Comparing resistivity and IP for archaeological applications

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Resistivity surveys have been applied to archaeological exploration for many decades, but induced polarization (IP) surveys are rarely tried. The relative benefits of these two types of survey were tested by measuring resistivity and IP pseudosections at two archaeological sites.

At each of these sites, the readings of resistivity and IP were strongly-correlated; this made it appear that one of the two surveys was not necessary. However, these correlations were quite different at the two sites; this is revealed in Figure 3. This figure also shows that the correlation between resistivity and IP changed at one site. While the value of these correlations is not yet known, any geophysical parameter that allows a distinction between soils must be examined for its possible aid to interpretation.

Blue text in this report marks hyperlinks to the figures that are at the end of the report. Those figures and captions provide an extended summary of this work.

Introduction

The parameters of magnetic susceptibility and electrical conductivity can be measured with a single electromagnetic induction instrument. These parameters are determined by the in-phase and out-of-phase (also called the quadrature phase) components of a magnetic field that passes through the soil; the magnetic field is slightly delayed in going through a conductor, while this field is not delayed further by passing through a magnetic object.

Similarly, a single, although different, instrument can measure both electrical resistivity and induced polarization. Induced polarization is revealed by a slow buildup of the soil's voltage when a current passes through; this delay is not found with resistivity. Induced polarization is applied primarily to the search for metallic minerals so that they may be mined. While the IP technique was given an archaeological test 40 years ago (Aspinall and Lynam 1970), it has seldom, if ever, been tried since then.

While the ideas and theory of induced polarization are more complex than they are for resistivity work, some authors have given good descriptions of the principles and procedures of an IP survey (Zonge, Wynn, and Urquhart 2005; Slater and Glaser 2003; Slater and Lesmes 2002; Parasnis 1997, chapter 5; Ward 1990; Fink and others 1990; Telford, Geldart, and Sheriff 1990, chapter 9; Sumner 1976; Bertin and Loeb 1976).

The sites

This experiment was done at the two locations that are marked in Figure 1. The work at Hopeton was funded primarily by the National Park Service; this test was a part of a large project that is coordinated by Mark Lynott (Midwest Archeological Center of the NPS). Huge earthworks at Hopeton Mounds form outlines in the shapes of a square and several circles; see Figure 2. A century and a half ago, these earthen ridges were distinct and about 1.5 m tall; today these ridges are so shallow and broad that they cannot usually be recognized by eye. Fortunately, the lower parts of these ridges have been buried and preserved by the soil that eroded from their upper sides. John Weymouth (University of Nebraska) discovered that these buried ridges cause distinctive geophysical patterns in magnetic and resistivity maps: A pair of resistivity anomalies form bands that straddle each side of the former ridge; a similar pair of magnetic anomalies are found parallel to and outside those resistivity anomalies. A summary of the archaeological and geophysical work at Hopeton has been given by Lynott (2009), and the upper drawing in Figure 2 is copied from one of his maps.

The test site at Biesterfeldt is shown in Figure 2. This experiment was funded primarily by Minnesota State University, and it was coordinated by Rinita Dalan (Minnesota State University at Moorhead). This site is much more recent than Hopeton, and it was visited by Europeans while the village was still occupied. While archaeological features are visible in part of the village; they have been plowed flat at the location of this test. A defensive ditch that enclosed the village was deep enough (1 - 2 m) that its lower parts have not been disturbed by plowing. The pseudosection crossed that ditch at a location where it shows no topographic evidence. Like the Hopeton site, there has been a slight amount of archaeological excavation at Biesterfeldt. These excavations and the geophysical surveys at the site have been summarized by Dalan and others (2007); the site plan in Figure 2 is derived from one that was supplied by Dalan.

The surveys at both Hopeton and Biesterfeldt were done in rural areas that are farmed. There were no metallic fences near either area, and neither pipes nor wires are buried underground. At both locations, the soils are well-drained and bedrock is deep. The ground surface was covered by grass or alfalfa at both sites, and no trees or bushes were nearby. At Hopeton, electrical wires were about 50 m distant, while they were over 200 m away at Biesterfeldt. At Biesterfeldt, other geophysical surveys (perhaps magnetic or resistivity) were being done in the vicinity of this work; at Hopeton, no other geophysical work was being done. The weather was clear during both surveys, and the soil was moist at both sites. The figures note the day on which each survey was done, and each survey required less than half of a day of field time.

The geophysical surveys

The geophysical measurements were made with a model MiniRes Super instrument (serial 120), manufactured by L and R Instruments (www.L-and-R.com). The excitation frequency of this instrument is 5 Hz. This meter is powered by four flashlight cells (size D) and its readings are shown on a Liquid Crystal Display (LCD) with a precision of 3 - 5 digits. After a measurement of resistance is made, a button is pushed and the IP reading is next displayed. These two values, in ohms, were written on paper as they were noted.

The instrument was operated with the pole-pole configuration of electrodes, which were stainless steel. The locations of the fixed (or reference) current (I) and voltage (V) electrodes are noted in Figure 2. These were about 45˚ apart, 30-m distant, and the voltage reference was placed near the average line of zero potential. While this was optimum for the resistivity readings, it may have been better to have set the reference electrodes 90˚ apart in order to minimize electromagnetic coupling between the wires to these electrodes during the IP readings.

The pair of moving electrodes were simply tall wooden poles with stainless steel rods driven into their bottoms; the voltage was measured at the forward electrode, while the current was supplied at the trailing electrode (which was moved infrequently). The voltage electrode was first stepped away from the current electrode, making measurements at intervals of 0.25 m, from 0.25 m to a maximum electrode spacing of 2.5 m. Both electrodes were next stepped forward 0.25 m and the voltage electrode was then stepped back toward the current electrode. This “expanding-collapsing” sequence continued down the line and the pattern of readings was that of a series of downward dipping lines that resulted in a parallelogram of data, as shown in Figure 9.

The MiniRes meter was supported with a strap around my neck so that it could be carried easily down the line of readings (the lid of the meter was removed). The moving wires to the reference electrodes were tied to my belt so that there would be no strain on the connectors at the instrument. Stakes next to those reference electrodes eliminated any strain on the connectors at the electrodes. At the Hopeton site, the resistance between the reference electrodes was about 4000 ohm. At both sites, the range setting of the MiniRes instrument was switched once during each expansion or contraction of the electrode spacing.

The resistance and IP readings were multiplied by twice pi and then by the electrode spacing to convert them to apparent resistivity or IP, in ohm-m. These values were gridded to rectangular cells of 0.125 by 0.25 m and then the pseudosections were displayed as contour maps. In the pseudosections, such as those in Figure 4 and Figure 9, the vertical scale is the negative of the electrode spacing, for this simplified the plotting of the data.

Findings of the pseudosections

The data from the Hopeton site are plotted in Figure 4 and Figure 5. Figure 6 through Figure 11 have the results from Biesterfeldt.

At Hopeton, anomalous areas with high resistivity were found about 5 m apart; one of these anomalies was about twice as strong as the other (see Figure 5). Figure 4 shows that the patterns found by the IP survey are almost the same as those from the resistivity survey. While several archaeological trenches have been excavated across the earthen ridges at Hopeton, no identification has yet been made of the culturally-emplaced soil that causes this pair of high resistivity anomalies.

At Biesterfeldt, the refilled trench was clearly detected as a low resistivity anomaly when the electrode spacing was large; see Figure 6. At a small spacing, the anomaly had a high resistivity; this is best seen in the modified plot of Figure 10. This change in the polarity of the anomaly appears to be caused by the stratification of the soil: On average, it has a resistivity of 50 ohm-m to a depth of 0.75 m; below that, the resistivity is about 250 ohm-m.

It appears that the soil that fills the trench at Biesterfeldt has a resistivity that is intermediate between the resistivities of the two soil strata through which it intrudes. At a shallow depth (in the topsoil), the intrusive soil appears to be a relatively high resistivity, while at a greater depth (in the subsoil), the same fill has a lower resistivity than the surrounding soil. There is a complication with resistivity surveys in that the polarity of an anomaly can be the opposite of the polarity of a feature's contrast if the feature is both shallow and narrower than the spacing between the measurement electrodes. This inversion has probably not affected this data because the contrasting soil of the fill does not begin until the depth is about 0.5 m (plowing has homogenized the shallow soil).

The discussions above are not necessary to the main point, which is a comparison of the two sites. However, if more than this summary is wished, further analyses of the data were given in the field reports on those separate sites (these are listed at the end).

The pseudosections that were measured at Hopeton and Biesterfeldt are compared in Figure 3. I do not know the reason for the distinctive difference in the slopes of the correlations that are plotted there. This difference could be a valuable parameter for distinguishing the soils at these two sites; however, it is not impossible that the differences might be caused by errors in the measurements, such as electromagnetic coupling between the wires to the reference electrodes. Sumner (1976 p. 180) has pointed out that the pole-pole array is poor at rejecting this coupling; however, Zonge, Wynn, and Urquhart (2005 p. 281) mention that the problem of coupling may not be severe for a shallow exploration such as this, for the wires are short.

The correlation in Figure 3 reveals that the data for Biesterfeldt fall along one thin band; that is, resistivity and IP are highly correlated at that site. The correlation was lower at the Hopeton site; the readings form a broader band, and the slope of that band changes. Where the IP readings are less than 0.75 ohm-m, the slope of the correlation is lowest. As seen in Figure 4, these low-IP values are found outside the area of the cultural anomaly. While the resistivity and IP readings themselves locate these archaeological features, it is interesting that these correlations also locate them.

The strong correlation between resistivity and IP can be removed. This has been done for the Biesterfeldt site in Figure 11; it does not appear to have improved the patterns.

Discussion and conclusions

Resistivity and IP measurements gave similar information at these two sites; in that sense, one of the measurements was a waste of time. However, there were some interesting differences between the sites, and it is possible that these differences supply additional information about the archaeological features and soils.

It was the difference between the two sites in the correlations of their readings of resistivity and IP that was most important. It appears that this type of difference can also be found at a single site; perhaps an interesting contrast in the soil can be revealed by these correlations that is not apparent in the readings of either resistivity or IP. If a map of both resistivity and IP was measured, these correlations could be done within windows of data that are shifted around the map. While a calculated value of phase angle does compare a single reading of resistivity to one of IP, it does not reveal the slope of the correlation of a cluster of readings. This analysis by a windowed correlation could therefore be similar to using a spatial analysis of a magnetic map to suggest the depth to magnetic bedrock.

The readings of resistivity and IP were highly correlated at these two sites; perhaps these two values will be correlated at many other sites also. Measurements of electrical conductivity and magnetic susceptibility that can be measured with a Geonics EM38 have shown little correlation at a half dozen sites where this comparison has been made. It is possible that this lack of correlation is due to magnetic soils remaining relatively stationary in their strata of formation for a long time, while the fine-grained or chemical components of soils that contribute to conductivity anomalies are rather mobile when groundwater moves through the soil.

Only two sites have been compared here. It will be valuable to test these correlations at very different sites. The IP measurements by themselves may provide good information at some sites, where resistivity tells little. It will be most important to test the value of IP at a site that had a metallic industry; the detection of metal fragments at that site would be analogous to the detection of metallic ores. Some sites with a metallic industry may also be detectable with other geophysical techniques. For example, the area of blacksmithing might also be revealed by a magnetic survey because of the iron artifacts; the area of a furnace might also be detected by a magnetic survey. An ideal application for an IP survey might be a search for the remains of a non-ferrous industry; there may be nothing but many small fragments of metal at some sites, and these fragments will probably be invisible to all other types of geophysical survey (they could be too small to be found with a metal detector).

It appears that IP surveys can also detect wood (Carlson 2004). While wood may be found with a radar survey also, this IP approach should be considered, particularly where the stratigraphy of the soil is too complex to reveal wood on a radar profile.

Review

Since I know relatively little about IP, I was grateful that Jeff Wynn (U.S. Geological Survey, Vancouver, Washington) could look at this report and give me his comments. Surveys with IP are a major part of Jeff's work, and he has always been interested in archaeological surveys (although he does primarily environmental and geological exploration).

Jeff thinks that EM coupling would probably not have caused any difficulty for these two surveys. He mentions that a good clue to this coupling is an increase in IP with depth (electrode spacing). Figure 4 gives no hint of this; while Figure 9 shows a pronounced increase in IP with depth, the resistivity shows a similar pattern, and both could have a similar origin, such as a shallow clayey layer.

I wonder if another clue to changing EM coupling might be an unusual variability of the IP readings that is not seen in the resistivity values. An example of this might be in Figure 9 near N872 - 874 at an electrode spacing of 0.75 - 1 m; perhaps the two abrupt changes in IP there might indicate that the wires from the meter to the pole-pole reference electrodes were shifted closer together for those readings. Since the IP voltages are only about one percent of the voltages of the resistivity measurements, it would be reasonable that the IP values would be most affected by EM coupling.

Jeff pointed out that EM coupling is more likely to become a problem when the electrode spacing is 100 m or more, particularly when the groundwater is rather conductive. Most deep-exploring IP surveys will employ the dipole-dipole array, for this minimizes the length of wire that needs to be laid on the ground and reduces EM coupling, although the voltages that are measured are low relative to those of the pole-pole array.

Jeff had good thoughts about the interpretation of the surveys. He mentioned that interesting cultural processes such as fires and features such as organic refuse may affect the oxidation-reduction of the soil, changing the amount of sulfides such as pyrite that may be created. These modifications might be detected by the IP measurements, while they could be invisible to resistivity. It is possible that wide-area differences in pyrite, or perhaps clay content, may be the origin of the differences in correlation that are shown in Figure 3. While these wide-area effects may have a natural, rather than a cultural origin, it may be valuable to investigate them further.

Jeff reminded me that the IP unit of ohms here is not conventional; however, the phase angle plots in Figure 4 and Figure 8 are often used for showing IP data. IP readings are frequently listed by their Frequency Effect (or Percent Frequency Effect, PFE). Frequency Effect may sometimes be calculated from:

(DC resistivity - AC resistivity) / (AC resistivity)

and so perhaps the readings here may approximate this value with:

[resistivity (ohm-m) - IP (ohm-m)] / [IP (ohm-m)].

IP readings are sometimes measured over a wide range of frequency, and then the Frequency Effect is determined at two quite different frequencies, and one of them is not DC. IP is also sometimes quantified by the values Chargeability, and also Metal Factor; it can be possible to convert between these differing quantities.

I thank Jeff for his ideas, and hope that I have not altered them above.

References

Aspinall, A., and J. T. Lynam, 1970, "An induced polarization instrument for the detection of near-surface features", *Prospezione Archeologiche*, 5:57 - 75.

Bertin, J., and J. Loeb, 1976, *Experimental and Theoretical Aspects of Induced Polarization* (2 volumes), Geopublication Associates (Berlin).

Carlson, Norm, 2004, "The international nature of geophysics", *FastTimes*, November, p. 3.

Dalan, Rinita, George Holley, Michael Michlovic, Erik Gooding, 2007, *Comprehensive Significance Study of the Biesterfeldt Site (32RM1), Ransom County, North Dakota*, report prepared for the Midwest Archaeological Center, NPS (Lincoln, NE).

Fink, James B., Edgar O. McAlister, Ben K. Sternberg, W. Gordon Wieduwilt, and Stanley H. Ward (editors), 1990, *Induced Polarization: Applications and Case Histories*, Society of Exploration Geophysicists (Tulsa).

Lynott, Mark J. (editor), 2009, Footprints: In the Footsteps of Squire and Davis: Archeological

Fieldwork in Ross County, Ohio, National Park Service (Lincoln, NE).
Parasnis, D. S., 1997, *Principles of Applied Geophysics* (fifth edition), Chapman and Hall (London).
Slater, Lee D., and David Lesmes, 2002, "IP interpretation in environmental applications", *Geophysics* 67(1):77 - 88.
Slater, L. D., and D. R. Glaser, 2003, "Controls on induced polarization in sandy unconsolidated sediments and application to aquifer characterization", *Geophysics* 68(5):1547-1558.
Sumner, J. S., 1976, *Principles of Induced Polarization for Geophysical Exploration*, Elsevier Scientific Publishing Company (Amsterdam).
Telford, W. M., L. P. Geldart, and R. E. Sheriff, Applied Geophysics (second edition), Cambridge University Press (Cambridge).
Ward, Stanley H., 1990, "Resistivity and induced polarization methods", pages 147 - 189 in: *Geotechnical and Environmental Geophysics*, edited by Stanley H. Ward, volume 1, Society of Exploration Geophysicists (Tulsa).
Zonge, Ken, Jeff Wynn, Scott Urquhart, 2005, "Resistivity, induced polarization, and complex resistivity", pages 265 - 300 in: *Near-Surface Geophysics*, edited by Dwain K. Butler, Society of Exploration Geophysicists (Tulsa).

Publication history:

19 July 2010: Added review by Jeff Wynn.

8 June 2010: Original report.

Reports of mine that are related to this one

Title: Geophysical tests in Biesterfeldt boreholes
Subject: Capacitance and magnetic profiles worked well; pseudosection and EM31 also
Date: 2008 Pages: 49 File: BoreBeis.pdf

Title: Radar and resistivity surveys at Hopeton Mounds
Subject: Report on field work in 2003
Date: 2003 Pages: 65 File: Bevan03b.pdf

Title: Resistivity pseudosections for archaeology
Subject: How to measure and interpret them.
Date: 2002 Pages: 39 File: Pseudo.pdf

Title: Analysis of depth using resistivity maps
Subject: Polarity reversal; estimates generally require knowing feature width
Date: 2010 Pages: 22 File: Resis2D.pdf

Title: The pole-pole resistivity array compared to the twin electrode array
Subject: Shows the advantages of the pole-pole array
Date: 2002 Pages: 12 File: Pole.pdf

Title: Conductivity or susceptibility?
Subject: Susceptibility survey appears to be better than conductivity
Date: 2007 Pages: 37 File: CorK.pdf

Title: A simple resistivity meter
Subject: How to build and use an inexpensive instrument; measurements are slow but good.
Date: 2002 Pages: 14 File: SimpleRho.pdf

Title: A switch box for Wenner resistivity measurements
Subject: Construct a circuit for offset Wenner readings
Date: 2002 Pages: 9 File: Switch.pdf

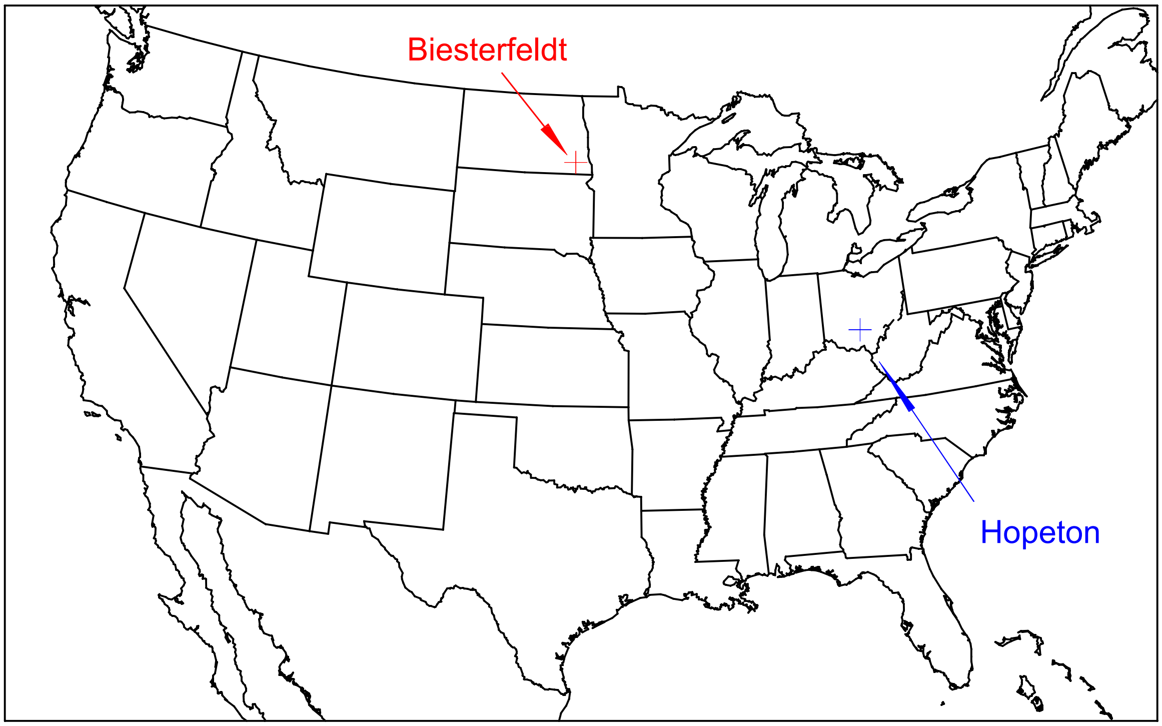

Figure 1: The two locations for these tests. Both are archaeological sites that were occupied in prehistoric or protohistoric (colonial) times. Remnants of earthen ridges and depressions are found at both locations, although the relief at the locations of this geophysical work is less than 0.5 m. At both sites, the soil has a large fraction of sand or gravel.

The Hopeton site is in Ohio, north of the town of Chillicothe. This ceremonial site was occupied in about 100 AD, and it is illustrated in the upper part of Figure 2.

The Biesterfeldt site is in the state of North Dakota, south of the city of Fargo. This village was occupied in about 1700 AD, and it is illustrated in the lower part of Figure 2.

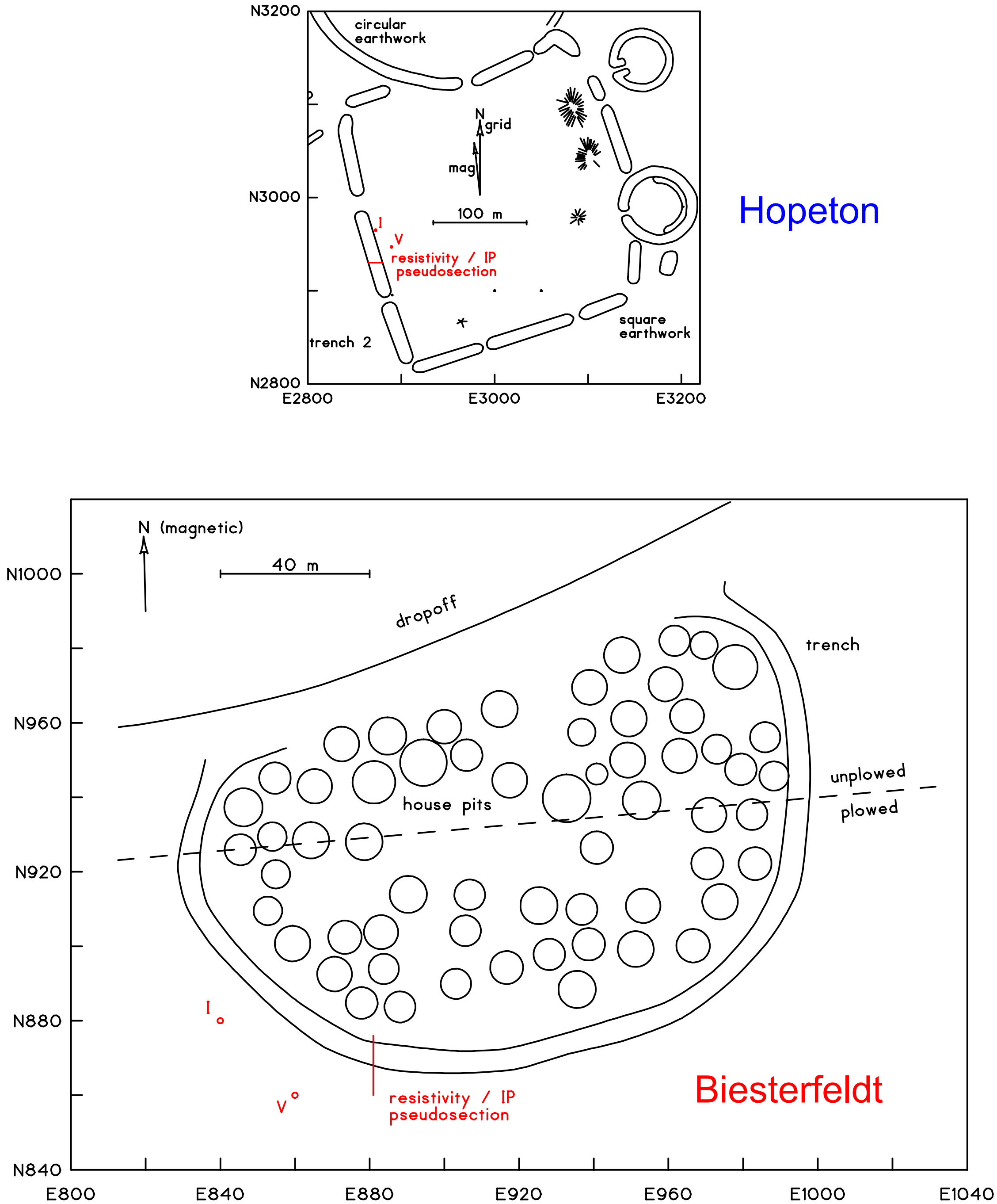

Figure 2: Large archaeological earthworks at the two sites. Pseudosections were measured along the red lines.

Part of the known archaeological features at Hopeton are mapped in the upper panel. An earthen ridge at this site outlines the pattern of a square; a large circle extends north from the top of the map and small circular ridges are found to the east. Because of erosion and farming, these former ridges are almost impossible to recognize at the surface; their shape is known from geophysical surveys and also archaeological maps from the 1840's.

The village at Biesterfeldt is mapped in the lower panel. Circles mark the broad pits where houses were once located; a ditch surrounded the village and a cliff is at the north. The ditch and house pits can still be seen in the northern section as shallow depressions. In the south, the land was once farmed, and the archaeological features are invisible there. Their locations are known from an archaeological map that dates to 1908.

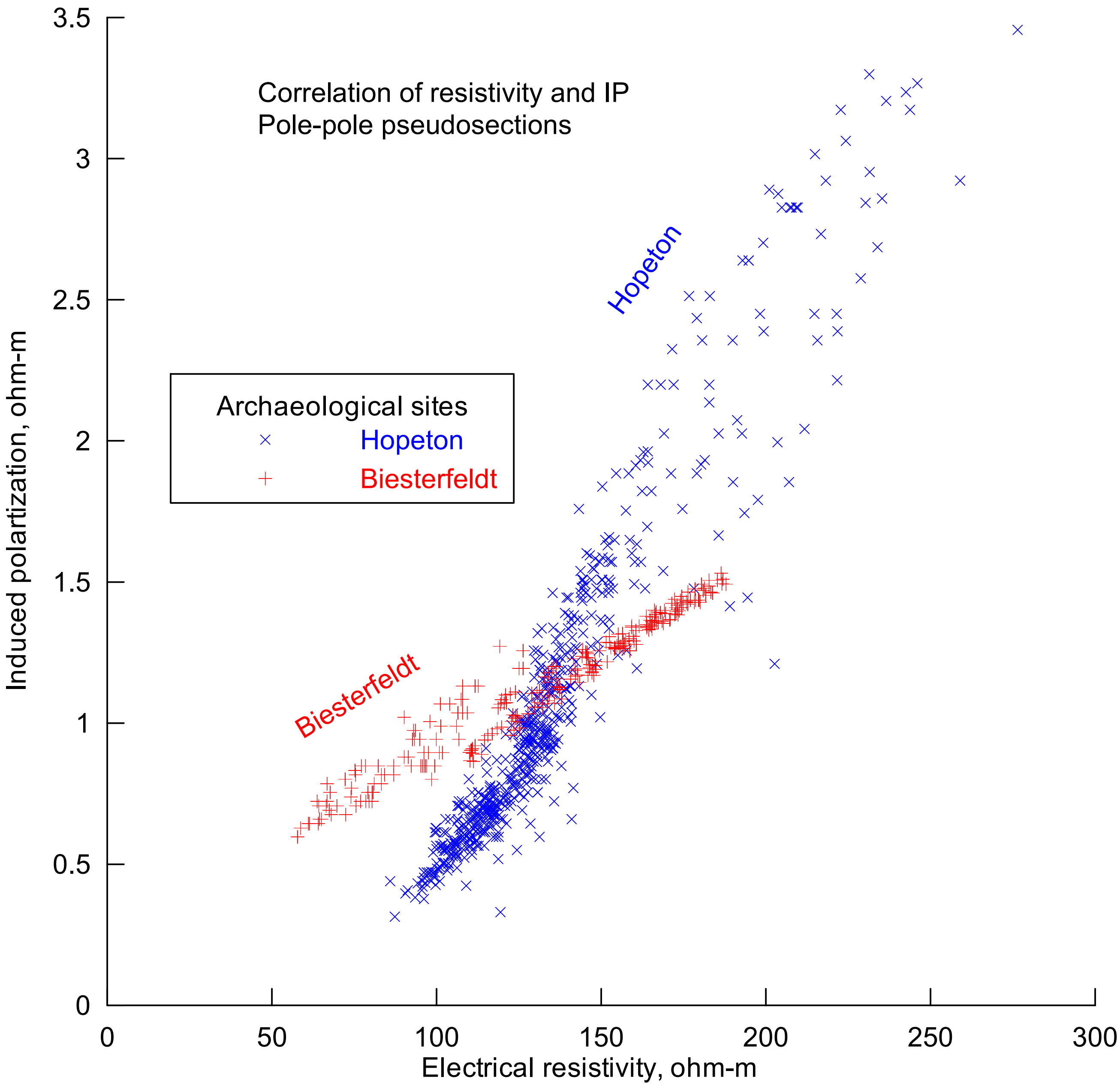

Figure 3: Correlations between electrical resistivity (horizontal axis) and induced polarization (vertical axis) at the two sites. At both sites, these pairs of measurements were found to be correlated so that the measurements fall along linear bands. The slopes of these bands are quite different at the two sites. The readings of IP from the Biesterfeldt site that are less than 1.5 ohm-m reveal a bend in the slope: For IP greater than 0.75 ohm-m, the slope of the band of clustered readings is greater than that found with lower IP.

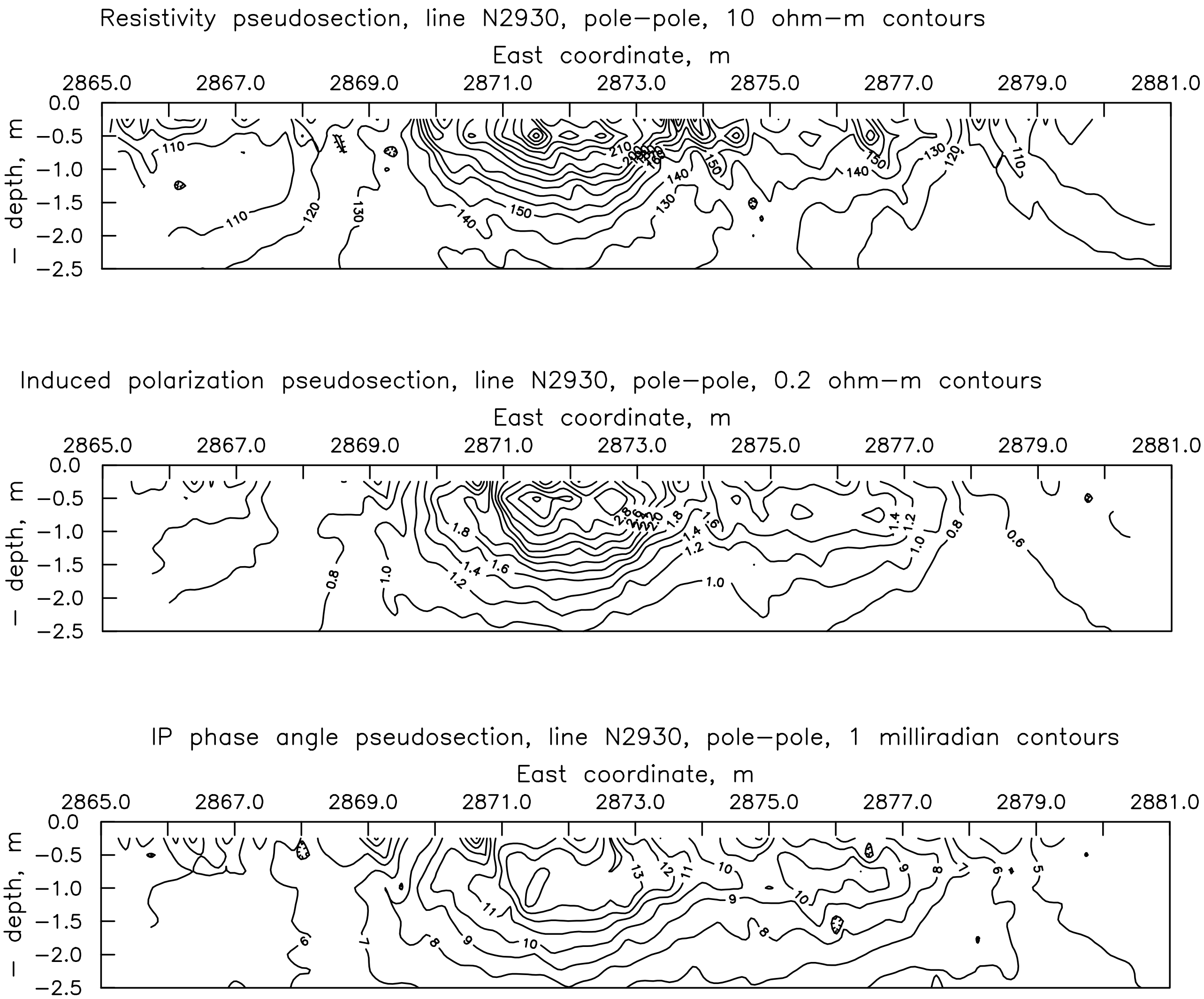

Figure 4: The pseudosection that was measured at Hopeton. The measurements of resistivity and induced polartization (both in ohm-m) are plotted in the upper two panels; the patterns are very similar for these two readings. The lower panel shows the calculation of the phase angle between these two measurements, in milliradians. This phase angle is the angle whose tangent is the ratio of IP to resistivity. The phase angle appears to have patterns that are slightly simpler or smoother than the original measurements.

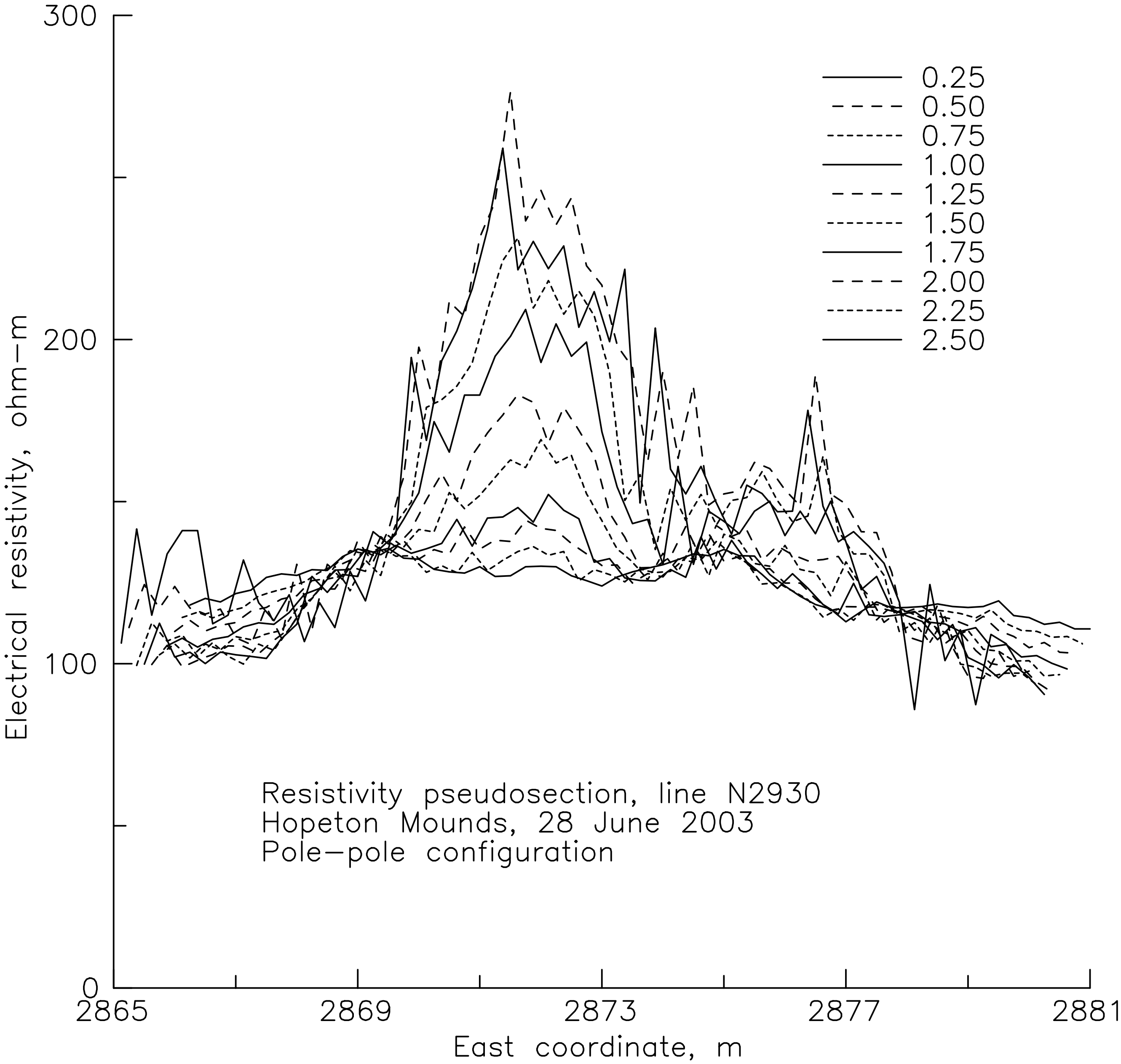

Figure 5: The resistivity measurements at Hopeton. The major peaks, near E2872, and the minor peaks, near E2876, are caused by soil contrasts within the underground remnant of the former earthen ridge. These features have high resistivity, and they are found on opposite sides of that former ridge. The readings are plotted for a range in electrode spacing from 0.25 m to 2.5 m. As is usual, the readings are more irregular (greater spatial variability) where the electrode spacing is small; this may be due to complex changes in the plow zone.

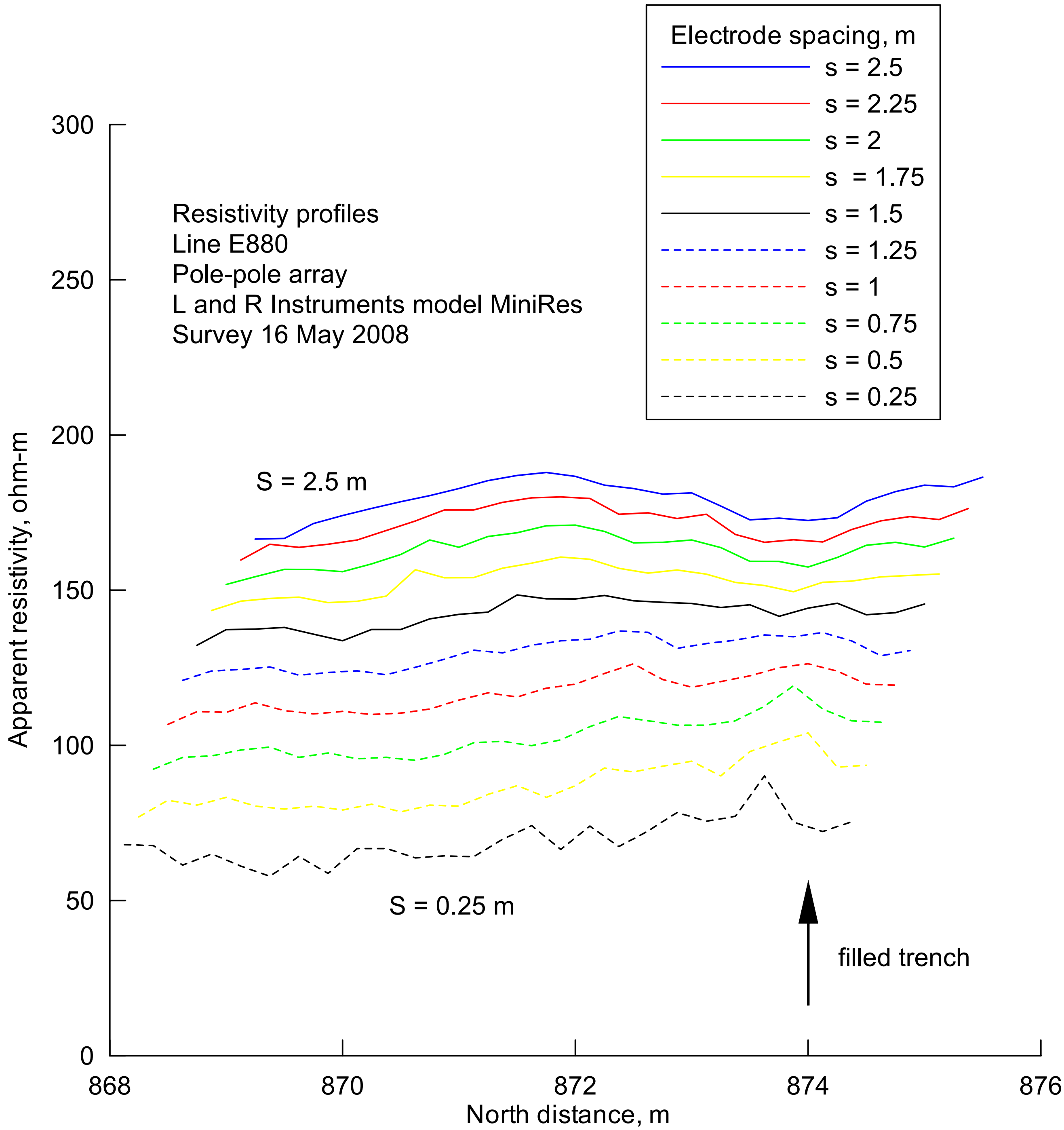

Figure 6: The resistivity measurements at Biesterfeldt. The filled trench is revealed by low resistivity where the electrode spacing is large; this trench also has faint high resistivity anomaly at a small electrode spacing. The separated curves for this plot show that the soil has a large stratification in electrical resistivity; this was not found at Hopeton (Figure 5); however, like the Hopeton site, the readings are most erratic at a small electrode spacing.

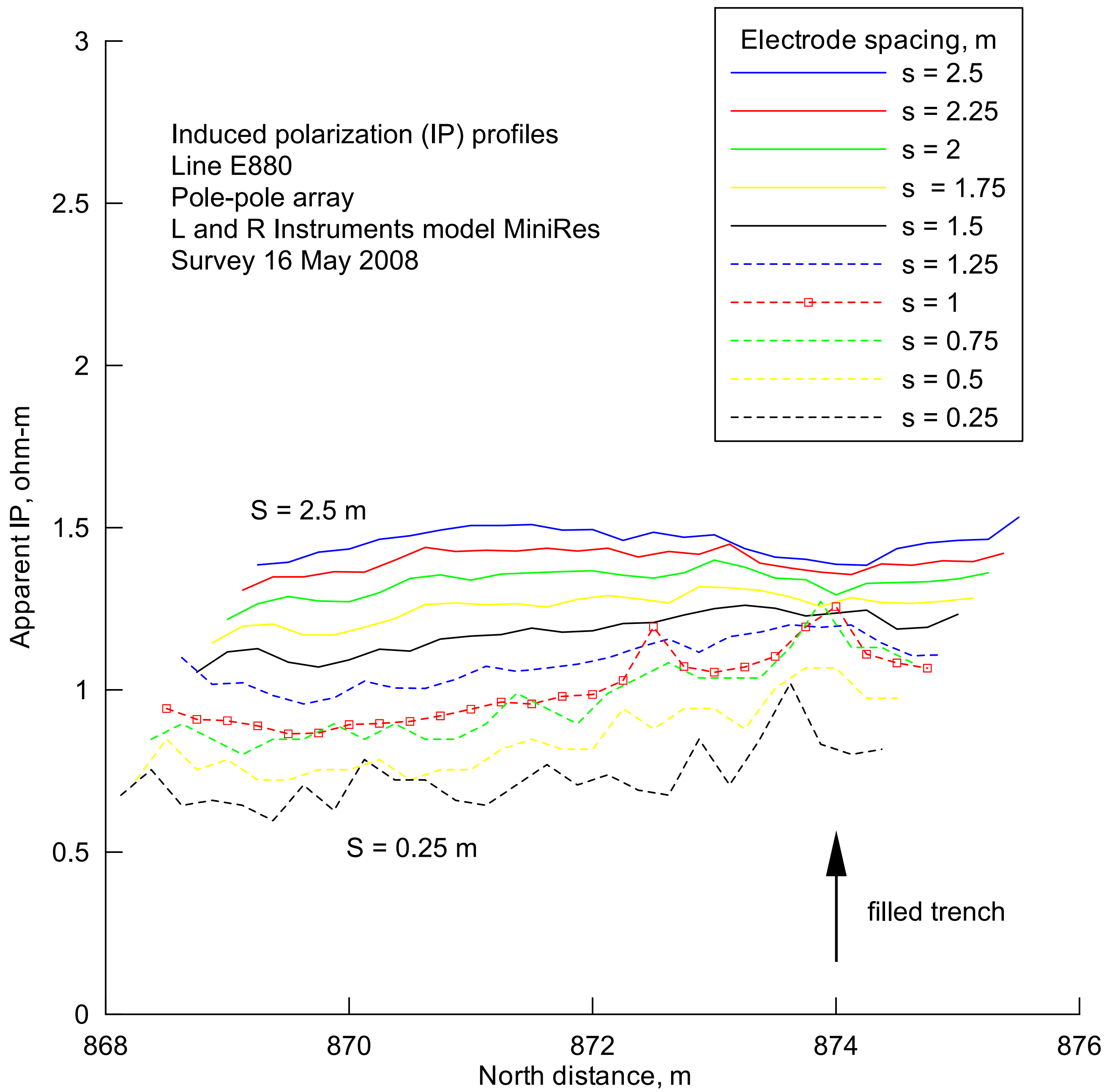

Figure 7: Measurements of induced polarization at Biesterfeldt. The anomaly caused by the filled trench is slightly fainter and less distinct than the resistivity anomaly in Figure 6. Several abrupt peaks in the readings (such as those for an electrode spacing of 1 m) may be caused by electrical interference from other geophysical instruments that were operating nearby; since the voltages that are measured by the IP survey are about 100 times smaller than those measured by the resistivity survey, this interference is reasonably larger with this mode of measurement.

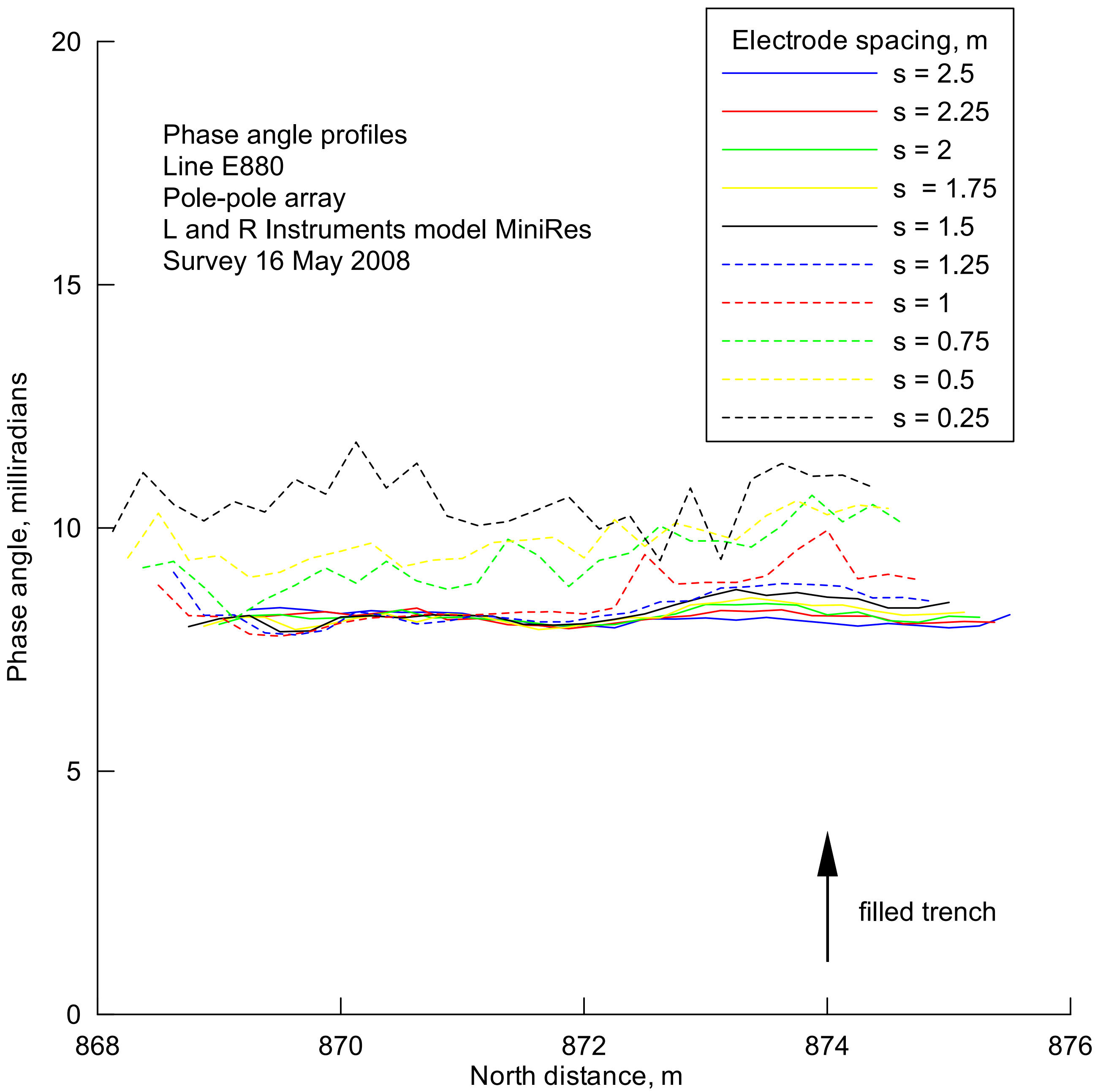

Figure 8: Calculations of the phase angle at Biesterfeldt. For electrode spacings of 1 m and greater, the curves are very smooth; they show small but clear differences at the filled trench. In addition, there is a weak anomaly at N869.6 which is not revealed by either the IP or the resistivity measurements by themselves. As at the Hopeton site, phase angles are quite small (10 milliradians = 0.57˚).

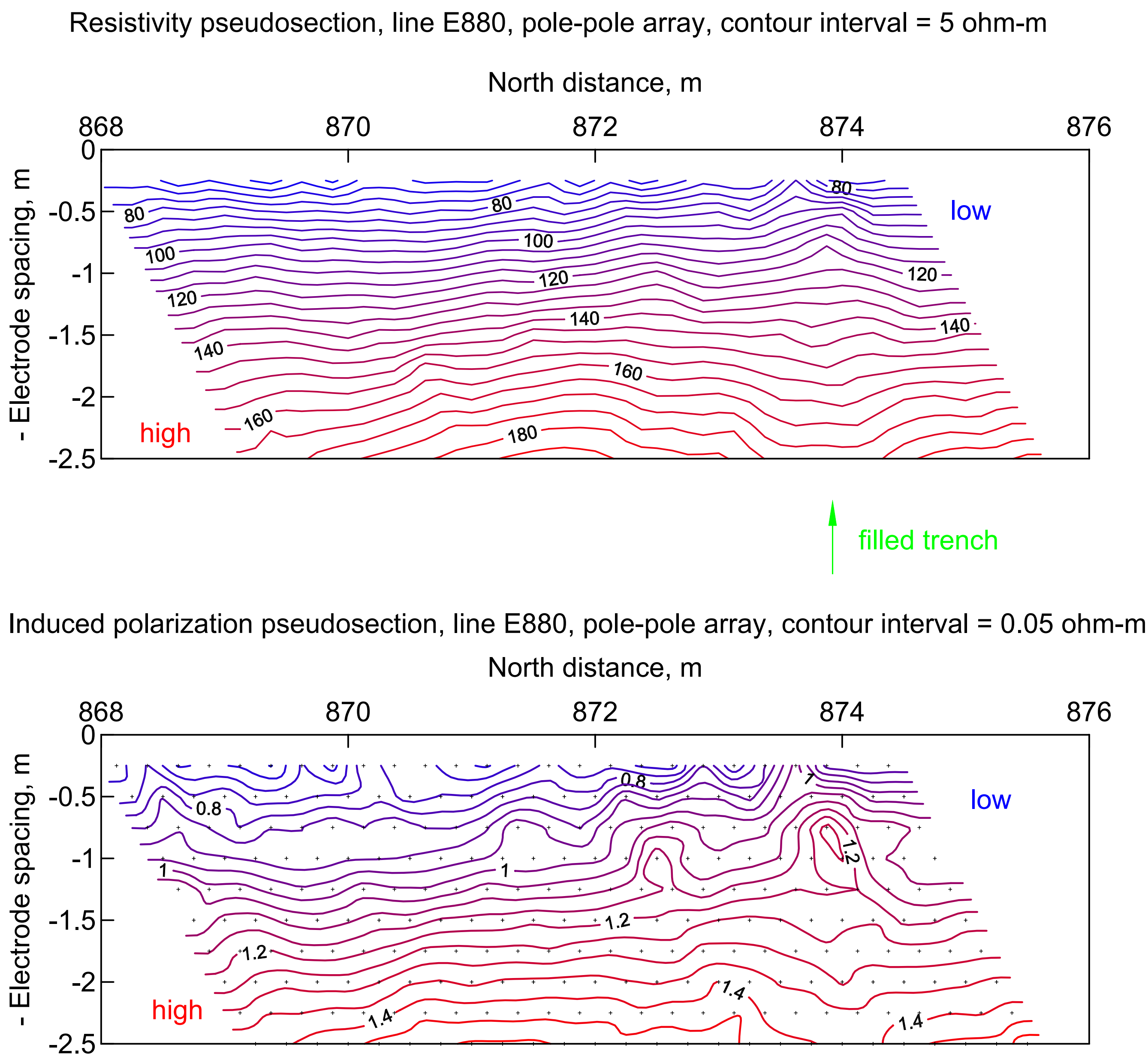

Figure 9: The two pseudosections that were measured at Biesterfeldt. This is just a different plot of the data in Figure 6 and Figure 7. Because of the large stratification of the soil, it is more difficult to see the anomalies here than in the curves of Figures 6 and 7. The dots in the lower panel locate the readings.

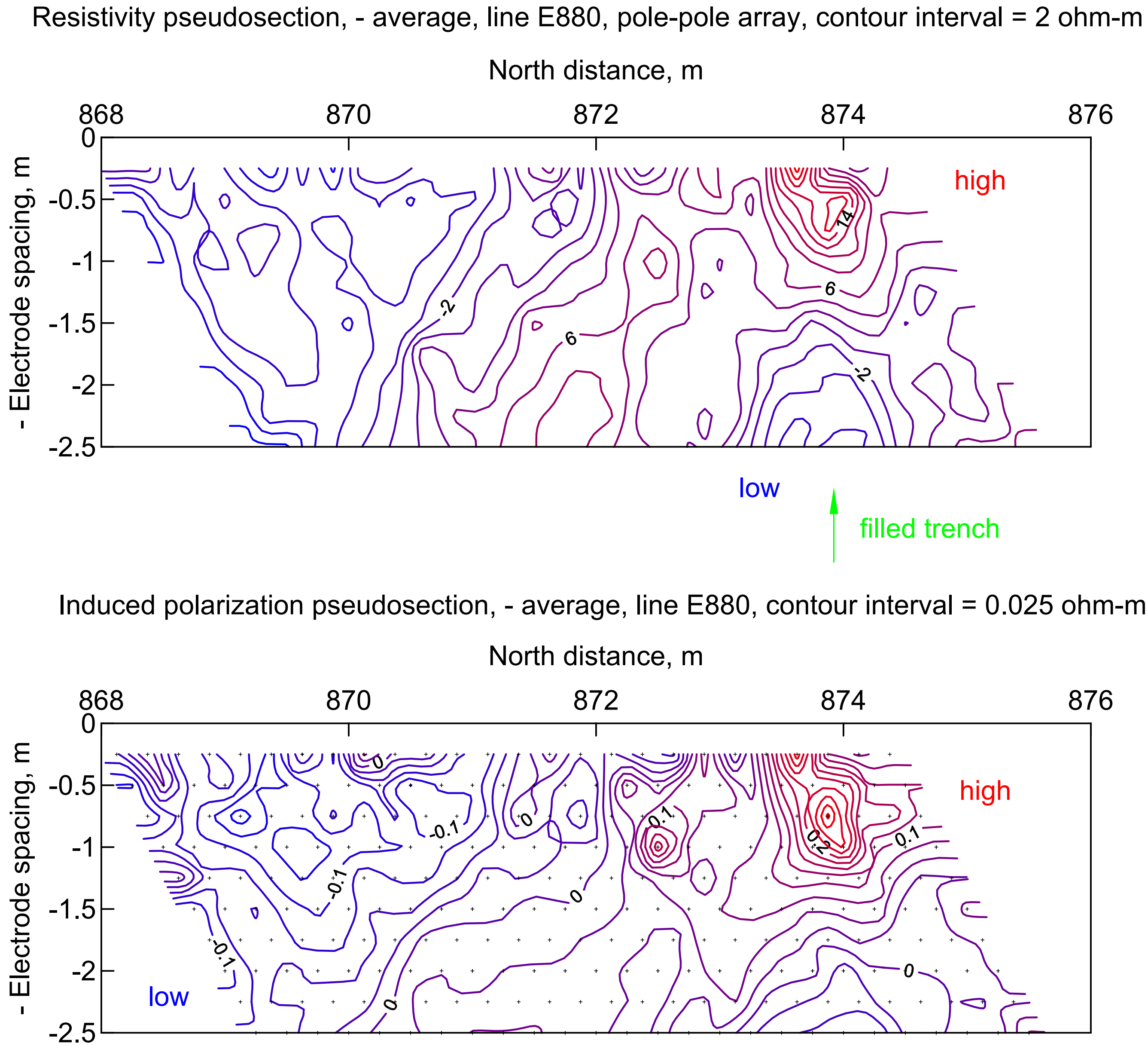

Figure 10: An improvement to the pseudosections. At each electrode spacing, the average resistivity or IP was calculated for the entire north-south span of the readings; this average was then subtracted from all of the readings at that spacing. This modification has removed the uniform pattern (depth gradient) that is found in Figure 9.

At the location of the filled trench, the resistivity pseudosection shows high values at a small spacing and low (relatively negative) values at a large spacing. However, at a spacing of about 1.25 m, the anomaly from the trench is quite faint. This change in the polarity of the anomaly may be because the soil that fills the trench has a resistivity that is intermediate between the resistivity of the topsoil and the subsoil.

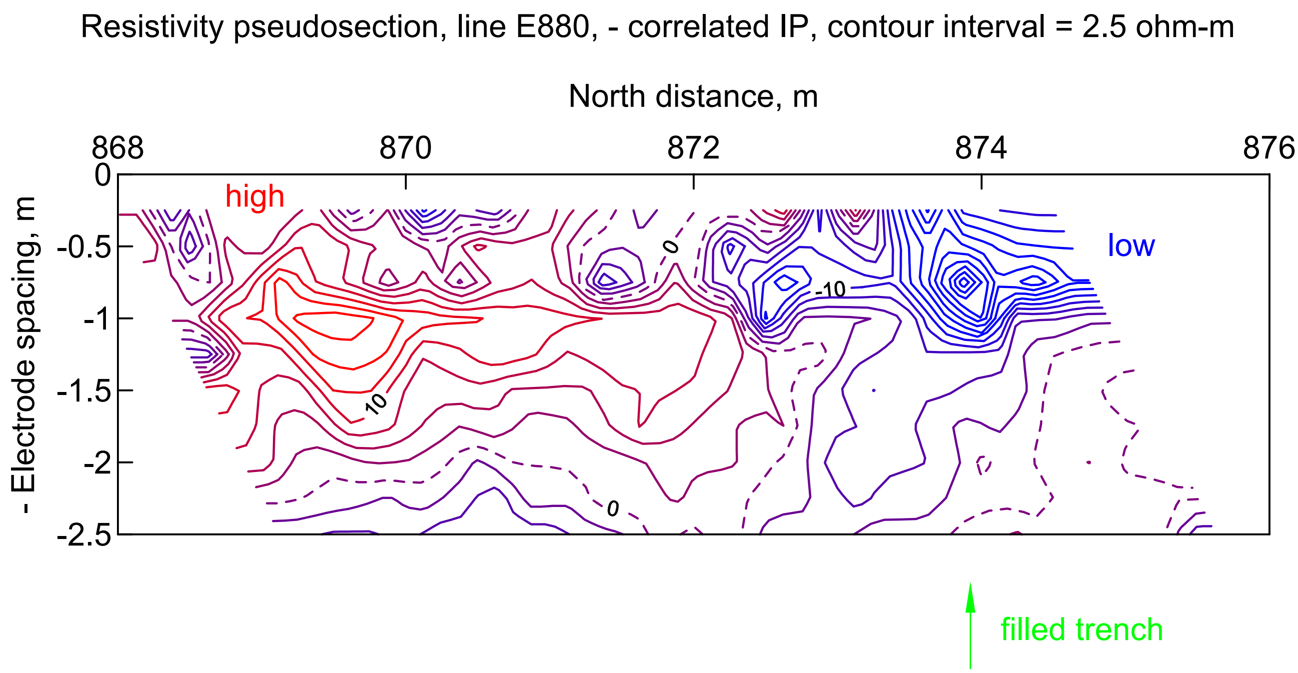

Figure 11: A de-correlation of the Biesterfeldt pseudosections. Figure 3 shows the linear correlation between resistivity and induced polarization, and this is:

Resistivity = 151.5 * (Induced polarization) - 39.1

From the IP readings at the bottom of Figure 9, these calculations of the correlated resistivity can be subtracted from the actual resistivity readings at the top of Figure 9. The result is plotted here. While this plot accentuates the measurement errors that were made, low values near the trench mean that the resistivity there was lower than what was implied by a perfect correlation with the IP readings. This plot does remove the strong depth gradient, but it does not appear to have aided an understanding of the data.