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A comparison of ground-penetrating radar, magnetic gradiometer and electromagnetic induction survey techniques at House in the Horseshoe State Historic Site

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1. Introduction

In the spring of 2013, University faculty and students were invited by officials at the North Carolina Department of Natural and Cultural Resources to lead fieldwork at House in the Horseshoe State Historic Site. A mutually beneficial partnership formed between institutions as a result, with the goals of learning noninvasive geophysical techniques to understand cultural landscapes of the past, while serving site specific management and academic research needs. In a pre-fieldwork consultation, the site manager informed the University remote sensing team of specific questions that might be answered with geophysical methods. It has long been surmised that the site contains burials associated with an American Revolution skirmish that occurred there in 1781 (Caruthers, 1854). The manager also indicated that the former location of the main house external kitchen was in question, as well as the locations of many other structures associated with the site's history as an agricultural plantation. Previous archaeological work and historical studies at House in the Horseshoe provided a background upon which geophysical survey and ground truthing could build (Baroody, 1978; Harper, 1984; Willcox, 1999).

The research tested ground-penetrating radar (GPR), and magnetic gradiometer, in addition to magnetic susceptibility and conductivity images produced using an electromagnetic induction meter. The surveys provided an opportunity to evaluate how each instrument resolves structural remnants, supported by ground truthing confirmation. It was anticipated that the evaluation of effective sensor combinations used in a fine sandy loam would allow the determination of how many instruments are necessary to effectively detect architectual features, and which to select for future work in similar contexts where a map of the buried architectural landscape is sought.

GPR transmits electromagnetic energy into the ground in the MHz to GHz range, recording the returning signal amplitude and travel time in nanoseconds, within a given observation time window. The velocity of propagating waves change as they travel through the subsurface depending upon relative dielectric permittivity (RDP) - the variable ability of materials to allow electromagnetic energy to be transmitted (Milsom and Eriksen, 2011). RDP is a known quantity for most geologic materials (Table 1). If the dielectric contrast, or more precisely, the coefficient of reflectivity between materials is great enough, waves can be reflected back to the antenna and recorded in GPR vertical profiles as an anomaly. Radar reflections typically occur where there are subsurface changes in the electrical or magnetic characteristics of soil or rock, as well as subsurface changes in water distribution, lithology, or bulk density (Conyers, 2013). While these changes in subsurface characteristics often correspond with phenomena that occur naturally in a physical landscape, they are also often the source of many types of archaeological features.

A gradiometer is a specially configured type of magnetometer that measures variation in magnetism in the shallow subsurface, in units of nanoTesla (nT) (Clay, 2001; Aspinall et al., 2009). Gradiometers take advantage of the earth's existing magnetic field to detect buried objects by using two magnetometers vertically separated by a given distance. Both sensors in a gradiometer unit are sensitive to the ambient geomagnetic field, with the lower sensor placed to detect magnetic features generally within the upper 2–3 m of the subsurface (Clay, 2001, Kvamme, 2006a). When the difference in upper and lower readings approach zero, there is no local difference in magnetic field strength. A wide variety of archaeological features are visible to magnetometers due to both permanent, remnant magnetic characteristics, and temporary magnetic response, magnetic susceptibility. Both characteristics are fundamental to understanding what objects are visible when surveying with a magnetometer or electromagnetic induction (EMI) instrument in the in-phase/magnetic susceptibility mode.

The magnetic susceptibility of a material is classified by the degree to which its magnetic moments (the orientation of electron orbits and spin around the nuclei of a material's atomic fabric) align with the direction of a temporarily imposed magnetic field (Lowrie, 2013). Electron orbits of paramagnetic and diamagnetic materials do not respond in organized parallel or anti-parallel tracks in a magnetizing field, and possess no remnant magnetism in the absence thereof (Moskowitz, 2018). While paramagnetic minerals do possess a very weak positive magnetic susceptibility, and diamagnetic a negative one, they are not

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Table 1
Relative dielectric permittivity values for common earthen materials.
Adapted from Milsom and Eriksen, 2011.

Material	Permittivity
Air	1
Ice	3–4
Fresh water	80
Salt water	80
Dry sand	3–5
Wet sand	20–30
Shales & Clays	5–20
Silts	5–30
Limestone	4–8
Granite	4–6
(Dry) salt	5–6

detectable by magnetometers typically used in magnetic mapping surveys, which are primarily designed to detect materials that exhibit ferro- or ferrimagnetic qualities (Milsom and Eriksen, 2011). Ferromagnetic elements such as iron, nickel and cobalt display a strong parallel alignment with an external magnetizing field, and also retain strong consolidation of orbit alignments in the absence thereof (Lowrie, 2013; Moskowitz, 2018). These metals are components of many types of artifacts that are potentially visible in magnetometer surveys of historic and prehistoric sites, as well as unwanted debris scattered about the near surface that potentially obscure signatures of interest.

Ferrimagnetism is a product of elemental compounds that display opposing or anti-parallel alignments that result in weakly permanent magnetic characteristics, as well as strong positive magnetic susceptibility. Common rock and soil compounds in this class that are important in magnetic surveying include iron oxides such as magnetite and maghemite (Clark, 2001; Milsom and Eriksen, 2011; Lowrie, 2013). Hematite is also an important compound that displays a weak remnant magnetism and magnetic susceptibility due to its canted anti-ferrimagentic response (Moskowitz, 2018), but can be converted to magnetite via reduction when exposed to temperatures as low as 200 C (Aspinall et al., 2009). These compounds are concentrated in surface soils as a part of natural pedogenic processes, and can be magnetically enhanced by human activity (including fire and organic waste), a factor that archaeological researchers frequently use to understand human land use of the past (Dalan, 2006; Aspinall et al., 2009). The general extent of human occupation areas are often the focus of surface probe or loop instrument magnetic susceptibility surveys (Clay, 2001; Horsley et al., 2014), while EMI and magnetometer instruments are capable of identifying individual features using higher sampling densities at greater depths. When there is a significant contrast in the susceptibility of the topsoil and the horizons beneath, archaeological features such as pits and trenches filled with topsoils having a greater susceptibility than the surrounding soil can potentially become visible to these instruments.

The tendency of humans to use fire in daily activities greatly enhances the magnetic susceptibility of ferrimagnetic soils, and can cause burned areas and objects to display a permanent, remnant magnetism, often referred to as thermoremnance (Kvamme, 2006a; Aspinall et al., 2009). As temperatures increase, the organization of magnetic moments in ferro and ferrimagnetic materials diminish. When these materials are heated above their respective Curie temperatures, any uniform organization of electron orbits is lost completely (Table 2). Upon cooling, the orbits become aligned in the direction of any superimposed magnetic field. Thus, burned soils and clay objects can appear in magnetometer surveys as dipolar features aligned with the Earth's magnetic field at the time of cooling (Clay, 2001; Aspinall et al., 2009).

The latest generation of EMI instruments with close coil spacing (~1 m) are able to measure two quantities simultaneously: soil electrical conductivity in quad-phase (in milliSiemens per meter or mS/m), and magnetic susceptibility in the in-phase (ratio of primary to

Table 2
Common magnetic materials and their Curie temperatures. Modified from Moskowitz (2018). AFM = Anti-ferrimagnetic.

Mineral	Composition	Magnetic order	T_c (°C)
Oxides			
Magnetite	Fe_3O_4	Ferrimagnetic	575–585
Hematite	αFe_2O_3	Canted AFM	675
Maghemite	γFe_2O_3	Ferrimagnetic	~600
Metals			
Iron	Fe	Ferromagnetic	770
Nickel	Ni	Ferromagnetic	358
Cobalt	Co	Ferromagnetic	1131

secondary field, in parts per thousand or ppt) (Doolittle and Brevik, 2014; Geonics Limited, 2015). This is accomplished via sending and receiving coils horizontally separated by a fixed distance. An electromagnetic field is generated by the sending coil that penetrates the ground, which in turn, induces a secondary electrical current in the subsurface that varies spatially in intensity based on the conductive properties of soil and the objects within it. Conductivity can be used to measure both horizontal and vertical variations in soil texture (Geonics Limited, 2015), and is sensitive to many kinds of metal (Bevan, 1998). It is a useful tool for mapping archaeological sites where earthworks are, or were, a dominant feature on the landscape, or where structural underpinnings or other large solid objects create discontinuity in the ability of soil to conduct electricity (Clay, 2006). Magnetic susceptibility measured by this instrument is a quantification of the alignment of the magnetic moments of soils and buried objects with a temporarily induced magnetic field, and is not sensitive to any remnant magnetism that may exist. In comparison, magnetometers passively map *any* spatial variation of the earth's magnetic field at the near surface, including temporary and permanent magnetic characteristics, and cannot discern the difference between the two forms as a matter of its functioning (Dalan, 2006).

2. Previous work

While each sensor discussed has a proven record of success when used by itself to identify archaeological features (Johnson, 2006), the advantages of using multiple methods has also been well-established, and is the preferred approach by many researchers (Clay, 2001; Kvamme et al., 2006; Maki and Fields, 2010; Henry et al., 2014; Stine and Stine, 2014; Thompson et al., 2016; Ullrich et al., 2016; Wiewel and Kvamme, 2016). Different sensors complement one another because they measure different physical characteristics, or dimensions of the subsurface (Clay, 2001; Kvamme et al., 2006; Ernenwein, 2009). Johnson (2006:12) explains that, "…not only do the different instruments detect different things, but often they see the same things differently."

Archaeological feature type and site conditions determine geophysical visibility of features, and therefore suggest which sensor or sensor combination is likely to perform best in a given context, but economic factors, educational goals and instrument availability also often play a dominant role in choosing instruments for subsurface imaging (Clay, 2001; Stine and Stine, 2014; Thompson et al., 2016). Gradiometer and GPR are often chosen as an instrument pair (Stine et al., 2013; Patch, 2016), as are conductivity and magnetometer (Clay, 2001), ultimately because of their complementary nature in a wide variety of contexts. Magnetic susceptibility surveys display only induced magnetism, and can be used in conjunction with magnetometer or gradiometer surveys to determine which features are displaying temporary magnetic characteristics and which are permanent (Dalan, 2006; Ernenwein, 2009). Research by Kvamme (2006b) integrated several geophysical datasets into a single image, including EMI (yielding conductivity and magnetic susceptibility), GPR, magnetic gradiometer, resistivity, and thermal