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Invited Paper

Geophysical Archaeology Research Agendas for the Future: Some Ground-penetrating Radar Examples

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ABSTRACT Archaeological geophysics research and its applications to archaeology are today positioned to move in a number of directions, building on successes in the past few decades. The basics of data acquisition, processing and interpretation are now commonplace, and along with a variety of new geophysical tools and software, readily available to most dedicated practitioners. It is now time to move beyond the basics to develop new areas of research for the coming decades. Here, we propose some future avenues that can be followed, using ground-penetrating radar (GPR) as an example. One avenue is the application of these techniques to test ideas about culture and history in ways not possible using traditional archaeological methods. Another is the application of sophisticated new equipment and three-dimensional processing methods that can produce greater precision in the products produced, while simplifying data acquisition and revealing more information about buried archaeological features. While we discuss below our ideas with regard to the future of GPR, these basic concepts and future pathways are potentially applicable to the other commonly used near-surface geophysical methods. Copyright © 2010 John Wiley & Sons, Ltd.

Key words: Ground-penetrating radar; research agendas; three-dimensional data acquisition; processing advances

The roots of archaeological geophysics: where we are today

Archaeological geophysics has gained wide acceptance in the past decade within the general archaeological community. There are now practitioners on all continents and the discipline can be found in the curriculums of many academic departments worldwide. Its roots lie in the natural sciences, where techniques were developed by scientists with geophysics, geology and physics backgrounds (Weymouth, 1986; Scollar *et al*., 1990; Aspinall *et al*., 2008). Results of the early studies and the methods developed are now taught in a variety of universities and research laboratories have in the past few decades been at least partially devoted to basic research on near-surface geophysical equipment, data collection, processing and interpretation directly or indirectly focused on archaeological analysis. As a result of this dedication, accompanied by advances in hardware and software, the four most widely applied techniques (GPR, electromagnetics (EM), magnetics and earth resistance) have advanced to the point where users have a wide variety of resources at their disposal to aid in basic data collection and analysis. It is now time for motivated archaeological geophysicists to refocus their efforts on a number of aspects of the science that will advance the discipline beyond what it was initially designed for, which was almost wholly as a discovery tool.

The roots of archaeological geophysics lie in its ability as a prospection tool to locate, map and produce images of buried cultural materials (Conyers, 2010). Indeed this international journal that publishes much

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of these results, the International Society for Archaeological Prospection and the annual conference of that society all include the word 'prospection' in their title. The 'tried and true' prospection methods that are the foundation of all geophysical archaeology were, for the most part, built on 'off the shelf' geophysical tools, and the most common tools have become readily available commercially at this time.

Most early surveys were conducted using what is now standard data collection and processing methods to produce maps and other images that defined 'anomalies' (which may or may not have had cultural significance). The maps and other images produced during those early decades of the discipline were often of great use to collaborating archaeologists as guides for excavations and other types of subsurface studies. The ultimate product of those studies, when evaluated for usefulness, was usually their success (or failure) to find interesting buried materials for archaeologists to study in more traditional ways.

Successes of these geophysical surveys were published and widely disseminated, with the better ones held up as triumphs of each method's ability to aid the archaeological community. Failures were often quietly forgotten, or remembered only in a negative context with comments such as 'I dug where he (the geophysicist) said and there was nothing there' or 'that method doesn't work here'. These types of failures often produced word-of-mouth intimations of failure, which in some circles gave the discipline as a whole a negative reputation. Often failures were not analysed further to determine why results were less than hoped for. Sometimes failures were the result of incorrect data collection by inexperienced technicians, or data were processed incorrectly using methods that were rudimentary at best. Other studies became labelled as failures because tools were applied that were inappropriate for ground conditions, or perhaps not capable of delineating the buried features that might have been present.

Whatever the reason for failures, these studies were quickly forgotten and relegated to the dark recesses of laboratory file cabinets, never again to see the light of day. In contrast, successes were considered triumphs of the method and often any study that produced usable results was considered an important reason to publish, as a way of affirming the discipline's usefulness. The published history of books and articles on archaeological geophysics have therefore been heavily weighted toward studies that consist of these general themes: (i) data were collected at a site using a certain tool; (ii) those data were processed in a certain way and produced a certain number of potentially useful maps or other images; (iii) those images that contained some interesting anomalies were sometimes tested using various excavation methods. Rarely were these articles concluded by discussing how a study might have produced new knowledge about ancient people or historical events. Often these types of conclusions were considered outside the focus of the authors as most studies focused mostly on the geophysics alone.

The published record of archaeological geophysics is weighted heavily toward these types of studies, which played an extremely important role in the discipline's development. Their results demonstrated a particular method's usefulness and applicability, and the best collection and processing techniques for each tool soon became common practice. This type of fundamental research is common to all developing disciplines.

At this point in time the archaeological geophysical literature is, while not saturated, at least very full of studies showing how to collect and process data from the four most common tools in a variety of conditions. That research has produced a substantial number of case studies that demonstrate general usefulness in many areas of the world. Of course, there is always room for more of these studies as they can show how general techniques and applications can be applied to new and different conditions and research studies. There are always new ground conditions and buried cultural features that challenge the geophysicist, and when new discoveries of this sort are made, their results should be disseminated so all can learn. However, we suggest that today's research in geophysical archaeology must advance beyond 'routine applications' for the production of images or delineation of anomalies for others to excavate.

Using GPR as an example, it is first important that all researchers apply tested and commonly used field procedures, sampling methods, robust data processing and informed interpretation. A general consensus has been developed, and published in the literature for standard 'single fold' GPR collection. Those procedures include profiles spaced no more than 25 cm apart using a 400 MHz antenna and energy slices thick enough (or overlapped enough) so that they encompass enough of the collected waveforms to reduce polarity changes (Leckebusch, 2003). Ultimately images from these basic collection and processing methods can be produced using single 'resampled values' of energy over a defined time range to produce accurate images (Linford, 2004; Seren *et al.*, 2007). Software available today make these basic steps very easy, as many years of developmental experience have been incorporated into their features.

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Ideas for the future of geophysical archaeology with GPR as an example

We believe that there are additional foci of archaeological geophysics that will play an even more important role in the near-future, which can potentially take the discipline beyond its traditional roots of 'prospection'. Some of the basic ideas of what we see as the future have already been published and are active research interests by many practitioners. Our purpose here is to discuss these basic topics generally (without producing an inclusive citation index), as a way to highlight some possible future research paths and themes. We will give examples from our own and our colleagues GPR studies to highlight some of these basic themes. We are aware of similar studies in the other common geophysical methods, which follow these same general research pathways.

Using GPR for understanding the past

Archaeological geophysical results are beginning to become a primary data source from which to study the human past, and not merely a preliminary step leading to standard excavation procedures (Kvamme, 2003). This enlarged use of geophysics has recently been made possible by advances in data collection and processing, both of which are the product of more powerful computers and the development of intuitive software. Two examples of how GPR has been used to do much more than just produce images of the ground are discussed below. These GPR case studies were conducted not solely to locate buried cultural remains, but to apply the resulting images and maps, integrated with standard subsurface testing, to directly test hypotheses about human behaviour.

In the American Southwest cultural connections between widely spaced communities in the high desert of the Colorado Plateau have been studied for decades. Connections between ceremonial, economic and political centres can be studied by understanding the existence of certain distinctive architectural features across the landscape. One of these definitive structures are large semi-subterranean circular structures called kivas that can be as much as 20 m in diameter, which appear to have been used for communal ceremonies. Long distance trade is hypothesized to have been related to these ceremonies, and so their presence or absence can potentially test ideas about prehistoric far-reaching connections of many sorts.

One area on the northwest periphery of a prehistoric 'central place' is located in southeastern Utah. In this area a number of large circular surface depressions whose diameters are consistent with large kivas are visible. Prior to GPR analysis these large circular depressions were assumed to show connections to the central core because they contained these large kivas. To test the hypothesis that a concentration of apparent large kivas was evidence of long distance prehistoric connections GPR surveys were conducted on five of the large diameter circular depressions (Conyers and Osburn, 2006). When this was done the circular walls of kivas were apparent, but it was found that only three of the five large depressions contained kivas and those were found to be small domestic-size kivas and not the larger ceremonial features that were assumed from the surface expressions (Figure 1). These results have necessitated a rethinking of the prehistory of this area, refuting previous hypotheses that tended to show strong regional connections of this site's inhabitants. In this study GPR mapping was conducted not just to locate buried features but to use an analysis of their functions to test ideas about regional cultural connections.

At the site of Petra in Jordan, GPR was also used to study the early history of this important desert city. One large grid of GPR reflection profiles was collected (Conyers *et al.*, 2002) and images of the shallowest buried architecture, within about 2 m of the surface showed a number of temples, platforms, water lines and possible water pools (Figure 2). Reflection profiles also showed a very subtle sloping reflection beneath this architecture, which appeared to be a living surface, hypothesized to represent the topography of the valley prior to the 1st century AD urbanization construction episode, which covered it and levelled the area for the impressive structures that the site is known for today. Horizon-specific maps were constructed along that surface, which showed the remains of simple buildings (Grealy, 2006) and possible pathways between them. Some of these buildings had earlier been exposed, described and dated along the north edge of the site. The orientations of these early buildings and pathways as mapped using the GPR images show that the cultural roots of Petra are exemplified by simple dwellings built in various orientations and placed on land that was suitable for building at that time. When the GPR images and the limited information from excavations were integrated it shows that only later in the history of the site, when long distance trade routes were established did social differentiation and monumental construction take place. This is in stark contrast to the earliest habitations that are much more like those of their

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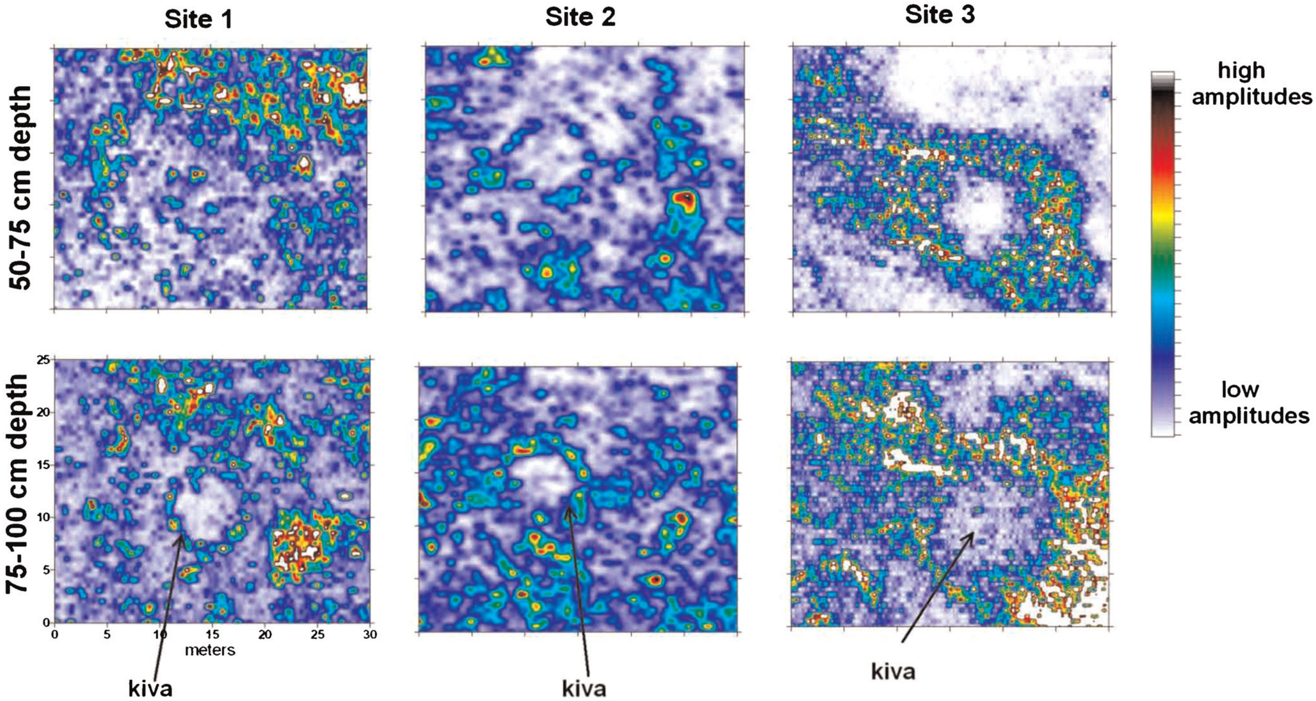

Figure 1. GPR amplitude slice-maps southeastern Utah, USA. Three small kivas were found in the large depressions, necessitating a re-evaluation of the prehistoric ceremonial and political connections in this area of the American Southwest. This figure is available in colour online at www.interscience.wiley.com/journal/arp

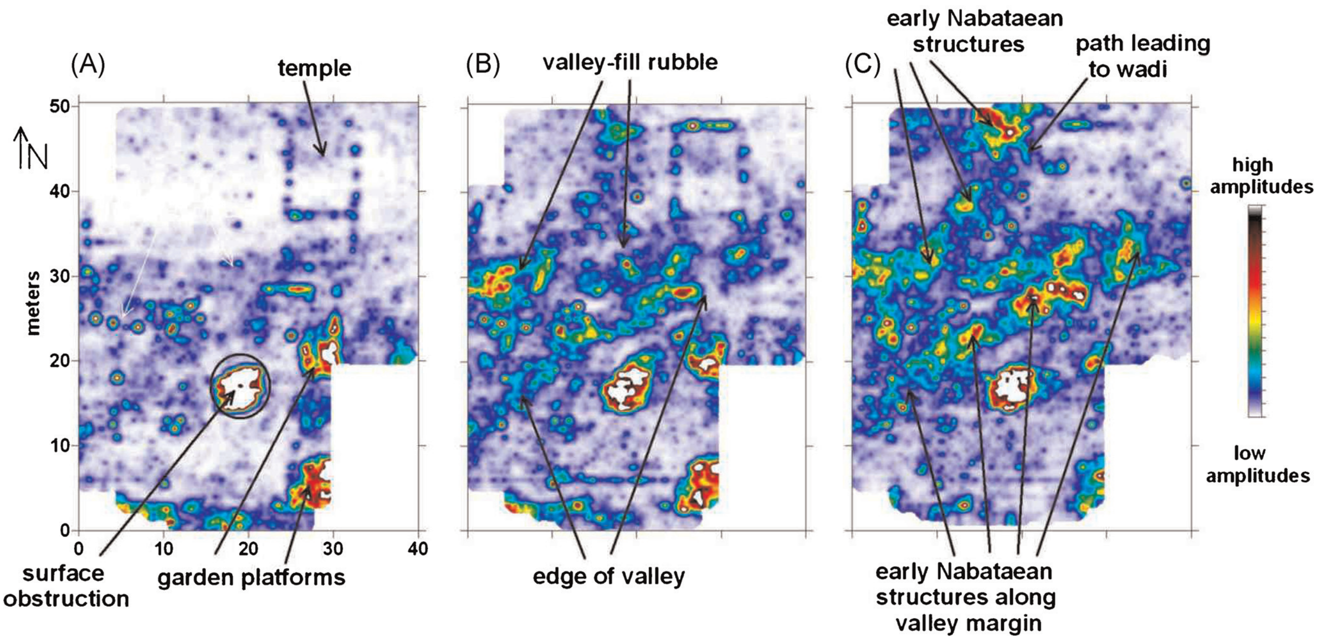

Figure 2. GPR amplitude slices from the Lower Market, Petra, Jordan. Slice A shows the buried buildings from 75 to 100 cm, which are late Nabataean and Roman period structures. Slice B shows rubble fill and the valley edge in a 25-cm-thick slice directly above a horizon that was an earlier living surface. Slice C is a 25-cm-thick slice directly on that earlier living surface showing the foundations and remains of early structures built along the sides of the valley, with a pathway leading to the water course to the north. This figure is available in colour online at www.interscience.wiley.com/journal/arp

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migratory desert-dwelling ancestors (Conyers, 2010). In this GPR study the architecture from two different periods within one small area of Petra demonstrates the very different types of city planning and social structure held by the inhabitants of Petra over four centuries. The three-dimensional GPR images were correlated to limited excavation information to date them and place the geophysical results within the overall site stratigraphy. This allowed for a mapping of the earliest structures in ways not possible with any other geophysical method, or indeed with standard archaeological techniques.

These are two examples of how archaeological geophysics has the ability to map significant areas of sites that would otherwise remain invisible using traditional excavation methods. If the geometry, orientation, placement and relationships among cultural features (and their relationship to the natural environment) can be mapped geophysically, then whole sets of new hypotheses about people can potentially be developed and tested. This is possible because geophysical methods have become quite standardized and commonplace. Solely finding buried archaeological materials need no longer be our only goal.

Data acquisition and processing advancements

Looking at the latest development of multichannel and multifrequency antenna systems, the collection of data over large areas can be done in an even shorter time than ever before. An understanding of GPR through many years of work with single-channel systems has produced a number of very sophisticated systems and their use is now becoming common (Leckebusch, 2009; Linford *et al*., 2009). Researchers in multichannel GPR systems have now produced large arrays of antennae to record the full three-dimensional wave field (Grasmueck *et al*., 2005). In this type of system many antennae in an array can both transmit and record radar energy from multiple sources (Figure 3) and hence even common mid-points (CMPs) can be recorded with ease. These arrays produce energy maps with very high resolution to potentially produce images of buried features such as single stones, staircases or the detailed spatial extent of walls (Leckebusch, 2000). This high resolution can be achieved only if the positioning of each reflection trace within a surface grid is accurate. One solution is to incorporate in the collected data stream spatial information from GPS or tracking total stations (Lehmann and Green, 1999; Young and Lord, 2002; Leckebusch, 2005). In urban or forested areas with poor GPS coverage, or in undulating terrain, inertial navigation systems (INS) can help to maintain accuracy. These systems normally are built with some gyros, accelerometers and magnetometers to determine the antenna movements in space. By properly combining all the available values they can fill in the gap of a bad GPS signal over some distance. This can be used not only for correct antenna position information but also to provide elevation and even antenna tilt data for topographic corrections and post-acquisition processing (Goodman *et al*., 2007; Leckebusch and Rychener, 2007). Some of these techniques are still in their infancy, but hold the promise for extremely accurate and detailed subsurface mapping that goes far beyond commonly used methods today.

Figure 3. The latest development in multichannel, multifrequency antenna systems with different polarizations: the 40 channel system called Stream EM from Ingegneria dei Sistemi, S.p.a. (IDS) (courtesy of IDS). This figure is available in colour online at www.interscience.wiley.com/journal/arp

Another focus of advanced GPR research comes in data processing and image production. This is especially true with multiple array systems where huge amounts of reflection information must be processed in three-dimensions. In the early years of GPR research there was a realization that even single-fold systems transmitted radar energy in the ground along very complex wave paths, with many waves recorded that had travelled to and from the surface antennae along complex pathways. This realization has led some researchers to develop sophisticated migration algorithms that are well suited for GPR (Streich and van der Kruk, 2006). Many of the seismic processing tools migrate data within complicated three-dimensional space, but they also tend to 'smear' recorded signals, leading to suboptimal results. In the future these problems can be overcome with

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additional testing and software enhancements, increasing the resolution of the three-dimensional methods. It will be a key to the future of using new tools and processing for GPR in archaeology.

Even with many of the recent GPR advancements in data processing in general, sophisticated processing is still very cumbersome and time-consuming. Data collection is often the easiest part of the process and many processing days are needed for every few hours of actual collection. Today multiple array systems necessitate many complicated manual steps, which can be simplified with internal software logic, once optimal processing methods have been developed. In the future the recording power of multiple antenna arrays, accurate surface placement of antennae and enhanced data processing of recorded waves will potentially produce high-precision images of the subsurface. The usual collection of data in rectangular grids with one transmitting and one receiving antenna could become almost obsolete in future years if these methods are perfected.

Other aspects of GPR that are becoming research topics by some are an understanding of attributes of radar wave propagation and reflection, such as changes in wave phase and an analysis of the multiple frequencies recorded by most wide-band antennae. Processing methods that can delineate and isolate subtle changes in radar waves recorded from the ground have the potential to allow for an understanding of the actual composition of buried materials (Böniger and Tronicke, 2010). These advances will allow not only the production of the accurate images of buried archaeological materials in space but also an understanding of their physical and chemical properties and therefore potentially their origin.

All future software and hardware developments must always be evaluated by how they help to solve archaeological questions. Hence an interpretation of the immense data sets over large areas will be required. Simple renderings of the data volumes successful on small grids are of limited help at large and or complex sites (Leckebusch *et al.*, 2001). The extraction of the geometry of buried features over large areas is perhaps one of the most challenging aspects of GPR research that must be addressed in the future (Figure 4). Manual interpretation of dozens of hectares becomes impossible with presently available antenna arrays and can only be done with assistance from software tools that are just being developed (Leckebusch *et al.*, 2008; Naser and Junge, 2009).

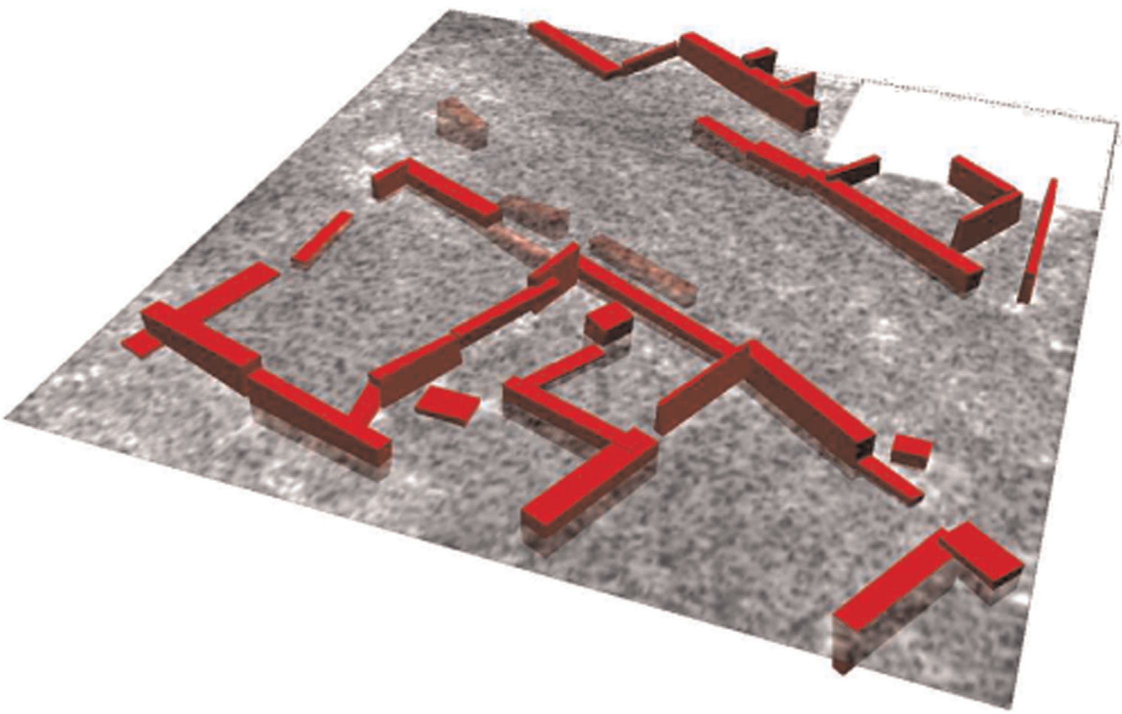

Figure 4. Semi-transparent depth-slice of the integrated reflection energy with the three-dimensional geometries of an automated feature extraction system in red. Size of the slice: 20 × 21 m. This figure is available in colour online at www.interscience.wiley.com/journal/arp

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Conclusion

While it is important and appropriate for archaeological geophysicists to continue working at sites using traditional acquisition and processing methods to prospect for buried cultural remains, we propose that researchers begin to move beyond these historical roots. There are still many advances to be made using these standard methods, and this is especially true with GPR when results can be incorporated with other data sets using data fusion techniques. One area of new and different research studies presented here, using GPR as an example, is the technique's application to historical and anthropological research that has previously been under the domain of 'typical archaeologists' who only dig in the ground. The other is advanced acquisition and processing techniques that can not only map the spatial extent of buried features precisely in three-dimensions, but also potentially determine specific material properties of the subsurface features such as stone, earth or brick. When these types of analysis are incorporated within a historical framework, ideas about the past can be tested and studied in ways not possible before. We conclude that archaeological geophysicists have only begun to use the tools at our disposal, and the discipline has an ability to go far beyond its traditional and historical applications of prospection.

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