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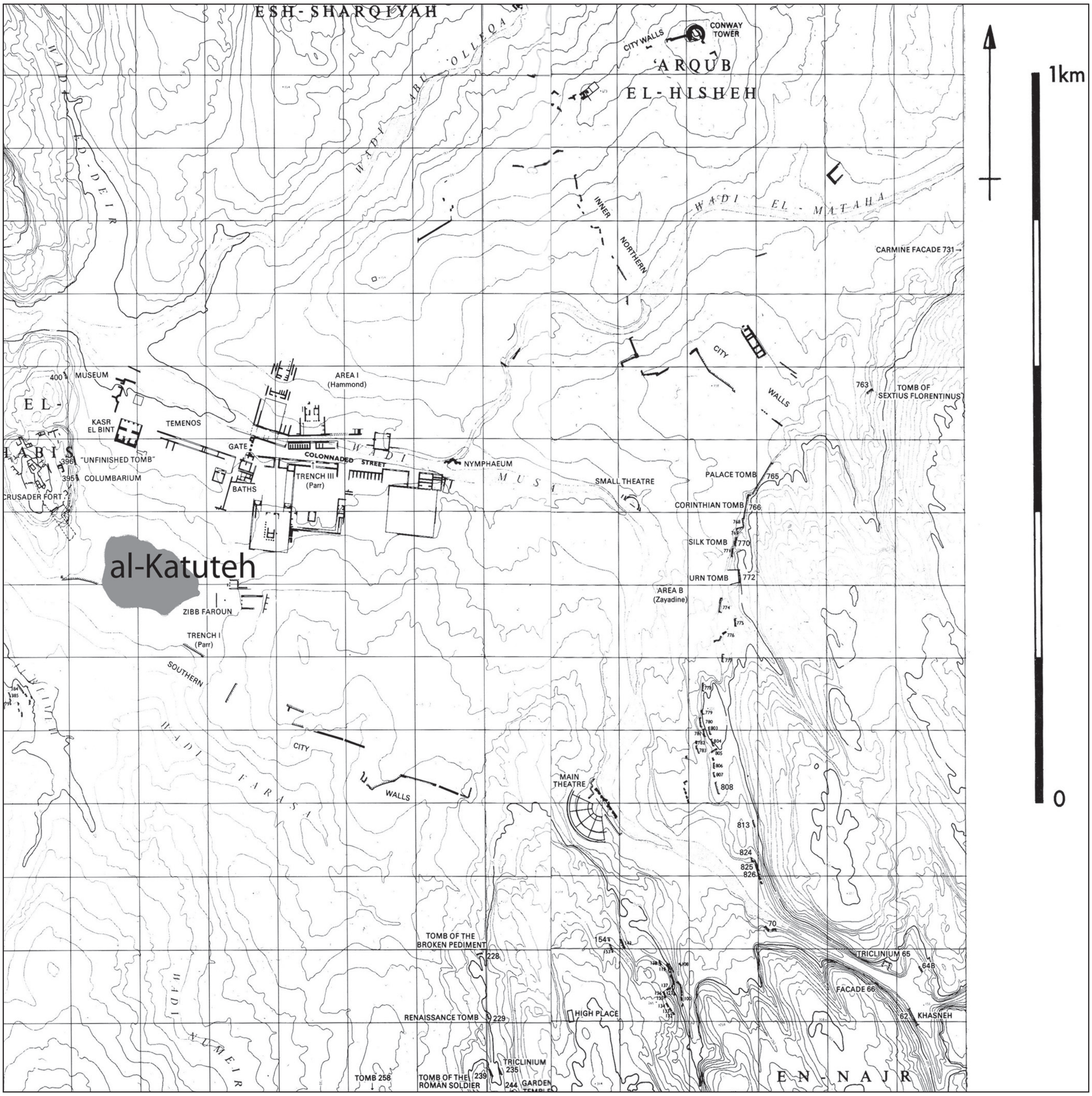
Geophysical Prospection at Petra: Methodical Research within the 2012 al-Katutah Campaign

Introduction: The Site and Excavation

The site of al-Katutah lies on a small hilltop in the centre of Petra (FIG. 1), rising to about 25 m above the valley floor. In January 2012 a joint research campaign by the University of Jordan, ʻAmman and the Johannes Gutenberg-University, Mainz resumed work on the hilltop site of al-Katutah in the centre of Petra (FIG. 1) where excavation was first carried out in 1981 by Khairy (Khairy 1984, 1986, 1990). The site, at the top of the slopes south of Qaṣr al-Bint and the colonnaded street, must have been significant for the urban development of Petra. Excavation located settlement layers from the second century BC to the late Roman occupation phase. While the preliminary archaeological results have been presented elsewhere (Koçak *et al*. 2013), this paper focuses on the geophysical and geoarchaeological exploration of the site.

The excavation concentrated on two areas on the hilltop of al-Katutah (FIG. 1). The trenches opened in Area E extended those of 1981. Due north, a paved courtyard clearly relates to that uncovered in 1981 (Khairy 1990: 3-5). The dimensions of the courtyard, and the location of its three enclosing walls, was determined by Ground Penetrating Radar (GPR -FIG 2). An unusual cistern, found at the western end of the courtyard, shows that the water supply system was far more complex than previously suspected. To the south several paved rooms from an early occupation phase also seem to relate to the court-system. However, later additions of walls suggest several phases of remodelling and possibly a change in the use of the building. Further excavation to the south and west is necessary to properly understand these complex structures. Evidence of early settlement was found in the southeastern trenches (Q12 and Q13) of the 2012 excavation. Several holes, which may relate to an early phase of tent usage within the Nabataean settlement, were cut in the underlying bedrock. Fragments of black-glazed pottery, from the layer covering these holes, show that they predate the second half of the second century or the beginning of the first century BC.

To clarify the wider context of these structures additional trenches were opened to the east of the hilltop, on the first terrace of the eastern slope (Area F). Here the pavements were much cruder and in large areas the floor consisted only of a flattening of the bedrock. Several superimposed walls indicate a long occupation period with a number of building phases up to Byzantine times. At present no immediate connection can be drawn between this area and the buildings on the hilltop. Geophysical survey, however, indicated a dense pattern of structures which may connect the two areas.

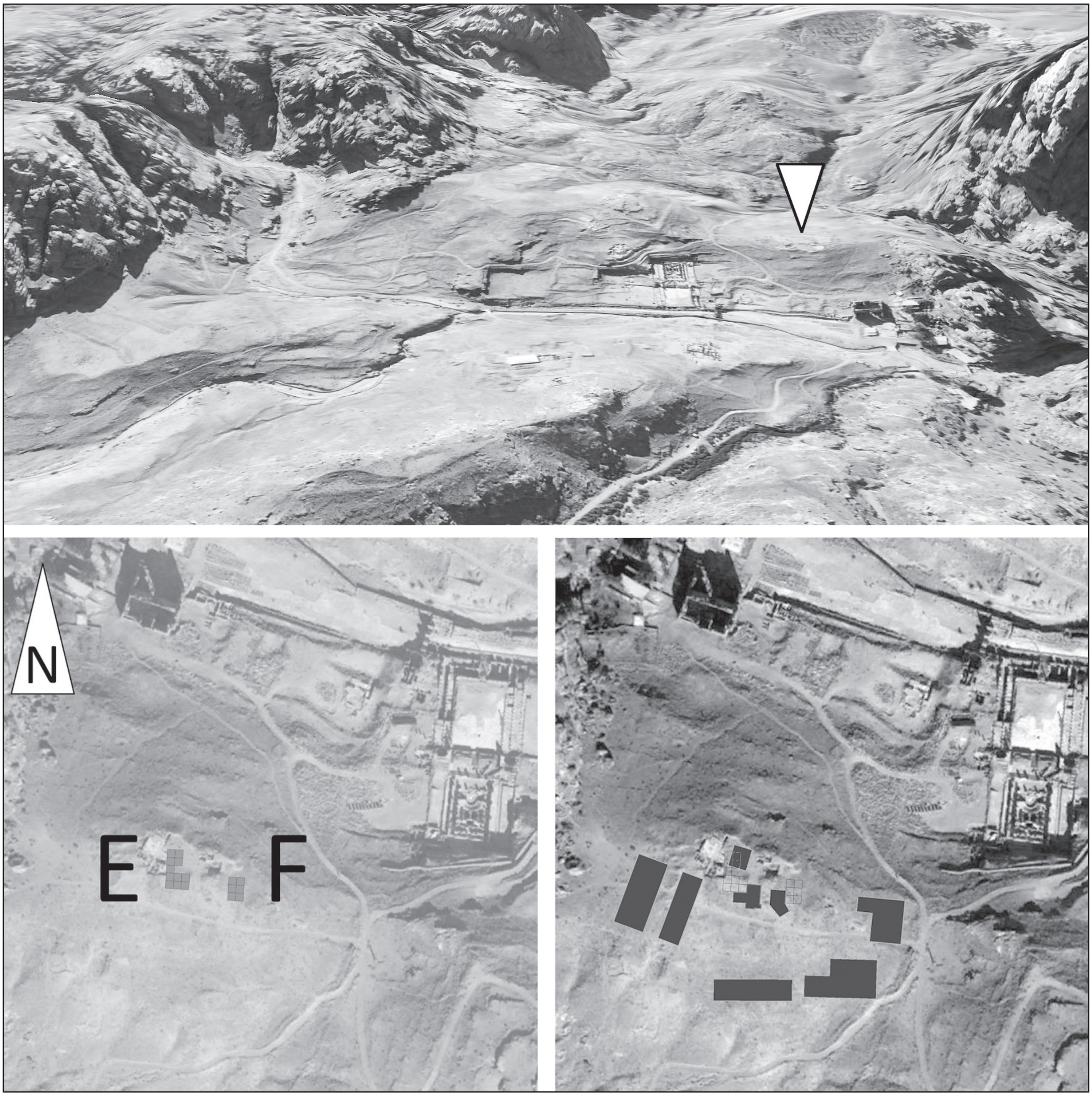


1a. The location of the site (McKenzie 1990: Map 7).

Archaeological Geophysics at Petra

A number of geophysical surveys have been carried out to map buried remains at Petra, with varying success. The earliest and most extensive, by Hammond in 1973 (Hammond 1974), was carried out using a combination of proton magnetometers, arranged as vertical gradiometers, and electrical resistance meters. The survey covered an area of 63900 m^2 – a considerable proportion of the site – at a spacing of 2 m between magnetometer readings. While the survey was not very successful in identifying potential remains it did enable Hammond to identify concentrations of building debris and thus define areas where excavation was likely to be more or less fruitful.

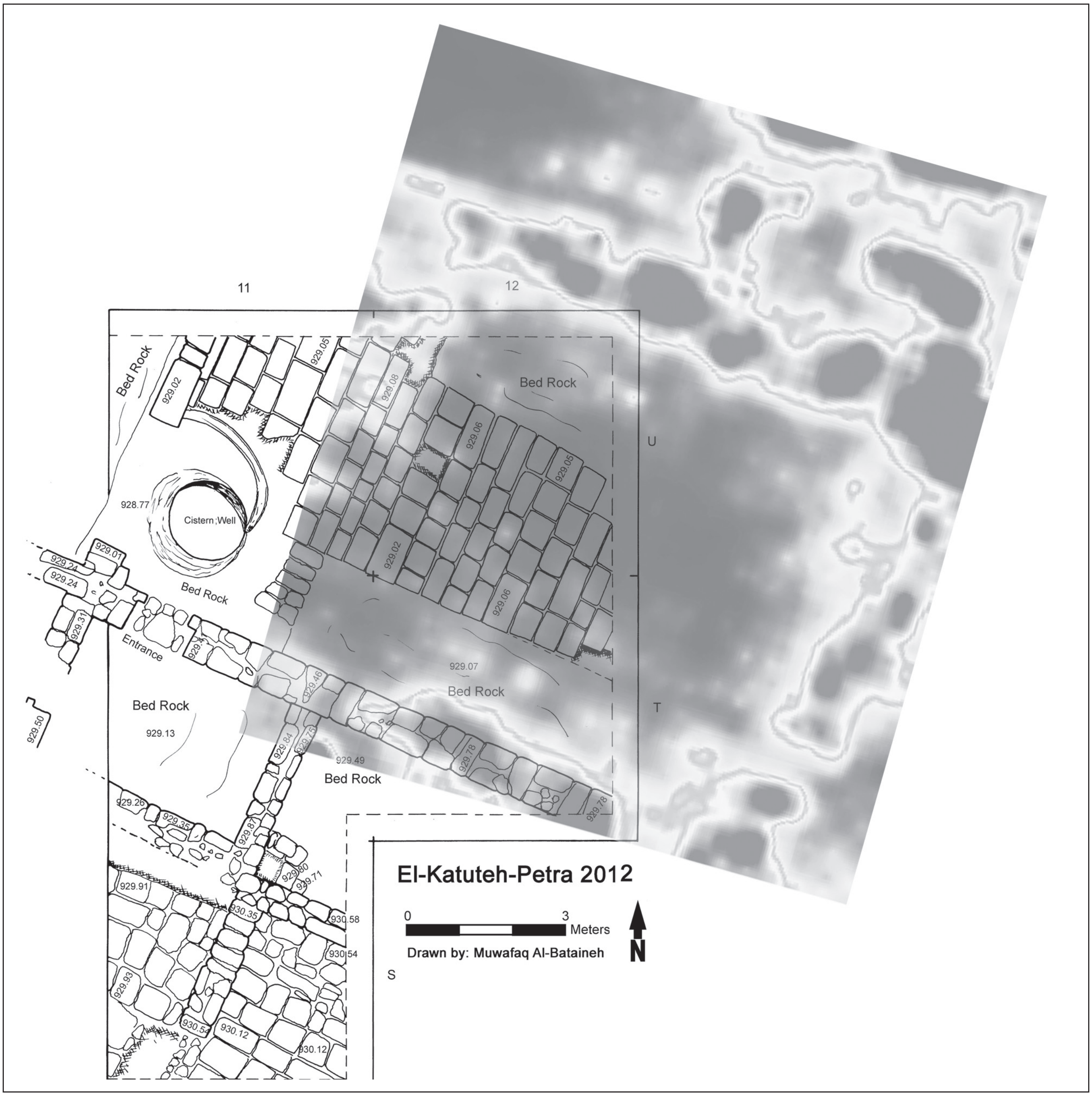
More recent surveys using ground penetrating radar (Conyers *et al*. 2002; Conyers 2011, Conyers and Leckebusch 2010; Urban *et al*. 2012; Urban *et al*. 2014) have identified a number of structures. They have, moreover, explored the difficulties in producing clear



1b. Excavation (left) and geophysical survey (right) areas (F. Berger/D. Jordan).

geophysical survey results in such a complex and diverse environment. Recent work near Petra (Urban *et al*. 2014) has demonstrated the value of more advanced geophysical data processing techniques and shown that there are further avenues to explore in the treatment even of routine geophysical datasets.

Archaeologists use a wide range of geophysical and remote-sensing methods to map buried remains without excavation. These can be very effective – revealing remains quickly and efficiently (Jordan 2009). But in complex sites, where there are many strongly contrasting geophysical effects, or in sites where remains are geophysically indistinct or deeply buried, they can entirely fail. A recent study by Bonsall *et al*. (2014) documented how even extensive geophysical survey using appropriate methods can fail to find significant remains over whole landscapes, with a considerable impact on site conservation. Such studies show how the right choice of method – in relation to the remains



2. Horizontal time-slice taken from the GPR survey across the paved courtyard. The reflections from the enclosing walls are shown (M Al-Bataineh/F. Berger).

being sought and their environment – can be crucial in effective geophysical prospection. Previous work, for example the Raunds multi-period survey (English Heritage 2008) has also shown that geophysical methods which are sensitive to the soil moisture state, especially electrical resistance survey, can produce much clearer images of buried remains when that state is optimal – but that judgements about what distribution of water this "optimal" state requires, and when and why that state occurs, are complex and poorly supported by our current knowledge.

Archaeological geophysics faces other challenges: we still do not know enough about the origins of the geophysical properties we detect in the components and structure of the remains themselves. Thus we are largely limited to interpreting geophysical survey results by matching the detected geophysical variations to

3. Buried walls typical of the al-Katutah site (M. Koçak/U. Mahler).

patterns of remains that we recognise by shape alone. We recognise, for example, that in the temperate, moist environments of northwest Europe, a stone wall buried in a fine-grained soil is likely to appear as a line of relatively high electrical resistance on an ER survey. There is, however, almost no published literature which describes the absolute bulk resistivity values of walls of different kinds, in different states of decay and in different environments. Extrapolations of the relative bulk geophysical properties of remains to very different environments, such as the dry soils of Petra, may not hold. Thus the surveyor cannot at present distinguish between variations in resistivity along the length of a wall which may be due to its depth, its structure or its context, nor extend such distinctions to new environments. This problem of under-interpretation is all the more acute for 3-dimensional survey techniques – essentially electrical resistance tomography and ground penetrating radar. Until we understand the 3-dimensional distribution of geophysical properties within remains, and the way they are affected by soil moisture behaviour over time, our interpretation of 3-dimensional surveys will be severely limited.

This sets the context for the research reported in this paper – the practical need to understand the range and origins of geophysical properties within buried remains, at Petra as elsewhere, in order to target survey methods effectively and interpret their results fully.

Though the complexity of buried remains makes such targeting and interpretation difficult, recent advances in geoarchaeology have significantly improved our understanding of the relationship between the origins of archaeological remains, their current components and structure, and their properties. This can be extended to exploring the origins of their geophysical property distributions.

Petra provides good opportunities for the development of such research. The site contains a range of archaeological structures, preserved to various degrees and buried within soils of a wide range of compositions in varying topographic situations. Exposed remains include, for example, well-jointed stone walls at less than 50 cm depth in fine-grained, stone-free strata on flat or gently-sloping sites. They also, however, include very poorly constructed walls, where stones are widely separated, and walls buried in stony strata at depths of 2m or more. Given this diversity we would expect geophysical prospection methods to provide clear images of some buried remains in some parts of the site but not in others, which corresponds with Hammond's observations (FIG. 6).

The importance of prospection at Petra has been underlined by a recent UNESCO report (35COM 7B.49), which emphasises the need to minimise excavation and thus to prioritise non-destructive methods. But for these to be useful, and well designed, we need to know what conditions influence the quality of results with each method, what is the distribution of such conditions and how they are further influenced by transient factors, especially by soil moisture. Thus prospection at Petra, obviously useful in itself to help preserve and study the site, needs to be targeted to those parts of the site where, on the basis of geoarchaeological criteria, our understanding of site geophysical behaviour predict that it will be most effective.

In order to address this our surveys and excavations at al-Katutah were designed to investigate the conditions affecting the geophysical detection of remains and their origins in the components and processes of site formation. We considered the prospection results in geoarchaeological terms – what clues exist as to how the components and origins of the soils, strata and structures produce the geophysical properties we detected? Given that the surveys and excavation could only examine properties in one small part of the site our work was also intended to establish a first set of simple, representative numerical models of typical buried wall remains. These, though naturally limited in generality and precision, could then be used to establish hypotheses about the geophysical behaviour of remains across the site, which we could test during future fieldwork. This current paper describes only the initial phases of this research which resulted from the brief campaign in 2012 but it sets the scene for future work.

The Geophysical Survey

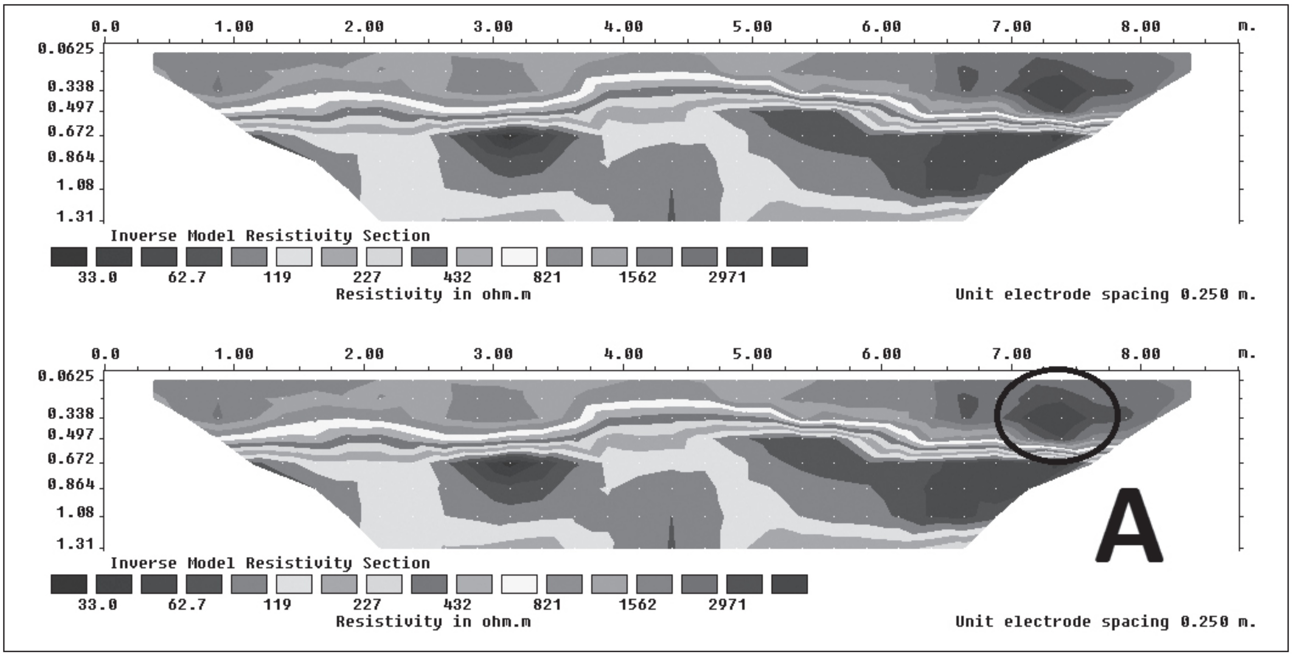
The excavations showed that parts of the al-Katutah complex were built on a natural, highly undulating sandstone surface which had been used as the floor of some buildings. The bedrock is a fine, light-coloured sandstone (Paradise 2005). The tops of the built structures were found to be buried within 50 cm of the soil surface. Vegetation is sparse, as across the whole of Petra, but the tubers and foliage of the Sea Squill (*Drimia maritima*) are common in patches and their roots extend to the rock beneath as well as between the stones of the built structures.

The presence of stone walls in a finer soil matrix, and the inference of occupation debris, suggested at the outset, that archaeological structures might be associated with contrasts in the electrical resistance, dielectric permittivity and magnetic susceptibility of the site. Thus it was inferred that survey with electrical resistance, magnetometers and ground penetrating radar might be fruitful. It was not possible in the time available to survey the whole of the hilltop so five areas of survey were completed around the hilltop and a further area around the excavations on the hilltop itself.

Electrical resistance tomographic (ERT) sections were recorded in eight areas of the site using a Syscal SwitchPro72 resistance meter. Measurements of resistance were recorded using double-dipole and Schlumberger arrays with 36 electrodes spaced 25 cm apart. The data were de-spiked and inverted using a Gauss-Newton algorithm with fixed horizontal regularisation of half the electrode spacing. Typical results (FIG. 4) show a complex pattern of resistivity distribution with variations between 30 and more than 3000 ohm-meters.

High, though variable, resistivity's (500 to more than 1000 ohm-metres) are associated with the uppermost 20 cm of the soil. The inverted profiles then show a sharp decline in resistivity with depth from the high surface values to values of 200 ohm-meters or less by 1 m. Finally some profiles show a rise, below 1 m, to values of 100-500 ohm meters.

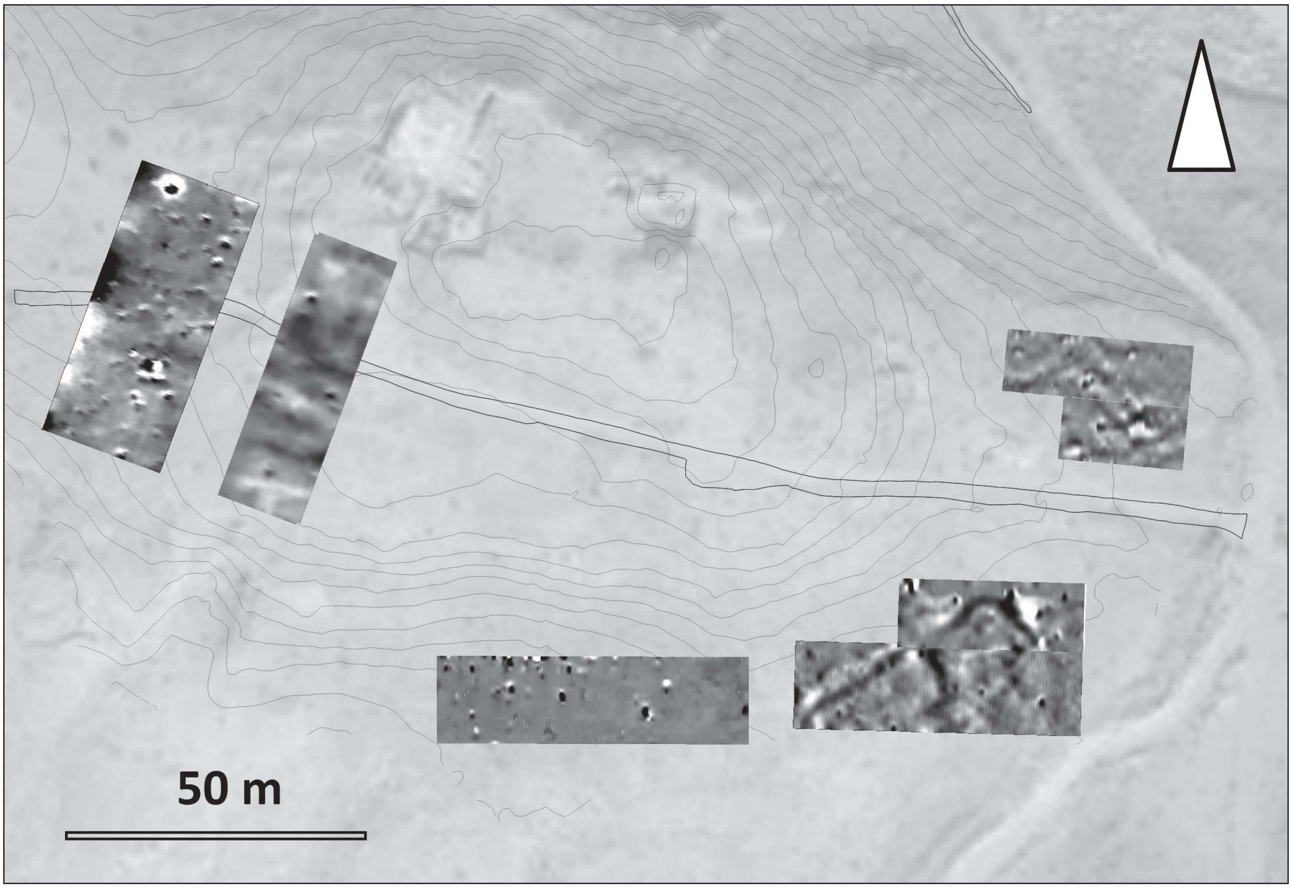
These values relate to the observed soil profiles. The high surface resistivity corresponds with the 20 cm-deep disturbed, loose, sandy surface horizon within which there are likely to be only resistive components and a lack of continuous conductive pathways in contact. The lower resistivities in the central 80 cm or more of the profile correspond with compact, firm strata which, though dry, present continuous



4. ERT sections. Circle A marks the location of the remains of a wall (D. Jordan).

5. GPR time-slice showing buried wall reflections in its topographic context (F. Berger).

pathways for conduction between the dominant grains of sand. The higher resistivities beneath correspond with the location of bedrock. In comparison with many igneous rocks the apparent resistivity of the rock is low since many of the Petra sandstones contain a high proportion of continuous pore-space filled with fine mineral matter through which conduction can occur. Thin sections of sandstones from the strata immediately overlying the rock surface show precisely such fine inter-pore fillings. Walls, confirmed by excavation, appear as volumes of bulk resistivity in a very wide range, between 200-3000 ohm-meters. These values appear consistent with the bulk resistivity of the sandstone from which the wall blocks was cut



6. Magnetic gradient values show coherent linear anomalies, corresponding to walls in the easternmost areas (F. Berger).

and the structure of the walls themselves.

Ground penetrating radar sections were recorded using a combined 200 and 600 MHz antenna along lines spaced at 50 cm intervals. The very stony ground made it difficult to move the antenna box smoothly over the surface and so larger stones were removed from some areas before each line was recorded. The GPR sections vary considerably in the clarity with which they reveal details of buried structures. It appears, however, that there is a progression of anomaly appearance from coherent to very incoherent. We hypothesise that this range is the result of variations both in the structure of the walls themselves and the distribution of coarse matter, fine matter and stones in the matrix around. This is, to some extent confirmed by our excavation data. Time-slices show the presence of the more coherent buried wall anomalies, clearly coinciding with well-constructed walls subsequently located in excavation. This is not, however, universally the case and further survey and excavation, as well as numerical modelling, are required to test whether this is the case.

The magnetometer survey was carried out with a 1 m Caesium gradiometer system taking measurements at 0.1 m intervals along lines 0.5 m apart. The data were despiked, interpolated and plotted as an image using a linear grey-scale.

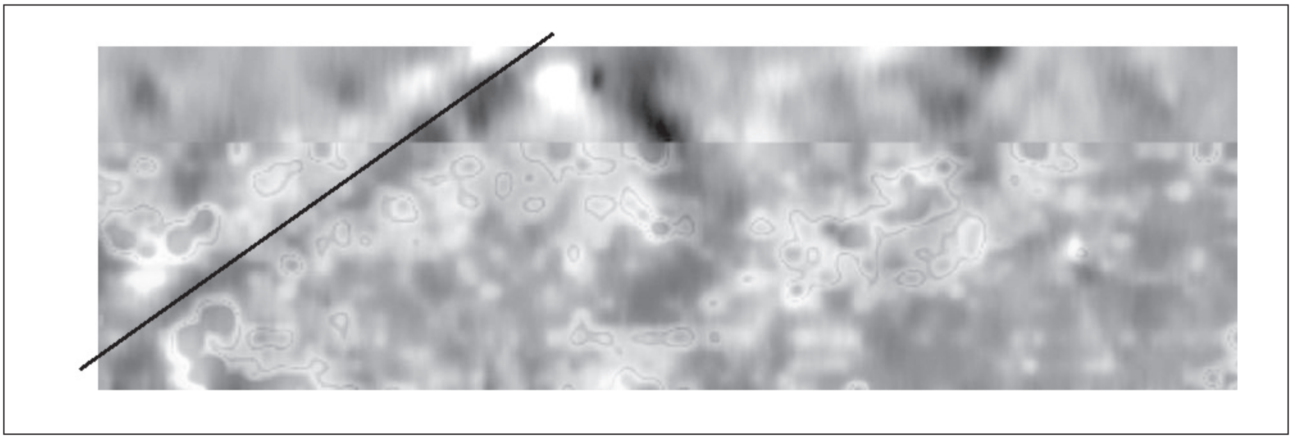
The results are variable. In two terraced areas to the east and southeast of the hilltop the magnetometry shows coherent, linear, negative anomalies of +/-10nT or less while elsewhere no such anomalies were identified despite the presence of buried walls visible at the ground surface. A closer examination suggests that the coherent anomalies correspond with areas where the walls are embedded in finer, less stony soil. Areas without such anomalies, conversely, appear to correspond with areas where there is an abundance of stone rubble around the wall remains (FIG. 6). The coherent anomalies to the southeast correspond closely with the pattern of GPR reflection (FIG. 7)

The Geophysical Properties of the Remains

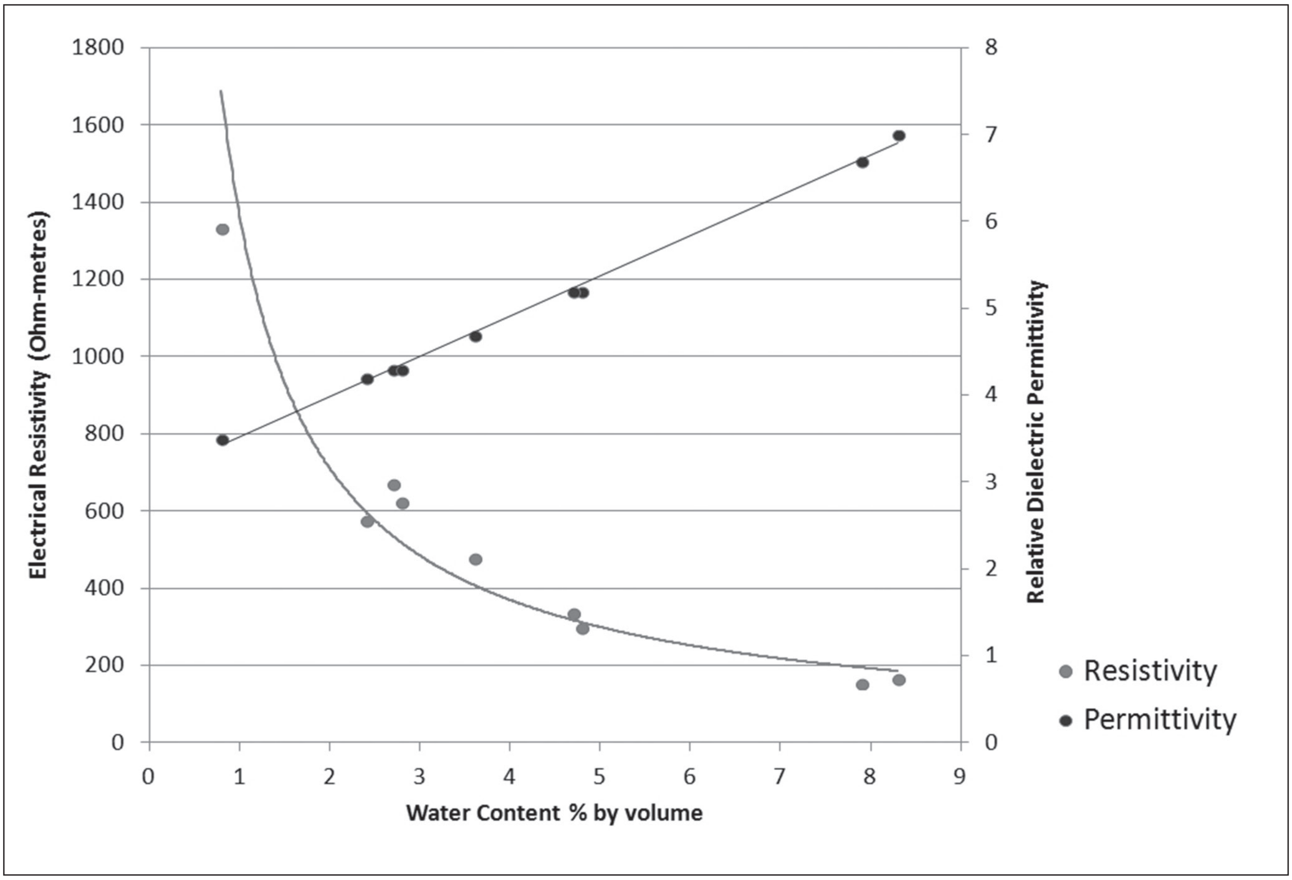
Taken together the geophysical surveys reveal patterns of variation which correspond with direct observations of the remains themselves in excavation. Coherent electrical resistance, dielectric and magnetic anomalies all appear to correspond to areas where there is a well-defined contrast between walls and matrix although the nature of that correspondence is complex. This usefully extends Hammond's (1974) observation of the correspondence of contrasting magnetic zones with the abundance of collapsed building material in the soil. The additional evidence for the 3-dimensional distribution of electrical resistivity and dielectric permittivity also suggest that Hammond's reconnaissance could be usefully extended into three dimensions using ERT and ground-penetrating radar over large areas. This is undoubtedly difficult at Petra because of the high surface electrical resistivity and abundance of rocks. These difficulties could be partly overcome by a combination of geophysical sampling, making sparse measurements rather than covering areas of ground with dense measurements. ERT and GPR could make use of short vertical profile lines and GPR could make use of air-launched rather than ground-coupled antennas.

Another significant problem, however, will be the need to choose the most appropriate conditions for survey. Although soils at Petra are dry through most of the year our surveys, in January, encountered both light rain and snow on several days – sufficient precipitation to gradually moisten the soil profile. Measurements of soil moisture (derived from dielectric permittivity) and electrical conductivity from two profiles are shown in FIG. 8. These values were taken from a range of strata from a single section (area E) both before and after rainfall. The soil water content varies between less than 1% and nearly 10%, resulting in a very wide range of electrical resistivities, from 156 to 1333 Ohm metres. Dielectric permittivity is correspondingly low, as expected, but increases sharply with water content.

The measurements show large contrasts in electrical resistivity and dielectric permittivity between dry summer and the moister winter conditions we encountered at al-Katutah after rainfall in the winter of 2012. This contrast suggests that survey results using GPR and ERT are likely to be quite different under these different conditions because geophysical contrasts between archaeological structures and their matrix are likely to change significantly as the soil wets and dries. As a result the choice of survey season will have a significant effect



7. GPR time slice (where wall edges are shown) overlain on magnetometry (greyscale). The black line marks a wall centre (F. Berger/D. Jordan).



8. The influence of water content on the soil geophysical properties which most directly influence ERT and GPR survey (D. Jordan).

on the results. Moreover multi-period survey, under moist and dry conditions, may provide much additional information on the soil hydrological response and thus on the physical properties of the strata.

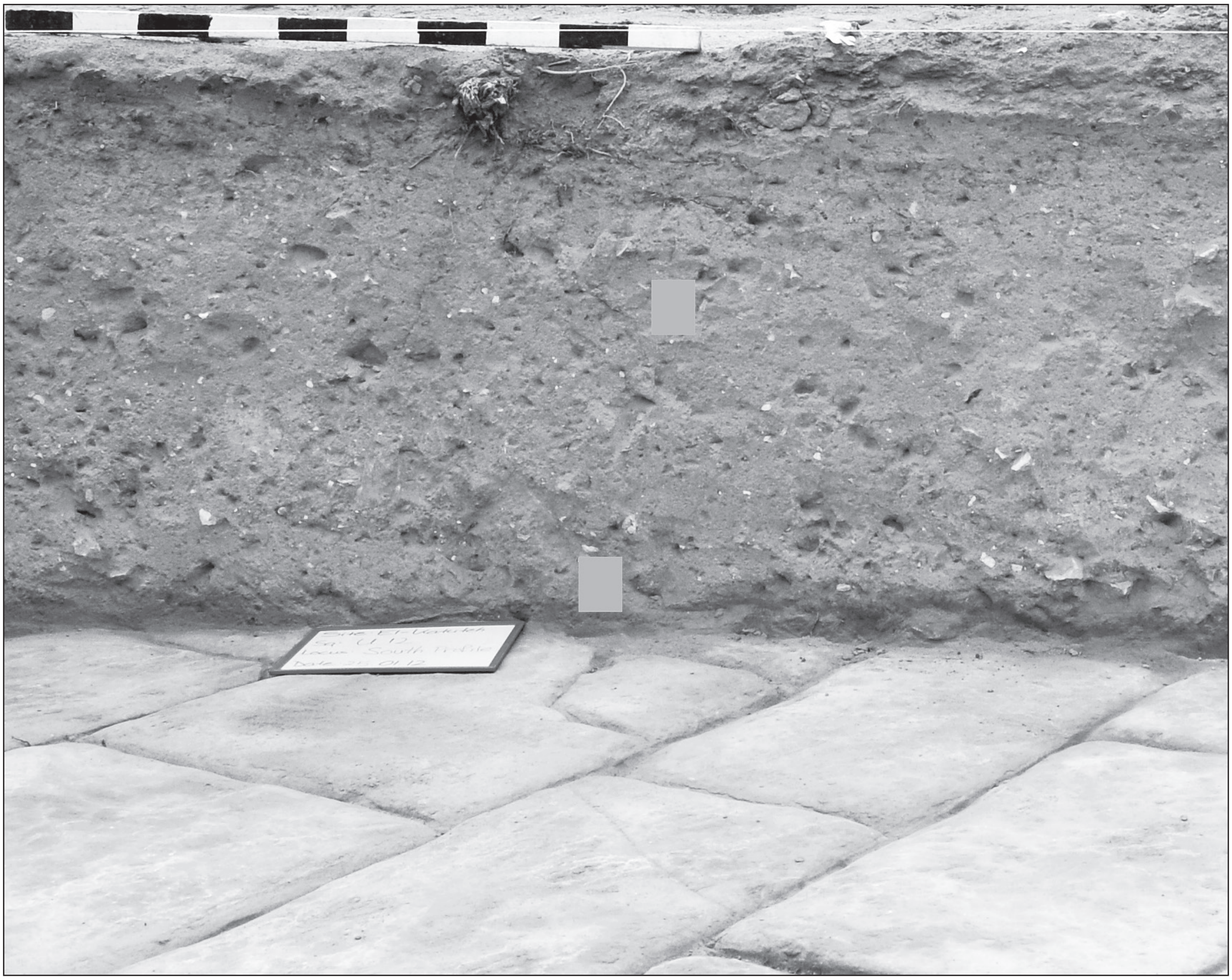
Site Formation Processes

The excavations at al-Katutah revealed a range of archaeological structures and strata. The soil profiles range from less than 50 cm to more than 1.5 m deep and consist principally of sandy loam to loamy sand. The profiles vary considerably in their degree of stratification. Some fine, sub-horizontal strata are clear and well preserved at a scale of less than 1 cm, with well-defined horizontal stone orientation and bands of darker, fine matter which have the appearance of occupation debris. These profiles are not very well sorted and appear to represent gradual accretion through occupation though there are some better-sorted fine colluvial components which have also accumulated in the rooms of former buildings on the slopes around the hilltop. Many of the soil profiles in the central buildings, however, have no discernible finer stratification and contain stones arranged without evident orientation, suggesting more rapid and uncontrolled accumulation. Darker bands of soil overlying the pavement or rock surface contain a relative abundance of roots, including the living roots of *Drimia maritima* which, unable to penetrate further, have extended laterally. Thus the dark colour may, in some areas at least, be no more than an effect of post-depositional organic root matter accumulation and not a residual stratum (FIG. 9).

Much of the ground surface around the site of Petra, including parts of the al-Katutah hilltop, is partly or completely covered in stones. Some of these are large (>30 cm) and some appear to be the *in situ* remains of wall structures. In addition a number of in situ structures, mainly walls, can be observed at the ground surface (Koçak *et al*. 2013). However, across much of the site, where the soil is finer, the abundance of smaller surface stones may result largely from the loss of fine matter from once deeper profiles through colluvial erosion – a process which we observed during rainfall and runoff at the time of our excavation. It is also possible that the same loss of fine matter is taking place due to wind erosion, which we also observed. The effects of this on the soil profile are clearly complicated by additions of fine windblown matter to the soil surface during storms. Some fine-sandy or stony layers at or close to the surface at the al-Katutah site, therefore, may also be the result of past surface erosion and accumulation, not the original stratigraphy.

In addition, the accumulation of fine matter in the lower parts of coarse stone accumulations, which we also observed at al-Katutah, may be the result of the *in situ* weathering of the sandstone itself. Similar *in situ* accumulation of fine soil between stones in clast-supported stone piles has been previously noted in mafic sandstones (Jordan 1998). The effect is that the stones appear to have been deposited into a layer of fine soil, which has in fact, gradually accumulated around the stones post-depositionally. A similar process may have taken place across much of Petra, albeit more slowly than in wetter climates where stones may be more prone to weathering.

Salt efflorescence was found on some stone surfaces and the lower parts of some exposed soil profiles. This suggests that the soil water is



9. Section with thin section samples in place (D. Jordan).

saturated or partly saturated in salts in some parts of the al-Katutah site although it is interesting that evidence for such soil salinity is not more widespread, especially since salt precipitation is a known risk to stone-built structures at Petra (Paradise 2005; al-Naddaf 2009).

The extent and diversity of the remains and the abundance and persistence of human activity means that it is difficult to locate what might be considered a natural soil profile at Petra, except for very young profiles associated with recent colluviation. The sparseness of surface vegetation and lack of soil profile formation in excavation spoil heaps around the site suggest that the dry environment has suppressed pedogenesis. The principal processes of pedogenesis evident in the profiles at al-Katutah, however, are shown by the thin sections (FIG. 10) to be the accumulation of organic matter from the tubers and roots of surface vegetation and the downward migration of solutes and fine particles in soil water during rainfall. The al-Katutah thin–sections confirm observations of profiles on site in revealing almost no pedogenetic structure and there was no evidence of bypass flow pathways following rainfall. Exposed profiles from former excavations, however, have been cut by small rain-water-fed gullies and there is a little evidence for the formation of incipient piping close to some profile edges, which may result from the solution of weak salt-precipitate binding.

The Geophysical Implications of the Geoarchaeological Observations

Magnetic

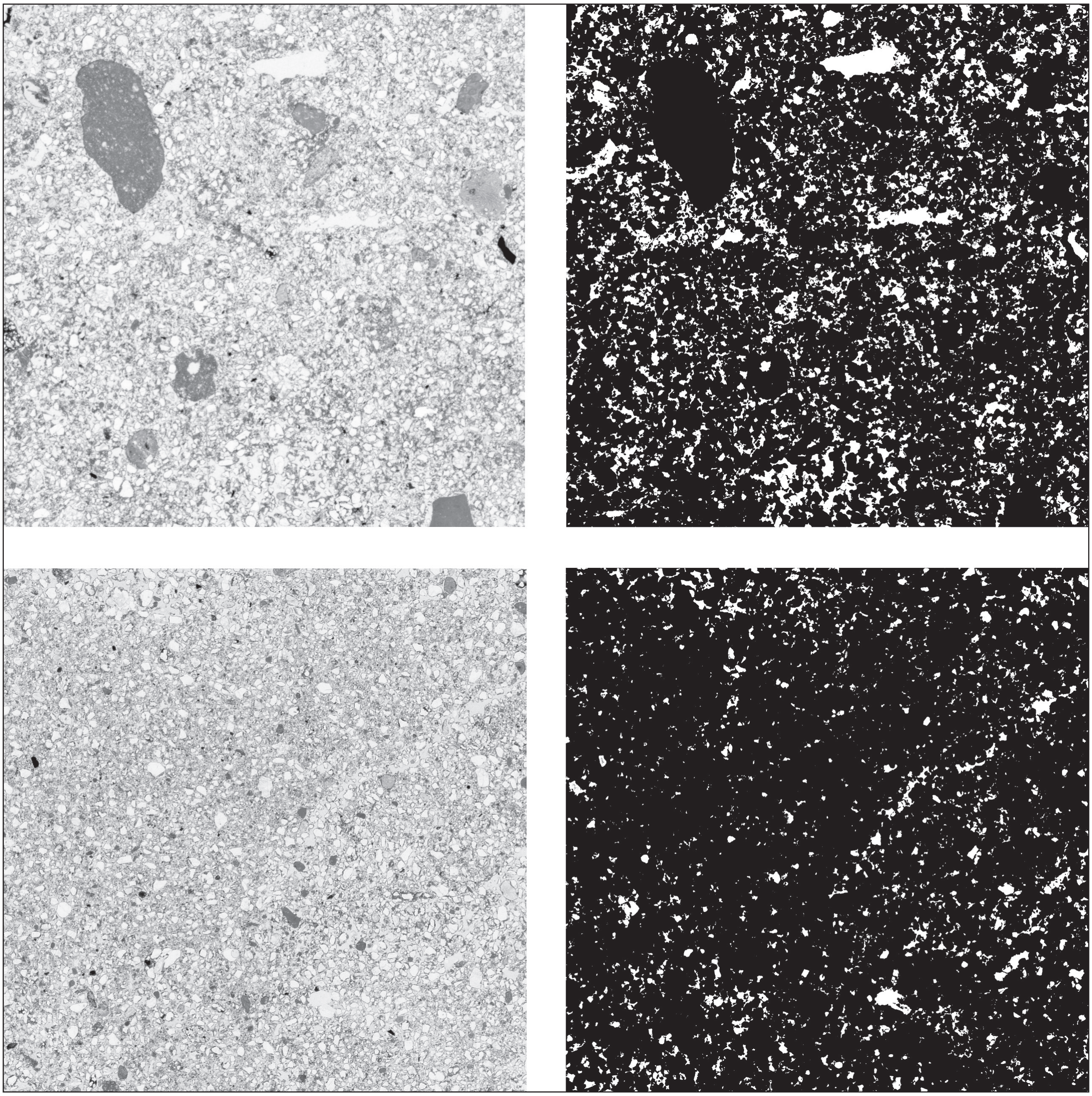
The variable, mostly weak, magnetic susceptibility of the excavated deposits corresponds with the relative scarcity of occupation debris and fine ceramic fragments visible in the thin-sections. This is interesting in itself since it suggests that some occupation deposits may have not survived in situ and that any former concentration of such deposits have been diluted by later additions of debris and wind-blown mineral matter. The result is that there is a relatively low contrast in magnetic field variation at the ground surface above buried walls. The findings explain Hammond's observation of subtle differences in the broad pattern of magnetic anomalies and of the strength of the total magnetic field in areas where occupation debris is present close to the surface when compared with areas where the ground is largely composed of building rubble or natural rock.

Ground Penetrating Radar

The patterns of reflection observed in GPR depend primarily on contrasts in dielectric permittivity (which create reflections) and the distribution of electrical resistivity (which determines the depth to which the radio waves penetrate). Both are closely linked to water content, as our measurements show. At the al-Katutah site the dry soil profiles have a low permittivity and a high electrical resistivity, allowing a good penetration depth of radio waves. It is striking, however, that the wetter soils, though not much wetter than the driest, have much higher permittivity and much lower resistivity. This suggests that one would obtain strikingly different GPR results soon after rain, once the moisture had diffused into the soil profile, than under the drier conditions which persist through most of the year. This will also have an effect on the clarity of reflections from stones, of low permittivity, in walls, which will be greater when the soil is moist than when it is at its driest. The same is true, however, for radar scattering from stones scattered within the profile implying that GPR survey under wetter conditions may produce clearer definition of walls in fine soils but greater scattering interference from stones elsewhere in the soil.

Electrical Resistance

The effect of water content on the electrical resistivity of the soil and the detection of



10. Thin section images from the upper (top) and lower (bottom) consolidated soil horizons. The left hand images show the samples in plane-polarised light, the right hand images show an abstraction of pore-space (white) derived from a combination of 90°- and 45°-crossed polarisation. The relative abundance of pore-space in the uppermost horizon and of fine matter infilling between sand grains in the lower horizon is very clear. This clarifies the connection between the higher electrical conductivity of the lower strata and the continuity of electrical conduction pathways through them. The upper horizon also shows a significantly greater abundance of coarse grains and stones which may be a result of the loss of fine matter through surface erosion (D. Jordan).

walls by ER survey is similar to its effect on GPR. The small variations in water content we recorded had a large absolute effect on electrical resistivity and thus on the contrast between the resistivity of the soil and of the walls embedded in it. As with GPR, the higher water content produces a greater contrast in signal – in this resistivity – between walls and soil but, unlike GPR, it may reduce the effect of stones on the bulk soil behaviour because electricity can flow around the stones more easily thus reducing their net effect.

Modelling Soil Water Content and its Geophysical Implications

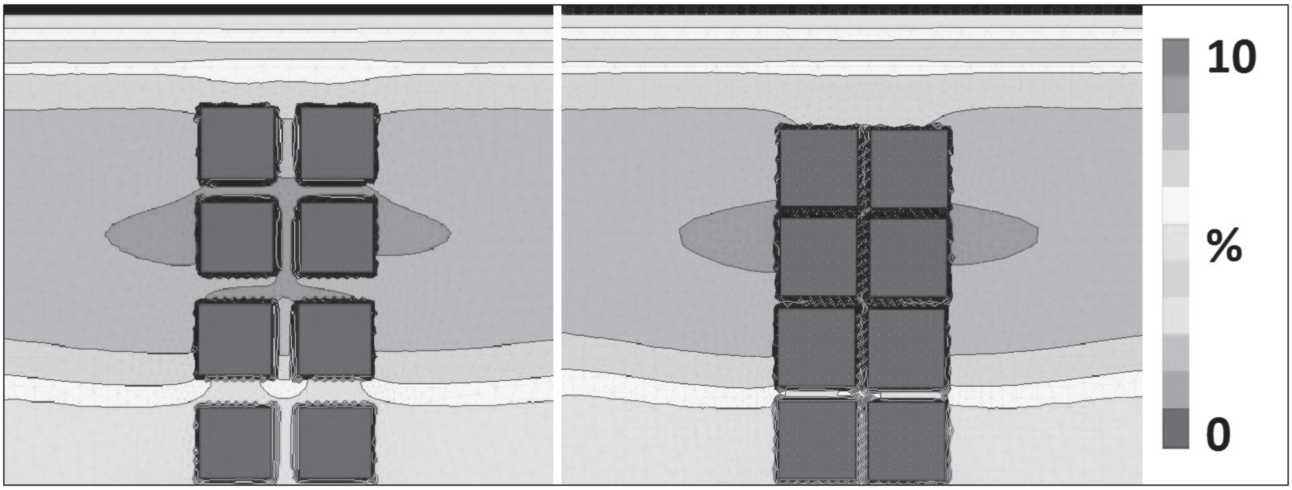
Given the demonstrated effect of soil water content on the nature and quality of GPR and ER survey at Petra we used the excavation data and analyses to create a suite of synthetic models describing water flow around archaeological remains typical of those found at El Katutah. The models represent walls of two different types, a compact wall of well-fitted blocks and a less-well constructed wall of blocks separated by about 10% by volume fine soil. The walls are embedded in a soil with the same texture profile as that recorded on site and overlie an almost-impermeable stone layer, again typical of the actual site. Thus the models, though clearly simplifications, are demonstrably realistic and may allow us to generate models of hypothetical geophysical behaviours which we can test in further fieldwork.

Figure 11 shows the buried wall hydrological models, constructed using the software Hydrus 2D (PC-Progress 2012). The upper surface is defined as an unvegetated atmospheric boundary subject to rainfall in which 1 cm rain falls each day for 5 days followed by 20 days without rain during which time the water disperses through the soil and evaporates, at a rate of 0.4 cm/day, from the surface. The side boundaries represent a horizontally continuous medium and the lower boundary is impermeable, a close approximation to the underlying rock. All points within the profile are initially given a water content of 5% and an initial period of 5 days are provided, without precipitation, for the model to stabilise.

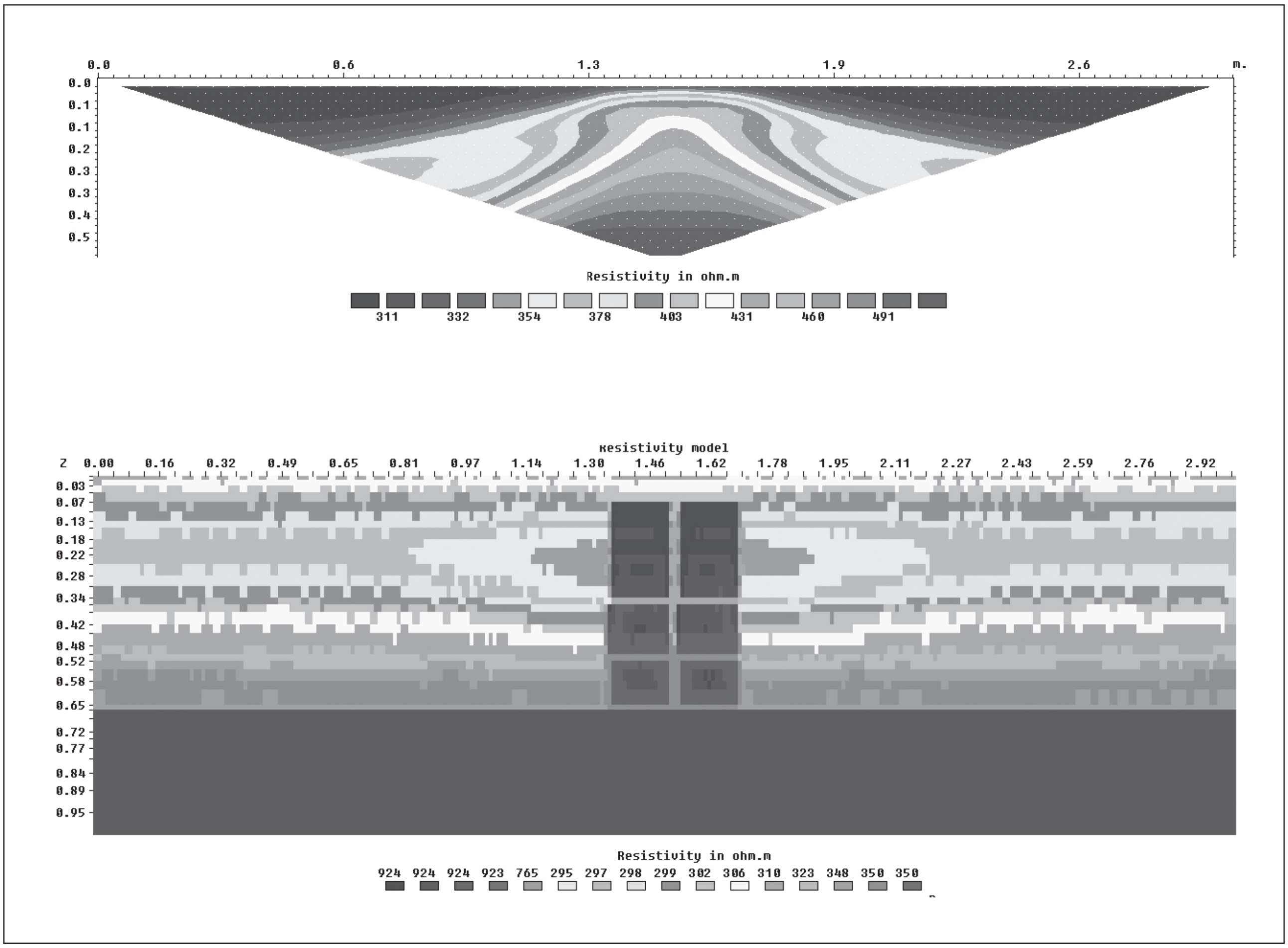
Figure 11 shows the profile water content after a period of 15 days when the water has infiltrated into the soil and walls. The left hand picture shows an open-structured wall, the right hand a much more closely jointed wall. It is apparent that the different structures have slightly different effects on the distribution of water in the profile after rainfall. More significantly for the geophysical surveys, the open-structured wall retains moisture in the broad, soil-filled volumes between the blocks of stone.

Water content values were taken from these models to create second models which used a semi-empirical equation (Rhoades *et al.* 1999) to combine water content with texture and salinity distribution values to calculate a distribution of electrical resistivity. The results are shown in FIG. 12.

These models predict values of electrical resistivity that correspond broadly with those measured in the field, both by FDR and by ERT inversion. Further models, which extend the range of conditions being modelled by adding representations of high resistivity variations (stones, for example) at the ground surface, were built using these same resistivity values.



11. Hydrological models of a buried wall with loosely-fitted stones (left) and tightly-fitted stones (right) (D. Jordan).



12. Electrical resistivity predictive model. The lower image shows the predicted resistivity values, the upper model shows the predicted pseudosection – the values of apparent resistivity which would be measured at the ground surface over such a buried wall (D. Jordan).

The models, taken together, show two things of particular significance: 1) walls with open structures permit the infiltration of water into the walls structure, as we would expect, and this lowers the bulk electrical resistivity contrast of the whole wall and the soil around to a half of the resistivity contrast for the well-fitted wall. The effect is to significantly reduce the clarity with which the wall can be detected by electrical resistance survey; 2) the addition of a small proportion of stones into the soil surface and the profile beneath has a dramatic effect on the clarity with which walls can be distinguished because of the degree to which they cause variations in the bulk soil resistivity over larger measured soil volumes. The combined effect of variations in water content and of surface stone content is to create much greater variations in the clarity of feature definition within modelled resistance surveys.

These observations have significant implications for the use of electrical resistance survey at al-Katutah, across Petra and at similar sites in such environments. They firstly imply that walls can be interpreted as well or poorly consolidated from a deeper analysis of ERT data, if some basic information about the nature of the soil profile is known. They also imply that ER or ERT survey can be significantly more revealing if it is carried out under both dry and wet conditions (though wet here means at most 10% water by volume), not least because the proportional difference in resistivity is very much greater in such normally-dry soils than in the moist soils of temperate climates. Finally, however, they imply that variations in the proportion and distribution of stones in the profile will have a significant impact on the clarity with which buried structures can be detected – a key consideration at Petra given the effects of surface stone concentration due to surface fine-matter erosion.

Two major pieces of work now await: firstly we must test the models by carrying out further survey and taking further measurements of soil properties in the field. Secondly we need to extend the models to include other remotely detectable properties strongly influenced by soil moisture including soil thermal and dielectric behaviour. These also will need further field testing and refinement.

Conclusions

Despite the evident difficulties of geophysical survey at Petra its iconic status and the need to avoid excavation makes efforts to adapt geophysical methods to the site especially worthwhile. This paper has shown how the combination of survey and geoarchaeological research can provide insights into the geophysical behaviour of the site which may, after further work, improve the targeting and interpretation of prospection. The challenges of further survey, geoarchaeological studies, modelling and verification remain.

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