, portions of which have been excavated and restored, the interior courtyard space where no features are expressed at the surface but where previous work has located secondary structure walls, and an isolated block of red granite. These tests were conducted as individual transects which passed over the target, each measuring approximately 10–15 m in length.

Compound test walls

Five transects crossed the southern exterior compound wall and mapped portions of the interior courtyard. The results from two of these transects are shown in Fig. 7. Profile 1 crossed an

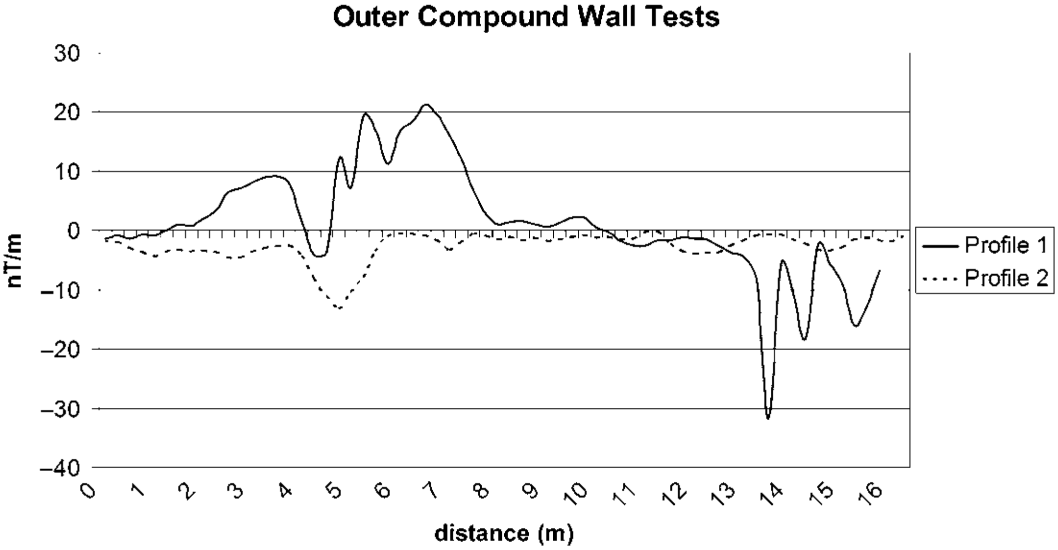

Figure 7. Magnetometer test transects over the exterior compound wall. The centre of the wall is located at approximately m 5–6 and *c.*50 cm beneath the instrument. Buried structures within the courtyard are indicated by the dipole anomalies between 12.5 and 15.5 m in Profile 1. (authors)

exposed portion of the compound wall that measured approximately 3.5 m wide. This segment of the wall was exposed at the surface; the outside edge started at m 5 of the transect, and the interior face of the wall was at m 8 of the transect. The wall is apparent in the test as a complex, multiple-peaked anomaly between approximately m 2.25–8.25. The anomaly ranges between *c.*–4 nT/m–+20 nT/m. The complex shape is due to the geometry of the magnetic field created by the mudbrick wall.

Profile two (Fig. 7) also crossed the wall, but where the wall was recessed. The wall was thinner at this point (*c.*2.5 m wide), and consequently the transect crossed the wall *c.*1 m further north here than it did in transect one (for example, at m 6). Additionally, the wall at this point was buried by an estimated 40 cm or more of non-magnetic overburden. As a consequence, the anomaly caused by the wall in this transect (between approximately m 3.7 and 6.8) has several features that distinguish it from the anomaly caused by the wall in Profile 1. Most notably, the anomaly is lower magnitude, and ranges between approximately –13–0 nT/m. The mean of this anomaly is also lower than where the wall is thicker and exposed (*c.*–6 nT/m versus 8 nT/m). In addition, the anomaly starts approximately 75 cm later, accurately reflecting the position of the recess. In Profile 1, the magnetometer recorded additional features towards the end of the transect (between m 12.5–15.5). These features were not apparent at the surface and probably represent interior, secondary walls.

In both transects, the magnetometer accurately mapped the position and shape of the exterior compound wall. In addition, it located interior walls that had minimal to no expression at the surface. Mean values for these transects were at or near 0 nT/m, indicating no significant sources of magnetic noise. This demonstrates that magnetometry effectively maps mudbrick archaeological features at Dahshur. This is significant in that it is not a requisite that the brick be fired. This has two implications: magnetometry, in addition to other geophysical methods, can applied to the site and environmental conditions at Dahshur, and these results support the interpretation of results from the Area A and B surveys.

Granite block tests

Two large granite blocks were also tested. These blocks measure 1.5 × 0.8 × 0.5 m, and 1.7 × 0.3 × 0.3 m. Red granite is an exotic, imported for construction purposes, and indicates monumental architecture (Habachi, 1950: 13, n. 1). Due to minute amounts of mafic mineral, granite and other similar materials are detectable by magnetic surveys under ideal conditions. These blocks were exposed at the surface and so do not reflect most archaeological conditions but do provide an opportunity to model magnetic signals and measure the actual response in the field.

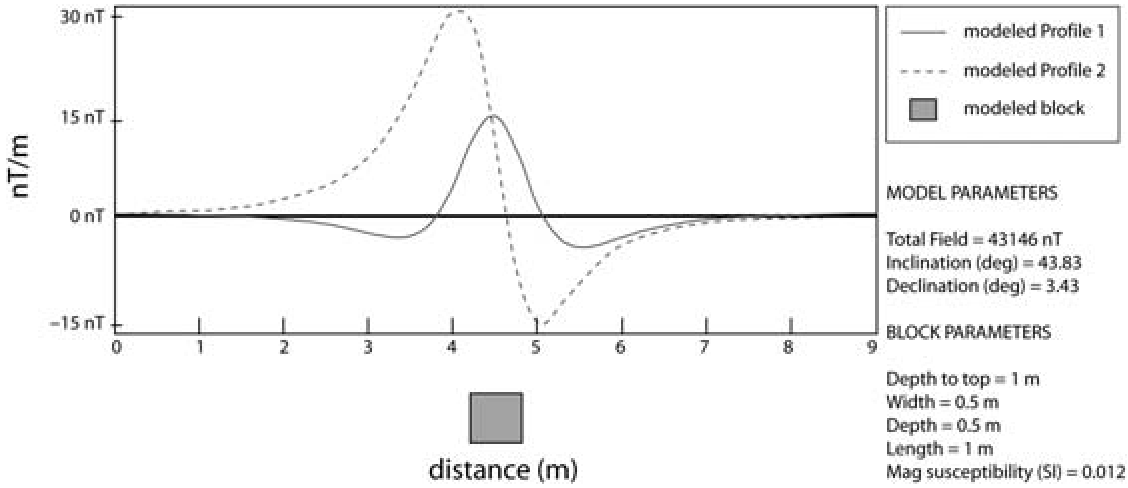

Figure 8. Tests of the magnetic response of granite blocks at the surface. The magnetic response along an 8-m transect across a modelled granite block of comparable dimensions to ones found at the surface of the Senwosret III complex, Dahshur. Profile 1 is oriented 0° to the block's magnetic poles while Profile 2 is oriented 90°. (authors)

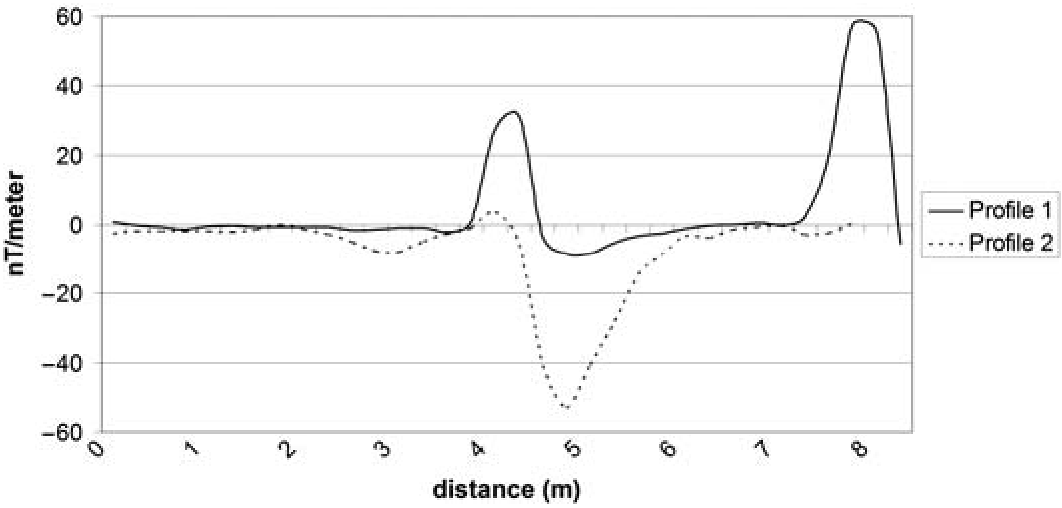

Figure 9. The results of field measurements of the magnetic response on actual red granite blocks found at the surface of the complex. The high anomaly at the end of Profile 1 is probably caused by modern debris buried just beneath the surface. (authors)

Figure 8 is the modelled magnetic response for a granite block of similar dimensions to those found at Dahshur within the same magnetic field. Magnetic field parameters for the geographic location and date of the survey were calculated using the IGRF10 model; the object was modelled as a granite block measuring 1.0 × 0.5 × 0.5 m and 1 m beneath the sensors. The magnetic susceptibility of the granite was estimated using values from Breiner (1999). The two profiles are from transects run at right-angles, crossing the block at 0° and 90° relative to its magnetic poles. The actual measured response is given by the two profiles in Fig. 9, between approximately 3.7 and 6 m on both transects. The modelled anomaly ranges between −7–27.5 nT/m; the measured anomalies (along both transects) range between −50–30 nT/m. There is close agreement between the geometry of the modelled and measured curves along the north-south transect, as well as the east-west transect, and the greatest difference is in the magnitude measured response. This difference can be attributed to an actual susceptibility that is greater or less than the value used in the model, variable differences between the sensor and the target during the survey, and/or magnetic poles within the actual block which do not precisely coincide with the modelled survey orientations. These factors not withstanding, the close agreement demonstrates that granite can readily be modelled, detected, and identified (based on magnetic response) at Dahshur. As this material is incorporated into architectural features, field tests and modelled results complement the results for mudbrick features and can aid mapping subsurface constructions of either material.

Conclusions

This brief geophysical survey was informative in many respects, confirming the presence of several known archaeological features. The survey demonstrated that magnetometry effectively maps mudbrick and granite archaeological features at Dahshur, and it is significant to note that it is not a requisite that the brick be fired. Magnetometry, in addition to other geophysical methods, can be applied with success to the site and environmental conditions at Dahshur. However, further testing is necessary before any reliable statements can be made regarding the location of the fifth, and possible sixth, boat. The use of ground-penetrating radar, which was not available for the 2007 survey, will be required to supplement the magnetometry and conductivity results in order to ensure the highest probability of locating additional archaeological features and artefacts, including the boat-burials.

Evidence suggests that the likeliest location of an additional vessel is the most obvious: protected under De Morgan's large backfill piles, south of the south-west corner of the outermost enclosure wall of the Senwosret III pyramid complex. The backfill is several metres deep and probably contains the remnants of the mudbrick mastaba excavated by De Morgan, which may obscure objects beneath. Another survey is planned for 2008, with different equipment which may detect archaeological features in or beneath the backfill, but due to the extensive disturbance at the southern part of the site the potential for near-surface geophysics is limited. Low-frequency radar or other depth-penetrating geophysical survey methods would provide the highest likelihood for detection, should any archaeological deposits remain and be accessible by remote sensing.

Acknowledgements

This project was made possible by approval from the Supreme Council of Antiquities (Egypt), assistance from Dr Zahi Hawass, and the exceptional patience and kind permission of Dr Dieter Arnold, as well as the support of Dr Adela Oppenheim and the Metropolitan Museum of Art's Egyptian Expedition to Dahshur. Our most sincere gratitude is due also to the following: Mr Emad in Cairo; Dr Mark Everett and Mr Douglas Sassen of the Department of Geology and Geophysics at Texas A&M University; Mme Amira Kattab of the American Research Center in Cairo; the Institute of Maritime Research and Discovery, Ltd.

Pearce Paul Creasman was responsible for organizational matters and the final conclusions presented above. Benjamin Vining was responsible for the interpretation and analysis of the geophysical data, including the analysis presented above. Samuel Koepnick was critical in the organization and collection of data. While not venturing to the field, Noreen Doyle was critical to the research and write-up of this work.

Notes

1. Royal boat burials, with or without their contents intact, are known from Early Dynastic royal graves at Abydos (Ward, 2000: 39–43; 2003) and Saqqara (Lehner, 1997: 80); the Fourth Dynasty pyramid of Khufu at Giza (Lipke, 1984; Lehner, 1997: 109, 118–19; Ward, 2000: 45–68); the Sixth Dynasty pyramid of Unas at Saqqara (Lehner, 1997: 155); and, dating to the Twelfth Dynasty, the pyramids of Senwosret I at Lisht, of Senwosret III at Dahshur, and of Amenemhat III at Dahshur (Arnold, 2002: 106).
2. Not only boats were treated in this fashion. A wooden canopy associated with a statue of Khufu was similarly disposed of (Lehner, 1997: 119). In the Sixth Dynasty, pottery used in the funerary meal was destroyed afterward (Ritner, 1993: 145–6), and tomb KV 54, a late-Eighteenth Dynasty cache in the Valley of the Kings, contained disposed materials from Tutankhamun's funerary meal, as well as from his mummification (Winlock, 1941; Reeves and Wilkinson, 1996: 126).
3. Several authors indicate that the boats were buried in mudbrick mastabas, notably Hassan (1946: 157) and Hawass (2004), but Arnold asserts that the vessels were buried directly in the ground (2002: 107). Observations during this survey suggest that Arnold is correct; it is important to note, however, that due to this ambiguity mudbrick mastabas were assumed to be present while planning for the survey.
4. While De Morgan discovered three boats near the secondary enclosure wall and 'trois autres barques semblables furent encore rencontrées dans les sables à 100 mètres environ au sud des premières' (1895: 82), our survey found the burial pits of the second two, not three, to be located approximately half of his estimated distance, only 50 m farther south (see Fig. 3). As the southern area of this site has remained relatively undisturbed since De Morgan's excavations, the locations of the burials are apparent, except where the backfill mound inhibited our survey.

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