Geophysical tests in the Jamestown fort

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Geophysical tests between a pair of holes that were bored on opposite sides of the well failed to predict the correct depth of that well. This failure was caused by the fact that an unsuitable procedure was applied. The fault has now been identified, and future tests can be made with a different procedure that should give better results.

Conductivity measurements at the bottom of the broad-area excavation detected about two dozen metallic artifacts; most of these are at a shallow depth underground. In addition, a broad and linear feature that has high conductivity was revealed; this may be a shallow ditch that was filled by nature in the distant geological past. These conductivity findings are summarized in Figure 3.

Hyperlinks to the figures (at the end of this report) are marked with blue text. Some of the sections of this report are detailed or technical; it is not necessary to read those sections in order to understand the findings of this test. The figures and their captions have been designed to include most of the important results of this work.

Introduction

How deep is it? This can be an important question before an archaeological excavation. Depth may be somewhat proportional to age, and it can be valuable to distinguish shallow objects that may be modern from features that are deep, and therefore may have a geological origin. During the excavation of a possible well inside the first fort at Jamestown, it is not necessary to distinguish ages; instead, it would be valuable to know how deep this feature extends so that its excavation can be planned. If the feature is deep, cribbing may be needed to support the soil on the sides of the excavation.

It can sometimes be easy to estimate depth from a geophysical survey, and Figure 1 gives an example of radar profiles across a well that had a diameter of several feet. Once the velocity of the radar pulse in the soil has been determined, it is a simple procedure to find the depth to the top of the debris that fills this well. A technical analysis of the findings of other geophysical instruments may also reveal the depth to the top of a feature, like a well.

It is always more difficult to determine the depth to the bottom of archaeological features with geophysics. This is usually due to the fact that the material at the top is detected so strongly that those readings obscure the faint effect of the bottom of the feature.

This result is partially shown in the radar profiles of Figure 1: The echoes become increasingly faint with greater depth, but no distinct bottom is seen. In fact, from these radar profiles, one could not say for certain that this feature was more than a few feet deep. This is because the apparently-deep echoes may simply be extended reverberations of the radar pulse between many metallic objects at a shallow depth in the well; this is common where fill contains metal or pockets of air. The effect can be compared to the optical difference between ice and snow. One can easily see through clear ice because it contains no air bubbles. Snow, however, has many pockets of air between individual snow flakes, and this causes light to be scattered from one air pocket to the next; snow is therefore translucent, and not transparent.

Since the well at Jamestown contains a large quantity of iron, a radar survey across that well would probably give a result like that in Figure 1, and it is unlikely that its depth could be estimated. However, if the fill within a feature is not complex and metallic, it can be easy to detect the bottom of that feature. The floors of cellars that are filled with moderately clean soil may be revealed with a radar.

Preliminary tests at the Jamestown well

The metal that is within the Jamestown well can, in principle, aid in the detection of that well and its bottom. The well at the Petersburg battlefield (Figure 1) could be identified as a well only because of the magnetic survey that was done there: A mass of iron that extends a long distance in a vertical direction causes a unique magnetic anomaly. When this pattern is found, it is known that the feature extends to a great depth (probably more than 10 ft). However, the true depth to the bottom of the metallic mass cannot be determined more closely. A magnetic test was done in the Jamestown fort (with a Geometrics cesium magnetometer) and it was found that the structural steel that supports the model of the fort (see the lower side of Figure 2) causes such an extreme anomaly that a magnetic exploration of the possible well could not be done.

In addition to the problem of the metallic fill, a radar exploration of the well would also run into the difficulty caused by the moderately conductive soil on Jamestown Island. Prior radar surveys there have not detected features below a depth of about 5 ft, and this is too shallow for detecting the bottom of the possible well. While the soil at Jamestown is rather sandy, it is more conductive than usual, and this conductivity is the source of the attenuation of the radar signal; it is possible that this higher-than-usual conductivity is caused by slightly saline water from the James River, although the clay that is deeper in the soil may also contribute.

The well at Jamestown was also tested with two different conductivity meters, both made by Geonics. A deep-exploring (about 15 ft) model EM31 instrument was tested, but the metallic model of the fort is so close that readings near the possible well could not be trusted. A shallow-exploring (about 5 ft) instrument was also tried; this model EM38 is sketched at the top of Figure 13. While this EM38 did not detect serious interference from nearby metal, its depth of exploration was too shallow for an estimate of the depth of the well. However, a map of the conductivity of the bottom of the wide-area excavation was made with this EM38, and those findings will be described later; for a preview, see Figure 3 through Figure 5.

Introduction to borehole geophysics

Even though surface-based geophysical tests of the well were not successful, borehole geophysics might still succeed. With borehole geophysics, the measurements are made much closer to the feature of interest than is possible at the surface; this accentuates the effects of that deep feature, while minimizing interference from objects at the surface.

A simplification of a borehole survey is shown in Figure 6. The upper panel is a cross-section of the soil. The soil that fills a well will probably be more conductive than the surrounding soil on Jamestown Island. This is because the fill contains metal and organic debris, and both of these are more conductive that the natural soil on the island, which is sandy. An electrical current will prefer to flow through the conductive fill of the well than through the sand.

As shown at the top of Figure 6, one can simply measure the electrical resistance between a pair of soil-contacting electrodes that are set at various depths in two holes that are bored on opposite sides of the well. When the current passes through the conductive soil, the reading of resistance is lower than when the current flows through the natural soil below the bottom of the well. The curve that is plotted at the bottom shows a possible result.

Since the soil itself might have a resistivity that naturally changes with depth, it is important to detect this effect. This unwanted effect can be tested by making another series of resistance measurements between a pair of bored holes that have no deep archaeological feature between them; this is shown in the right-hand side of Figure 6. If natural stratigraphy is the same between the pair of reference holes as it is between the pair of holes that straddle the well, then the difference between the two curves can distinguish the effect of the fill in the well.

While Figure 6 shows the basic idea of borehole geophysics, the procedure there has a major problem: It is difficult to get a good and consistent contact to the soil on the side of a bored hole. If the electrical contact is poor, the measured resistance may increase and this may falsely suggest that no fill was detected. There is a possible solution to the problem of poor electrical contact: If many contacts were made to the soil (perhaps with an apparatus that is like the bristles of a brass brush) and if measurements were made at close intervals of depth (so that erroneous readings can be discarded) then perhaps this simple resistance procedure could work.

Resistance measurements across the well

However, all geophysical surveys are done with an alternative procedure that is more complex, but which gets around most of the difficulty of poor contacts. Rather than using two contacting points for a resistance measurement, four contacts to the soil are made. At two of these four contacts, a current is sent through the soil; at the other two, a voltage is measured. The ratio of these two (voltage divided by current) is a resistance. The secret to the success of this method is the fact that essentially no current flows between the contacts where a voltage is measured; therefore a rather poor contact there has little or no effect on the voltage that is measured. Furthermore, by calculating the ratio of voltage to current, the effect of a poor contact and its variable current is corrected; a bad contact at the current electrode causes both the current and the measured voltage to be reduced.

Figure 7 illustrates three different borehole surveys that have separate electrodes and contacts for both current and voltage. That is, these are all four-electrode measurements, rather than the two-electrode measurements that are mentioned with Figure 6. In two of the procedures shown in Figure 7, one pair of electrodes is placed at a location that is distant from the area of survey; these distant electrodes are indicated with the infinity symbol (horizontal 8).

The arrangement that is sketched in the upper left panel of Figure 7 was the one that was applied at Jamestown Island; this configuration is called the cross-well pole-pole resistance procedure. The results of this test are plotted in Figure 8. While this finding looked rather clear and certain in the field, it was later discovered that there is a serious flaw in the procedure.

The error was first revealed by a borehole that was made through the fill of the possible well on the day of this borehole work. The excavators used my one-inch diameter Oakfield auger (and soil sampling tube) to drill a hole through the bottom of their excavation. The soil was found to be clearly organic to a depth of about 8 ft below the general level of the excavation (the surrounding rather flat soil surface), and a hard object was encountered at that depth. Therefore, this feature is clearly deep, and is almost certainly a well. Excavation is always better than a geophysical guess!

Procedures for this borehole resistance test

The details of the resistance survey are described here; this information is for the record and this section can be bypassed. A later section, titled "Wide-area tests in the excavation" may have further details of interest.

The two reference electrodes were set to the north of the excavation. The current electrode was placed just inside the reconstructed palisade, while the voltage reference was near the bottom of the rise on the north side of the former Confederate fort. The reference electrode for current was set about 75 ft north of the borehole test, at coordinate E9594.5

N9981.3 ft. The exact location of the reference electrode for voltage could not be determined with the EDM, for the spot is low and hidden by trees; however, it was very close to E9578.0 N10,041.5, and therefore about 150 ft north of the well. The electrical resistance between these reference electrodes was found to be 831 ohm.

The resistivity meter was a Gossen model Geohm 3. This low-power instrument was selected deliberately, even though its accuracy is also low. The instrument can have a voltage as high as 40 V along the wires to its current electrodes; if a person breaks the electrical connection and allows the current to flow through their body, this can cause an electrical shock that is similar to that from an electric fence. A higher-power resistivity meter, such as my L and R Instruments model MiniRes, can generate a voltage of several hundred volts, which can be lethal. While this high-powered meter would allow a better precision and accuracy (the readings in Figure 8 have only two digits of precision), this meter is too hazardous to operate where other people are nearby.

Even with the lower-powered Geohm 3, the test was set up to eliminate hazard to visitors. The two contacts where the highest voltage can be found were kept inside the fenced area where visitors did not go; one contact was always in a bored hole, and therefore out of harm's way. The voltage reference electrode has no hazardous voltage associated with it. While this was set outside the fenced area, it was placed where visitors did not go and the wire to this reference electrode was elevated above a path where a few passers by walked (just outside the palisade).

Four holes were bored through the bottom of the excavation with a 3-cm (about 1 7/32 inch) diameter Oakfield auger. The first hole was just a test of the auger (on 31 March) at the north side of the excavation; the location is mapped in Figure 2. Sandy soil was found between the surface and a depth of 1.5 ft; in the deeper span to about 3 ft, the soil was quite sticky and clayey; in the bottom span (to a depth of 4' 9") the soil was a sandy clay. This test showed that one can easily auger through the soil here; some soils can be so cemented, wet, or stony that it is impossible to either auger a hole or to keep a hole open.

The three bored holes near the well are located in Figure 2 as A, B, and C; these holes were readily augered to a depth of slightly more than 9 ft. At that depth, the sandy soil was quite wet, but not saturated with water; there was no suggestion that the holes collapsed or that the water table had been reached. The soils were similar to those found in the first hole although there appeared to be less clay in the soil of the three holes near the well. The three holes were approximately along a straight line; their separations were as follows: A - B = 17.0 ft; B - C = 16.6 ft. As seen in the sketch of Figure 14, the line between holes A and B does not pass through the middle of the well; this causes a minor decrease in the geophysical anomaly that could be measured here. The locations for holes A and B were selected to be as close to the well as possible, while disturbing the work of the excavators as little as possible.

The locations for each of these four prospective borings was first tested with a trowel scraping by an archaeologist on the staff; this allowed me to be certain that no archaeological features were suggested there. No hint of cultural soil was found in the augered soil. After the work was finished, most of the soil that was extracted from the first boring was replaced in that hole; wooden dowels plugged holes A-B-C. No samples of soil were saved.

This borehole test was made on 17 April 2009. On that date, the excavation of the well had already begun. The soil surface there was no longer flat (as it was on 31 March); half of the well had already been excavated to a depth of about 3 ft, as sketched in Figure 14. The air that fills the excavation has an infinite resistivity, as compared to the soil that was removed; however, its volume was probably still small enough that the excavation did not have a serious effect on the measurements.

The borehole resistance probes were simple. They were three plastic water pipes; these were PVC tubing with a diameter of 1 1/16" and a length of 10 ft. Each tube was cut in half so that, at most, a 5-ft section of pipe would extend above the ground (minimizing bending and weight); wooden dowels and brass screws allowed the upper 5-ft span to be fixed to the lower tube when it was deeper underground.

The soil-contacting electrodes were springy brass wires. These wires were mounted on a flattened dowel at the bottom of each plastic pipe. Each electrode was composed of four brass wires (two U-shaped sections) that were fastened under brass screws. Two electrodes were placed on each probe, and these were spaced by 5 cm; both electrodes were shorted together. With two electrodes, each with four wires (whiskers), a good contact to the soil was certain.

Markers were placed along the white pipes at intervals of 1 ft from the midpoint between the pair of electrodes; measurements of resistance were made at these intervals. The pipes and their probes could be held at the measurement depth by wedging each pipe against the side of its bored hole using a plastic tent peg.

Measurements were started at a depth of 1 ft underground, and all three electrodes were set at the same depth. Pairs of resistance readings continued at intervals of 1 ft to a depth of 9 ft. After the first series of readings, the entire set was repeated. These two series are shown as #1 and #2 in Figure 8.

Because of the unusual readings near a depth of 6 ft between holes B and C, a few extra readings were made at slightly different depths near 6 ft. This repetition and the additional readings show that the high values of resistance there are definitely caused by a feature in the natural sediments at hole C. Nothing further of the character of this feature is known; no feature was recognized during the augering of this hole. The feature may simply be a lens of clay or gravel that has a thickness of less than 1 ft.

The curves in Figure 8 show high resistance at a depth of 1 ft. This is probably caused entirely by the insulating effect of the air above the soil's surface.

Different methods for the measurement of borehole resistance

This section is rather technical and can be bypassed.

Figure 7 is a sketch that shows three different procedures that can be applied to borehole resistance measurements. The cross-sections are simple approximations of a low resistivity volume (the fill within a well) that is surrounded by high resistivity soil (which is sandy).

The procedure shown at the upper left was applied during this test at Jamestown. The resistivity meter was operated in the pole-pole configuration, and two stationary (reference) electrodes were set at a large distance (noted as infinity in the drawing). It seemed logical that this would be a good procedure; with at-surface resistivity surveys, the greatest anomaly is found where a feature is located between the two moving electrodes of a pole-pole array.

Unfortunately, this pole-pole array is not suitable for borehole work. This finding was determined by calculations with the computer program Resis2PC, written by Abijit Dey and modified by Ted Asch (see the paper: "Resistivity modeling for arbitrarily shaped two-dimensional structures" by A. Dey and H. F. Morrison, in Geophysical Prospecting, March 1979, vol. 27, no. 1, p. 106 - 136). The cylindrical fill of a well was approximated by a filled rectangular trench; this 2D model is shown in Figure 9. Pole-pole calculations were made at different depths next to this trench, and Figure 9 has the findings. The anomaly caused by the conductive feature is minor; the feature is also apparent as high resistivity, rather than low. If the calculation of a 3D model could have been made, the anomaly would have been even fainter.

The calculations in Figure 9 were checked with a different computer program, Res2Dmod, written by M. H. Loke (see www.geoelectrical.com). While Loke's program is derived from that of Dey, it still allows a moderately-independent test. The results of this calculation are plotted as a pseudosection in Figure 10, and this also reveals the faint anomaly that will be measured between the two borehole electrodes when the pole-pole array is applied.

This Res2Dmod program shows that a clearer anomaly would be found by measurements in a single bored hole next to a possible well. The procedure is sketched in the lower left panel of Figure 7: The current and voltage electrodes are both in the same hole, and the spacing between those electrodes is set to be about the same as the distance from the side of the bored hole to the well.

The findings of the calculations from Res2Dmod are plotted in Figure 11; note that this is still a 2D calculation, and so this calculated anomaly would be greater than the measurements of a feature (like a well) that is actually three-dimensional. The important measurements from Figure 11 are extracted and plotted in Figure 12.

A third procedure for detecting a well is sketched at the upper right panel of Figure 7. With this method, a current is sent through the soil between the two bored holes. Voltage electrodes are offset from those current electrodes, and the ratio of the measured voltage to the applied current is a resistance, in ohms. While this procedure is similar to that shown in Figure 6, since the voltage and current electrodes make contact at separate points, there should be less difficulty with a variable contact resistance at the current electrodes. This procedure is similar to what is called a Kelvin connection in general electrical work. While calculations have not confirmed the suitability of this procedure, it appears to be the one most likely of success.

Wide-area tests in the excavation

A map of the electrical conductivity of the soil at the bottom of the wide-area excavation was measured on 31 March 2009. The findings of this survey are plotted in Figure 3; it is likely that most of the metal objects that have been located are either known already or are unimportant. A band of conductive soil crosses the area. This probably is natural, but it is not impossible that the high conductivity could be caused by cultural chemicals (such as salts) in the soil. As an example of this, former stables have been detected by this type of measurement because of the high conductivity that can remain from the manure of the animals.

In Figure 3, two of the metal-locating symbols (an X and an asterisk) include the label M1 or M2. It is likely that the metallic object at M1 is the mass of lead that is exposed at the surface of the excavation. I did not note this exact location because, at the time of the survey, I did not recognize that this was metal (it looked like a lump of concrete or clay). Fortunately, one of the excavation crew members later mentioned this metal.

The metallic object at M2 is within the fill of the well, and this object gave the strongest anomaly (this just means that the object there is large and/or moderately shallow). On 7 April 2009 (when the excavation of the well was just about to start) I tested the location of this anomaly with a high-resolution fluxgate magnetometer, a Walker Scientific model FGM-5DTAA instrument. The small size of this instrument's magnetic sensor allows rapid measurements to be made at the soil's surface with a spacing of 1 cm or less. A scan across the surface revealed a typical bell-shaped magnetic anomaly and the half-width rule could be applied along the line of measurement: The points where the anomaly fell to half its peak value were marked on the soil along the profile; the maximum depth of the underground object that causes the anomaly is then about equal to the distance between these half-maxima. This analysis indicated that there was an iron mass very close to E9618 N9908 that was at a depth of 13 inch or less and whose weight was 2 pounds or less. Since so many iron objects were later excavated from the fill of the well, this geophysical finding had little importance. In other circumstances, where excavators may not expect metallic artifacts, it could be valuable to have a preview of an object that will shortly be encountered at a greater depth.

In the geophysical summary of Figure 3, two oval features are marked northeast of the well. It appears that metallic objects were detected in the unexcavated soil within those features; see the X near the middle of each oval. While this is the most likely conclusion, because of complexities in the response of the EM38 to small features, it is not impossible that there are no metallic objects in those two features; instead, conductive soil that fills the features might have been detected.

The EM38 conductivity survey gave essentially no detection of the grave (labeled in Figure 2). No unusual readings were found near the fireplace either. The area of survey crossed an unexcavated part of the cellar, but there was no anomaly there. These failures of detection simply mean that the contrast of the soil at those features was too faint or that the features were too small to be detected by the EM38.

Figure 5 shows that there was a high conductivity anomaly near the middle of a feature at e18 n24; another high conductivity anomaly was found near e8 n27 and near the excavation of the cellar. In both cases, it is not impossible that metallic features are at a greater depth there (perhaps more than 1.5 ft underground). While shallow metallic objects are detected with low or negative readings, deep metallic objects can be revealed as conductivity highs.

Details about the conductivity survey

The geophysical summary shown in Figure 3 is derived from the conductivity data that are plotted in Figure 4 and Figure 5. Technical details about this work follow.

The coordinate system that is applied to the archaeological work was also used for this geophysical survey. Since the East and North coordinate numbers are greater than 9000, relative values were used for the work wherever the simplicity of fewer digits might minimize errors of recording or allow a better understanding of locations. The point E9600 N9900 was defined as a relative coordinate of e0 n0. A relative coordinate can be identified by its small numbers or by the lower case letter e and n (or w or s) that precedes the number. The border of Figure 2 shows the full coordinate numbers, and also these relative values.

The locations and shapes of the features that are mapped in Figure 2 are only approximated; Figure 2 is just a sketch whose purpose is to aid the understanding of the geophysical work. While the metallic mesh on the east side of the excavations could be detected strongly by a conductivity instrument, the survey was kept away from that mesh. The steps at the south side of the excavation are wood and had no effect on the geophysical instruments.

The lines that are drawn within the excavation in Figure 2 mark features that were visible at the surface; these lines were scribed on the soil's surface by the excavators. A deep cellar was excavated on the left side of Figure 2. While this cellar probably extends to the east, that part has not been excavated; instead, a rope marks the extrapolated path of the cellar wall. A fireplace and its brick have been exposed at the eastern end of the building. A metal-working area had been revealed at the northern side of the excavation, and this location is approximated in Figure 2.

The original readings of conductivity are plotted in Figure 4. This survey was made with a Geonics EM38 electromagnetic induction meter on 31 March 2009. The magnetic dipoles of the instrument were oriented in the vertical direction and the bar of the instrument was aligned north-south. The EM38 was carried just above the surface of the excavation, in a thermal shell of Styrofoam (to minimize drift of the readings). Readings were recorded at intervals of 1 s with a Metrosonics model dl-3200 data logger; on the surface, these readings were made at intervals of 1 ft along north-south lines that were spaced by 1 ft. Recordings were made on north-going traverses. During data processing, the readings were shifted backwards along their lines of traverse by 2 ft; this corrected for a lag in the recordings. As revealed by the test in Figure 13, electrical interference caused no difficulty to this survey.

The conductivity map of Figure 5 has contour lines drawn at intervals of 1 mS/m (millisiemen per meter). Readings of apparent conductivity that are less than zero are not contoured; these locations are shown at about three locations by white "eyes" within an area with dense contour lines. These negative readings are certainly caused by metal.

The smoothed map of Figure 4 was derived from the data in Figure 5. Readings outside the range of 10 - 20 mS/m were first truncated to those limits. Then, the average reading within each 3 ft x 3 ft square was calculated, and that average is mapped in Figure 5. While this averaging clarifies large-area patterns and eliminates or reduces small-area patterns, some of the small, but intense, anomalies that are common in Figure 5 will still be apparent in Figure 4.

On 7 April 2009, a reconnaissance was made across the excavation with a Geonics EM31 conductivity meter. While the model EM38 instrument detected underground features to a depth of about 5 ft, the EM31 will detect features that are as deep as about 15 ft. While there was an increase in conductivity of roughly 2 mS/m over the fill of the well, the nearby metal of the fort model makes this finding unreliable. A continuation of this conductivity test outside the excavation may have traced the pipe and wire that end at the south side of the excavation (see Figure 3) where those lines extend to the southeast.

The typical reading of conductivity with the deep-exploring EM31 was about 15 mS/m; this is the same as the average conductivity that was found with the shallow-exploring EM38. This suggests that the deep soil at this site does not become unusually conductive, which says that there may be no increase in clay or the salinity of groundwater at that greater depth.

The field work for these geophysical tests was done on March 31, April 7, and April 17, 2009. The weather was pleasant on each of those days, and there was no rainfall during the field work.

Conclusions

It is unfortunate that this borehole resistivity test was flawed by my improper procedure. Perhaps the calculations that were made after the field work should have been done before that test was started; this could have allowed a good method to be applied. However, those calculations are sufficiently tedious and uncertain that it is sometimes better just to try an experiment in the field. Two procedures that are better for borehole resistivity work have been described here, and both of these are suitable for future tests.

A related, but more complex, procedure called tomography could also be tested at some future time. Computerized tomography is called a CAT (Computerized Axial Tomography) scan in the field of medical X-ray imaging. Geophysical tomography is much more difficult and uncertain than is X-ray tomography. While X-rays travel on essentially straight lines, this simplicity is not found with geophysical tomography, which may be done with electrical currents, radar pulses, or seismic (sound) waves. With these geophysical sources, the path of the current, radar signal, or seismic wave changes significantly with the materials that are encountered. This causes the paths to be uncertain and this greatly complicates a geophysical study. While an image that is created by tomography would be crisper (have a higher resolution) than an image that could be created with the simple procedure that was applied here, geophysical tomography can never approach the acuity of an X-ray tomogram.

Additional advantages of tomography are the fact that moderately complex shapes and locations can be defined in the volumes that are explored. Tomography might also allow smaller features to be revealed than could be detected by the simple procedure of this field test. However, all geophysical methods are rather limited in their spatial resolution: Small diameter wells can be detected only if measurements are made close to them.

There are two major disadvantages to geophysical tomography. First, it may require a good number of bored holes, so that features between these holes can be "examined" from many different directions; these extra holes are more likely to damage unknown archaeological features, and one might ask: “Why not just bore through a feature if the alternative is so many holes”. Second, tomographic surveys are quite complex in their analysis. This complexity means either a lot of time writing a computer program, or a lot of expense buying someone else's program (the cost is a few thousand dollars or more).

In geophysical exploration, the seismic method is most commonly applied for tomography (compared to radar or resistance tomography). Resistance tomography has been tested for its medical applications; see the book "Electrical Impedance Tomography" that was edited by J. G. Webster.

If magnetic measurements were made in a bored hole, it is possible that this could separate iron that is deep in the fill of the well from the interfering masses of iron that are found at the surface. While the sensor of my fluxgate magnetometer can be operated in a 2-

inch diameter bored hole, the maximum depth that I can test is about 5 ft.

Acknowledgments

I thank Bill Kelso for not only allowing this test, but for encouraging it. He knew that this work would not aid his excavation, since he will completely extract the well's fill; however, he was happy that this test might aid future archaeological investigations where a complete excavation may not be done.

Geophysical surveys are rarely done in excavations. While this is partly due to the fact that the surveys may not be needed, it is also partly due to the problem of interference between the geophysical equipment and the on-going excavation. Bill and his excavation crew cheerfully allowed me to intrude on their work. The excavation staff, which includes Dave Givens and Danny Schmidt, not only explained their excavation finds, but they located my geophysical grid and the locations of my tests with the aid of their EDM.

The excavations are very popular with visitors; there were frequently groups of fifty or more who were given talks about the findings (some of the speakers were Preservation Virginia volunteers). While this large attendance caused the site to be rather noisy (and therefore made it difficult for one to concentrate) it is good that these visitors (who are the sponsors of the work) can check on progress. A few individuals were even interested enough in my esoteric part of the investigation to ask me about it.

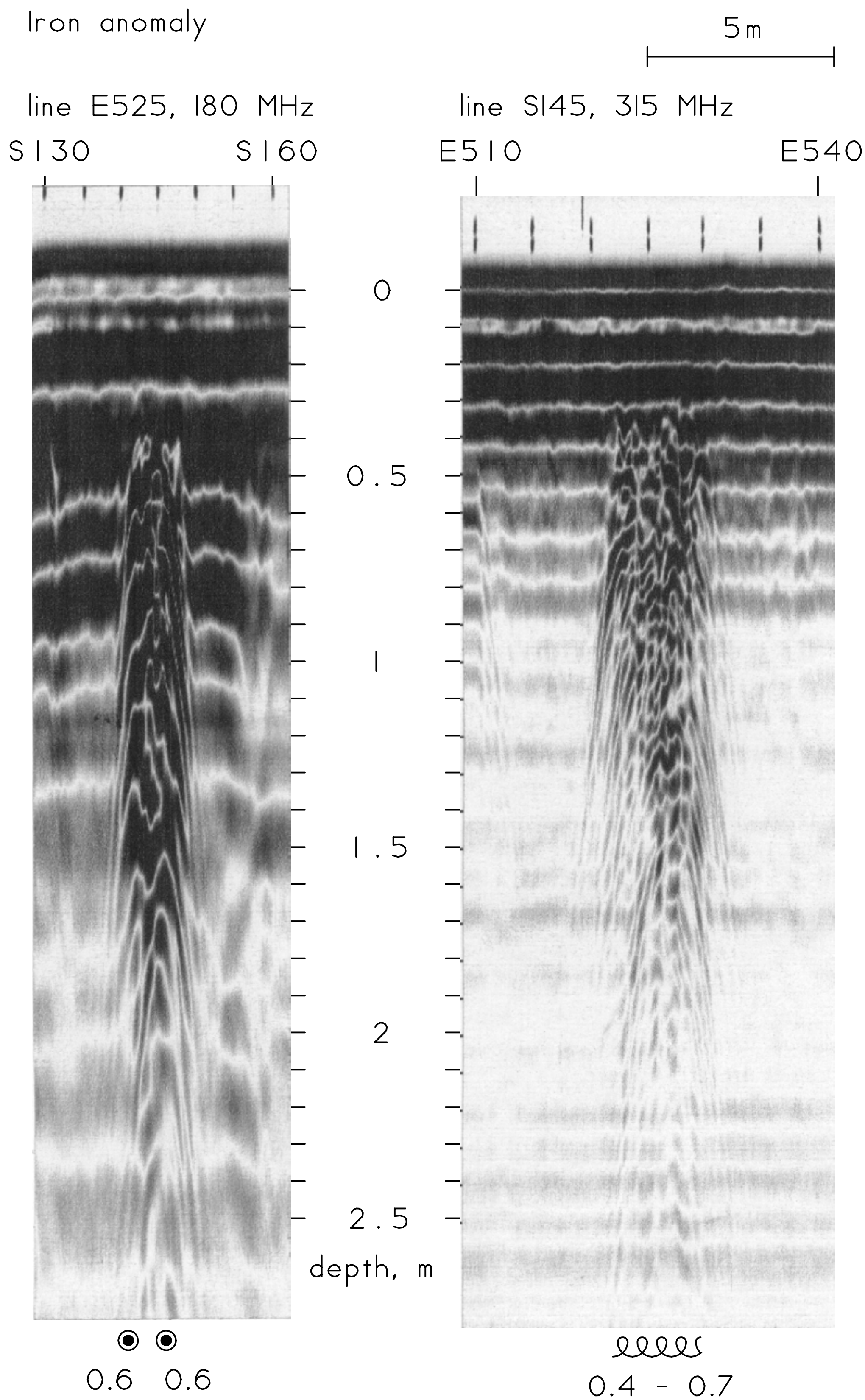


Figure 1: The radar echo of a well. The two radar profiles show spans that are each 30-ft wide. The vertical band of echoes in each profile is caused by a cluster of metallic objects that fill this dug well. The upper end of the well is detected at a depth of 1 - 2 ft (0.3 - 0.6 m). While the radar echoes extend to an apparent depth of more than 2.5 m, objects were detected in the well to a maximum depth of 1.2 m. The profile on the left is from a radar that had a moderate resolution, while the profile on the right shows a higher resolution; the size of the echo patterns reveals this difference in resolution. This well was found adjacent to Fort Morton on the Petersburg National Battlefield.

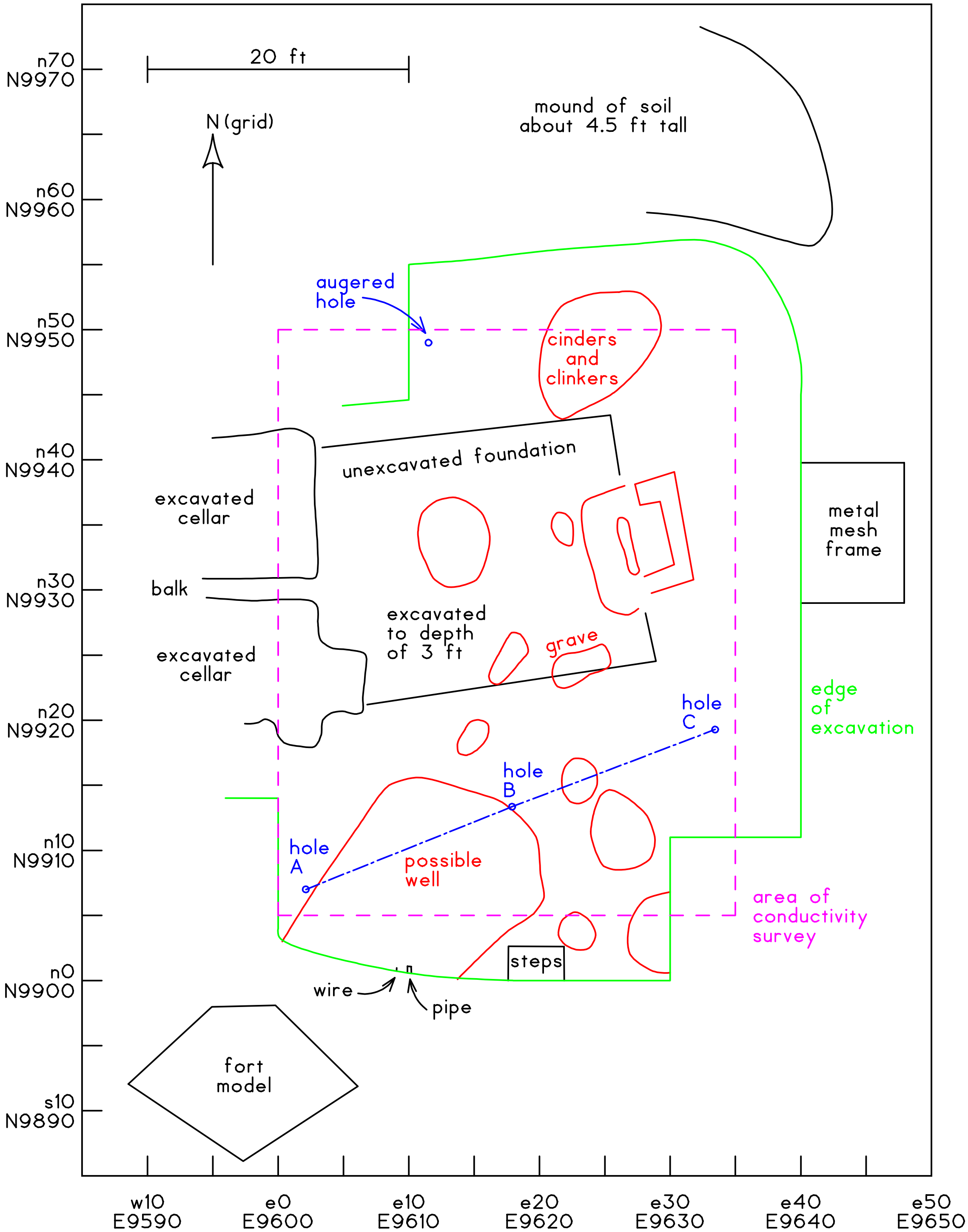


Figure 2: The area of exploration within the early fort on Jamestown Island. This sketch map is only an approximation of the locations of features that were exposed in the excavation, which was about 3 ft below the surrounding surface. This map does not include the steel posts of a rope fence on the south side of the excavation. The line A-B-C across the possible well locates the three bored holes of a geophysical test.

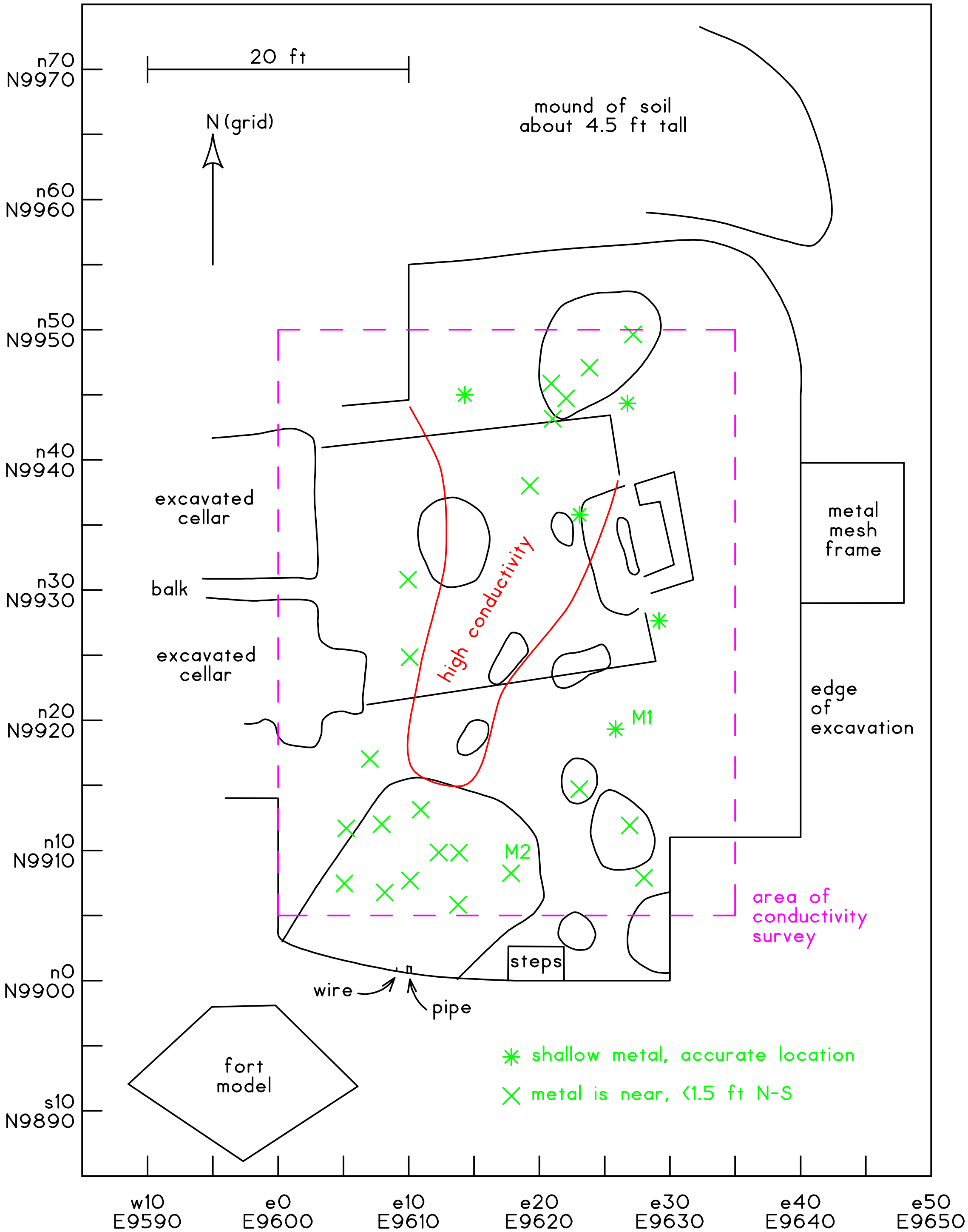


Figure 3: The findings of a conductivity survey. A band of high conductivity extends north-south across the area; this pattern may have a natural origin. Asterisk and X symbols locate where metallic artifacts are likely to be found at a shallow depth. The locations of the objects marked with an asterisk are more certain than those marked with an X.

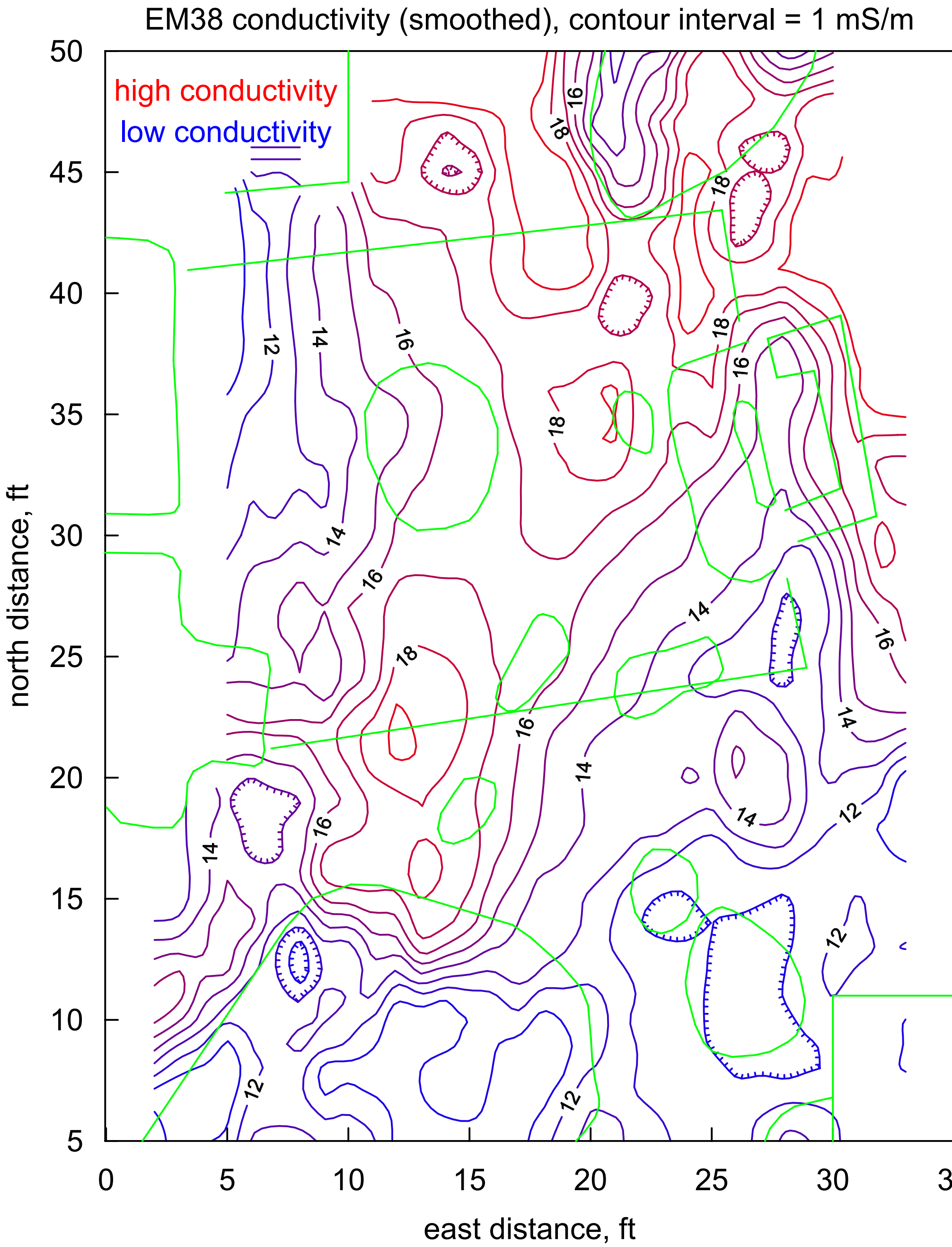


Figure 4: Broad patterns in the conductivity map. High numbers mean that the soil has a greater fraction of silt or clay than usual, or that it is somewhat saline or otherwise contains conductive materials. This map is a smoothing of the measurements that are plotted in Figure 5; some patterns that are about 5 ft wide here may just be unwanted remnants of anomalies in Figure 5 that are intense and have a small area.

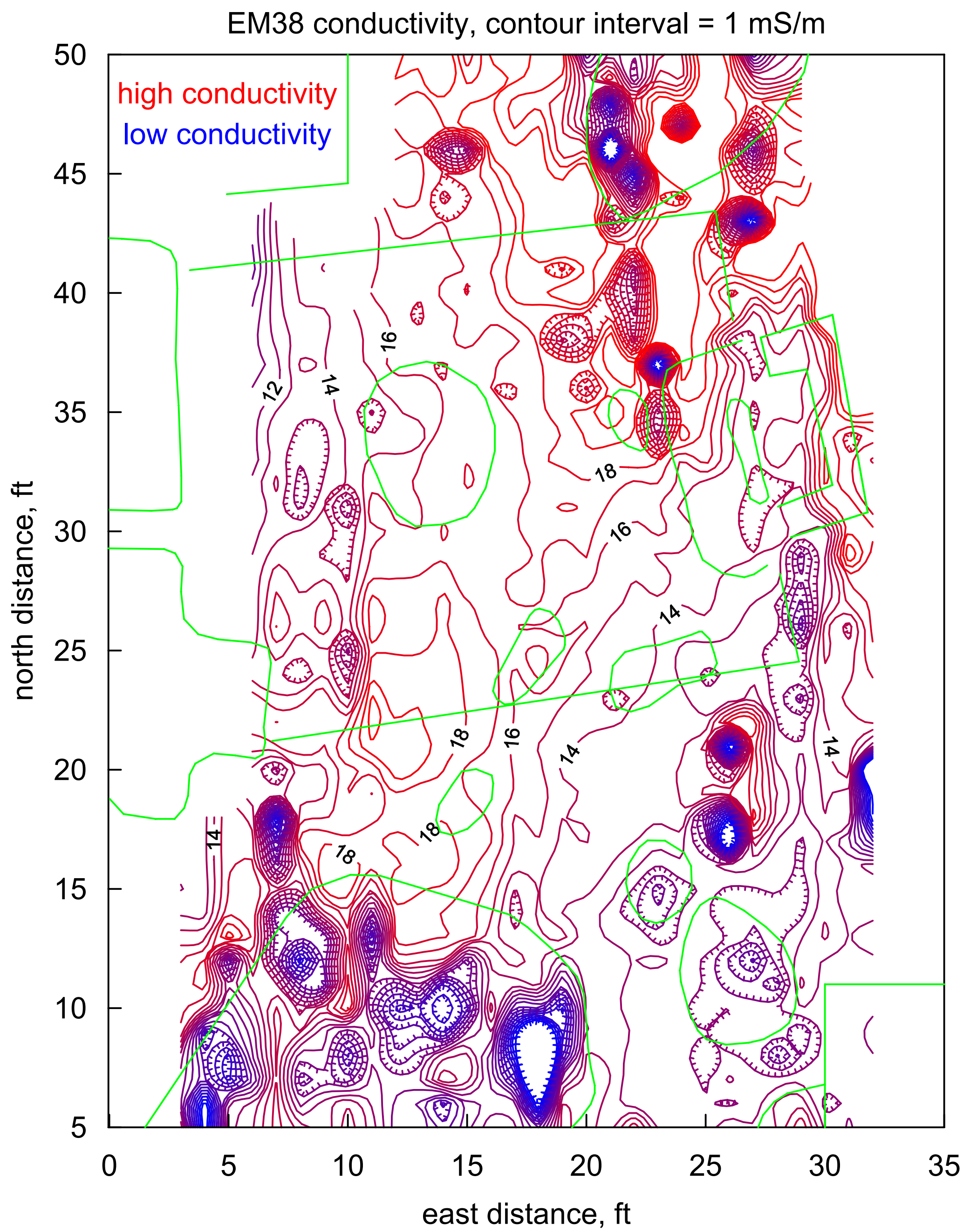


Figure 5: A conductivity map of the bottom of the excavation. Intense low readings are probably caused by shallow metallic objects; these lows are revealed by dense contour lines that have tick marks along their length. Note that these patterns are found primarily at the south (within the possible well) and at the north (where refuse from a metal industry was found). Pairs of lows that are aligned north-south and which are spaced by about 3 ft are caused by metallic objects midway between those two lows. Green lines show the features and boundaries that are plotted in Figure 2.

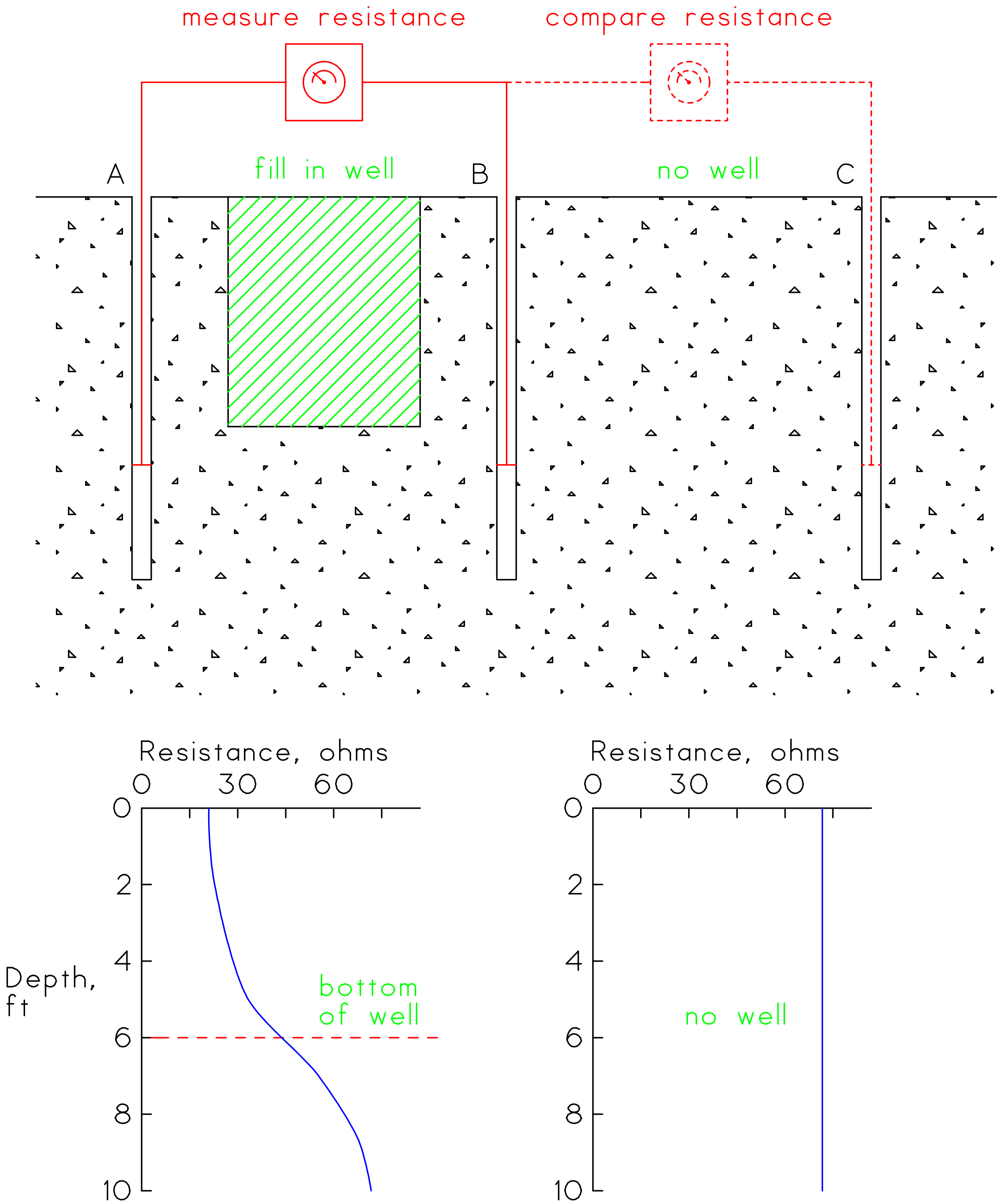


Figure 6: Geophysical measurements between bored holes. The cross-section at the top shows three bored holes; one pair straddles a deep feature like a filled well. The electrical resistance of the soil between the pairs of holes can be measured, and the values may plot as shown at the bottom. Conductive fill in the well can cause the readings to be low until the measurements are made below the bottom of the well. This procedure is simple but it is not practical; Figure 7 shows alternative methods for this type of borehole investigation.

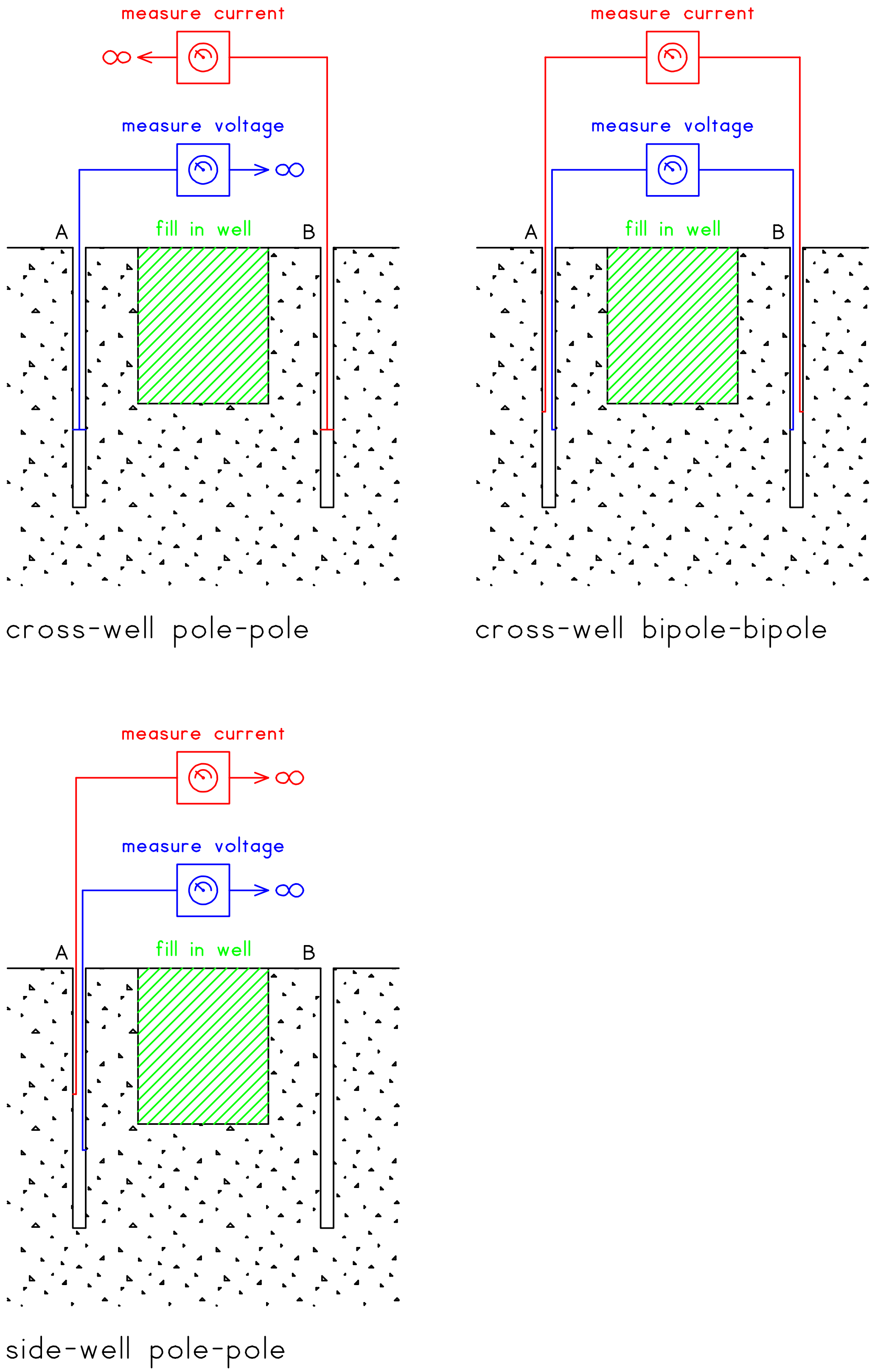


Figure 7: Three procedures for estimating the depth of a well. The borehole method that was applied to this test is shown at the upper left; this method was later found to be defective. The procedure sketched at the upper right should give better results, and the method in the lower left requires only one bored hole.

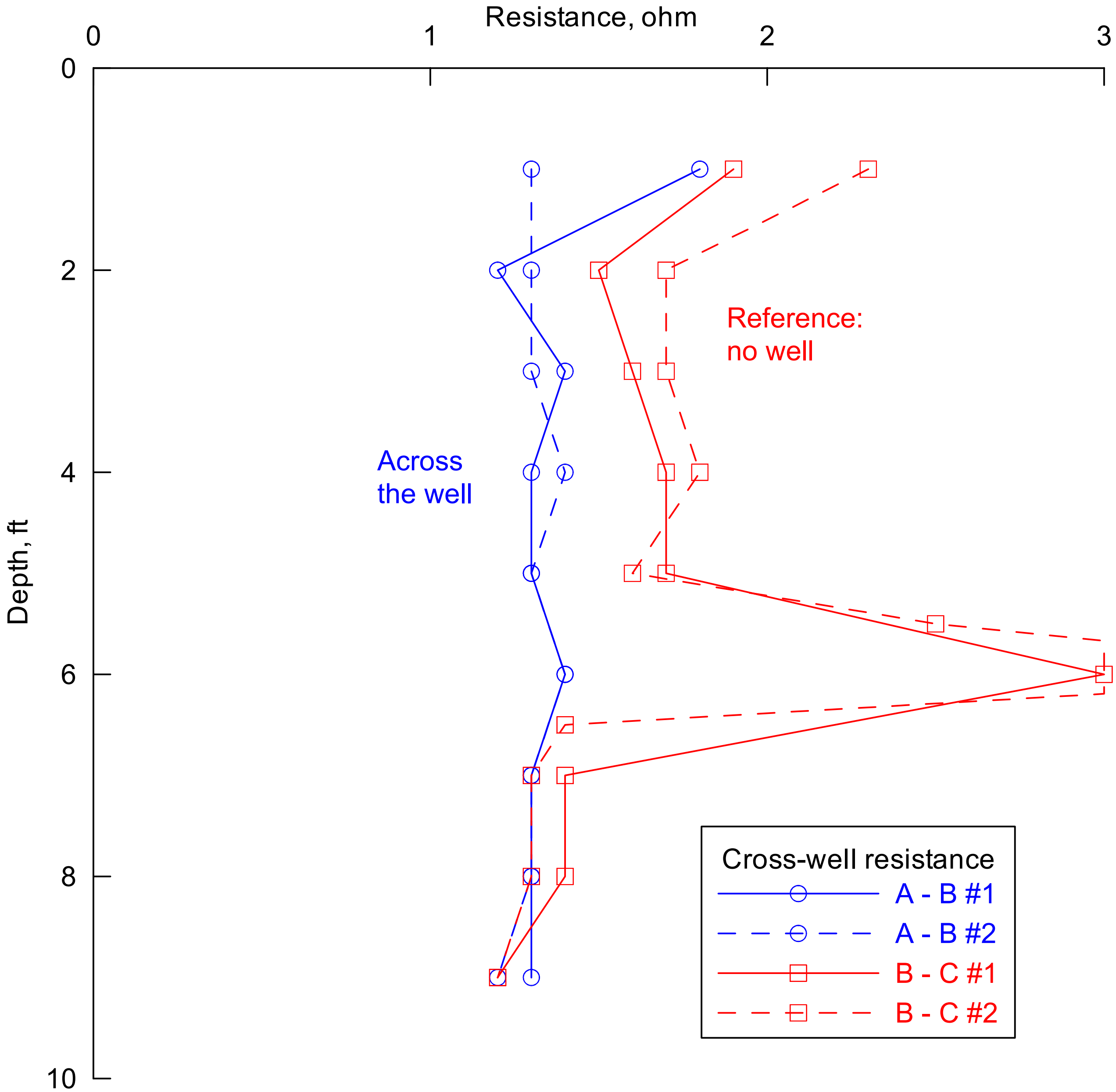


Figure 8: Measurements of resistance between pairs of bored holes. At a shallow depth, the curves (A-B compared to B-C) differ; at a depth of 7 ft and greater, the curves are almost the same. This implied (incorrectly) that the bottom of the well could be at a depth of about 7 ft. Extreme readings at a depth of 6 ft are caused by an unknown (but natural) feature along the side of hole C.

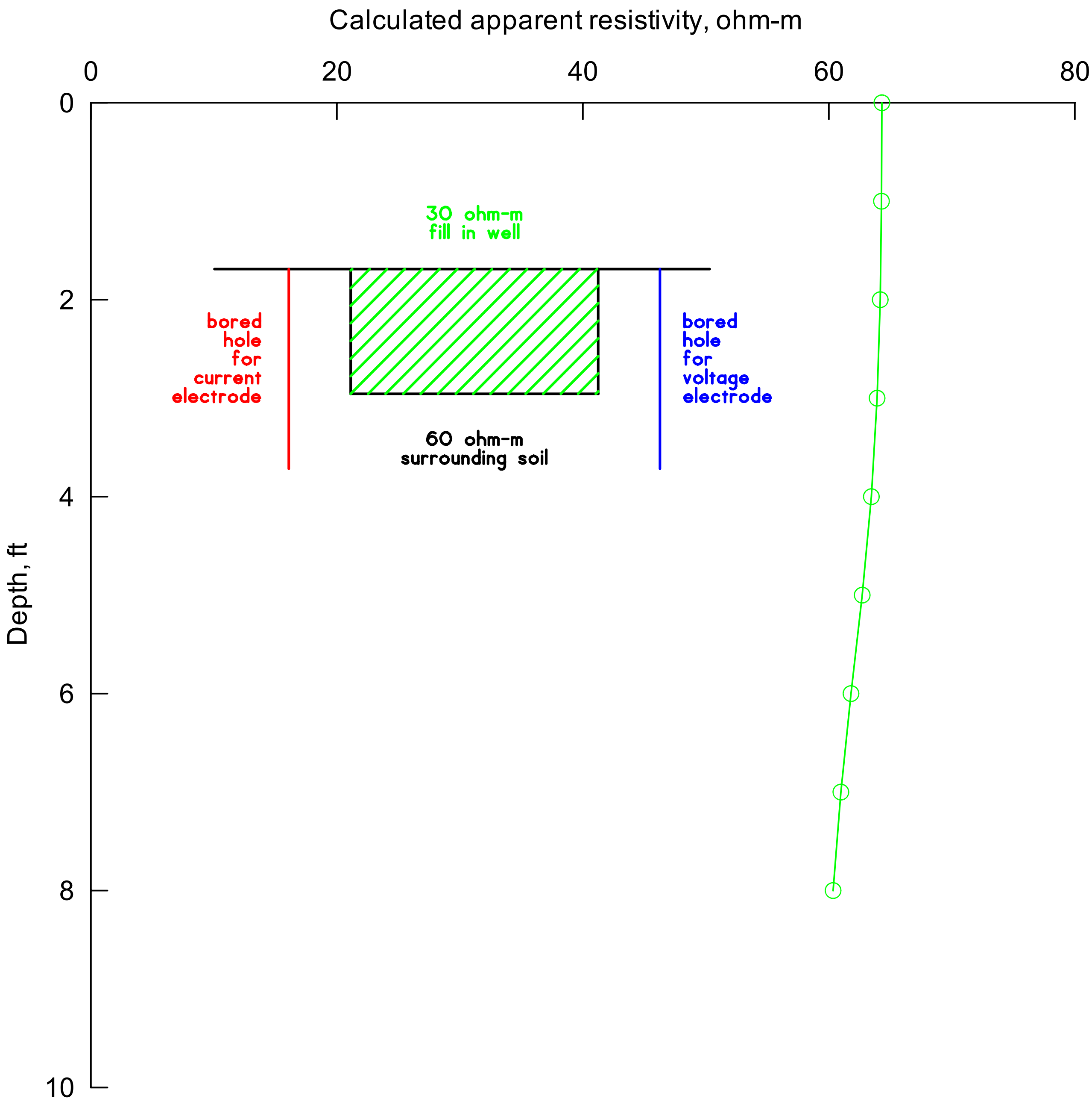


Figure 9: The calculation of resistivity across a possible well. The curve shows little change in the values near the depth of the assumed bottom of the well; this well and its fill was assumed to be 5 ft deep and 10 ft wide. The electrical resistivity of the fill was assumed to be half that of the surrounding soil. This calculation suggests that the geophysical procedure that was applied for this field test could not have detected the depth of the fill in that well.

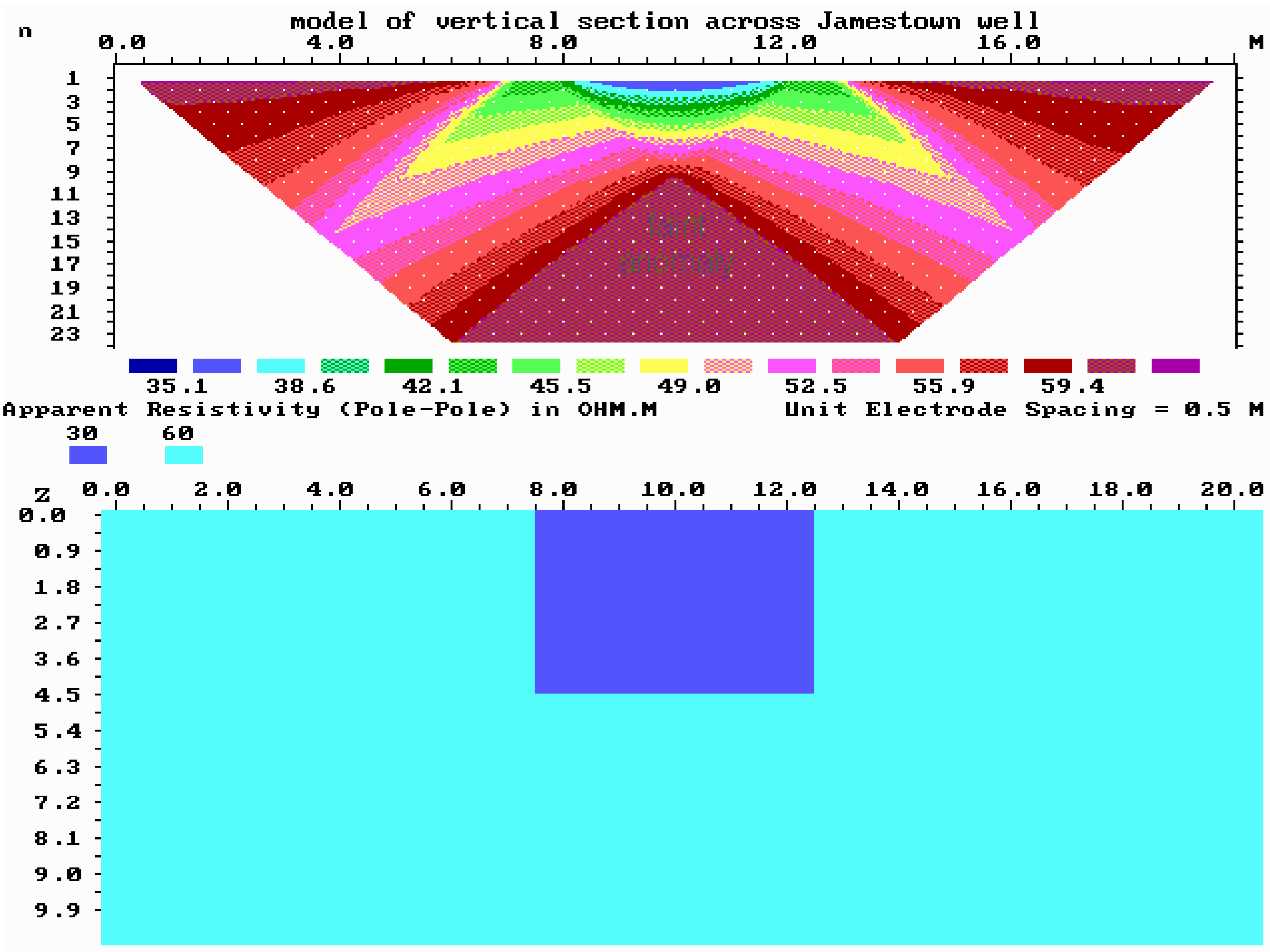


Figure 10: A failing of the pole-pole cross-borehole test. It gives anomalies that are unusually faint for features that are between the pair of sensing electrodes. When the spacing between the electrodes is greater than the diameter of the feature (as it must be for this borehole survey), the fill material is almost invisible.

The lower panel shows the cross-section of the resistivity model that was analyzed. This is a half-space that is a vertical cut through two bored holes on the sides of a low resistivity square feature; that is, this is a downwards view at half of the feature.

The upper panel is a plot of the calculated resistivity of this model, with a minimum electrode spacing of 0.5 ft. The "n" value on the left shows the multiplier for the actual electrode spacing. For n>=10, the electrode spacing is greater than the width of the feature (5 ft) and therefore the electrodes are outside the feature. Note that the calculation then gives apparent resistivity values that are almost the same as the surrounding material (60 ohm-m). Large anomalies are found only where one electrode is over the conductive fill.

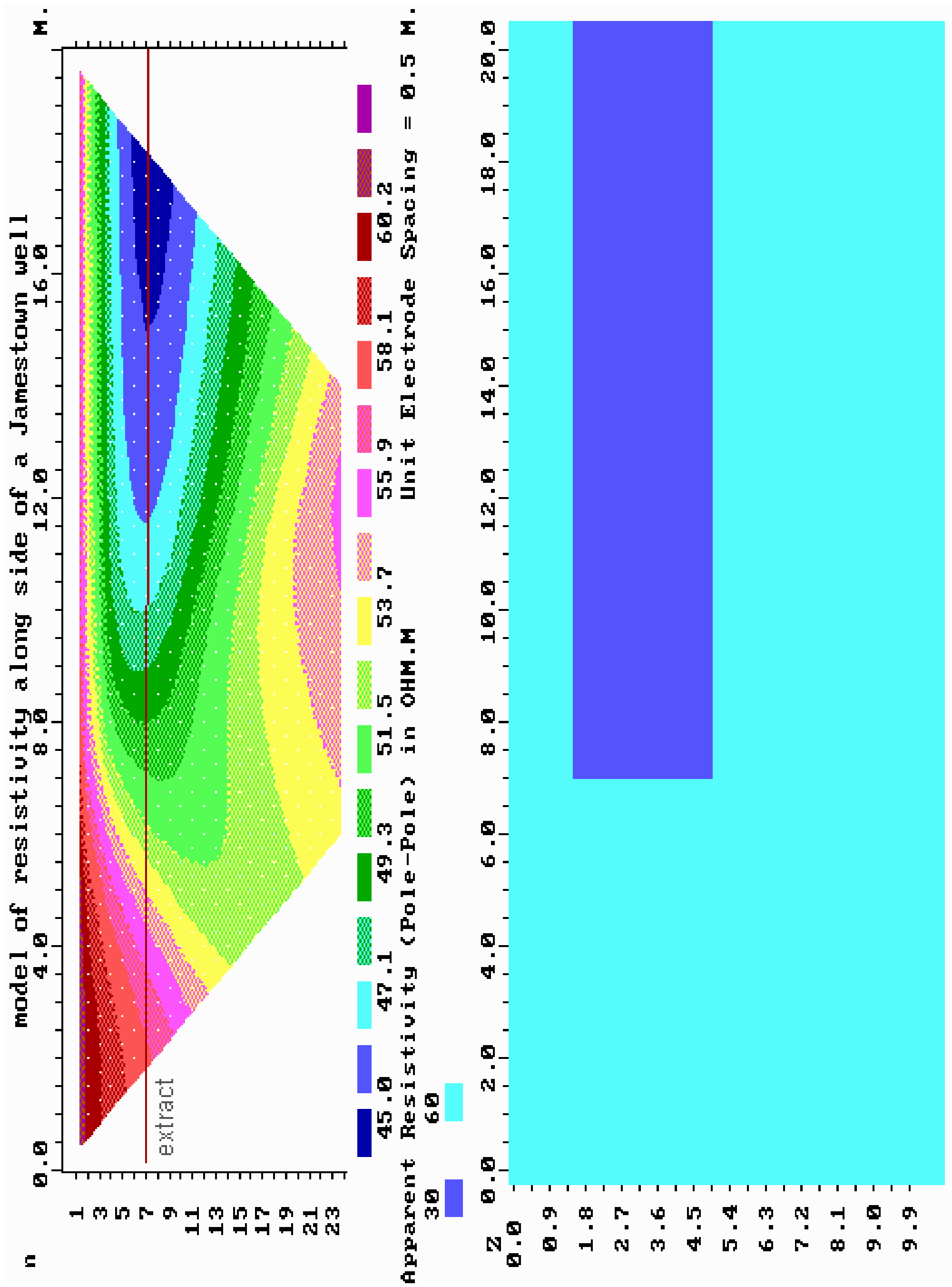


Figure 11: Resistivity readings from a single bored hole. This calculation approximates the measurement illustrated at the lower left panel of Figure 7. The cross-section of the model on the right is now a vertical section through the fill of the well. The pole-pole calculations on the left again show the anomaly as it changes with vertical position and also electrode spacing (0.5 ft x n). The anomalies are greatest at n = 7, and the values from this vertical line are plotted in Figure 12.

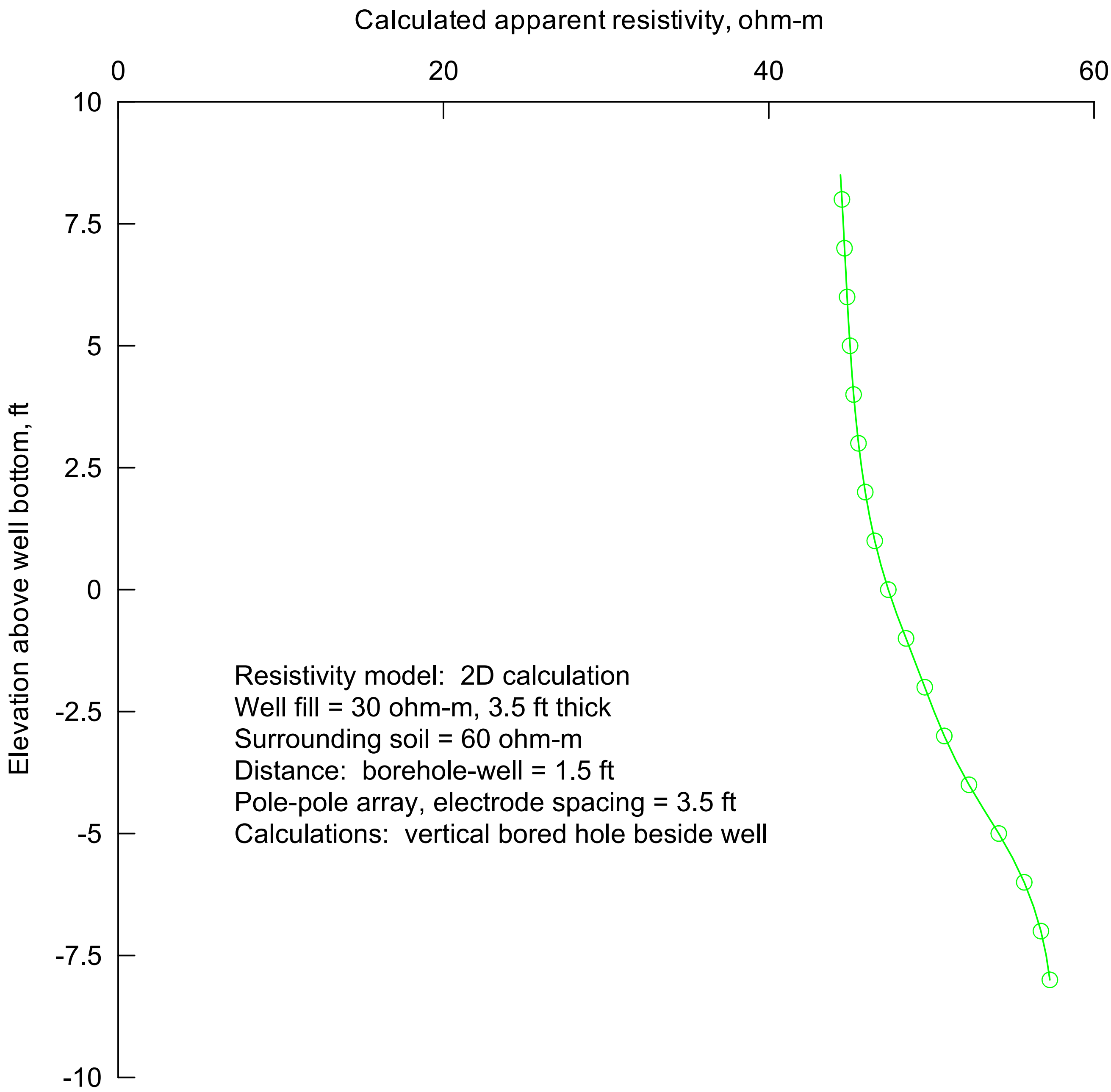


Figure 12: The calculated anomaly of a resistivity measurement in a single bored hole. The resistivity model is shown in Figure 11, and these values are for an electrode spacing (pole-pole) of 3.5 ft along a vertical line adjacent to a filled well.

At a large depth, the resistivity value approaches 60 ohm-m, the value assumed for the surrounding soil. At a shallow depth, the resistivity is greater than the 30 ohm-m value that was assumed for the fill. At intermediate depths, the resistivity changes as shown along the curve here. It is possible that the bottom of the fill might be suggested by the depth where the curvature of the readings in a plot like this is greatest.

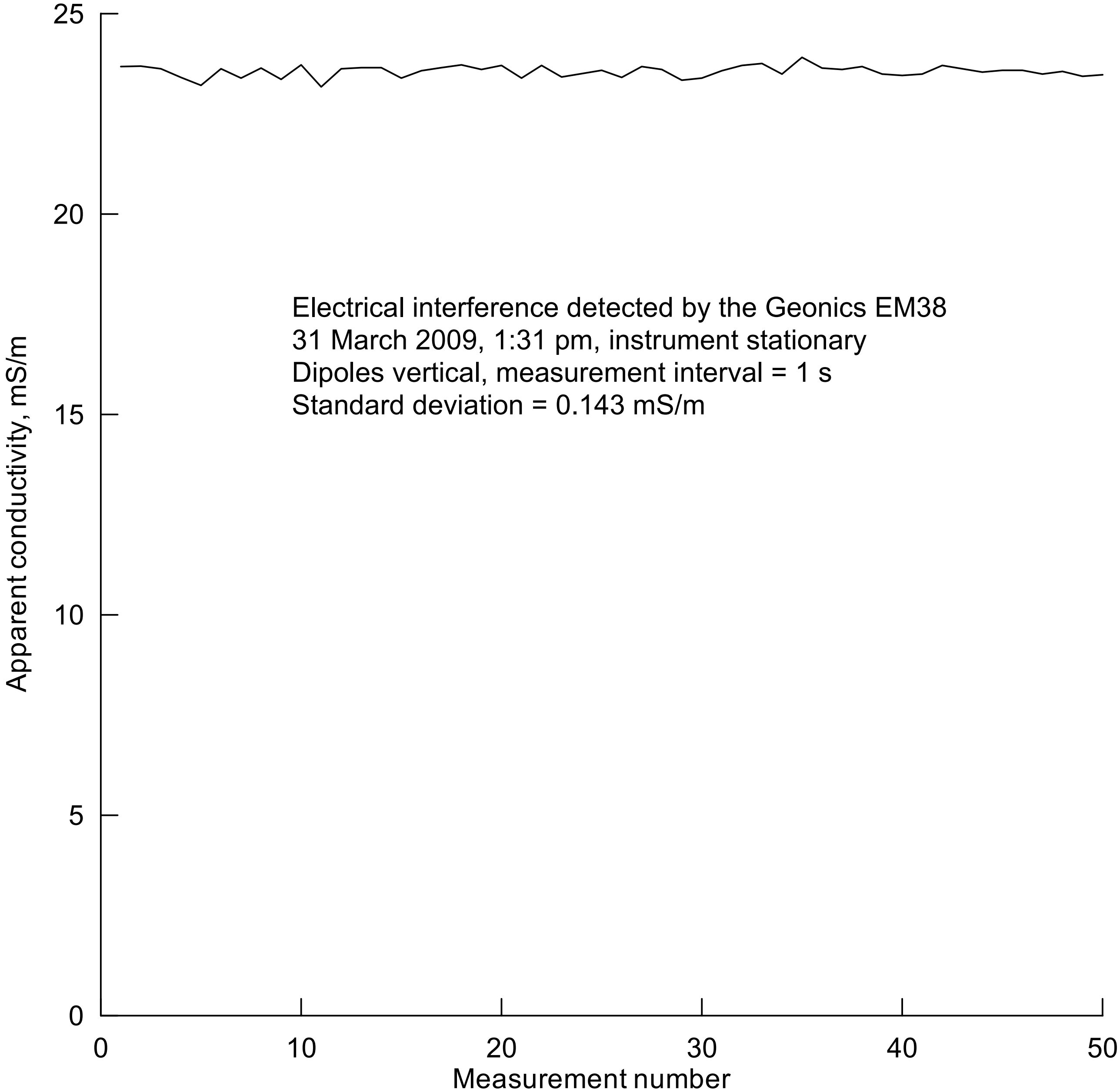
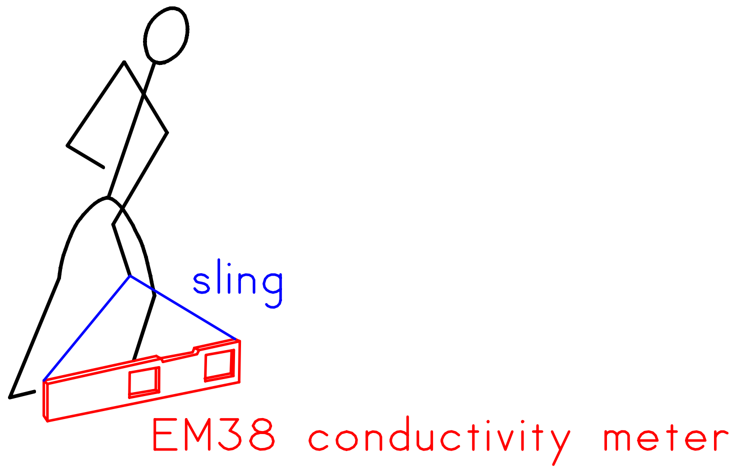


Figure 13: Noise interference to the EM38 conductivity meter. This effect was minor; the interference was slightly greater than that of a typical rural area. The effect of noise was tested by making a series of readings with the instrument stationary.



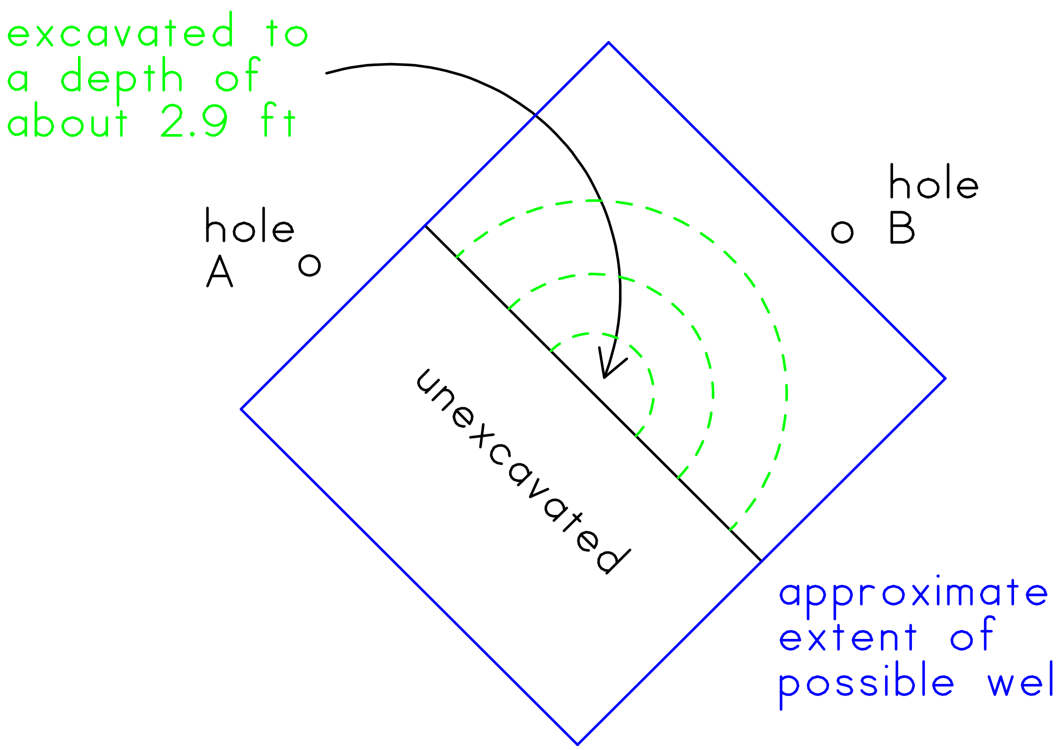


Figure 14: The EM38 conductivity meter. It is sketched in the upper panel; the data logger is not included there.

A rough drawing of the excavation at the well is shown at the bottom; this approximates the excavation on 17 April 2009, when the borehole resistivity test was made. On that date, one half of the possible well had begun to be excavated. The excavation levels approximately followed the stratigraphy of the fill, and so the lower surface was somewhat cone-shaped, with its deepest point at the middle. The locations of two adjacent bored holes are also approximated in this sketch.