Geophysical mapping of historic cemeteries

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Abstract:

Although the non-invasive nature of geophysical survey recommends it for mapping unmarked graves, cemeteries can present a number of technical challenges that can limit its usefulness. Ground penetrating radar (GPR) is often the only geophysical method considered for mapping historic cemeteries, but its success is very dependent on favorable site conditions. Other methods can be very successful when appropriately applied, and may be favored by settings unsuitable for GPR. Case studies illustrating GPR, electrical resistance, and magnetic surveys on historic Euro-American cemeteries are presented, with discussion of the capabilities and limitations of the methods and their appropriate application.

Introduction

Cemeteries are unique in many ways as a subject of study in archaeology. Whether archaeological investigation is undertaken for preservation, for cemetery management, or for research, respect for the dead and for descendant communities is of paramount importance. Ethical and legal considerations related to this affect every aspect of archaeological practice. On a methodological level, this generally means that disturbance to the site must be minimized if not entirely avoided.

Because geophysical survey is non-invasive, it would seem an obvious choice for cemetery investigations, and several geophysical methods have been successfully used to map historic graves. Very often, however, geophysical surveys of cemeteries have failed to yield useful results. From intermittent success and failure have come many lessons about applying geophysics in a challenging context, and an acceptance that conditions at some cemeteries may not be suitable for any geophysical method.

When appropriately applied, geophysical survey has a very good likelihood of yielding useful results. Appropriate application includes not only designing surveys that can resolve cemetery patterning, but also fully integrating geophysical methods with the goals and methodology of the archaeological investigation.

Although minimizing impact to the site is a primary concern in cemeteries, geophysical survey has other potential benefits for archaeological investigations generally. Most significantly: it can provide unique information unavailable by other means; it can expand the area that can be effectively studied; and it can lower the cost of research.

The purpose of this paper is to provide archaeologists and historians an overview of the potential and limitations of geophysical survey in historic cemetery studies. Three of the most successful methods (ground penetrating radar (GPR), electrical resistance, and magnetic survey) are discussed. The emphasis is on case studies and general application concerns; specific technical parameters are not discussed. Prehistoric cemeteries, while subject to similar ethical and legal considerations, present a different set of technical challenges, and are outside the scope of this paper. Geophysical methods for archaeology are treated in greater depth by Clark (1996) and Gaffney and Gater (2003).

Applications for geophysics in cemetery investigations

The most basic need in cemetery investigations may be to document the presence of graves and the extent of the cemetery. Missing or misplaced grave markers are very common on historic cemeteries, and records may be absent or inexact. Often even the limits of the cemetery are unknown.

Some of the specific uses of geophysical survey include:

- Locating unmarked burials
- Finding the extent of a cemetery
- Fitting historic cemetery plats to their physical location.

- Determining used/unused areas for cemetery management
- Cost assessments and planning for exhumations
- Targeting exhumations and minimizing exploratory excavation

Other less typical uses of geophysics can include:

- Locating clandestine graves (historic or modern)
- Locating mass graves associated with battles or massacres
- Verifying past exhumations or cemetery removal

Geophysical survey is most often used in conjunction with other complementary methods of investigation, both archaeological and historical. Multiple sources of data can contribute synergistically to a much more effective interpretation. The effectiveness of geophysical survey for achieving research goals should be therefore considered in terms of its role in an interdisciplinary program.

GPR

GPR is probably the best-known and most widely applied geophysical method for cemetery investigations. Under good conditions it can be very effective, and can detect small targets at greater depth than other methods. Unfortunately, GPR is subject to severe limitations and is not effective on many – perhaps most - cemeteries. Its success is very dependent on specific site conditions, and can be very difficult to predict. Examples of GPR surveys are shown in Figures 1 and 2.

GPR functions by sending high frequency electromagnetic waves into the ground from a transmitter antenna. Some of these waves are reflected back to the surface as they encounter changes in the dielectric permittivity of the matrix through which they are traveling, and are detected by a receiver antenna. The amplitude and two-way travel time of these reflections are recorded and used to construct a two-dimensional plot of horizontal distance versus travel time. Data collected in the field are stored for later analysis, and may be viewed in real-time during data collection. A more complete and

technical discussion of the method can be found elsewhere (Conyers 2004; Conyers and Goodman 1997; Annan and Cosway 1992).

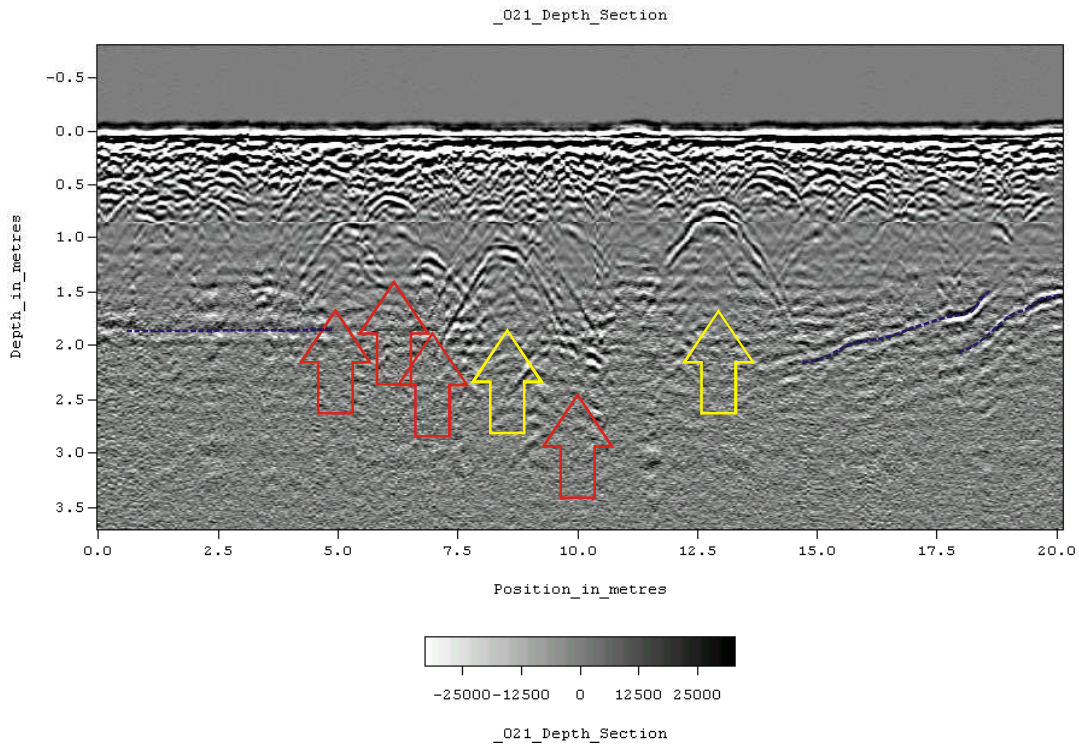

Figure 1. GPR profile from an historic cemetery in Alabama.

Blue lines indicate horizontal and sloping reflectors, probably limestone bedrock. Arrows indicate hyperbolic reflections due to discrete reflectors. Those indicated correlate with an area containing depressions and possible vernacular grave markers, and are thought likely to result from burials. Shallower hyperbolic reflections are likely to be caused by tree roots (Jones 2004).

GPR data are traditionally examined as profile maps of individual transects. Time-slicing is a technique for constructing planview maps of an area isolating specific depth ranges. This not only makes interpretation of the data in the horizontal plane much more intuitive, but also allows us to isolate specific depths (or more properly, the two-way travel times of reflected waves) for examination. Data for time-slice analysis must be collected systematically at closely-spaced (generally ≤50cm) transect intervals.

The GPR can detect human burials in several ways. It may detect the disturbed soil of the grave shaft, or breaks in the natural stratigraphy or soil profile (Bevan 1991). It may also detect the coffin, bones, clothes and other articles in the burial. Reflections may be caused by air voids within the skull (Mellet, 1992) or the coffin. It has also been suggested that the decomposition of bones may leach calcium salts into the surrounding soil for many years, which may change the electrical properties of the soil, making it visible to the radar (Mellet, 1992).

In general, sandy, homogeneous soils favor the use of GPR, and in these conditions it is often the preferred geophysical method. Clayey, silty, and alkaline soils tend to have high electrical conductivity, which can cause excessive attenuation (conductive loss) of the GPR signal, limiting both depth of investigation and resolution (Annan and Cosway 1992). Rocky or heterogeneous soils can also greatly reduce the chances of success by scattering the GPR signal and by and causing a extraneous reflections (poor signal to noise ratio). Other conditions that can negatively affect GPR data are excessive moisture, large amounts of metal (either above or below ground), rough terrain, and excessive physical obstacles to survey.

GPR Survey: Ellis Cemetery

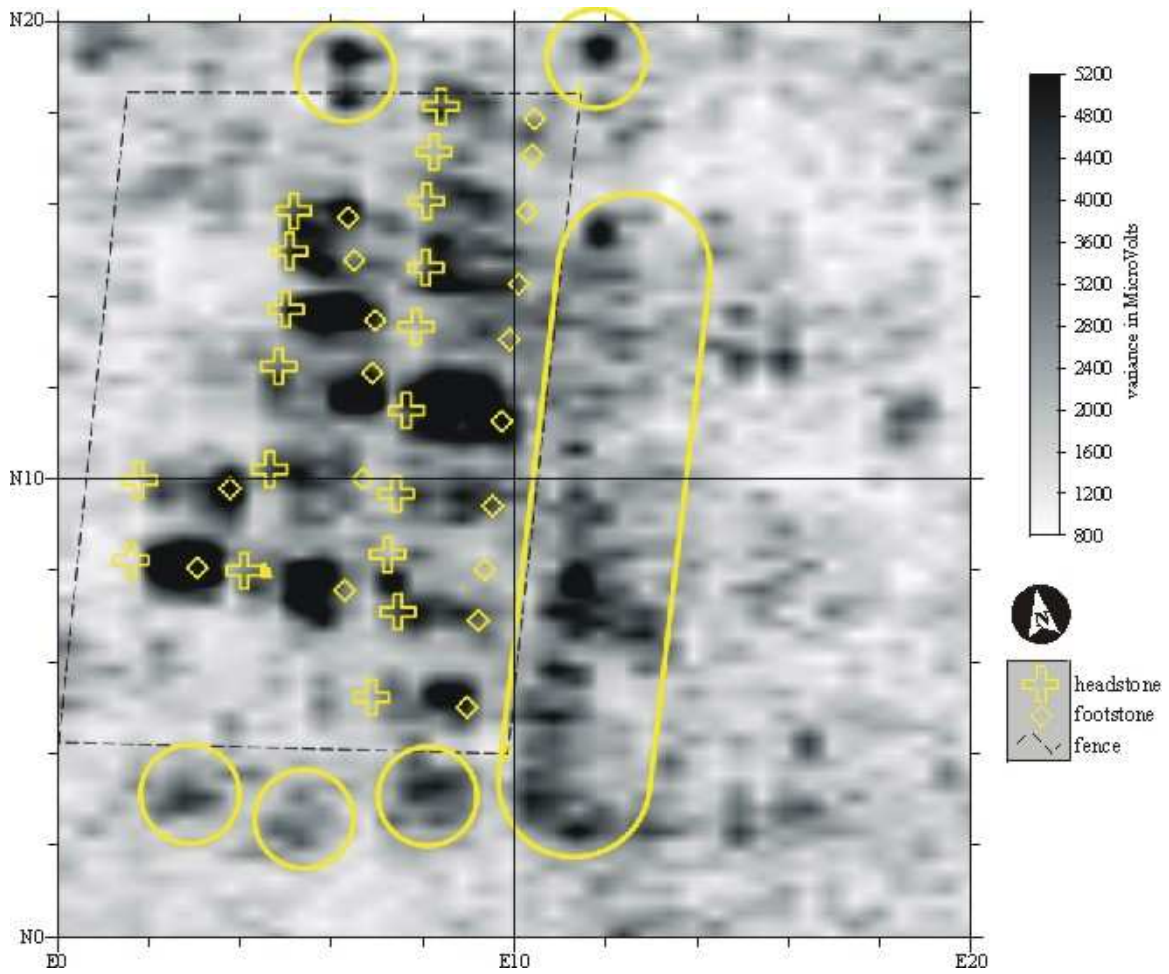

Figure 2. Time slice (planview) map of GPR survey results from the Ellis Cemetery.

The Ellis Cemetery dates from the mid-19th century. It is located on what is now Fort Bragg, North Carolina. Graves in this family cemetery are not as closely spaced as those in most public cemeteries, and individual graves are generally well-defined. Less distinct patterning outside the modern fence suggests the possibility of unmarked burials (Jones and Maki, 2003.

Resistance Survey

Although resistance methods are more limited than GPR in their ability to detect low-contrast features at great depth, they may detect patterning caused by the disturbed soils within grave shafts. Resistance survey may be

effective where site conditions limit the effectiveness of GPR, and can be a valuable adjunct, even when conditions are favorable to GPR. Resistance survey is perhaps most effective clayey or silty soils, but can be effective under a wide range of conditions. It is the most widely effective of the methods discussed here but it is also the slowest, which is its principal disadvantage.

In general, resistance data must be collected at a sample density of at least four samples per square meter to effectively resolve the patterning of individual graves. Sample patterning and instrument configuration should be adapted to the scale and geometry of cemetery patterning. Resolution is affected by soil moisture, and resistance survey should be avoided in excessively dry or saturated conditions. Resistance survey may not be possible in some extremely dry conditions.

Graveshafts may appear as either high-resistance or low-resistance anomalies, and may appear as both within the same cemetery. Small-scale variance and anisotropy (directional bias in resistance values) are also possible indicators of disturbed soils (Dalan and Bevan 2002).

Figures 3 and 4 are typical examples of resistance surveys.

Resistance survey: Minneapolis Pioneers and Soldiers (Layman's) Cemetery

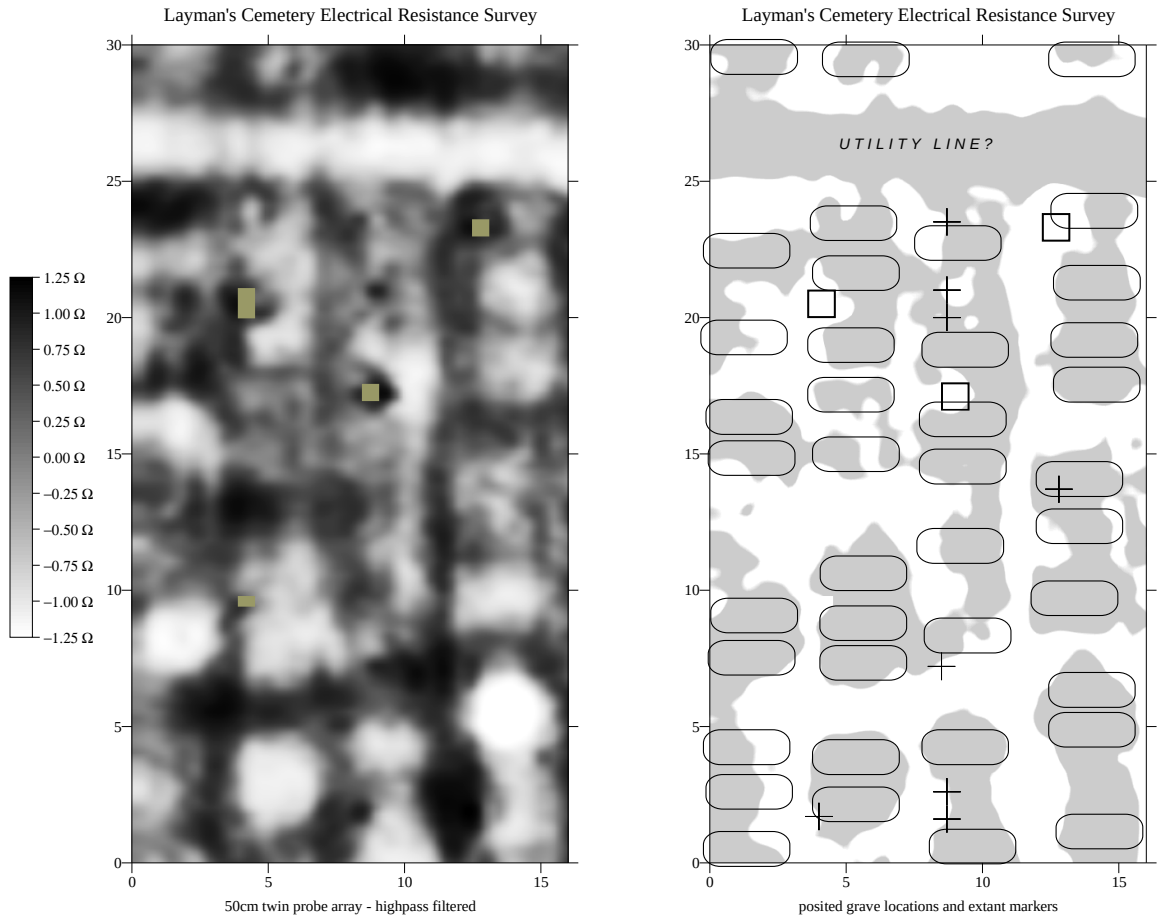

Figure 3. Resistance survey results and interpretations, Minneapolis Pioneers and Soldiers (Layman's) Cemetery.

Rows of burials are readily apparent in this 19th century cemetery. Although some individual graves are posited in the interpretation at left, a high density of burials obscures their individual expression. Grave markers are indicated as squares (family marker) and crosses (individual marker) on the interpretive map. There are clearly many unmarked graves in this area (and throughout the rest of this 10 acre cemetery, which suffered many years of neglect). It is interesting to note that the few grave markers in this area do not appear well correlated with the rows of graves, suggesting that markers may not be in their original locations. It is not clear whether the suspected utility line might be intrusive into burials (Jones 2005).

Resistance survey: Saint Mary's Cemetery, Minneapolis, MN

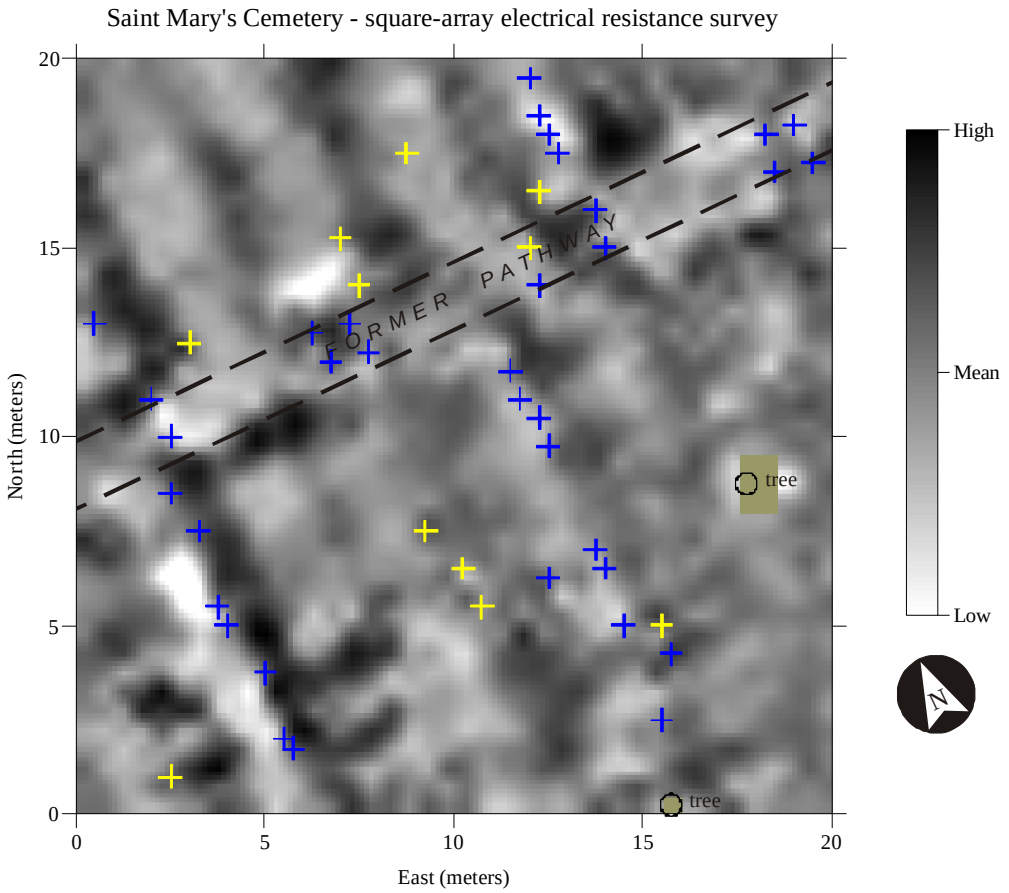

Figure 4. Resistance survey results, Saint Mary's Cemetery.

Blue Crosses indicate late 20th century grave markers. Yellow crosses indicate older grave markers, mainly late 19th century. Grave markers (old and new) are mainly flush headstones. Many of the graves are infants and children. Resolution of individual graves is inconsistent, but rectilinear patterning associated with rows of graves is apparent. . The former pathway was removed prior to 1960 and the space used for burial plots. Although this cemetery has been well maintained, it is clear that there are numerous unmarked graves, or graves whose markers have subsided and become buried. This dataset was collected with an experimental 50-x-50cm square array, which can measure anisotropy as well as overall resistance.

Magnetic Survey

Magnetometers can be very rapid and effective tools for mapping cemeteries under certain conditions, but must be used judiciously. In many cases igneous rock (as monuments or occurring naturally) and ferrous metal dominate the magnetic environment, obscuring subtler patterning. In other cases these highly magnetic materials form components of burials, rendering them highly detectable, e.g.: steel or iron in caskets, coffins or vaults, buried grave markers, and other monuments of stone or brick. Other materials may be mapped that give indirect evidence of grave patterning, including landscape elements such as paths and roads, metal debris from former fences, and even plastic flowers that have degraded, leaving their wire stems.

Where igneous rock, metal, and brick are not present, magnetometers can detect more subtle anomalies caused by concrete or organically enriched, disturbed, or compacted soils. In the absence of highly magnetic components, historic burials often appear as a weak magnetic low. A magnetic low may result from the replacement of topsoil (which typically has enhanced magnetic susceptibility) with subsoil or mixed soils in the filled graveshaft. It should be noted, however, that the organic components of graves can cause enhanced magnetic susceptibility (Linford 2004), but this effect is typically weak and at greater depth.

Due to variations in burial practices, burials within a single cemetery may have varying expressions. Graves may appear as both positive and negative anomalies within the same cemetery.

Magnetic Survey: Wyandotte County Cemetery

The example in Figure 5 is a small portion of a larger multiple-method investigation, which is discussed in the section **Multiple-method investigations** (below)

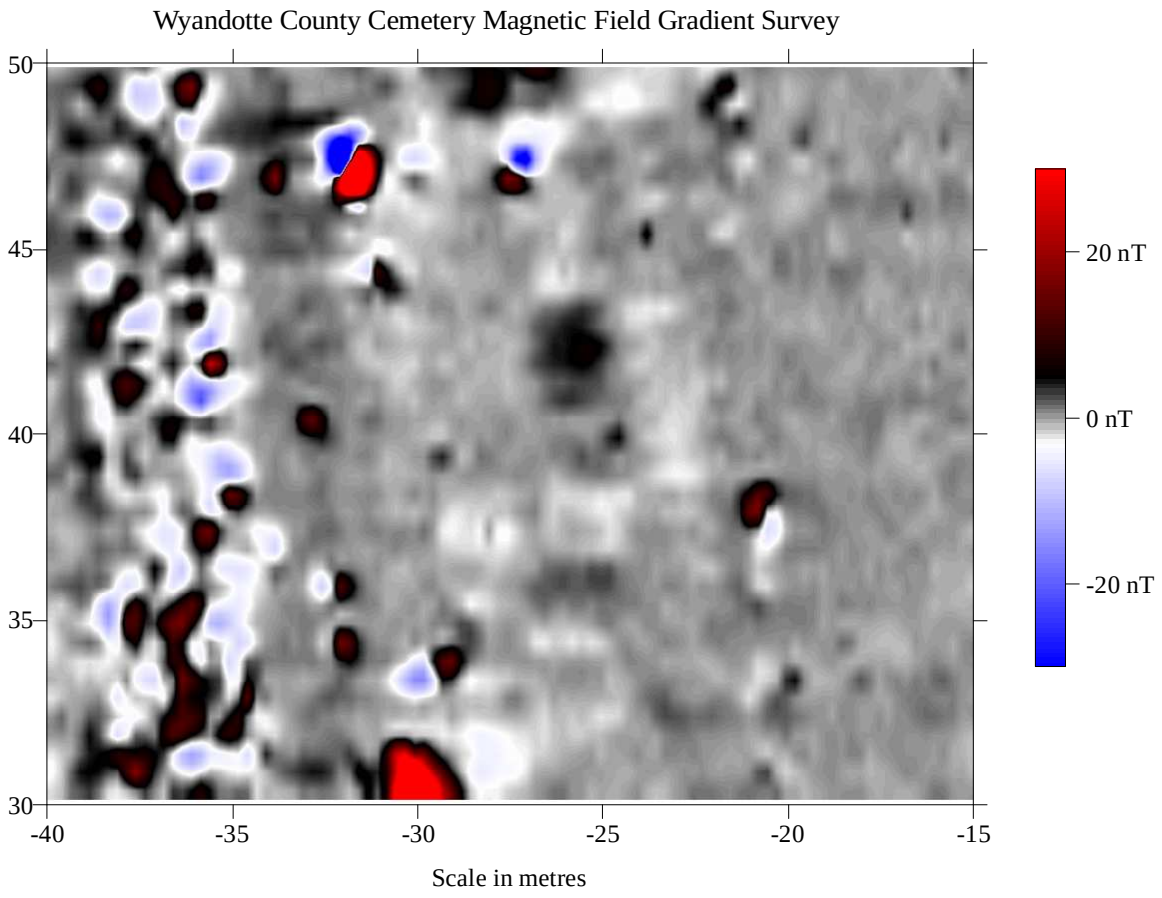

Figure 5. Wyandotte County Cemetery magnetic survey (detail).

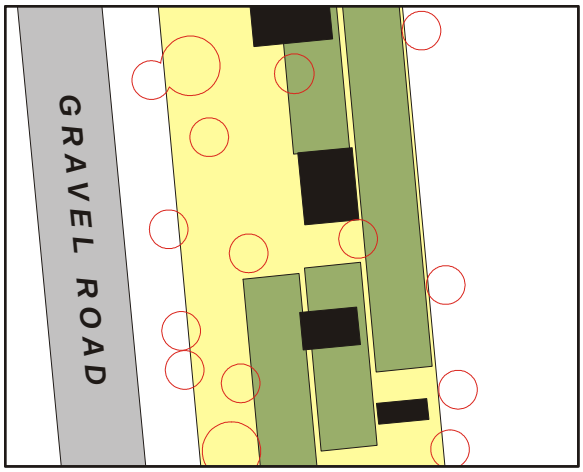

Figure 6. Interpretation of Wyandotte County Cemetery magnetic survey (detail).

The yellow area in the interpretive map at left represents the extent of apparent cemetery patterning. Although suspected burals vary in the distinctness of their expression, the patterning and orientation of anomalies within this area is strongly diagnostic.

Most suspected burials are expressed as weak magnetic lows (green), thought to result from soil disturbance. Similar patterning occurs throughout much of the yellow-tinted area but is not marked because it is weak or indistinct.

Other suspected graves are expressed as moderately strong magnetic highs, thought to be associated with vaults or steel caskets.

Red circles indicate discrete, mostly bipolar anomalies. These may be associated with ferrous metal objects, or with buried grave markers. While not distinctly patterned, their distribution coincides with the area of suspected cemetery patterning To some extent these strong anomalies obscure the weaker expression of suspected burials. The gravel road is expressed as a concentration of small bipolar anomalies due to igneous rock in the road gravel.

Other methods

The great majority of geophysical surveys have employed the methods already discussed, both in cemetery studies and in other archaeological contexts. Other methods have also been used for cemetery survey, and emerging technologies may prove to be effective. The methods discussed below have achieved some degree of success in mapping cemetery patterning, although they have not been as extensively used as those already discussed.

Electromagnetic (EM) conductivity instruments have a response that is comparable to that of resistance meters (conductivity being the inverse of resistance). They have not been widely used for cemetery survey, but some

useful results have been obtained (e.g. Kvamme 2001). The instruments are generally less sensitive than resistance meters to the same phenomena, but they do have a number of unique properties. In particular, they may be used in some conditions that do not favor resistance instruments, and they have a much higher rate of survey.

Magnetic susceptibility is a property that is becoming increasingly important in archaeological studies. Variation in susceptibility is one of the phenomena that may be indirectly detected by magnetic surveys, but susceptibility may be more directly measured by susceptibility meters. Susceptibility data collected at high sample density may be used to map disturbed soils in graveshafts. Some EM conductivity instruments are also capable of simultaneously measuring magnetic susceptibility (e.g. Kvamme 2001).

Thermal infrared (IR) imaging has had some interesting results, but has not been widely applied in cemetery studies. The use of thermal IR in archaeology is very dependent on transient environmental factors. The effect of factors such as seasonality and daily temperature cycles must be thoroughly understood in order to effectively use thermal IR methods (Heitger 1991).

Penetrometers measure the resistance of soil to the insertion of a cone-tipped rod. Although the probe is not inserted deeply, penetrometers are more intrusive than other geophysical instruments. Penetrometer testing has been found to be effective for locating graves (e.g. Trinkley and Hacker 1999). Although some instruments have digital data loggers, a very slow per-sample rate of testing makes penetrometers impractical for large-scale systematic survey. Penetrometers are not effective in rocky soils (Dalan and Bevan 2002).

Multiple-method investigations

In many settings, it may be advantageous to use multiple geophysical methods. Not only does this increase the likelihood of success with at least one method, it can greatly enhance interpretability. Because each geophysical method responds to different properties, multiple data sets are

complementary rather than redundant. Even where multiple methods do not each yield unique relevant information, correlation between multiple datasets can enhance the level of confidence in interpretations – an important consideration where subsurface testing may not be performed. The following case studies also touch upon the integration of geophysics with conventional historical and archaeological investigation.

Wyandotte County Cemetery

The Wyandotte County Cemetery (Kansas City, KS) was known to contain at least several hundred burials. Only two grave markers were present, and the locations of other burials and the limits of the cemetery were not precisely known. A program of archaeological research was undertaken to define the limits of the cemetery integrating non-invasive geophysical techniques with conventional archaeological methods.

The geophysical investigation consisted of electrical resistance and magnetic gradiometer surveys of portions of the cemetery. GPR was not used because the high conductivity of the soils. Geophysical survey interpretations were tested by limited excavation. Because of the large size of the cemetery, it was not surveyed in its entirety. The sampling strategy was designed to define the cemetery boundary at intervals that could be reasonably interpolated. The western boundary, which was adjacent to proposed road construction, was given more complete coverage.

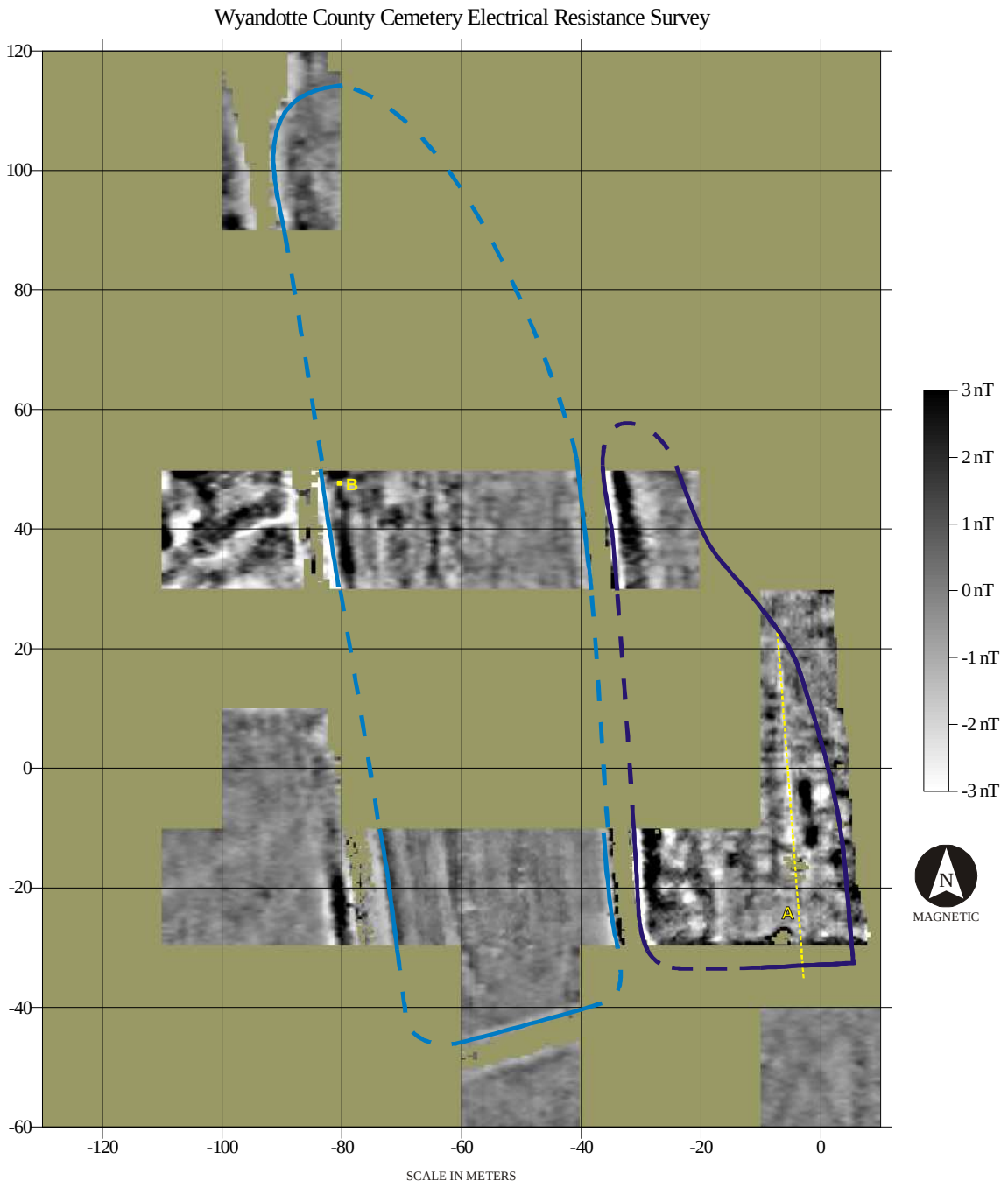

Figure 7. Wyandotte County Cemetery resistance survey.

Resistance survey (above) showed distinct patterning in the older portion of the cemetery (outlined in dark blue). Graves appear as north-south rows of low-resistance anomalies. Response in the newer part of the cemetery (outlined in light blue) is more ambiguous, showing linear patterning, but not clearly resolving individual graves. This large-scale linear patterning in the newer portion of the cemetery seems to be largely related to gentle terracing, although graves are apparent in the magnetic survey (below). The difference in response between the areas may be due to the terracing. Graves in the older portion are on a fairly level hilltop, and graveshafts may show greater contrast against undisturbed soils there, than in areas disturbed by terracing.

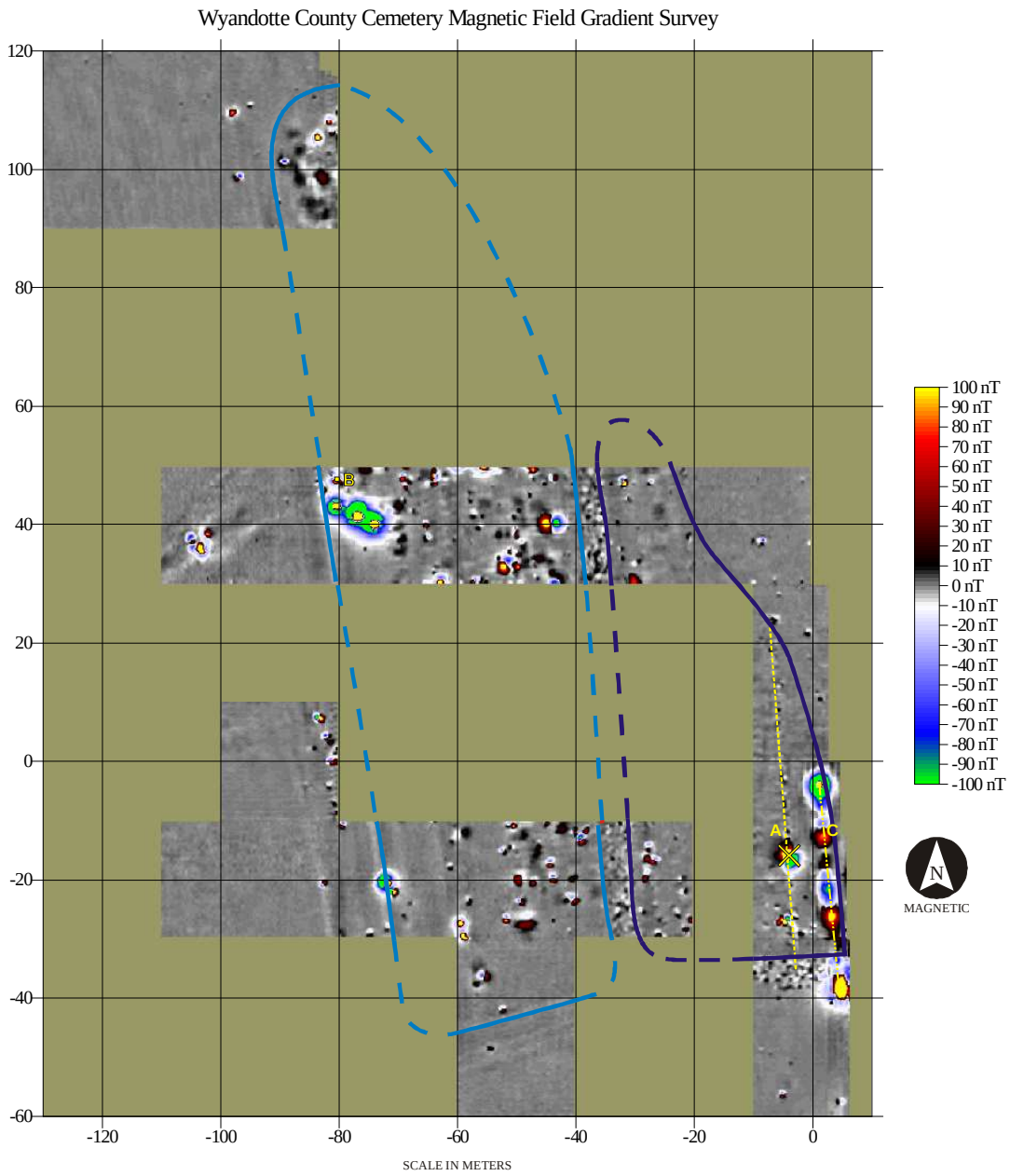

Figure 8. Wyandotte County Cemetery magnetic survey.

A small portion of the magnetic survey results (above) are discussed in the section ***Magnetic survey*** *(above), which gives examples of different expressions of graves. In general, graves in the older part of the cemetery are expressed more subtly, mainly as faint magnetic lows. Graves in the newer part of the cemetery tend to be expressed as stronger magnetic highs – probably due to vaults or metal coffins - although a range of expressions is seen. Strong bipolar (having both positive and negative components) anomalies are likely to be caused by metal or igneous rock (granite grave markers?) near the surface. A gravel road and path (marked A) are visible, as are more subtle anomalies caused by terracing and dirt roads. A single granite grave marker near the surface is located at the point marked B. The very strong linear anomaly is thought to be caused by a (posited) lightning strike on a former fence and on a nearby cross (marked with a yellow X); Laboratory testing of associated materials is pending.*

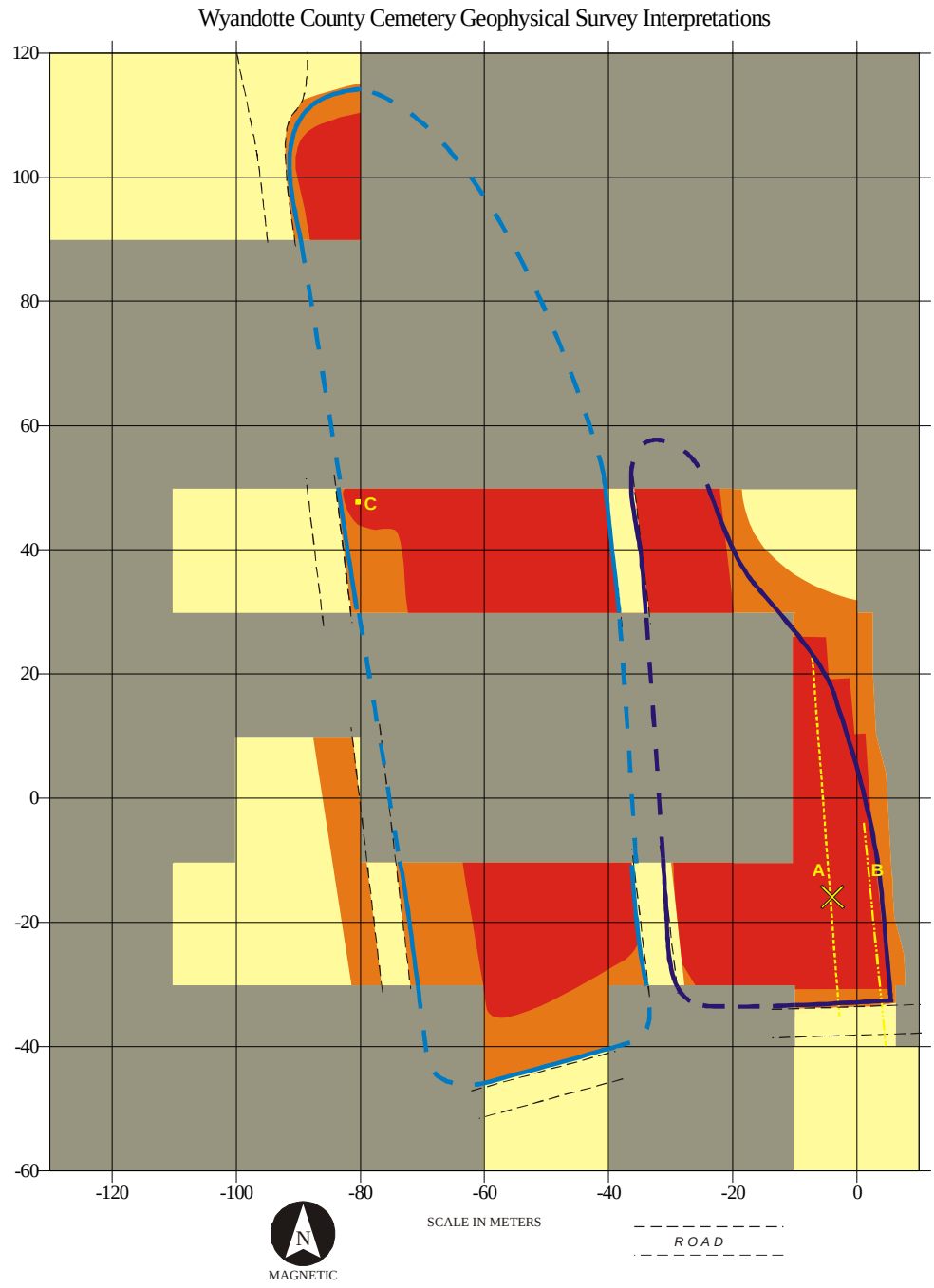

Figure 9. Wyandotte County Cemetery general interpretations.

Areas thought to have positive evidence for the presence of burials are indicated in red. Orange indicates ambiguous or circumstantial evidence for cemetery patterning. Older and newer portions of the cemetery are outlined with dark and light blue outlines, respectively; these outlines are dashed where they are interpolated. Landscape features such as roads and topography were also considered in making these interpretations and in interpolating between survey areas.

While both methods were successful in detecting graves in portions of the cemetery, either method by itself would have given an incomplete or ambiguous picture. Resistance survey provided better resolution of graves in the older part of the cemetery, while magnetic survey responded better to graves in the newer part of the cemetery. Limited excavation largely confirmed initial interpretations based on survey results. Graves exposed during excavation showed shroud burials in the older part of the cemetery, coffin burials in the newer part, and an absence of burials outside of the posited cemetery boundaries. This variety of burial practices is reflected in a range of different geophysical expressions. This illustrates the value of using multiple geophysical methods, especially where burial practices or other conditions may vary within the cemetery. The unsuitability of GPR to the soils at the site shows the importance of pre-survey reconnaissance as well as underscoring the danger of reliance upon a single geophysical method.

Manard Baptist Church Cemetery

The Manard Baptist Church Cemetery (34MS407) is located on Camp Gruber, near Muskogee Oklahoma. Reports that the cemetery was moved with the establishment of Camp Gruber are not supported by archival research. There is therefore a degree of doubt as to whether all (or any) of the graves were removed.

The investigation consisted of magnetic field gradient and Ground Penetrating Radar (GPR) survey of the recorded location of the cemetery. Survey results are shown in Figures 10 and 11, and interpreted in Figure 12. The objectives of the geophysical investigation were to map graves and other cultural and natural patterning at the site to aid in defining the location and extent of the cemetery, and to provide evidence for the presence or absence of intact graves. The investigation was successful in mapping the patterning of the cemetery

The geophysical investigation was successful in mapping patterning clearly associated with the historic cemetery. Although there are areas of some

ambiguity, reasonable limits of the extent of the cemetery may be defined with some confidence based on the geophysical survey results.

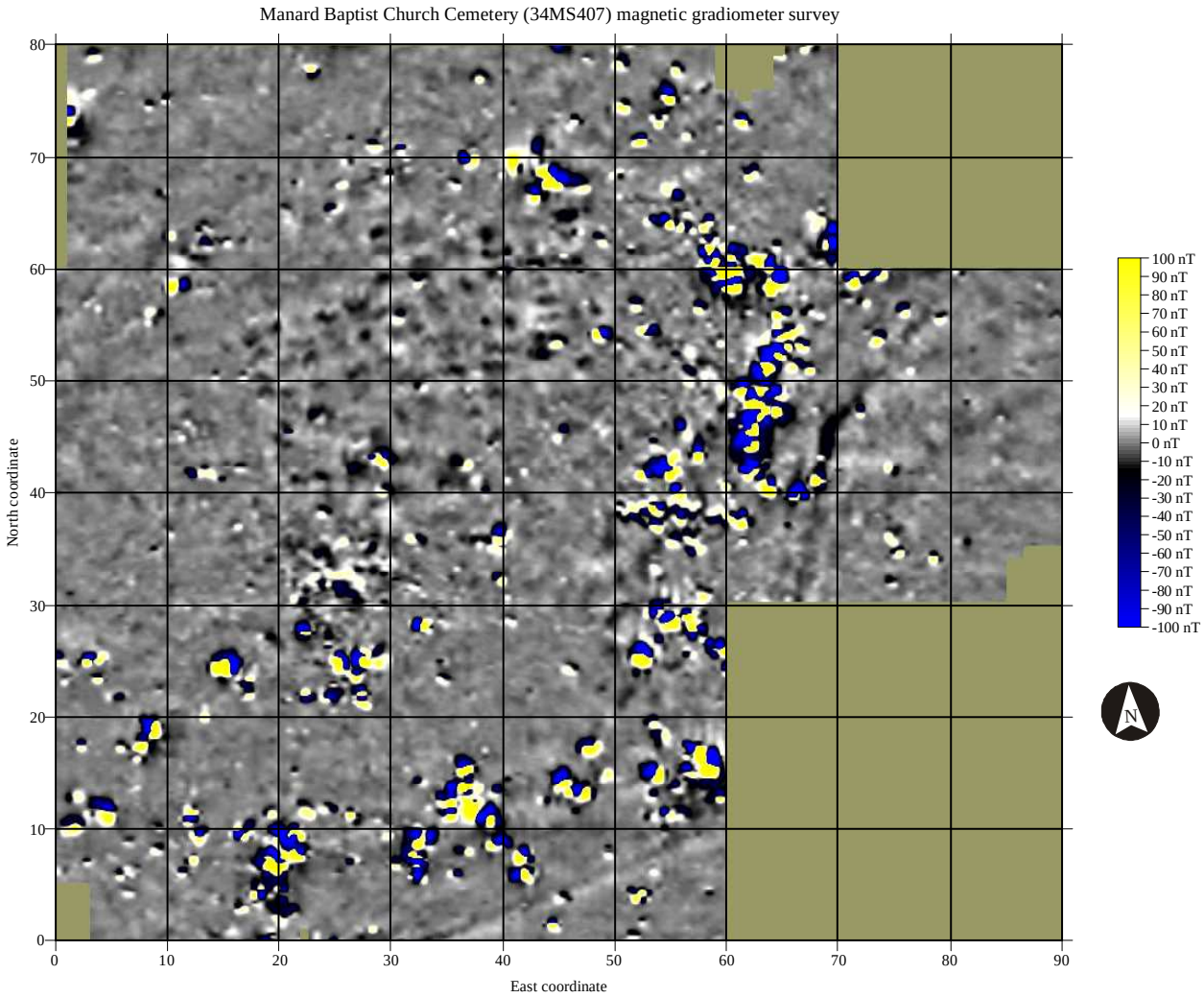

Figure 10. Manard Baptist Church Cemetery magnetic survey results.

Strong magnetic anomalies (in the blue and yellow ranges of the color scale) are mainly caused by historic/modern ferrous metal, although igneous rock and brick are other possible sources. These permanently magnetized sources typically appear as bipolar anomalies, although sometimes only one pole is detected by the survey. Disturbed and compacted soils due to graves, roads, etc. are expressed more subtly in the grayscale range of the color scale. These are typically induced-field phenomena, caused by preferential flow of the earth's magnetic field through materials with varying magnetic susceptibility. Cultural interpretations of these data are illustrated and discussed in Figure 12.

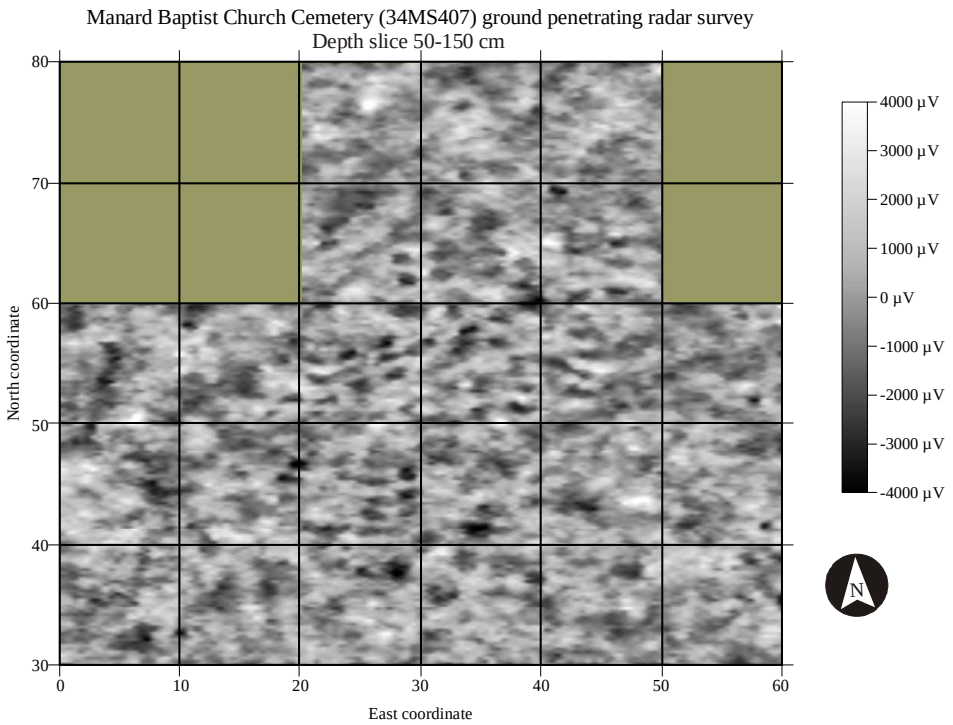

Figure 11. Manard Baptist Church Cemetery GPR survey results.

Positive deviations from the mean (lighter shades) represent areas of greater reflected signal. Negative deviations may express a lack of subsurface reflectors in a more homogeneous medium, or it may express signal loss due to greater conductivity. In this case, suspected graves appear somewhat atypically as low-amplitude anomalies. Cultural interpretations are illustrated and discussed more specifically in Figure 12.

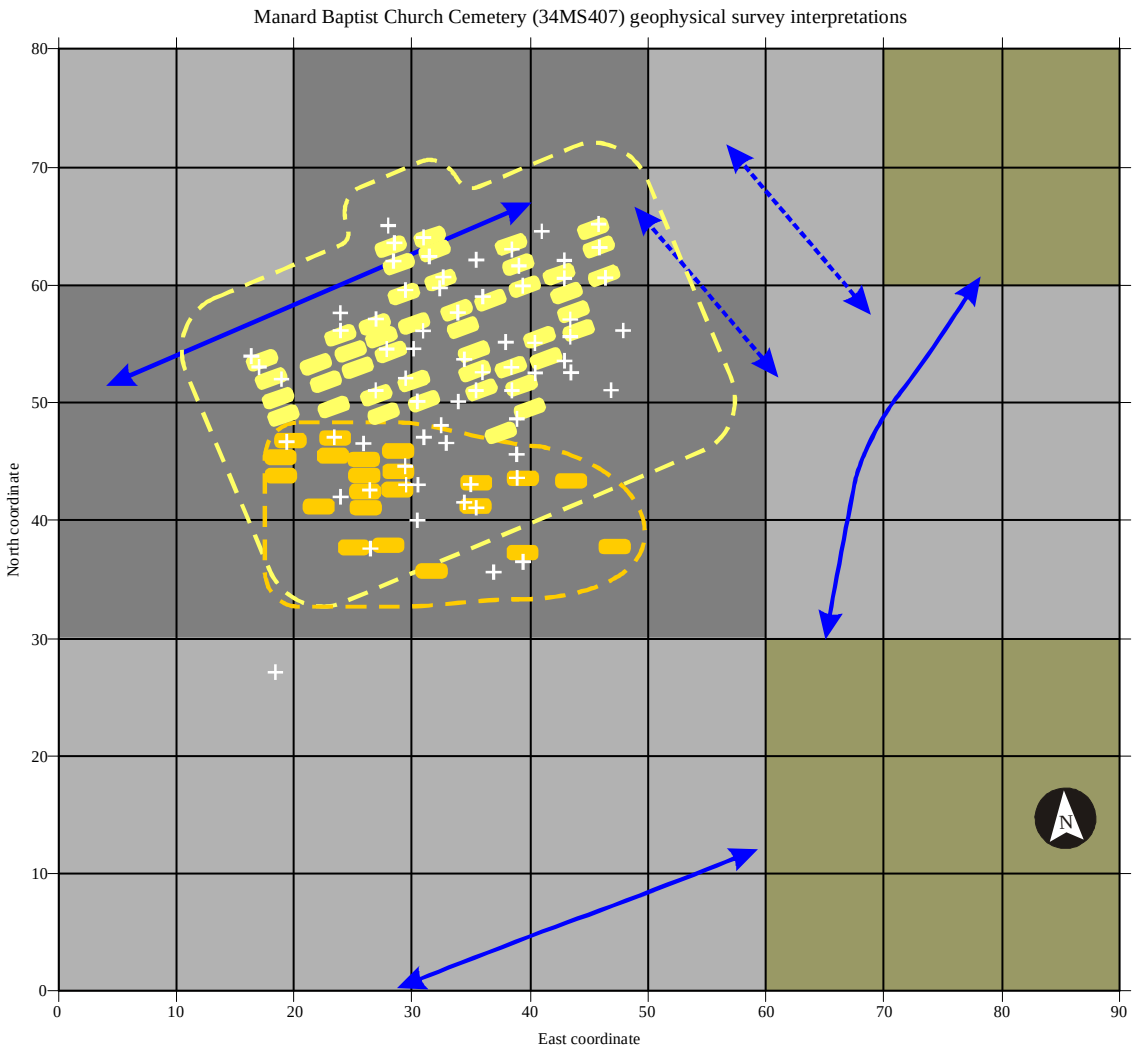

Figure 12. Manard Baptist Church Cemetery geophysical interpretations.

The interpretive markings above are based on an interpretation of both datasets and of landscape features. They are overlaid on the data plots with additional discussion in succeeding figures. The area shaded in light gray indicates magnetic survey coverage. Dark gray shading indicates coverage with GPR as well as magnetic survey.

Yellow markings indicate apparent cemetery patterning having an orientation of approximately 16° west of true north. This appears most obviously in the magnetic data, but is also expressed in GPR data. Orange markings indicate apparent cemetery patterning oriented very closely to the cardinal directions. This patterning is most apparent in the GPR data, although there it has less obviously patterned correlates in the magnetic data.

White crosses indicate topographic depressions thought to be associated with graves (or with their exhumation). The appearance of posited graves suggests that if graves have been removed, they were individually exhumed by hand excavation. Machine excavation of entire rows of graves would not preserve the patterning of individual graves that is apparent in these survey results.

Blue lines indicate linear anomalies or trends in the magnetic data thought to express former roads. Those on the eastern and southern edges of the survey area are visible topographically, and are associated with remnants of wire fences. A dashed line indicates poor definition and relatively low confidence in the interpretation as roads.

The question of whether intact burials remain at 34MS407 is perhaps the most compelling issue related to the cemetery. Unfortunately, this cannot be conclusively answered based on these survey results without subsurface testing. The inconsistent orientation of patterning in different areas of the cemetery is a curious aspect of these results. While no specific insights into this unusual patterning can be offered at this time, it may suggest questions of archaeological or historical interest.

Other application concerns

Site conditions

Site conditions are a critical consideration in designing a successful survey. Choice of instrumentation and methodology, scheduling, budgets, and overall feasibility are all affected by the cultural and physical contexts of the cemetery. Conditions that should be considered include:

- Age of cemetery
- Burial practices
- Monument types and landscape features
- Ethnicity, status, and other factors that may affect the archaeological record
- The presence of metal as debris, fences, utilities, etc.
- The use of metal and igneous rock in monuments and burial features
- Detailed characterization of soils
- The presence and composition of rock and gravel.
- Vegetation
- Physical obstacles to survey

Sampling strategy

Sampling strategies should be adapted to expected feature types and patterning, site conditions, instrumentation, research goals, and time and budgetary considerations. While the subject is complex, the generalizations offered in this overview may be helpful.

No meaningful consideration of survey design or budget can occur without considering sample density. Although appropriate sample densities differ between each instrument, the sample interval should be proportional to the scale and contrast of anticipated features. Cemeteries are rather challenging subjects, and experience has shown that transect intervals of 0.5 meters or less, with multiple readings per linear meter along each transect are generally required for good results.

The patterning and orientation of sampling are also important. Bias introduced by sampling patterns can obscure cemetery patterning, or introduce "false positives" that resemble cemetery patterning.

Spatial Control

The usefulness of survey results is dependent on accurately locating anomaly sources within the survey area. Accurate and repeatable spatial control is critical in both grid layout and data collection. It is assumed that for the present cemetery surveys will be conducted by sampling in a formal grid pattern, sampling along parallel transects. GPS-controlled instrumentation is becoming increasingly effective, but these systems have not, at the time of writing, demonstrated spatial resolution accurate enough for cemetery mapping.

The best means of assuring good spatial control is an accurate and permanently referenced survey grid system. The grid should be established using a total station or other instrument capable of decimeter-level accuracy. The grid system may be permanently referenced using two or more permanent datums. Geographic coordinates may be sufficiently accurate for referencing the grid system if differential or RTK GPS is used, but would require a similar instrument to reestablish the grid. Mapping of surface features is often done in conjunction with staking the survey grid. An accurate map of known graves, depressions, and other surface features can be invaluable for interpretation and presentation of survey results, and can be useful references when locating positions on the ground.

Interpretation

Interpretations of geophysical data may be considered as hypotheses to be tested. Testing may involve invasive techniques, but cemetery studies must often rely on non-invasive means to verify or refute interpretations. These may include complementary geophysical methods and comparison with historical data and landscape features. Interpretation becomes an iterative process of hypothesis generation, testing, and refinement of initial interpretations.

Ground truthing

The results of a geophysical investigation will be better understood if ground truthing is performed on selected geophysical anomalies. At a minimum, the surface should be inspected for evidence of anomaly sources. Anomalies may be found to be associated with depressions or other cemetery patterning, or with trees, topography, or other phenomena that are not of direct interest. The degree of invasive exploration will depend on the degree of disturbance considered acceptable and logistical factors. Invasive exploration may employ a number of techniques, ranging from minimally invasive techniques, such as coring or penetrometer testing, to surface stripping or complete excavation.

Summary

Appropriately applied, geophysical methods can be an effective tool for subsurface mapping of cemeteries. GPR, resistance, and magnetic methods are each adapted to a different set of environmental and archaeological conditions, and have all been used with success. Other established and emerging technologies have potential for cemetery investigations as well.

Ideally, geophysical methods should be part of an integrated program of research that considers historical, archaeological, environmental, and other available data. The shortcomings of geophysical survey results are mitigated (and its strengths complemented) when used in conjunction with other archaeological and historical data sources.

Historic cemeteries can be very challenging subjects for geophysical survey. Different burial practices result in a variety of responses with different instruments, and older or ephemeral graves tend to have extremely subtle geophysical expressions. Fortunately, even where response to individual graves is very weak or indistinct, the larger scale patterning of rows of graves is often diagnostic of cemetery patterning.

Instrumentation, sampling strategy, and other survey design parameters must be adapted to unique site conditions and specific research goals. Research and reconnaissance is critical for good survey design and consistent success. As geophysical surveys become more common and more successful in archaeology, it is good practice to note relevant conditions even when geophysical survey is not immediately anticipated.

Interpretation of geophysical data should integrate other available sources of data in generating initial interpretations. Where ground truthing may be performed, interpretation becomes an iterative process o f hypothesis generation, testing, and refinement of initial interpretations. In the case of the present study, initial interpretations were broadly confirmed by ground truthing results, resulting in greater confidence without fundamental revision.

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