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Archaeological geophysics: 3D imaging of the Muweilah archaeological site, United Arab Emirates

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ABSTRACT

The sand-covered Muweilah archaeological site in the United Arab Emirates (UAE) is a unique Iron Age site, and has been subject to intensive investigations. However, excavations are time consuming and may require twenty years to complete. Thus geophysical surveys were undertaken with the objective of characterising the site more expeditiously. This paper presents preliminary results of these surveys.

Ground penetrating radar (GPR) was tested as a primary imaging tool, with an ancillary shallow time domain EM (MetalMapper) system. Dense 3D GPR datasets were migrated to produce horizontal (plan view) depth slices at 10 cm intervals, which is conceptually similar to the archaeologists' excavation methodology. The objective was to map all features associated with anthropogenic activity. This required delineating extensive linear and planar features, which could represent infrastructure. The correlation between these and isolated point reflectors, which could indicate anthropogenic activity, was then assessed. Finally, MetalMapper images were used to discriminate between metallic and non-metallic scatterers.

The moderately resistive sand cover allowed GPR depth penetration of up to 5 m with a 500 MHz system. GPR successfully mapped floor levels, walls, and isolated anthropogenic activity, but crumbling walls were difficult to track in some cases. From this study, two possible courtyard areas were recognised. The MetalMapper was less successful because of its limited depth penetration of 50 cm. Despite this, the system was still useful in detecting modern-day ferruginous waste and bronze artefacts.

The results (subject to ongoing ground-truthing) indicated that GPR was optimal for sites like Muweilah, which are buried under a few metres of sand. The 3D survey methodology proved essential to achieve line-to-line correlation for tracking walls. In performing the surveys, a significant improvement in data quality ensued when survey areas were flattened and de-vegetated. Although MetalMapper surveys were not as useful, they certainly indicated the value of including other geophysical data to constrain interpretation of complex GPR features.

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INTRODUCTION

Muweilah in the United Arab Emirates (UAE), is at present the only known Iron Age II (1100–600 BC) site in the arid desert zone of southeastern Arabia (Magee, 1996) (Figure 1), and is subject to intensive excavations by Sydney University. Full characterisation of the site by conventional archaeological techniques could take up to twenty years. Since this is not feasible in terms of time, money, or heritage purposes, trial geophysical surveys were undertaken in February 2001 with the objective of characterising the site far more rapidly. It was hoped that geophysics can be used as a broad-brush technique to target much smaller zones of interest for detailed excavation.

Three-dimensional (3D) ground penetrating radar (GPR) was tested as a primary imaging tool, with a very shallow time-domain EM system (MetalMapper) in a supporting role. The datasets presented form a subset of the study, and are chosen to highlight the usefulness of using geophysics at a sandy desert archaeological site.

The material complexity of the site is significant and is attested by the first evidence of writing (Magee, 1999), iron (Magee, 1998), knowledge of bronze working, and the presence of long-distance exchange networks (Magee, 1996). In addition, the site has sophisticated interlocking mud-brick (*pisé*) and stone and *pisé*

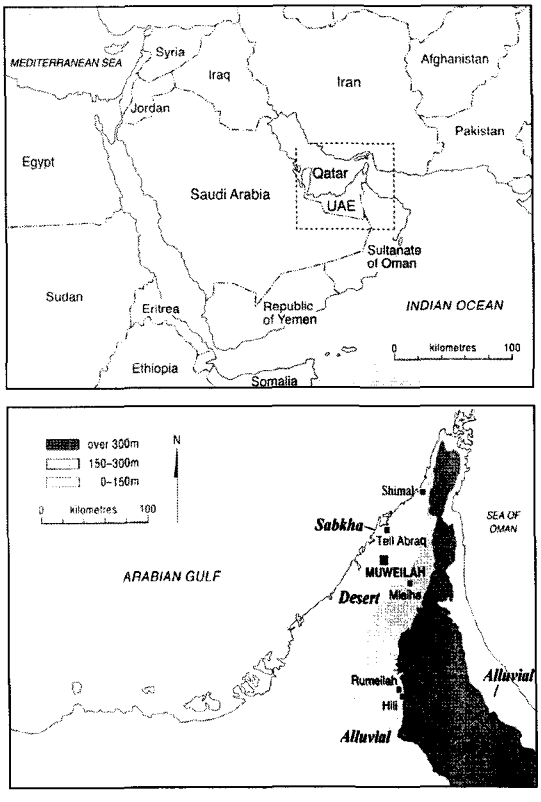

Fig. 1. Maps showing the location of the United Arab Emirates and Southeastern Arabia (comprising the UAE and Oman). Muweilah lies about 15 km from the coast in the desert zone of Southeastern Arabia.

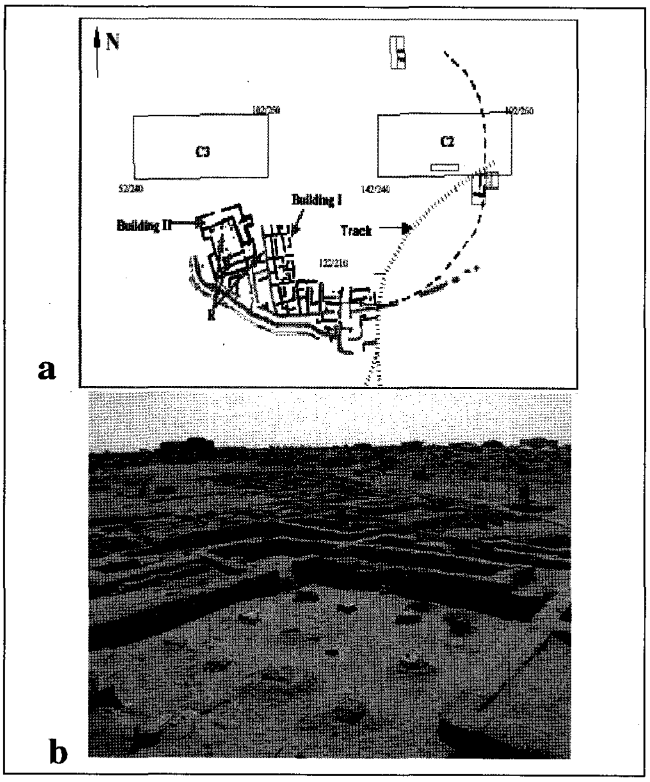

Fig. 2(a). Plan view of the ~1 ha excavated site, and the location of survey areas C2 and C3 marked with their coordinates in metres. *Pisé* walls are in black, and stone and *pisé* walls are in grey. The enclosing outer wall, inferred from previous magnetic gradiometry interpretations, is shown by a dashed line. The reconnaissance areas for the MetalMapper are indicated by the letter R.
(b). Partial view of the excavations, showing walls, floors, and column bases in the foreground.

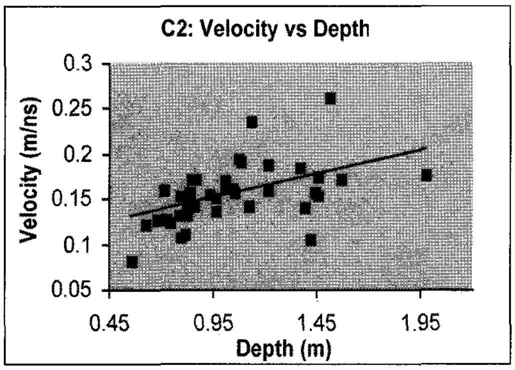

Fig. 3. Velocity analysis for area C2, showing velocities that were picked from hyperbolae. A linear regression through these hyperbolae is also shown.

walls—features that are unparalleled in other Arabian Iron Age sites (Magee, 1996) (Figure 2). Muweilah consists of numerous small rooms possibly used for domestic occupation (Building I) and a large columned building (Building II) that may represent the economic and political centre of the site. The presence of this extensive settlement challenges previous assumptions that such arid environments were too hostile to be habitable (Magee, 1996).

A stone and *pisé* wall encloses the entire settlement, and the location of this is partially inferred from magnetic gradiometry surveys undertaken in 1998 (Blau et al., 2000) (Figure 2). Magnetics also identified other archaeological features such as pits and ovens, but results were heavily affected by modern-day waste such as corrugated iron sheeting. Furthermore, the effective depth sensitivity of gradiometry was only about 1 m, which precluded investigation of significant areas under thicker sand cover. Magnetics is also insensitive to features such as bones, pots, or stone walls.

GPR along with EM were therefore used at Muweilah in an attempt to overcome the limitations of the magnetic gradiometer. It was hoped that GPR would provide not only good depth penetration, because of strong dielectric contrasts between the sand and archaeological features, but also a 3D image of the site. EM was used to support the GPR interpretation by mapping out bronze artefacts, and delineating the presence of modern-day metallic waste that could cause spurious GPR anomalies.

SITE DESCRIPTION AND METHODOLOGY

The walls at Muweilah are normally buried beneath 0.2–2 m of unconsolidated sand, depending on surface topography. Floors are generally 0.5–1 m deeper than the wall level (Figure 2b). These are often just natural floor levels underlain by a palaeo-surface consisting of fossilised dunes. Factors complicating the application of GPR are mobile aeolian sand dunes up to 2 m in elevation, which were sporadically covered with scrubby vegetation, as well as modern-day waste (including corrugated iron sheeting) buried shallowly to a depth of tens of centimetres.

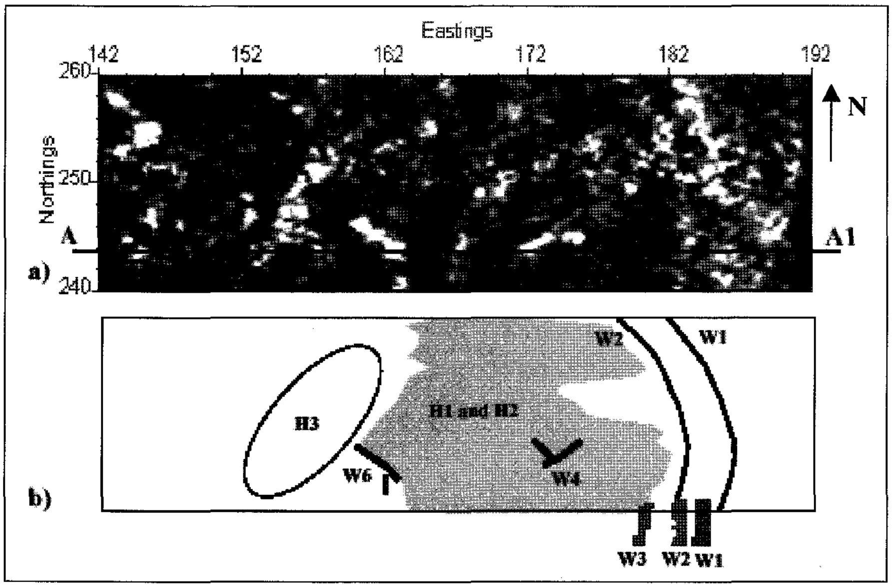

Fig. 4(a). 3D-migrated depth slice in area C2 at 1.0 m (archaeological level). A–A1 shows the location of the cross-section shown in Figure 5.
(b). Interpretation of features appearing in the depth slice in (a), together with existing archaeology in solid grey. W1 & W2: stone and *pisé* walls; W3, W4 & W6: *pisé* walls. Shaded zone: courtyard area with sand dunes (H1) truncated by hard-packed floors and bounded at depth by geological beds (H2). H3: geological cross-bedded structures.

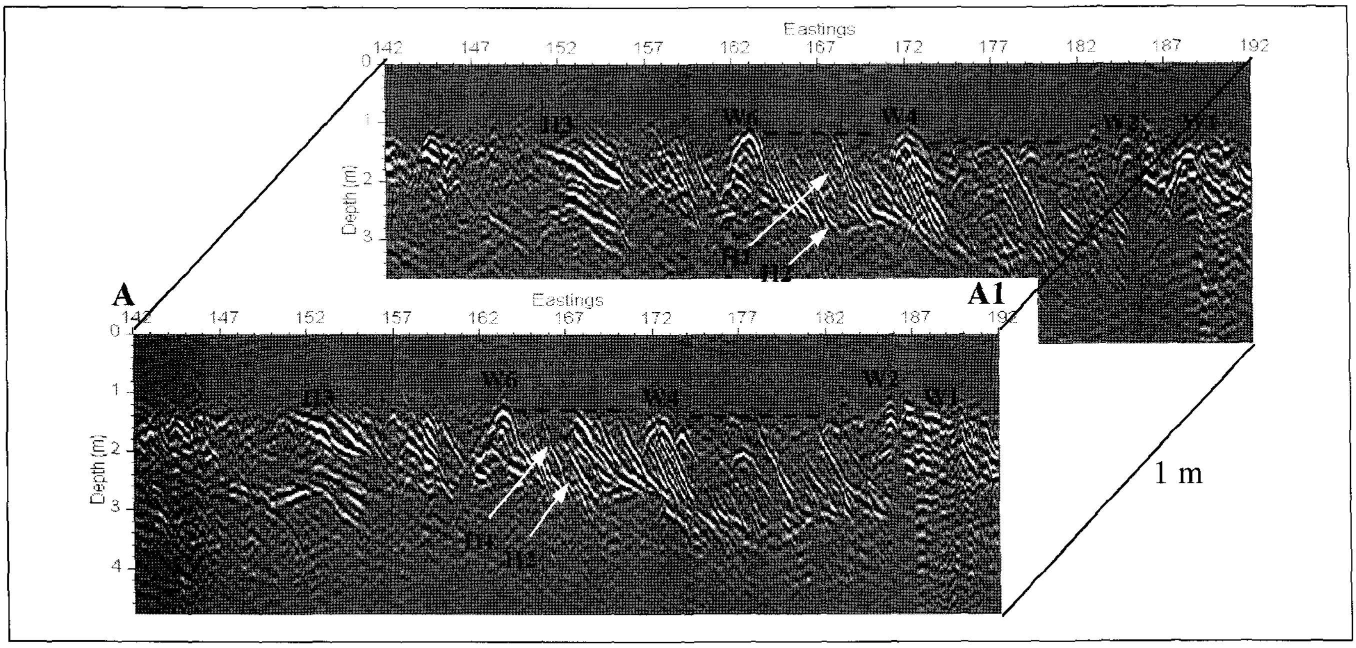

Fig. 5. Two typical east-west cross-sections from area C2 with 1 m line spacing between profiles. Location of A–A1 is shown on Figure 4a. Features H1 are east-dipping sand dunes truncated by hard-packed floors (dashed lines) and bounded at depth by near-horizontal geological beds (H2). W1 & W2: stone and *pisé* walls; W3, W4 & W6: *pisé* walls. H3: geological cross-bedded structures. Note the continuity of all the features between the two cross-sections.

GPR data were acquired (using a GSSI 500 MHz SIR-10 system) from two focus areas: C2 and C3 (Figure 2). Both areas are 50 m x 20 m in size, and they were surveyed in both the east-west and north-south directions to detect structures running in perpendicular directions. It was expected that walls could be difficult to correlate from line to line, thus a dense 3D dataset was essential.

It was hoped that cultural features similar to those in Buildings I and II would be detected in these areas. These include steps, walls, and column bases, as well as smaller features such as groundstones, ceramic vessels, and bronze and iron artefacts.

Area C2 was surveyed to benchmark previous magnetic gradiometry data, and to delineate the outer wall. Line spacings of 0.25 m were used, based on the expected depth to archaeological features being about 0.5–1 m.

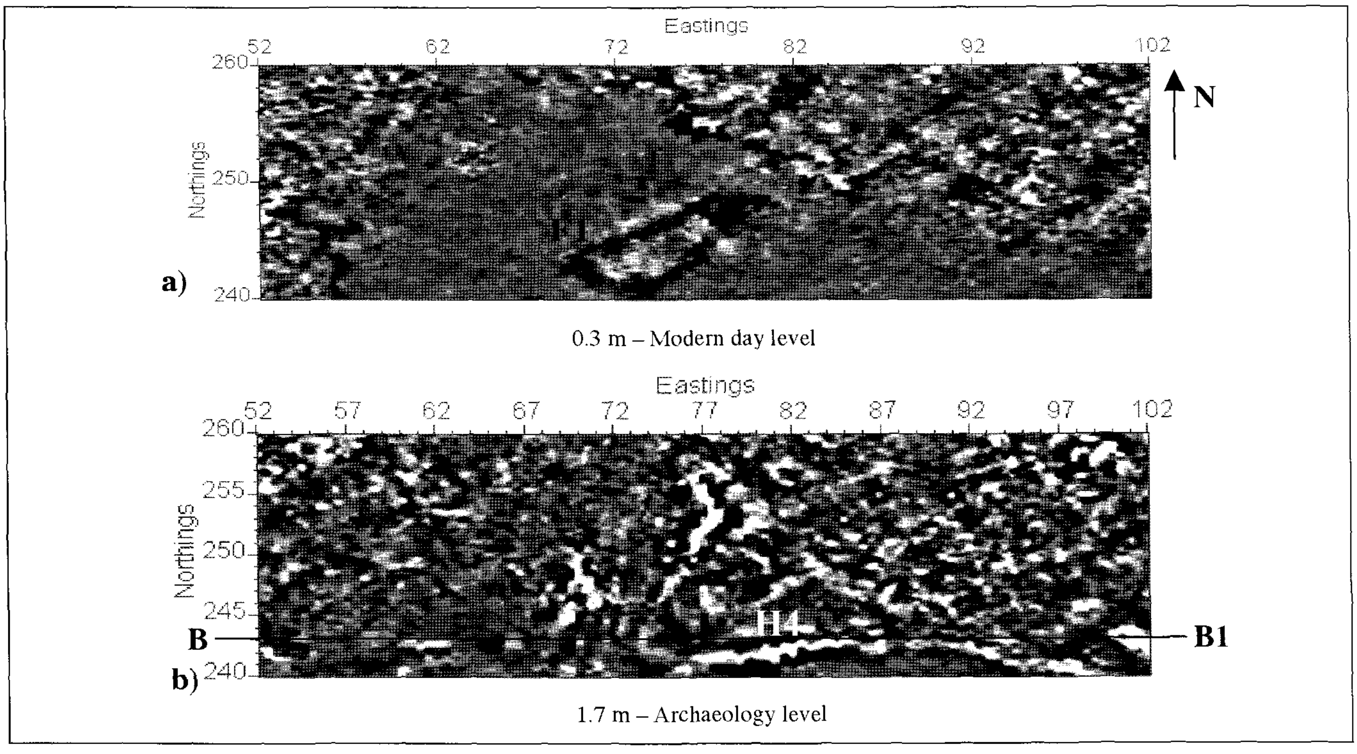

Fig. 6. 3D-migrated depth slices in area C3 at 0.3 m depth (a), and 1.7 m depth (b) (archaeological level). H4: extensive floors—probably defining a courtyard area and F1: polygon feature—probably modern-day refuse. Line B–B1 is the location of a cross-section that is shown in Figure 7.

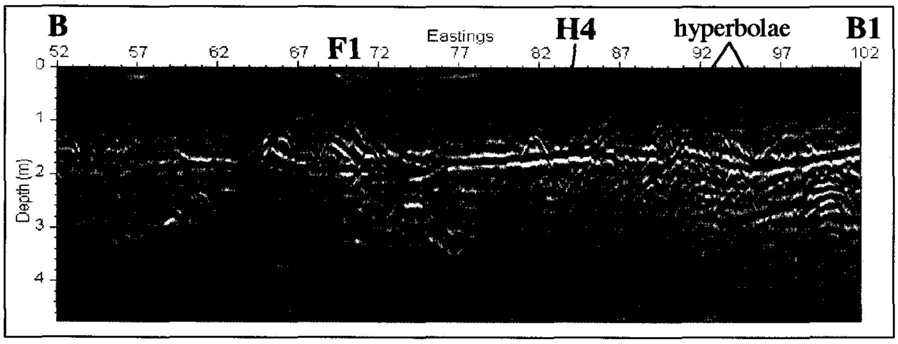

Fig. 7. Typical cross-section from area C3. The location is shown on Figure 6 (B–B1). F1: polygon feature and H4: floor surface. Notice the numerous hyperbolae above H4.

Area C3 was surveyed to delineate the outer wall, which is thought to continue through this area, and to establish the capability of providing penetration through thicker sand cover, where previous magnetic gradiometry surveys were ineffective. The area is relatively flat with hardly any vegetation as 2 m of the overlying sand was removed by bulldozer prior to surveys. Line spacings of 0.5 m were used and the expected depth to features was about 1.5 m.

The Geometrics MetalMapper is a high-frequency time-domain EM (TDEM) system with a data logger. Transmitting and receiving is achieved through the same flat coil, which is embedded in a circular "dish", and in appearance it is similar to a metal detector. The MetalMapper however, has an added imaging capability and a depth penetration of about 0.5 m. As with all TDEM systems it is only sensitive to relatively conductive targets. The MetalMapper was used to support the GPR, which cannot discriminate between metallic and non-metallic targets.

The MetalMapper system can map in the AC (alternating current) and DC (direct current) modes. The AC mapping mode was preferred as the signal drifted extensively in the DC mode. Areas C2 and C3 were mapped at line spacings of 0.5 m.

The actual signal output appears to be a combination of induced electromagnetic field responses measured at different time gates, with the gates chosen to enhance the response of highly conductive targets. The time gates and combinations thereof were not however clearly defined in the system documentation. The data were therefore used empirically, with the assumption that it provided some qualitative measure of the product of target conductivity and size, much as for a conventional large-scale TDEM system.

The reconnaissance mode (where the system is used to detect isolated anomalies in real-time) was also used in the area of active excavation (indicated by the symbol R in Figure 2). The advantage of applying the system in this area is that most of the sand and associated modern ferruginous waste had already been removed. Unlike the mapping mode, however, data are not digitally recorded in the reconnaissance mode. Instead, the operator recognises anomalies by the variation in the sounds generated by the MetalMapper.

DATA PROCESSING

GPR data were processed using the Centre for Mining Technology and Equipment's Seiswin software package. Datasets were filtered prior to 3D migration to remove coherent and incoherent noise. The processing stream began with 1D frequency-domain filtering to remove high- and low-frequency noise, median subtraction to remove horizontal banding, and a median filter to reduce random noise. Velocity analyses were also undertaken to convert radargrams from two-way time to depth, and as a crucial preparatory step in determining the quality of 3D migrations.

Velocities were extracted by interactively matching Seiswin computer-generated hyperbolae to the real hyperbolic diffraction patterns in the datasets. From this, it was recognised that there were apparently random lateral variations in velocity, and that the velocity seemed to be increasing with respect to depth in areas C2 (Figure 3) and C3. It was important then to incorporate a depth-varying velocity during migrations, as otherwise the reflections would not have effectively collapsed to their true subsurface positions.

Data were then migrated in 3D, using a Kirchhoff diffraction-stack migration, onto depth slices at 10 cm intervals to depths of ~2.5 m for both C2 and C3. Migrations are presented as horizontal (plan view) depth slices (Figure 4a and Figure 6a) to mirror the excavation style of investigating, then removing, one layer at a time. The MetalMapper dataset (in mapping mode) from C2 was also median filtered for destriping, and this is presented as a colour image in which warm colours refer to high intensities, and cool colours signify low intensities (Figure 8).

RESULTS AND INTERPRETATIONS

Ground penetrating radar

The highly resistive sand cover allowed GPR depth penetration of up to 5 m. Selected 3D-migrated depth slices from C2 and C3 are shown in Figures 4–7, along with un-migrated cross-sections. The interpretation of the migrated plan is complex, and relies on cross-sections and ground-truthing. Generally, three major types of features are observed: planar features representing floors and cross-bedded stratification (H1-H4); linear features which show up as strong individual hyperbolae on cross-sections and are easily recognised as linear on the migrated slices (W1, W2, W4, W6); and point sources recognised as isolated weak to strong hyperbolae on cross-sections, but not on the migrated plans. Most point sources appear to be archaeological, as they cluster around dominant features of obvious cultural origin, and they may relate to pottery or stone artefacts, or corner reflectors from small internal walls and steps.

In area C2, two significant outer stone walls (W1, W2) were recognised from both depth slices and cross-sections (Figures 4 and 5). This correlates well with excavations on the boundary of the survey area as well as the previous magnetic gradiometry data. The *pisé* wall (W3) was however not apparent in the migrated plans or the cross-sections. It may have been removed by erosion or fire. Another possibility is that the crumbling baked clay material used did not provide a sufficiently well-defined interface to cause a strong coherent reflection. Two internal walls (W4, W6) are also observed, with parts of W6 being confirmed by excavation. W6 is recognisably mud-brick in composition.

Floor surfaces (dashed lines in Figure 5) were recognised by the abrupt truncation of palaeo-features, which were later identified as fossilised dunes (H1). Although the east-dipping H1 features are not visible on the depth slices, they are clearly seen in cross-sectional profile (Figure 5). H1 is bounded at depths of ~3 m by a near-horizontal geological horizon of unknown origin (H2).

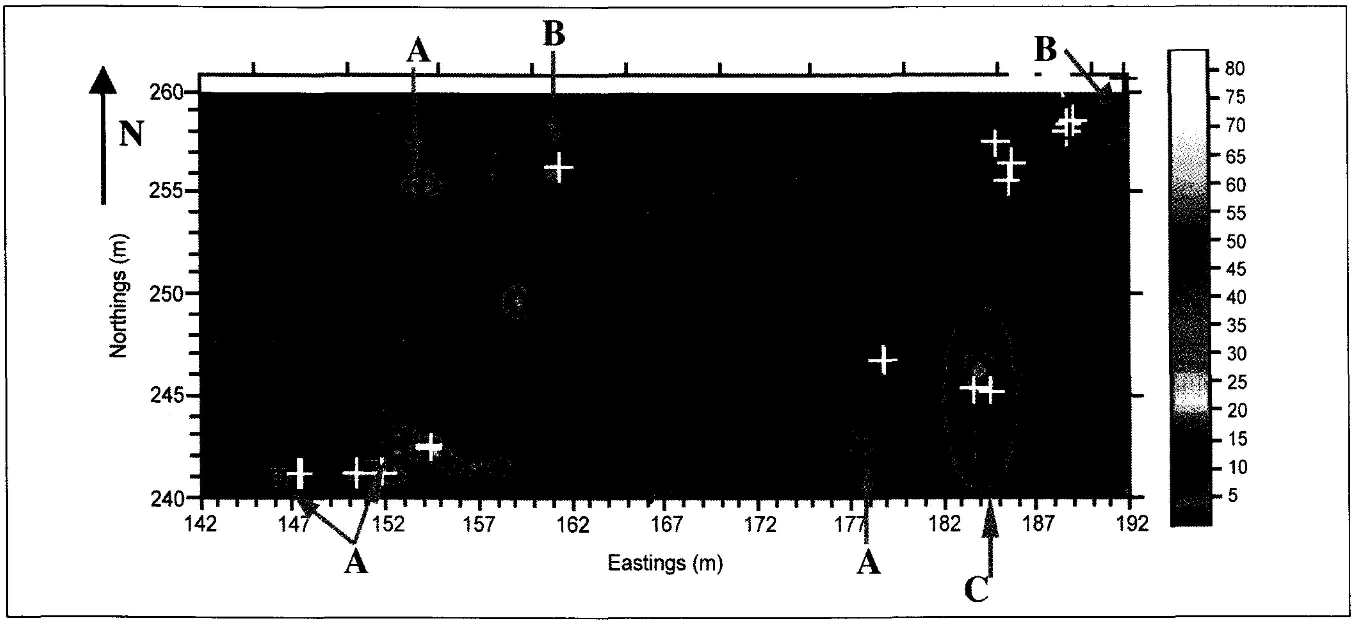

Fig. 8. EM intensity image from area C2. The crosses are anomalies detected during reconnaissance mapping. They are classified as strong (red), moderate (white), and weak (green). A: indicates strong correlations with GPR hyperbolae; B: indicates weak correlations; C: is associated with the wall (W2). Warm colours indicate strong intensity.

H1 and H2 extend through part of area C2, and from this it was concluded that the region represents a courtyard area. Archaeologists have recognised from previous excavations at Muweilah that courtyards are exposed to significant cultural activity, often acting as waste sites for discarded stone and ceramic artefacts. This supports the theory that H1 is a courtyard, as numerous hyperbolae representing small stone and ceramic finds are found above H1 (and confirmed by limited excavation). The area marked as H3 is thought to have geological cross-bedded structures.

In area C3, there was a complete absence of linear features indicative of wall or room-like structures (Figures 6 and 7). A strong polygonal feature (F1) was observed at a depth of 0.3 m (Figure 6a), but this is probably waste material as it is well above the expected depth to any archaeological features. F1 is also likely to be non-metallic, as it was not detected by the MetalMapper, which is very sensitive to metal objects.

Another striking feature is a strong planar structure (H4), conjectured to be the floor of another courtyard area as numerous hyperbolae are observed immediately above it (Figure 7). Although H4 is a planar surface, it appears linear in the depth slice (Figure 6b). This is because the feature is not completely horizontal and it varies in depth from 1.3–2.1 m, as observed from cross-sections.

It is interesting to contrast the interpretations of the planar features in areas C2 and C3: H1–H3 are conjectured to be geological in origin, based on the interpreted cross-bedding. H4, however, is thought to be archaeological because of the absence of apparent cross-bedding, as well as because of the presence of a number of hyperbolae above it, suggesting cultural activity. Such a well-defined floor is unusual at Muweilah, so the courtyard interpretation and the absence of linear features (as well as the absence of the expected stone and *pisé* boundary wall) are subject to test by excavation.

The data quality in area C3 is significantly better than that in C2. This is due to the improved coupling of the GPR signal to the ground over the flattened and de-vegetated surface. Variable coupling due to the rough terrain in C2 causes partial de-correlation of the data, requiring additional filtering to obtain acceptable migrated images. Considerable lateral variations in velocity were further inferred during the velocity analyses, and the inability to incorporate this information may have degraded the focusing ability of the migration step. These variations may be related to changes in moisture content.

MetalMapper

A full data image was acquired over C2 and is plotted in Figure 8, together with the positions of anomalies recognised during reconnaissance mapping. Data from the mapping and reconnaissance modes provide a useful cross-check on mapping reliability. The isolated anomalies were classified as weak, moderate, and strong (crosses), depending on the intensity of the audio detector. The majority of the crosses correlate well with high-amplitude zones on the images, with most being centred on the mapped anomalies themselves. The strong anomalies relate mostly to zones where ferruginous material was often visible on the surface. The anomalies seem to be clustered in distinct areas, with those marked A having strong correlations with GPR hyperbolae, B marking those having weak correlations, and the zone marked C being closely related to the wall (W2). Anomalies in the northeast corner most likely relate to an old spoil heap from previous seasons. The true origin of these anomalies will only be recognised after further excavation.

Calibration trials were conducted over a test strip under which metallic objects, differing in size and orientation, were buried at several depths. Results indicated that the maximum depth of penetration of the MetalMapper was about 50 cm, which is insufficient to reach floor levels in most areas. Consequently, the technique was most useful for tracking very shallow modern waste, and as a reconnaissance mode mapper over areas that have already been partially excavated. Due to its limited depth penetration, the system only has niche applications in shallower archaeological sites. These include partially excavated areas and in exploration for a possible gravesite at Muweilah (where larger metal artefacts are expected). Regarding general application within an archaeological setting, it would be of significant benefit if the depth penetration of the system could be increased to 0.75–1 m.

A full data image was also acquired over area C3, where archaeological features are expected to be buried under ~1.5–2 m of sand. As expected, there are very few anomalies detected due to the inferred 0.5 m penetration capability of the MetalMapper. Any bronze artefacts will thus be too deep to be detected. Furthermore, the area does not appear to be significantly contaminated with modern waste.

Data acquired in reconnaissance mode over the partially excavated area (R in Figure 2) were more useful than the mapping mode. This was because much of the sand overburden had already been removed and so the transmitter-receiver dish was closer to the cultural levels. A number of anomalies were detected, most of which were associated with small pieces of bronze.

DISCUSSION AND CONCLUSIONS

The highly resistive sand cover at the Muweilah archaeological sites allowed GPR depth penetration of up to 5 m. GPR successfully mapped planar features such as floor levels, linear features such as walls, and isolated anthropogenic activity. By careful spatial correlation of the various features, two possible courtyard areas were recognised. However, there was limited evidence for the interlocking rooms seen in other areas. In some cases crumbling walls were difficult to track. The reason for this must still be established. In the event that some walls are not detectable by GPR, alternative approaches such as resistivity imaging should be assessed.

The biggest challenges facing GPR in this application are that it maps interfaces indiscriminately (whether these are anthropogenic or not), and that spatially intricate dwellings can produce very complex GPR responses. It is thus important to use an inferred model for the site to guide interpretation and planning, and to incorporate other information sources in the interpretation.

The main limits on data quality were the varying topography, scrubby vegetation, and sand dunes, and it is proposed that such areas be flattened wherever possible. It is preferable however to conduct surveys before archaeological stripping has placed anthropogenic features too close to the surface. This has the effect of limiting the development of the characteristic hyperbolae associated with point reflectors, due to the limited angular aperture of the GPR antennas.

Changes in velocity as a function of moisture and sand variations may also have played a role in degrading the focusing achievable with the migrations. Vertical variations in velocity were accounted for, but the approach was not capable of incorporating some of the significant lateral variations that were observed. More sophisticated software is required to incorporate these variations.

The results (subject to further excavation tests) indicated that GPR is well-suited to assist archaeological investigations at sites like Muweilah, which are buried under a few metres of sand. The 3D survey methodology proved essential to achieve line-to-line correlation for tracking spatially complex three-dimensional features. Plan view migration of data was very useful in tracking linear and planar features, but is fundamentally ill-suited to the delineation of point reflectors. Thus, GPR interpretation will undoubtedly continue to require both plan view and cross-section formats.

GPR is capable of imaging some of the complex elements at Muweilah although further surveys will be required to assess precisely the detail to which GPR can map. It does appear however that GPR can fulfil the role of a broad-brush technique to rapidly assess large areas. Its use will guide the ongoing excavations by indicating areas of inferred cultural or geological activity.

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REFERENCES

Blau, S., Denham, T., Magee, P., Biggins, A., Robinson, J., and Jasim, S., 2000, Seeing through the dunes: Geophysical investigations at Muweilah, an Iron Age site in the United Arab Emirates: *Journal of Field Archaeology*, **27**, 117–129.

Magee, P., 1996, Excavations at Muweilah. Preliminary report on the first two seasons: *Arabian Archaeology and Epigraphy*, **7**, 195–213.

Magee, P., 1998, New evidence of the initial appearance of iron in southeastern Arabia: *Arabian Archaeology and Epigraphy*, **9**, 112–117.

Magee, P., 1999, Writing in the Iron Age: the earliest South Arabian inscription from southeastern Arabia: *Arabian Archaeology and Epigraphy*, **10**, 43–50.