Magnetic and Electromagnetic Induction Studies at Archaeological Sites in Southwestern Jordan

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ABSTRACT

In support of ongoing archaeological excavations in southwestern Jordan, a number of geophysical studies have been performed in this region. The work reported was executed in three different years and, in the first year, electromagnetic induction, magnetometry, and ground penetrating radar studies were performed at three sites in the region known to have buried stone walls. While integrated geophysical methods were planned, this first field experience revealed that electromagnetic induction provided, by far, the most useful results and this became the mainstay of subsequent geophysical investigations. To date, five large sites and numerous smaller sites have been surveyed ranging in dates of occupation from the Pre-Pottery Neolithic to the Iron Age. Results from three of the larger sites are reported here. These sites are sufficiently large that they cannot be completely excavated in a single field season and the results of the geophysics are used to identify the most interesting areas at a particular site for subsequent excavation. At the oldest site, the Pre-Pottery Neolithic, the three-dimensional structure of buried stone walls are characterized. At an Iron Age site, walls and magnetic artifacts within a fortress are revealed and a possible tomb containing metal artifacts was discovered immediately outside of the fortress. A third site surveyed, a Biblical copper mine, was exploited by cultures spanning several millennia.

Introduction

In 1997, the authors began an effort to support a long-term excavation project in southwestern Jordan by archaeologists from the University of California at San Diego. The initial area of geophysical studies and excavations is in Wadi Fidan. Wadi is the Arabic word for a dry riverbed and this region is characterized by steep terrain cut by wadis. Wadi Fidan is a westerly drainage from the mountains of south-central Jordan into the Wadi Arabah rift valley approximately 50 km south of the southern tip of the Dead Sea. The Wadi Arabah now defines the border between Jordan and Israel and the three sites considered here are several kilometers east of the rift valley (Fig. 1). During the 1999 and 2000 geophysical investigations, additional sites were surveyed both within and outside of Wadi Fidan.

The first geophysical efforts focused on sites associated with the production of copper during the Biblical period (Early Bronze Age, about 2500 BCE). The planned efforts at this time were to (1) non-invasively map buried stone walls at two sites, one an area believed to have been used for the production of copper from ore and the other a nearby village and (2) characterize the extent and time period(s) of exploitation at known copper mines. Three techniques were selected for use in this initial study; ground penetrating radar (GPR), magnetometry, and electromagnetic induction (EMI). These methods were selected because large areas needed to be surveyed and the archaeological team needed interpretations in near-real-time to guide their excavations. It was anticipated that GPR would be the primary method for mapping buried stone walls and magnetometry was considered in the event that either the walls were composed of magnetic rocks or that the non-magnetic stone walls existed in a paleomagnetic soil background. EMI was to be the primary technique for mapping seams of copper ore.

Both GPR and magnetometry failed to delineate the buried stone walls. Although the radar penetrated to the necessary depth using 100, 200 and 400 MHz center-frequency antennas, no evidence of walls appeared in the data suggesting little dielectric contrast between the walls and surrounding soil. Some, but not all, of the stones of the walls were magnetic as were numerous stones that cluttered the ground surface. As a result, it was impossible to distin-

Figure 1. **Map of Jordan showing the area of geophysical studies.**

guish surface magnetic features from those only centimeters deep. EMI performed much better than the other methods. The stone walls appeared as negative linear and rectilinear features in the quadrature component of the data. A plausible explanation is that, although the soil is extremely dry, it still has enough moisture to manifest a conductivity contrast with the walls. Thus, the walls appeared in the EMI data as an absence of conductivity. This hypothesis might appear inconsistent with the failure of GPR since GPR will respond to both changes in dielectric and electrical conductivity. It must be recognized that the conductivity of the soil is low and, for low conductivity, the GPR response will be dominated by changes in dielectric. During 1997, walls at the two Biblical sites were mapped by EMI using a GEM-2 (Won *et al.*, 1996) as was a nearby, much older, pre-pottery Neolithic (PPN) site. The results of the 1997 effort have previously been reported (Witten *et al.*, 2000).

Here, some results of the work conducted during 1999 and 2000 are presented. These are from three sites: additional broadband EMI surveys at the PPN site as well surveys conducted at an Iron Age site and at a copper mine. Each site is considered individually.

The Pre-Pottery Neolithic Site

The Pre-Pottery Neolithic (PPN) site is a well preserved village that specialized in the production of beads. It occupies a small granite island at the mouth of the Wadi Fidan at the extreme western end of the Faynan drainage system where it empties into Wadi Arabah. The granite bedrock is overlain by a conglomerate on which the stone walls were built. At the time of the geophysical studies, these walls were buried in a fine soil. From a small pilot excavation, the site was dated to 8000 BCE based on the architectural construction and cultural affiliation of the uncovered artifacts. As "ground truth," these walls and their anticipated extensions into the unexcavated area were delineated with EMI. In the 1999 study, prior to excavation a small area was surveyed with broadband EMI, again using the GEM-2. The purpose of this effort was to quantify the three-dimensional wall structure.

It has been shown (Won, 1980) that frequency can be used in EMI measurements to provide depth information. Since the time-varying magnetic fields employed in EMI penetrate to greater depths with decreasing frequency, depth sounding can be accomplished by acquiring data over a range of frequencies where depth is approximately inversely proportional to the square root of the probing frequency. This depth-to-frequency relationship has been demonstrated theoretically and experimentally (Won, 1980) and by field measurements and forward modeling (Witten *et al.*, 1997). Thus, presenting measurement position along a line as the horizontal axis and inverse frequency as the vertical axis, an out-of focus image over a vertical cross-section can be displayed. This is analogous to the display of seismic data as time slices where each time slice can approximately be considered as an out-of-focus image of reflectors at a certain depth. Figure 2 is such an image where several walls (medium gray) are clearly visible within the soil background (light gray) along with the underlying conglomerate (black).

Following the geophysical survey, this site was excavated. This excavation revealed remarkably well preserved walls with door and window openings (Fig. 3) and, in many areas, these walls reached heights of about 3 m. The patterns of these walls are in agreement with those delineated with EMI; however, in the absence of a rigorous inversion, depth comparisons cannot be made. At 10,000 years old, these walls are among the oldest yet discovered and are contemporary with those at Jericho.

The Iron Age Site

Several kilometers north of Wadi Fidan and in a separate drainage there is a sprawling site known as Khirbat en-Nahas, meaning ruins of copper. The site lies on a large terrace on the south bank of the Wadi al-Ghuwayb and is about 10 hectares in size, making it one of largest pre-industrial copper-working sites in the Levant. The main periods of occupation of this site are during the Iron Age (about 900 BCE) and Roman/Byzantine periods. Excavation of this site was conducted in the fall of 2002; however, results of this excavation are not yet available. A thorough analysis of this industrial production center will provide a key for examining Edomite state formation, the nature of local versus settled interactions, and relations between Edom (during this period, the area east of the Wadi Arabah was known as Edom) and other Iron Age sites in the Near East.

As part of 1999 geophysical studies, small selected locations at this site were surveyed with EMI and

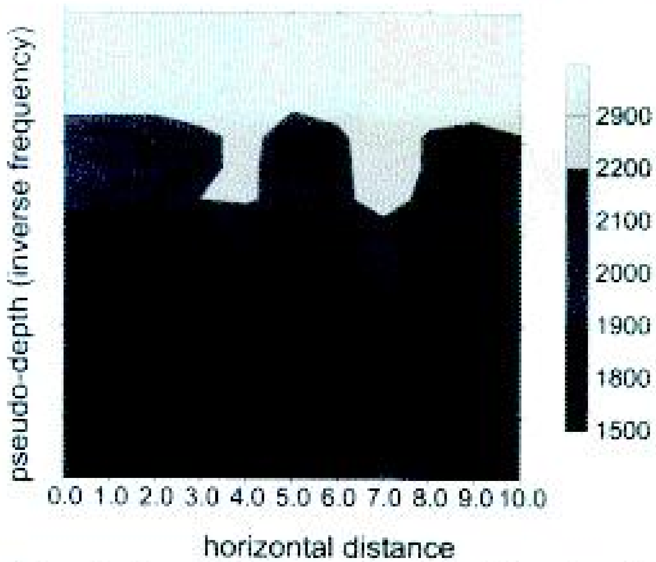

Figure 2. A vertical cross-section derived from broad-band EMI data at the Pre-Pottery Neolithic site. The horizontal distance is in meters.

magnetometry, two of which are considered here. The subject survey areas are associated with the remains of a massive stone-walled fortress occupying approximately 3500 m^2. Data were acquired for both the interior of the fortress and a 10 m wide strip outside of the fortress and adjacent to one of its walls (Fig. 4). The purpose for the survey in this area is that the architecture on the outside of a fortress wall, particularly at a corner, provides valuable information as to the nature of its construction. One corner of the interior of the fortress could not be surveyed because of the unstable rock pile that is a remnant of wall collapse.

Figure 5 presents the quadrature data for the perimeter strip (Fig. 4) as gray-scales. There are a number of relatively low (negative) conductivity features apparent in the quadrature data but the one of interest here is near circular and

Figure 3. Close up photograph of the stone wall construction at the Pre-Pottery Neolithic site.

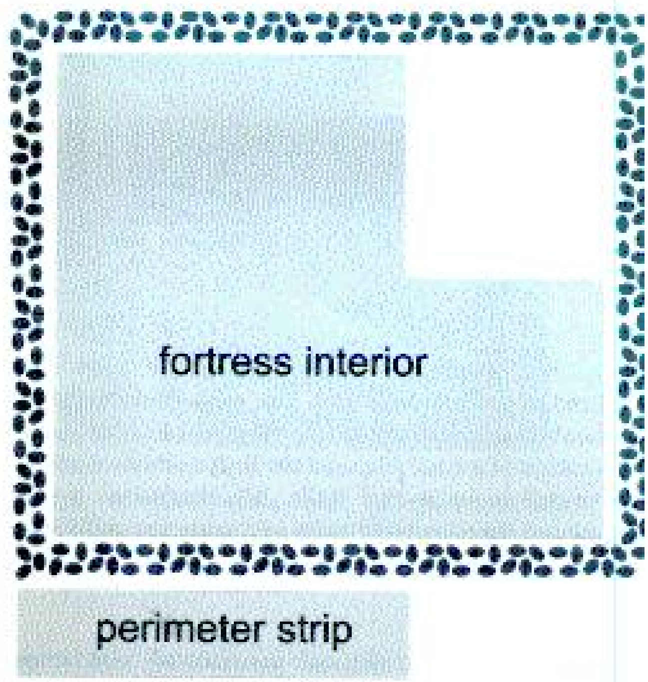

Figure 4. Map showing the two surveyed fortress areas, one within the stone-wall enclosure and a 10-m wide strip immediately outside.

marked by the solid circle in the figure. Based on this information and surface artifacts, Jordanian archaeologist M. Najjar believes this to be a tomb. Based on past experiences with EMI in mapping buried stone walls in Jordan, it is likely that the tomb is built of stone and appears in the quadrature data because the stone walls have a lower electrical conductivity than the non-negligible conductivity of the surrounding soil. Stone walls typically occur as linear or rectilinear patterns, and this pattern is mimicked in the EMI quadrarure data. Because EMI data were assumed to be acquired by walking straight parallel lines at a constant speed, there can be some deviation to this pattern resulting from slight deviations in both walking speed and direction. Potential buried stone walls are annotated as black lines on Fig. 5. The area of low quadrature response within the dashed circle on Fig. 5 is a pile of rocks. This area appears as a relative low because the measured response is that of the soil. The reduced response within this area is not a direct result of the presence of the rock pile but rather an indirect response associated with elevating the measurements above the soil. This occurs because both the transmitted and induced time-varying magnetic fields decrease with distance so that elevating the measurement point can diminish the measured response, even in the absence of changes in subsurface electrical conductivity.

A conducting object can be manifested in both the in-phase and quadrature components of EMI data. The relative responses in these components will depend on the object's

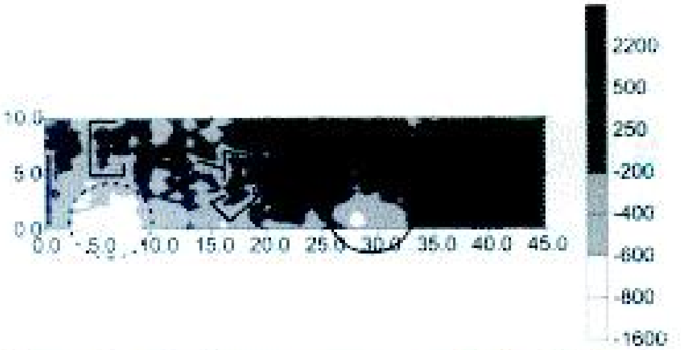

Figure 5. Quadrature component of the EMI data acquired at the Iron Age site. The solid circle indicates the location of a suspect tomb, the dashed circle shows the location of a rock pile, and the lines indicate features interpreted to be buried walls. All dimensions are in meters and the measured units are parts per million of the primary field.

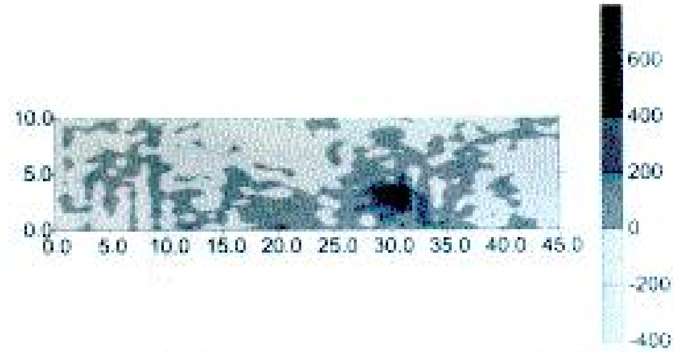

Figure 6. In-phase component of the EMI data acquired at the Iron Age site. The strongest response (rendered in black) is believed to be metal artifacts within the tomb. All dimensions are in meters and the measured units are parts per million of the primary field.

electrical conductivity, magnetic permeability, size, shape and orientation relative to the illuminating field (Won *et al.*, 1998). Magnetic permeability only influences the in-phase response and only at relatively low frequencies. For the high frequency considered here (15,210 Hz), high conductivity objects, particularly those made of metal, generally produce a much stronger response in the in-phase component of the EMI data. Of all sites in Jordan surveyed to date, it is only this particular area that offered any useful in-phase information. The companion to the quadrature data shown in Fig. 5, in-phase data is presented in Fig. 6. There is one strong in-phase response (black) evident and this is nearly coincident with the tomb. This suggests that there is a metal artifact, or a group of metal artifacts, within the tomb. If the in-phase and quadrature components produced responses to the same feature, these responses would be perfectly coincident. Comparing Figs. 5 and 6, it is clear that the in-phase and quadrature responses associated with the tomb and metal artifact are not quite coincident suggesting that these responses are associated with adjacent but different features.

Within the fortress, both the quadrature component of EMI and magnetometry provided results of archaeological significance. Figure 7 presents the EMI quadrature response within the fortress area as a gray-scale plot. As in the strip outside of the fortress (Fig. 5), there is some evidence of buried stone walls and these are annotated by black lines. The surveyed area would be a rectangle if not for the missing quadrant in the upper right. This area was omitted because it is too steep for data acquisition. This is a large stone pile which is presumably a result of the collapse of a large structure associated with this corner of the fortress. The relative low, apparent in the vertex of the missing corner, is associated with elevated measurements over the lower reaches of this large stone pile.

Magnetic data within the fortress was acquired using a Geometrics 858 cesium vapor magnetometer. As with the EMI data, acquisition was carried out by walking straight parallel lines at one meter spacings and sampling at a rate of five samples per second. Assuming that the walking speed is constant and that the walking lines are truly straight, the acquired data can be interpolated onto a regular grid and subsequently plotted. Figure 8 presents the magnetic data as gray-scale plots. As annotated by the circles, there are 18 magnetic anomalies that appear as distinct dipoles. Visual inspection suggests that these features are approximately the same size, orientation, and depth. Furthermore, their pattern does not appear random, indicating that their relative positions have some yet to be determined significance. It should also be noted that these features do not appear on the EMI in-phase data. This would imply that either these objects are non-metallic or are composed of a ferrous metal but are too small to be detected with the GEM-2.

The intent of the magnetic survey within the fortress was to determine the presence of magnetic features that could be ferrous artifacts. For this reason, and because of time constraints, data were acquired in the above-described manner. To further quantify these features, their characteristics were estimated using a Levenberg-Marquardt algorithm (Press *et al.*, 1992). This procedure is similar that given in Norton and Witten (1998) where the coordinates and components of the dipole moment of each magnetic feature are estimated from localized data. Because the magnetic data acquired within the fortress shows some spatial variations in the background field (Fig. 8), the non-linear estimation procedure was extended to simultaneously estimate variations of this background field. It should be noted that estimations of this type are sensitive to spatial measurement density and position accuracy. Had the presence of these

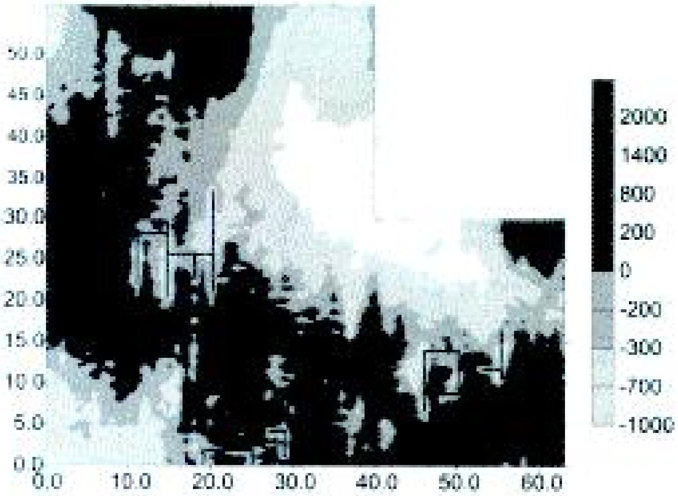

Figure 7. Quadrature EMI data acquired within the fortress at the Iron Age site. Lines indicate suspected buried stone walls. All dimensions are in meters and the measured units are parts per million of the primary field.

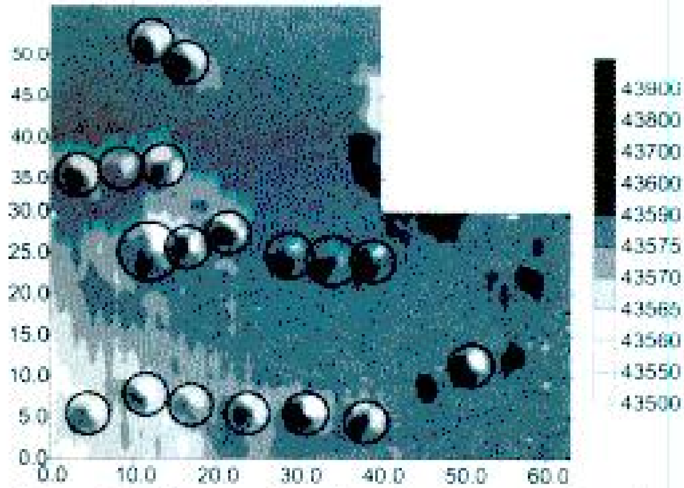

Figure 8. Gray-scale plot of the magnetic data acquired within the fortress at the Iron Age site. Similar dipoles are circled. All dimensions are in meters.

magnetic features been anticipated, a more rigorous data acquisition procedure would have been executed.

The estimation yielded depths to magnetic features that vary between 15 cm and 1 m, with almost all occurring at depths between 30 and 80 cm. The dipole moment estimates indicate that almost all features have their dipole moments oriented near vertical but the estimates of the magnitude of the dipole moments vary by almost 100%. Several factors should be considered in reviewing these estimated parameters. First, the area within the fortress is not flat. There are slight irregularities in surface elevation that occur both gradually and abruptly. This topography likely post-dates the site so that variations in estimated depth may be accurate. In this case, these features were either all buried at the same depth or were placed on the ground surface. Furthermore, the estimation procedure assumes that all measurements are made at the same elevation. Variations in measurement elevation that occur locally as a result of walking over small piles of stones are not properly accounted for in the estimation procedure, leading to inaccuracies in all estimated parameters. There are additional inaccuracies in horizontal position that result from deviations in walking straight lines. These occur because there are obstacles within the fortress, such as large boulders, that were walked around rather than over. Evidence of this is apparent in the circled magnetic feature at about (25, 5) in Fig. 8. This magnetic feature has two negative poles. It is unlikely that this is actually the case, but rather a result of passing over the same spot on two successive walking lines. One measure of how well the estimated dipole moment parameters fit the data is to use these estimates to forward model the data. This was done for each of the 18 magnetic anomalies and the synthetic responses subsequently subtracted from the measured data. For most of the features, the dipole anomaly was totally removed by this subtraction leaving only several nT of noise. The parameter estimation was less robust for a small number of features, particularly the one with two negative poles, where clear dipole responses remained after subtraction of the synthesized response. Figure 9 shows a comparison of the magnetic data in the vicinity of one dipole anomaly and the data synthesized based on the estimated dipole parameters for this feature. As is expected, the contours for the modeled data is smooth while the those for the actual data are far more irregular with evidence of the spatial variations that are not associated with a single dipole source.

The Copper Mine

An ancient copper mine in southwestern Jordan was surveyed with EMI during the summer of 2000. The copper ore body underlying this site is part of the DLS (Dolomite Limestone Shale) unit that characterizes much of the Faynan area. The mineshafts and tailings spread over an area that encompasses approximately 7.54 hectares. According to Hauptmann (Hauptmann 1989), the DLS ore body was first exploited during the Early Bronze Age. Copper ore is known to exist at this site because seams are visible at outcrops. It is known that this site was previously mined because of a partially open drift on a steep slope. Furthermore, there are mounds on the site that have a cone shape. These features are debris piles around vertical shafts used to access the copper seams. As mining proceeded, spoils were deposited at the vertical shaft openings producing mounds that would eventually slump, giving rise to their characteristic shape. Over time, these shafts have completely closed as a result of collapse and depositional

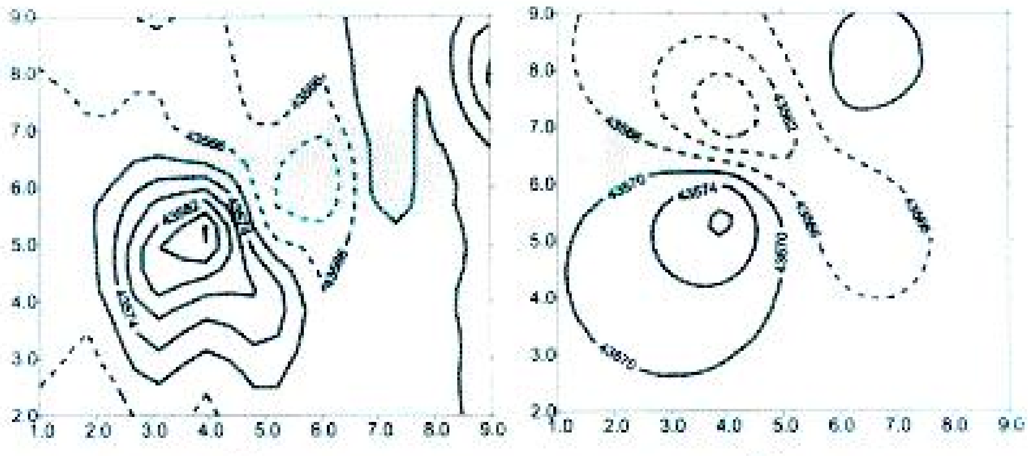

Figure 9. Contour plot of (a) the magnetic data as measured in the immediate vicinity of a dipole anomaly and (b) forward modeled data based on the estimated dipole source parameters.

forces. At this site, mineshafts cluster in two areas. The first and largest of these is about 3.84 hectares and consists of a small plateau delineated on the north and south sides by secondary drainage channel. Additional mines are located on a relatively steep limestone incline facing north and overlooking the main mineshaft cluster.

The quadrature component of the EMI data clearly reveals the presence of the former shafts as near circular low responses. Figure 10 shows the EMI quadrature data as gray-scales around one such mound. Rather than one shaft within the mound, three are clearly evident. Two of the most important discoveries made by the EMI study relate to the pattern of vertical mine shafts and the ore bodies themselves. The discovery of a cluster of three mineshafts suggests two main phases of mining. The largest shaft probably dates to the Early Bronze Age while the two smaller shafts nearby were probably constructed during the Iron Age.

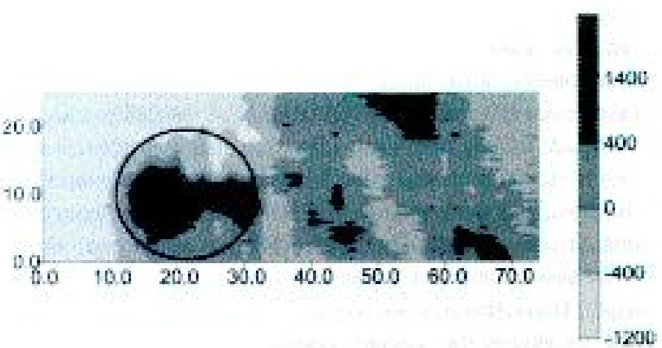

Figure 10. EMI quadrature data showing three vertical shafts within a single mound at a formerly utilized copper mine. All dimensions are in meters and the measured units are parts per million of the primary field.

Conclusions

EMI has been successfully used at a number of archaeological sites in southwestern Jordan. It was discovered that buried stone walls can be delineated in the quadrature measurements and this is likely a result of a small, but measurable, differential moisture content. These measurements can be made quite rapidly and have proven to be an effective means to identify areas where buried architecture is present. Results of this type can serve as a guide for archaeological excavation. At an ancient copper mine site, EMI measurements identified a pattern of vertical shafts that provided insight into the periods over which this site was exploited.

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