Directions of Magnetization

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Abstract

The anomalies in a magnetic map may be analyzed for estimates of the directions of magnetization of the bodies that are underground. The directions from a group of anomalies may be plotted, and this plot may reveal that the directions are clustered. These clusters may differ from one survey location to another, and this may provide additional information about those sites or distinctions between them.

The directions may tend to be close to that of the Earth's present magnetic field; this may mean that objects have recently been fired (burned) in place, or that induced magnetization predominates (these latter objects might be refilled pits). The directions may be widely scattered; this may reveal the random remanent magnetization of objects that have been moved since their firing (examples could be igneous stone or compact steel objects). The directions may be near the horizon, but otherwise scattered; this could be caused by elongated steel artifacts or perhaps by isolated bricks. The directions may be near the horizon and toward magnetic north; perhaps this indicates elongated iron objects (which may have a greater induced magnetization than steel). Finally, the directions may be clustered near the Earth's field, but offset from that field; in principle, this could reveal ancient, but in-place, fired bodies such as hearths or furnaces.

Keywords: archaeology, magnetic survey

1   INTRODUCTION

Why estimate directions of magnetization? These directions may answer questions about the objects that are underground: Have they been fired in place or not; are they iron or steel? If the direction of magnetization is estimated, other important parameters of the buried objects (depth, volume, or mass) may be determined more accurately. The direction might also allow an estimate of the date that the object was created.

The direction of magnetization of an object is suggested by an adjacent pair of magnetic anomalies, one a high and the other a low. The calculated magnetic maps of several compact magnetic objects (which cause dipolar anomalies) are plotted in figure 1A; the directions of total magnetization that have been assumed for these objects are plotted in figure 1B. Plots of direction, like figure 1B, may reveal differences from one area of survey to another more clearly than the original magnetic maps. Additional detail about this and others is given in an appendix.

Much can be told about differing directions of magnetization by simply studying a magnetic map; perhaps one may prepare two plots. The first plot can show the orientation from each magnetic high to its paired low, and the second plot can show the ratio of the amplitude of each magnetic high to its paired low.[1]

In this first plot, the orientation of the magnetic low relative to the high is strongly affected by the declination angle of the body's magnetization; however, the angle from the high to the low is typically closer toward magnetic north than the actual direction of magnetization in the body. In the second plot, the ratio of the amplitude of the magnetic high to the low is affected by the inclination angle of magnetization; however, as a magnetic object is extended in a horizontal direction, the magnitude of its low will increase relative to its high, even though the direction of magnetization remains the same. This is another way of saying that high/low ratios are not always a good indicator of the inclination angle. While a visual examination can reveal that the direction of magnetization differs from the direction of the Earth's field, other procedures allow the direction to be estimated more accurately.

The procedure that has been applied here is magnetic modeling of the objects that cause the anomalies; the calculated field of a magnetic model that matches the measured map most closely can reveal the direction of magnetization in the object. Many interesting archaeological features are less than 1 m in size; these may be metallic artifacts, cooking hearths, or refilled pits. The magnetic field of these compact objects can often be approximated by the field of a simple magnetic dipole. For larger features, such as filled cellars or trenches, magnetic anomalies may be modeled with a collection of rectangular boxes.

If the magnetic objects that are underground are not compact, or small relative to their depth, their magnetic anomalies will still be bipolar (that is, they will have an adjacent high and low), but the anomalies will be more complex than those in figure 1A. It is important to determine high-low pairs of anomalies that are associated with each single object. This association

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[1]C. C. Schnetzler and P. T. Taylor, "Evaluation of an Observational Method for Estimation of Remanent Magnetization," *Geophysics* 49 (1984): 282–290.

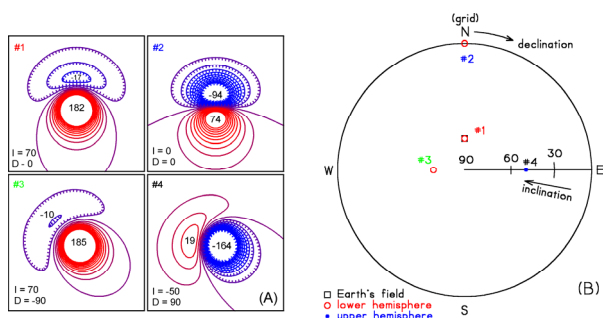may best be revealed by the high-low pair that has the greatest lateral magnetic gradient.

Figure 1. *Examples of magnetic maps and the magnetic directions of objects. (A) Calculated maps; anomalous lows have hachures along their contour lines. The inclination angle (I) and declination angle (D) of the object's magnetic field is listed with each plot. High and low anomalies are noted near the peaks, and contouring is not complete. (B) Directions of magnetization are plotted with circles (for inclination > 0) or dots. A small square (at example #1) locates the assumed direction of the Earth's field.*

A wide variety of computer programs is available for automating the inversion of magnetic measurements and thereby approximating magnetic models. If a dipole is a suitable model, a free program from Geometrics can be applied; this is MagPick, and it is available at www.geometrics.com. Several commercial programs can also be applied. Magnetic models with a wide variety of geometries can be solved with the Potent program from Geophysical Software Solutions (www.geoss.com.au) and the Model Vision program from Encom (www.encom.com.au). The Emigma suite of programs from PetRos EiKon (www.petro seikon.com) includes a section that solves for dipolar models using a semi-automated procedure that begins with Euler deconvolution.

The analyses here were done with programs that were written for this study; the general principle of this type of program, like that of the other programs above, has been described by Johnson.[1] For the programs that were applied here, the models were dipoles, with a single dipole providing the model for a single anomaly.

2   EXAMPLES OF MAGNETIC DIRECTIONS

The earthwork of Fort Morton is mapped in figure 2; this fort was constructed in 1864, during the Civil War between the northern and southern states of the U.S. This earthen fort was leveled after the war; while the area is now a smooth and grassy field, the filled-in trenches of the fort were readily located with a ground-penetrating radar. As part of the geophysical survey,

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[1]W. W. Johnson, "A Least-squares Method of Interpreting Magnetic Anomalies Caused by Two-dimensional Structures," *Geophysics* 34 (1959): 65–74.

magnetic maps were measured over two parts of the buried earthwork. These are identified as areas A and B in figure 2; the areas are about 33 m distant from each other.
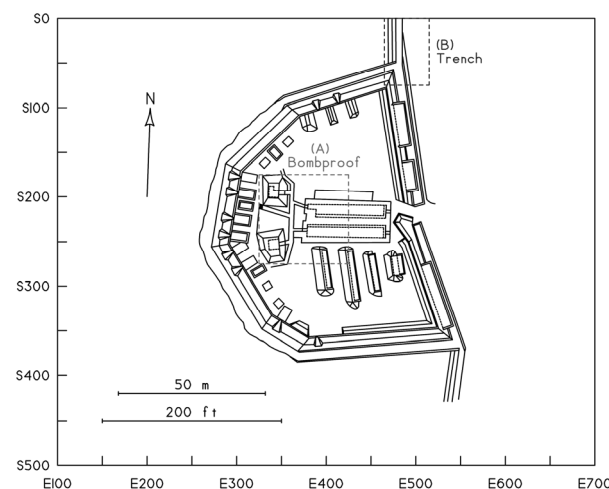

Figure 2. *Fort Morton on the battlefield of the U. S. Civil War (1864) at Petersburg, Virginia.*

The two magnetic maps are plotted in figure 3. The map of figure 3A was measured near the middle of that fort; two powder magazines (for storing explosives) and several bombproofs (earthen-roofed trenches for sheltering soldiers) were in this area, but are now invisible. The northeastern corner of the fort is included in figure 3B; the band of magnetic anomalies near E500 is just east of the main fortification trench for the northern army.
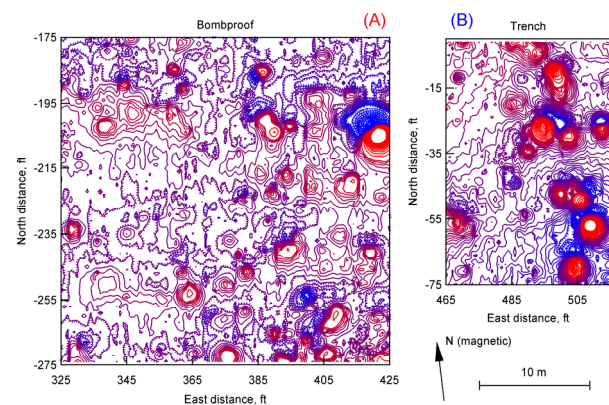

Figure 3. *Magnetic maps (total field) of two parts of Fort Morton. The interval between contour lines is 1 or 5 nT. The height of the magnetic sensor was 0.75 m and the measurement spacing was 0.3 m.*

Most of the magnetic anomalies in figure 3 are similar to those that may be caused by compact magnetic objects; most of these objects are probably iron or steel artifacts that are underground. About 20 anomalies were analyzed in each map by assuming that the bodies could be approximated by magnetic dipoles. The directions of magnetization of these bodies are plotted in figure 4. The important finding of this analysis was

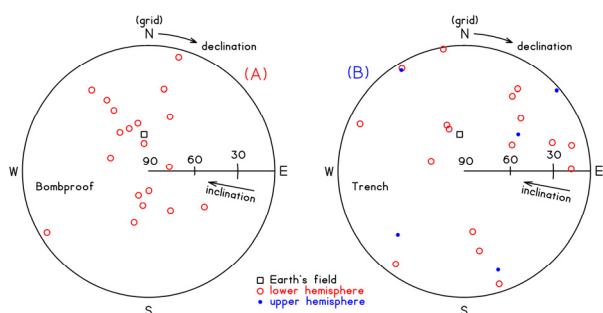the difference in the directions of magnetization in the two areas.

Figure 4. *Differences in the direction of magnetization at Fort Morton. In (A), inclinations are all positive, and near the Earth's field (marked with a square). In (B), directions are scattered and some inclinations are negative (marked with dots).*

The scatter of directions in figure 4B suggests that the objects there have strong remanent magnetization that has a random orientation. Perhaps some of these are compact steel objects; no stone is found in this area. In figure 4A, the directions are close to that of the Earth's magnetic field. It is possible, but unconfirmed, that the wooden structures that were formerly in this area were destroyed by fire, and this has remagnetized many iron and steel artifacts. Perhaps, instead, the objects in area A (the bombproof) are compact iron artifacts and their magnetization is primarily induced. These speculations have not been tested by excavation.

A magnetic survey that was done at another Civil War battlefield (on the Robinson farmstead at Manassas, Virginia) also found magnetic directions (21 dipoles) that tended to cluster near the direction of the Earth's field; the house at this location was destroyed by a fire. Another survey, at the site of the partially-exposed wreck of a wooden ship (at Griswold Point, near Old Lyme, Connecticut), found a similar clustering (10 dipoles); however, no evidence of burning was visible there.

The rather random angles shown in figure 4B were also found during a survey of part of the 17th-century settlement on Jamestown Island, Virginia, as revealed by 38 dipoles. Another location with random angles was found at a historic cemetery at Scott Air Force Base (Illinois), with an analysis of 7 dipoles.

While the causes of some of these patterns are not known, other distributions of directions have an origin that is more certain. Figure 5 illustrates a type of plot that is frequently found. It is reasonable that these shallow angles of magnetization are caused by elongated steel artifacts. Elongated artifacts may be disks, sheets, bars, or rods. When these are lost or discarded, they will probably lie rather flat on the soil's

surface; they will later be buried by bioturbation[1] and the growth of plants. Artifacts that have a strong magnetization will generally be magnetized in their long direction; the archaeological importance of this has been pointed out by Weymouth.[2] This directionality is enhanced by demagnetization.
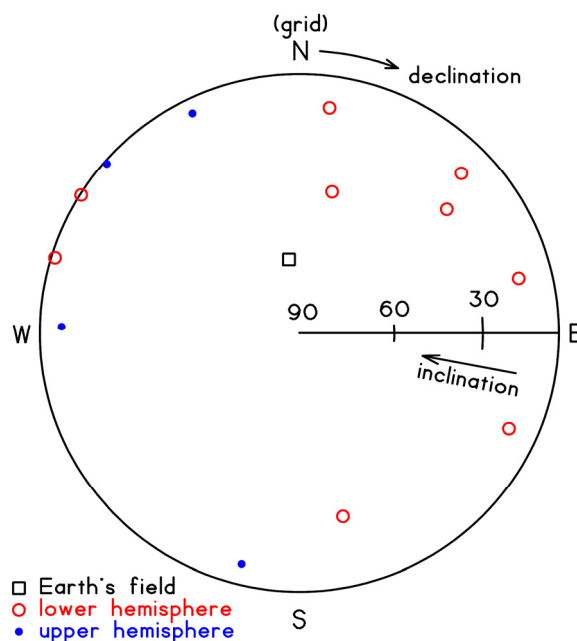

Figure 5. *Angles of inclination that are near zero. The magnetic map that was analyzed for this plot had 13 anomalies that could be approximated by dipoles. Almost all of these have a direction of magnetization whose inclination angle is very low; the declination angles are scattered.*

Demagnetization can be important to consider for objects that are iron or fired earth. In the normal calculations of the magnetic anomaly of an object, the object is assumed to be magnetized by the Earth's field. If the object is not very magnetic, this is a good assumption. However, an object made of iron or fired earth can be so magnetic that the magnetic field inside the object is strongly affected by both the Earth's field and also by the field from other parts of the object (or from nearby objects).

Demagnetization causes two effects. First, it reduces the amplitude of the magnetic anomaly of an object below what one would have estimated from the magnetic susceptibility of the object; this explains the origin of the term. Second, demagnetization changes the direction of magnetization of objects that are not

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[1] W. R. Wood and D. L. Johnson, "A Survey of Disturbance Processes in Archaeological Site Formation," in *Advances in Archaeological Method and Theory*, vol. 1, ed. M. B. Schiffer (New York: Academic Press, 1978) 315–381.

[2] J. W. Weymouth, "Geophysical Methods of Archaeological Site Surveying," in *Advances in Archaeological Method and Theory*, vol. 9, ed. M. B. Schiffer (Orlando: Academic Press, 1986) 311–395.

compact; this is important for archaeomagnetic dating. Objects that are elongated or flattened will have their direction of magnetization moved somewhat toward the length of the object; see figure 6. Detailed descriptions of these effects may be found in Guo et al.[1]
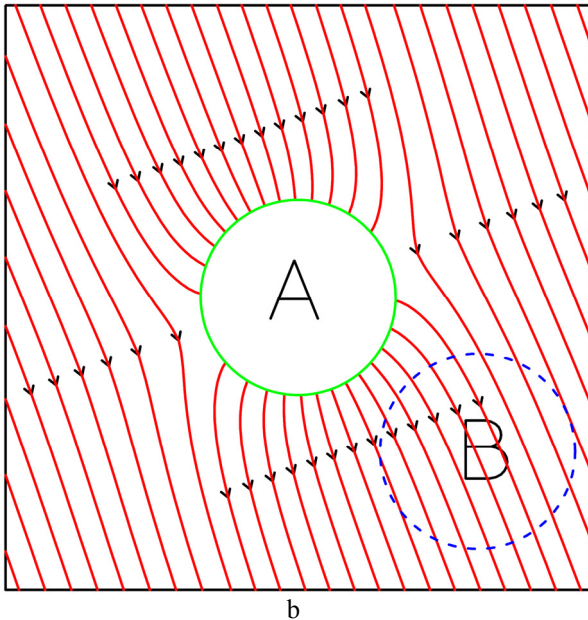

Figure 6. *Demagnetization. A circular magnetic body at A warps the Earth's magnetic field toward that body; lines of flux are mapped with arrows. If another body, B, is placed near A, the direction of the field that magnetizes body B is not that of the Earth's field; instead, the direction is somewhat toward body A.*

Magnetic anomalies at archaeological sites are strongly affected by the ratio of remanent to induced magnetization of artifacts; this is called the Q ratio. In general, iron artifacts from the 19th century and earlier appear to have low Q ratios. However, steel artifacts from the 20th century are much more likely to have high Q ratios. If a Q ratio is high, remanent magnetization predominates, and the directions of magnetization can be scattered; if the Q ratio is low, the directions of magnetization must all be near that of the Earth's magnetic field.

The Q ratio of a magnetic artifact can be approximated with a quick test using a magnetometer.[2] With the magnetic sensor stationary, determine the background field without the artifact. Now bring the artifact near the sensor, rotate it at a constant distance, and search for the approximate magnetic high and low relative to the background field; these extreme values will be found on opposite sides of the artifact. If the magnitude of the high is about equal to the low, the Q ratio is very high. If no magnetic low is detected (the magnetic field does not drop below the background), the Q ratio is less than one. In between these two, the Q ratio is intermediate, and greater than one.

A test of 30 small modern iron or steel items gave the following findings: For 17 items, the Q ratio was very high; for 8, the Q ratio was intermediate, and greater than 1; for 5 objects, the Q ratio was less than 1. High Q ratio is often found with objects that must be very hard, such as knives. Low Q ratios are more likely to be found with iron, and also steel objects that must be tough or malleable, such as a wood-splitting wedge or a railroad spike. A separate test of seven historical iron artifacts found an average Q ratio of 0.5. Steel drums may have a low Q ratio also;[3] this is probably because the steel must be malleable so that a drum will not crack when it is dropped.

The directions in figure 5 were found at the now-vacant site of the former Union Academy building at Appomattox Court House, Virginia. Similar plots were revealed by magnetic surveys at the locations of two other former buildings in this historic town: The Prior-Wright house (10 dipoles), and the Connor/Sweeney cabin (17 dipoles). Other archaeological sites with similar plots were found by surveys at the location of the Fairview cabin on the Civil War battlefield at Chancellorsville, Virginia (14 dipoles), Gunston Hall at Mason Neck, Virginia (5 dipoles), and Meriam's Corner at the Minute Man National Historical Park in Conrcord, Massachusetts (5 dipoles).

A good number of archaeological sites have revealed directions of magnetization like that shown in figure 7. Inclination angles are rather low, and there is a distinct tendency for the directions to cluster near magnetic north (but not at the inclination of the Earth's field). It is possible that many of the objects here are made of old iron, rather than modern steel; this may have archaeological importance. As a further speculation, perhaps elongated iron or steel artifacts have been burned in a fire.

While single bricks are seldom isolated or resolved by a magnetic survey, bricks may show this pattern also. This is because bricks are often fired in a kiln while resting on their medium-sized edges; if the inclination angle of the Earth's magnetic field is steep, the strong remanent magnetization of the bricks will be in a direction that is nearly parallel to the large face of the brick. When a brick is discarded, this large surface will most commonly lie parallel to the soil's surface; then the inclination of the magnetization of each brick will tend toward the horizontal.

The pattern of the directions of magnetization in figure

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[1] W. Guo, et al., "Systematic Error Analysis of Demagnetization and Implications for Magnetic Interpretation," *Geophysics* 66 (2001): 562–570.

[2] S. Breiner, *Applications Manual for Portable Magnetometers* (Palo Alto: Geometrics, 1973).

[3] D. Ravat, "Magnetic Properties of Unrusted Steel Drums from Laboratory and Field-magnetic Measurements," *Geophysics* 61 (1996): 1325–1335.

7 has also been seen at five other archaeological sites. At Appomattox Court House (discussed above), it was revealed at the Peers House (10 dipoles) and the site of the Academy Dwelling; next to the Watt house (29 dipoles) at the Richmond National Battlefield near Old Cold Harbor, Virginia; at the Taylor house (66 dipoles) on the Petersburg Battlefield in Virginia (next to the area of figure 3); and at the former site of the Bullock house (46 dipoles) near Chancellorsville, Virginia.
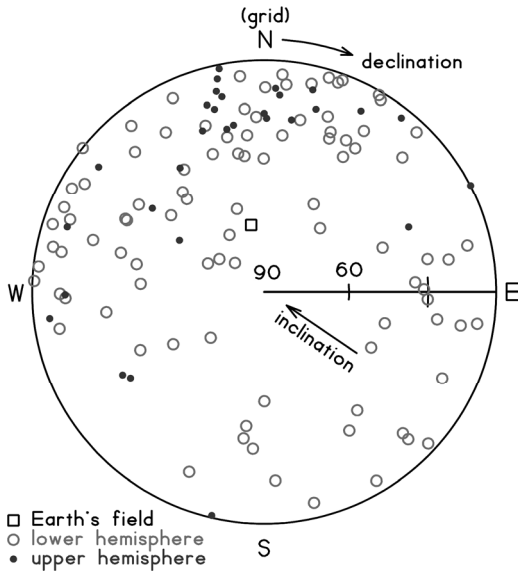

Figure 7. *Angles of magnetization that are nearly horizontal and toward the north. These directions were found for small magnetic objects that were detected near the West House, on the Richmond National Battlefield (in Virginia).*

Very few archaeological excavations have tested these findings about the directions of magnetization of artifacts. This is partly because most of these magnetic surveys have been done in U. S. national parks, where the fewest possible excavations are made, for the parks are protected from the damage of development. However, at one location, an excavation clearly identified the artifact that caused a distinct magnetic anomaly. At the Peers House at Appomattox Court House, an anomaly had a dipolar model with an inclination angle of $2°$ and a declination angle that was $23°$ from magnetic north. The excavation at this location found a sheet of iron with a dimension of 18 by 61 cm and a mass of 0.4 kg at a depth of about 25 cm.[1] While the orientation of this plate was not recorded, it was probably extended horizontally. The low inclination angle agrees with this.

Figure 8 is an example of a cluster of directions that is neither near the Earth's field nor near the horizon. This

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[1] M. Kostro, *Archaeological Identification Study and Evaluation of Geophysical Prospecting at Appomattox Court House National Historical Park, Virginia* (Williamsburg: Department of Archaeological Research, Colonial Williamsburg Foundation, 2002).

is the only example that has been found like this; it is probably just a coincidence. It is expected that fired features from a prehistoric period are underground at this location, and the directions of magnetization in those features could reveal that the direction of the ancient field differed from the current direction. However, the scatter of directions is large. Also, it is not reasonable that the ancient field would have been as far to the west as is implied in figure 8; in the last few thousand years, the Earth's field in the U.S. has only rarely had a declination that differs by more than $25°$ from true north.[2]
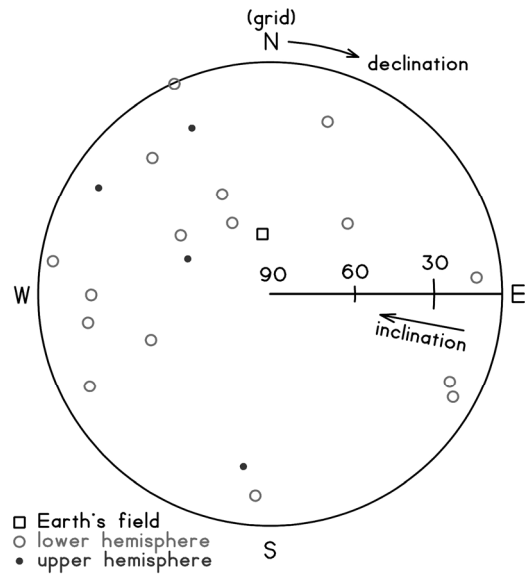

Figure 8. *Magnetic directions that cluster to the west of north. Some of the magnetic anomalies could have been caused by fired earth and stones at cooking hearths. In principle, this clustering could indicate a different direction of the Earth's field at the time of firing, but this is unlikely here.*

3 CONCLUSIONS

Magnetic maps are typically distinguished by the shapes and the amplitudes of the magnetic anomalies within them. The directions of magnetization of the objects that cause these anomalies also provide valuable information about differences between the areas of survey.

While these directions may individually have a low accuracy, a clustering in the directions can still reveal differences from one magnetic map to another. The best directions may be determined where anomalies are isolated from each other and where magnetic measurements have been made close together so that small errors in the measurements have little effect on

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[2] R. S. Sternberg, "Archaeomagnetic Dating," in *Chronometric Dating in Archaeology*, ed. R. E. Taylor and M. J. Aitken (New York: Plenum Press, 1997) 323–356.

the analysis. Errors in the estimates of magnetic directions may result from the overlap of anomalies or interference between them.

Plots that show directions of magnetization can be examined. It is valuable to note if the directions cluster near the horizon or near magnetic north. It is possible, although not proven, that these directions might distinguish sites where artifacts of iron, as opposed to steel, may predominate; therefore, this can suggest the ages of the occupations of those sites.

Directions of magnetization have been determined for groups of objects at 19 archaeological sites. For one-third of these, directions were scattered around the horizon; for another third, directions were clustered near the northern horizon. The remaining third of the locations were evenly divided between no clustering and clustering toward the Earth's field.

The directions of magnetization that are determined will be more accurate if the spacing between measurements is somewhat smaller than that of a normal, reconnaissance survey. The analysis of each direction takes only a few minutes.

4 APPENDIX: DETAILS ABOUT THE FIGURES

Further information about the surveys and analyses is given here.

Figure 1. (A) The calculations assume a dipolar moment of 1 Am^2 at a depth of 1 m below the calculation surface; the contour interval is 5 nT and the calculation square is 4 m on a side. The Earth's field has a magnitude of 50,000 nT. (B) This is a Lambert azimuthal equal-area plot;[1] the remaining directional plots here have this same projection.

Figure 2. The left side of this earthwork (on the west) faced the fortifications of the southern army; ten V-shaped patterns along that western arc locate openings for cannons. A pair of powder magazines is found behind the front of the fort. The horizontal and vertical features near the middle of the fort are bombproof shelters for soldiers. This is a tracing of a map that was prepared during the Civil War.

Figure 3. Abrupt changes in the spacing between contour lines reveal the switch from a contour interval of 1 nT to 5 nT; contouring is not complete for extreme anomalies. Measurement traverses were made in a north or south direction. Note that many magnetic lows are faint or invisible in the area of survey at the bombproof. A broad-area magnetic low in the southeastern corner of figure 3A is caused by an underground iron-filled well at E526 S144. These surveys were done for the National Park Service (NPS) at the Petersburg National Battlefield in 1992. The buried fortifications were delineated best with a ground-penetrating radar. Many examples here are from battlefields of the U. S. Civil War.

Figure 5. This magnetic survey was done at the site of the Union Academy. Except for a few flat stones, there is no visible trace of the former building. The magnetic survey was done in 2000. The height of the magnetic sensor was 0.7 m and the measurement spacing was 0.3 by 0.76 m.

Figure 6. If the line between bodies A and B is either parallel to the direction of the Earth's field or perpendicular to it, demagnetization causes no change to the angle of the local magnetic field.

Figure 7. The 125 directions in the plot were determined from a total-field magnetic survey that was done in 2001. The survey was done in an area of 5100 m^2, using a measurement spacing of 0.6 m by about 0.2 m; the sensor height was 0.5 m. The site is on a property that is just east of the Malvern Hill Unit of the Richmond National Battlefield.

Figure 8. These directions were found as part of a magnetic survey that was done for the U.S. Army Corps of Engineers in 2002. The survey was done on the partially-excavated surface of a prehistoric site (36AL488) in the town of Leetsdale, Pennsylvania, using a total-field magnetic gradiometer with its lower sensor at a height of 0.15 m. The spacing between measurements was 0.25 m by about 0.04 m.

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[1]J. P. Snyder, *Map Projections—A Working Manual* (U. S. Geological Survey Professional Paper 1395 (Washington: U. S. Government Printing Office, 1987).

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