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Application of the Self-potential Method to Archaeological Prospection: some Case Histories

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ABSTRACT The self-potential (SP) method is very rarely used in archaeological prospection because related phenomena are not very well known. The aim of this study is to discuss the different SP phenomena that might be observed at archaeological sites, and therefore the SP method was applied at different archaeological sites in Anatolia (Turkey), such as Acemhöyük, Amorium, Burgaz and Ulucakhöyük archaeological areas and the Sinop amphorae workshop site. These studies indicated that SP anomalies existed over both burned or unburned materials at archaeological sites, such as walls, pits, kilns, etc. Furthermore, SP anomalies were also found over areas of complex soil distribution and visible physical changes on the surface. Other kinds of SP anomalies were also observed in those archaeological structures located very close to the coastline. These results were confirmed by archaeological excavations, which were carried out after geophysical surveys in the areas studied. All the studies supported that electrokinetic and electrochemical potentials might be the main cause of SP anomalies in the buried archaeological structures. The SP data collected with the gradient and total measurement techniques were processed by forward and inversion methods, and the main SP parameters (h, Q and x_0) were determined. In addition, the SP results were compared with other applied geophysical methods such as resistivity and magnetic. Copyright © 2004 John Wiley & Sons, Ltd.

Key words: Anatolia; archaeological prospection; electrochemical potential; electrokinetic potential; self-potential

Introduction

The self-potential (SP) survey is one of the oldest methods in geophysical exploration, and it is still used for solving many problems in applied geophysics. The SP method was first used by Robert Fox whose aim was to detect underground copper sulphide deposits in Cornwall, England in 1830. The first systematic research on the self-potential method was carried out by Petrowsky (1928) in the determination of potential distribution on a polarized sphere. Heiland (1940) determined the electrical field distribution of a vertical polarized dipole producing an SP anomaly at any point. The SP method has been used in different geological and engineering problems such as mining exploration (Sato and Mooney, 1960; Lögn and Bolviken, 1974; Corry, 1985), hydrogeology (Rao, 1953; Bogoslovsky and Ogilvy, 1974; Semenov, 1974; Schiavone and Quarto, 1984), engineering and environmental geophysics (Bogoslovsky and Ogilvy, 1977; Bogoslovsky *et al.*, 1977; Corwin, 1990), dam and embankment seepage control (Bogoslovsky and Ogilvy, 1970a,b, 1973; Bogoslovsky *et al.*, 1979; Fitterman, 1983; Black and Corwin, 1984; Butler, 1984), geothermal (Zohdy *et al.*, 1973;

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Anderson and Johnson, 1976; Corwin and Hoover, 1979; Corwin *et al.*, 1981; Fitterman and Corwin, 1982; Ercan *et al.*, 1986), tectonic particularly earthquake prediction (Corwin and Morrison, 1977; Fitterman, 1978; Morrison *et al.*, 1979; Varotsos and Alexopoulos, 1984a,b; Honkura and Kuro, 1986; Di Bello *et al.*, 1994), volcanic eruption (Zablocki, 1976; Di Maio and Patella, 1994; Di Maio *et al.*, 1996) and archaeological prospection (Wynn and Sherwood, 1984; Drahor *et al.*, 1996; Cammarano *et al.*, 1997).

This study aims to discuss the different SP phenomena responsible for anomalies on archaeological sites, such as electrokinetic, electrochemical and other SP effects. It is known that the SP method is concerned essentially with mapping buried structures and altered soil as well as burial oxidized metallic objects. In addition, the equipment is much cheaper than other geophysical equipments for field practitioners and archaeologists. However, data collection is rather difficult and this process should be applied very systematically during the survey. Thus, the other aim of this study was to evaluate the appropriate survey procedures, which were very important to obtain good quality data in SP surveys. Therefore, the SP method has been used at different archaeological sites in Anatolia, such as Acemhöyük Assyrian Trade Colonies artificial hill, Sinop amphorae workshop sites and Burgaz, Amorium and Ulucakhöyük archaeological areas. The Acemhöyük and Amorium areas were destroyed by a large fire in antiquity, and the Sinop Amphorae Workshop sites contain numerous amphorae kilns that were also exposed to high temperatures in ancient amphorae workshops. Consequently, the initial physical and chemical properties of the archaeological materials have been extremely altered. The SP data collected with the gradient and total measurement techniques were interpreted using forward and inversion methods, and deterministic parameters such as polarization focal depth (h), polarization angle (Q) and distance of the origin from the reference point (x_0). The SP results were also compared with other applied geophysical methods such as resistivity and the magnetic. The case histories that are presented here show that SP anomalies are correlated with burnt structures such as walls and kilns. Probably the influence of high temperatures leads to a significant alteration of the soil properties within these structures. Moreover, it is known that in pits their filling material cause SP anomalies. Streaming potentials along extended wall structures have been observed by Wynn and Sherwood (1984). Archaeological excavations confirmed these results. The SP studies suggest that electrokinetic and electrochemical potentials might be the main cause of SP anomalies over buried archaeological structures.

Self-potential method and its archaeological application

The purpose of the SP method is to measure variations in natural potentials, which can be measured between any two points on Earth's surface, i.e. natural potentials from less than a millivolt to over one volt. The SP anomalies are caused by temperature, pressure gradient, porosity, fluid migration, resistivity variation and moisture content of soil (Schiavone and Quarto, 1984; Ercan *et al.*, 1986; Corwin, 1990; Drahor *et al.*, 1996). These physical variations are the main causes of ion accumulations along the discontinuities (Ercan *et al.*, 1986; Drahor *et al.*, 1996). Electrical potentials are called mineral and background potentials in mineral surveys. Mineral potential and its phenomena have been known since the 1920s and used in mineral exploration, especially in the search of massive sulphide ore bodies. From massive ore bodies such as pyrite, chalcopyrite, covellite and other good electronic conductors, large negative SP anomalies are obtained, and the general phenomena were described by Sato and Mooney (1960). This potential is unidirectional and stationary in time, whereas background potentials vary with time (Reynolds, 1997). The background potentials are the main reason for anomalies in geothermal, hydrogeology and engineering geology investigations, and in archaeological prospection. Background potentials include those caused by telluric currents, cultural activity and bioelectricity. There are two types of time-variable potentials: electrokinetic and electrochemical. Electrokinetic potential occurs because of an electrolyte flowing through a capillary or a porous medium, and this potential is called streaming, electromechanical or electrofiltration potential. Electrokinetic phenomena are the main generator of potential anomalies in archaeological areas (Wynn and Sherwood, 1984; Drahor *et al.*, 1996). The first of the known SP applications in archaeological prospection was carried out by Wynn and Sherwood (1984) at different archaeological sites in the USA (Fort Washington, Piscataway and Harpers Ferry sites). According to Wynn and Sherwood, 'Variations in soil porosity and clay content caused by digging and back filling should give rise to variations in the voltage measured by an SP survey. Buried stone foundations should also affect the measured SP; a solid, relatively non-porous body should interrupt the vertical water flow and give rise to an SP voltage positive above it. A loose stone assemblage, with many cracks and a relatively larger downward movement of water might, conversely, give rise to an SP negative on the ground above it, if the same streaming potential is going on in the overlying soil.' Electrochemical potentials occurring in diffusion and Nernst (or shale) potential forms can be taken as two separate situations. The main causes of diffusion potentials are differing ion concentrations within the groundwater solution and their varying mobility. These potentials generate anomalies of a few tenths of a millivolt. The Nernst potential occurs owing to the differences of potential between the two potential electrodes inserted into a medium that contain different concentrations of solutions (Reynolds, 1997). In this study, the SP anomalies obtained over burnt structures are completely based on observational and experimental results. These anomalies are generally observed over *in situ* burial structures, which are constructed from extremely burnt sundry brick and other brick materials, and burnt soils. These might have been exposed to very high temperatures. According to Drahor *et al.* (1996), SP anomalies can be produced by burnt pits, walls, kilns and in areas where chemical changes are significant. It is known that the physical and chemical properties of these materials are changed because of the burning process, and high magnetic values are generally observed over these materials at archaeological sites. This phenomenon was first determined by Le Borgne (1955, 1960). He proposed it as an alternative mechanism for reducing and oxidizing in ferric conversion, and postulated a fermentation effect, produced in soil by alternating dry and saturated conditions. Furthermore, he considered that susceptibility enhancement by burning was the most significant among these factors. A number of experiments and observations indicate that oxidation is important (Le Borgne, 1955, 1960; Tite and Mullins, 1971; Mullins, 1977; Clark, 1990). Sato and Mooney (1960) have determined the activities of ferrous and ferric ions in equilibrium with each other in the self-potential method. They found that the concentrations of ferric and ferrous ions are independent of the pH. According to Nourbehecht (1963), any two materials in contact, with dissimilar diffusion rates, will tend to produce SP if there is a chemical potential gradient cutting across their common boundary. Oxidation-reduction problems are dealt with in much the same way as concentration diffusion problems. Nourbehecht (1963) determined that, in the presence of electronic conductors, the potential is determined essentially by the concentrations of the minor elements capable of undergoing oxidation-reduction reaction, such as iron and manganese. This ability depends on the oxidation state of the ions in the electrolyte. Mn^{4+} and Fe^{3+} are examples of ions in porewater that can receive electrons and thus reduced. Among these minor constituents, iron occurs in rocks in fair quantities, however, its solubility is very low. Thus, the ionic concentration can be computed from knowledge of all the reactions and the free energies involving iron (Nourbehecht, 1963). These are well-known methods of chemical thermodynamics (Pourbaix, 1949; Garrels, 1960; Nourbehecht, 1963). The oxidizing ability of groundwater is controlled by its oxygen content. The porewater inside the overburden will regularly be renewed by rainwater containing a large supply of oxygen. Therefore, the porewater in the overburden will have high redox potential (Lile, 1996). Thus, it can be thought that such similar phenomena may be occurring over the buried archaeological structures, which consist of materials with ferrous and ferric ions. According to Drahor *et al.* (1996), SP anomalies with positive polarity and very high magnetic values would generally be obtained over burnt walls and zones within the soil, which were verified by excavations revealing burned structures. In this study, the SP anomalies were also observed over burnt and unburnt structures in different archaeological sites and the results were verified by excavations.

The survey procedure and interpretation

Although the costs for SP equipment are lower and the survey procedure appears to be easier than other electrical methods, SP data collection is rather difficult, and involves numerous procedures that must be applied very carefully during the survey process. The SP equipment consists of a digital multimeter (≈10 MΩ input impedance), two non-polarizable electrodes (Cu–$CuSO_4$, Pb–$PbCl_2$, Ag–AgCl, etc.), connecting wires, the length of which is chosen according to the purpose of the survey procedures, and a tool for digging electrode holes. Electrodes and their properties have always been very important factors in geophysical prospection, and there are four techniques commonly using non-polarizing electrodes in exploration: resistivity, induced polarization (IP) and complex resistivity, SP and magnetotelluric (MT). There are two kinds of measuring systems in SP: using a roving potential electrode for regular intervals and using a fixed electrode for monitoring of time-variable changes. Therefore, long-term drift is quite important in all shallow SP measurements, and this effect is minimized by low-drift electrodes. There are two different measurement techniques in SP exploration: gradient and total field. In the gradient measurement technique, two movable non-polarizable electrodes are used and the observation point is the mid-point between the two electrodes. In the total field measurement technique, one measurement electrode is fixed at the base station, and the other electrode is moved along the survey line. The potential gradient technique is faster and more practical than the total field technique with regard to data acquisition. However, it has some disadvantages in terms of data quality. These are: suspicious anomalies that generally are generated by cumulative errors, electrode polarization, drift effects, time-varying potentials, soil contact effects and reading errors (Corwin, 1990). In fact, this technique may be more sensitive to changes along the surface and in lateral irregularities in the subsoil than the total measurement. This situation may be useful in archaeological prospection applications because these irregularities and changes usually exist in archaeological areas (such as walls, ditches and different soil types and contents). Contact resistance effects are also very important in SP surveys at archaeological sites. Electrode contact resistance ranges from a few hundred ohms in water or highly conductive soil to several megaohms in snow, frozen soil, or very dry or rocky soil (Corwin, 1990). Therefore, it is important to measure and record electrode contact resistance at each station. If there is no momentary variation in the medium, the contact resistance generally shows a good similarity between the stations.

The SP measurements are also affected by topographic changes, corroded buried metals and pipelines, power sources, unwanted streaming potentials and daily temperature changes. Topographic correction is usually neglected in archaeological survey because most archaeological sites do not contain significant topographic changes. Power sources may generate constant relative potentials in the earth surface, and these may be an important noise source. In areas that contain buried corroded pipelines and metals found very close to the surface, positive or negative SP anomalies with large amplitudes can be obtained (Corwin, 1990). The potentials arising from bioelectric activity of plants, trees, etc., are sometimes as large as several hundred millivolts, and the anomalies are observed as a sharp negative form (Telford *et al.*, 1976). In this case, anomalies of interest may be lost because of dense plants and bushes that are present in some archaeological sites (Drahor *et al.*, 1996). Therefore, areas that contain power sources, corroded pipelines or metal, plants and bushes must be carefully mapped in archaeological prospection. Telluric currents are also important noise sources in SP survey; these potentials become unimportant noise sources when the electrode spacing is chosen to be small, such as 10 m or less. Although daily temperature changes are generally not an important factor in SP studies at archaeological sites, small changes can occur in the SP anomaly in the event of a rapid decrease or increase in daily temperature.

In archaeological prospection, the geophysical data are generally collected using a gridding survey procedure, which is practical and important to facilitate the interpretation, and can be readily used in archaeological SP investigations. In this procedure, the grid interval should be small, and it is practical to choose small electrode separations (such as between 1 and 6 m). As known, the inner polarization difference of non-polarizable electrodes changes with time and other unknown factors. This phenomenon is observed as a noise during data collection, particularly during monitoring processing. Furthermore, the soil may change over small intervals, producing archaeological and some engineering problems. This situation usually can be visible on the surface (e.g. burnt, oxidized soils, etc.). In this situation, the correction points may be affected seriously. Thus, the SP data collected by the gridding technique cannot be corrected sufficiently in archaeological and engineering studies. Furthermore, inner voltage changes between electrodes may be generated owing to daily temperature changes in the soil and difference of polarization in the liquid electrodes. Moreover, different voltages may occur owing to a bad contact, viscosity changes in the mud and length of time in the measuring process. All these changes affect the SP data collected in the area and also the correction points, which are controlled by the inner voltage differences between the measuring electrodes. Thus, these changes can camouflage the real anomalies. The SP anomalies are generally low in amplitude in archaeological and engineering studies. For this reason, these changes can importantly affect the survey, and prevent the location of the surveyed targets. Thus, a systematic correction measuring process, which is similar to the classic correction used in magnetic prospection, should improve the data quality in near-surface research. At the beginning, a base point should be determined for an SP survey on a two-dimensional grid system in the investigation area. This base point should be used as a reference station for all the measurements. Furthermore, this base point should be checked to determine any drift effect after completion of measurement of every profile. Thus, if any drift occurs in this point, it can be removed from data by a correction process. The checking process of the base point should be continued throughout the measurement process. Thus, the operator can monitor any electrode drift or telluric variations, and the erroneous data may be cleaned of these undesired effects. Furthermore, it may important to record the data along two directions, which are perpendicular to each other. In the measuring process, data should be taken very carefully, and factors such as type of the soil, moisture, geology, geomorphology, presence of plants and topographic effects should be noted (Drahor, 1993a,b, 1994; Drahor *et al.*, 1996). Other survey procedures are explained in detail by Wynn and Sherwood (1984), Corwin (1990) and Drahor *et al.* (1996). The measurement time takes approximately 1 min at every measurement point for gradient and total techniques. Thus, one profile of 20 m length could be measured in 20 to 30 min in flat surface areas, and an area of 20×20 m could be measured in half to one day depending on the grid intervals.

Field data from SP applications corrected for drift and electrode polarization effects are generally interpreted qualitatively. Many researchers have calculated the total and gradient anomaly curves for different geometrical bodies, such as point current, horizontal line, spherical, cylindrical and vertical dipole sheets, by means of modelling (Heiland, 1940; Rao *et al.*, 1970; Telford *et al.*, 1976; Fitterman, 1979; Bhattacharya and Roy, 1981; Murty and Haricharan, 1985). Burial archaeological structures are generally found in vertical and horizontal forms in the soil. The sources of such anomalies may be interpreted by assuming an inclined sheet model. The other models have been discussed by Drahor *et al.* (1996) in detail. In this study, the inclined sheet model was calculated for shallow bodies at different depths and polarization angles, and gradient and total curves of these models are obtained (Figure 1). The values used in this process are as follows:

$P = 100$ mV (electrical dipole moment)
$delx = 1$ m (sampling interval)
$Q = 0°, 15°, 30°, 45°, 60°, 75°$ and $90°$ (direction of polarization measured clockwise from positive x axis)

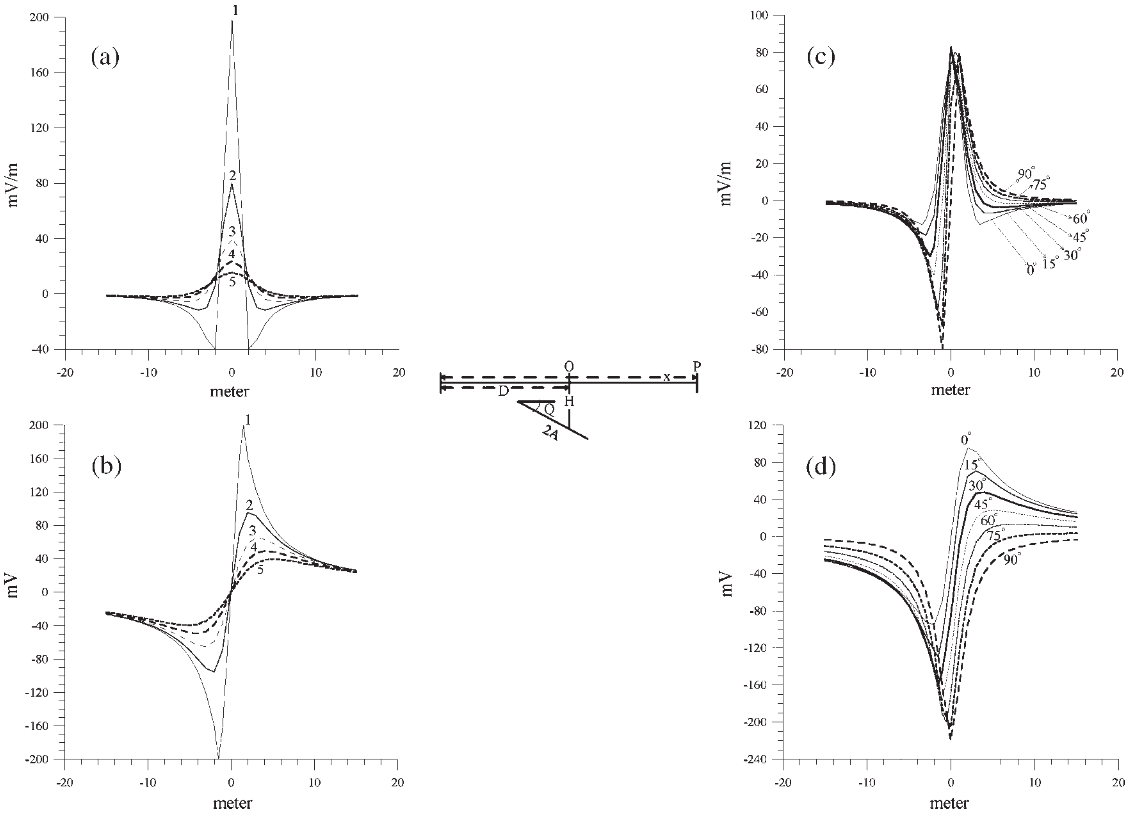

Figure 1. The inclined sheet is calculated for shallow bodies at different depths and polarization angles ($P = 100$ mV, $delx = 1$ m, $D = 15$ m, $N = 31$): (a) gradient; (b) total curves at different depths ($Q = 0°$, $h = 1$, 2, 3, 4 and 5 m); (c) gradient; (d) total curves at different angles ($h = 2$ m, $Q = 0°, 15°, 30°, 45°, 60°, 75°$ and $90°$).

$D = 15$ m (distance of the origin from the reference point M)
$N = 31$ (number of observations)
$h = 1$, 2, 3, 4 and 5 (depth to the centre of the inclined sheet)

As can be seen from the curves in Figure 1, the amplitude of the model curves suddenly decreases as the depth of the model is increased, and the amplitudes of all model curves have higher values than ± 5 mV tolerance, which can be accepted between values of 5 and 10 mV, in gradient and total graphics (Figure 1a and b). Moreover, it can be seen that the polarization angle is another important parameter for the interpretation of these curves. The SP anomaly is directly affected by this parameter, which controls the shape of the anomaly (Figure 1c and d). Modelling studies confirm that the sheet-type model gives the most appropriate anomalies for the gradient and total SP values in archaeological prospection.

An easy and fast method to determine parameters such as depth, polarization angle and distance values from the source position to a reference point is the nomogram technique (Bhattacharya and Roy, 1981; Murty and Haricharan, 1985). In the past few decades, many researchers (Fitterman and Corwin, 1982; Ram Babu and Atchuta Rao, 1988; Jagannadha Rao *et al.*, 1993, etc.) have used the inversion technique. The SP anomalies over sources in the form of spheres, horizontal cylinders and inclined sheets are interpreted by an inversion process. The problem here is to evaluate the unknown model parameters. Initial estimates for model parameters are made and modified by iteration process. In each iteration, the theoretical anomaly and root mean square (RMS) error are calculated using the modified parameters, and the inversion process is continued until the RMS error is a minimum (Ram Babu and Atchuta Rao, 1988). In addition, the unknown model parameters can be evaluated by using another inversion technique introduced by Jagannadha Rao *et al*. (1993). This technique uses Marquardt's (1963) optimization procedure for parameter estimation. Calculations are repeated several times until the objective function decreases below an allowable error. In this study the inversion techniques presented by Ram Babu and Atchuta Rao (1988) and Jagannadha Rao *et al*. (1993) were applied successfully to data obtained from different archaeological areas. Parameters such as the angle between the axis of polarization and the horizontal (Q), depth to the centre (h), and shift of the point vertically above the centre of the body from zero potential value (x_0) were estimated using forward and inversion techniques and horizontal projections of the polarization centres were obtained. In presenting the data, the three parameters that were calculated by forward and inversion techniques for every SP anomaly were placed on a measuring grid with x and y co-ordinates. Thus, the investigation area is modelled using these parameters, and burial structural boundaries were illustrated as horizontal projections. The objective is to determine the borders and the relationships between buried archaeological structures by considering especially the polarization angles.

There is always a contact between two different media, which are separated by positive and negative polarities, and this contact is named as the axis of polarization in the SP method. The polarization angle is also given between the horizontal surface and the axis of polarization, and it is a very important parameter because it determines the direction of polarization of the body in the SP method. In this study, the borders of the buried structures could be determined by using the polarization angles. In this process, the main aim is to determine whether or not the anomalies give the same polarization angle on a unique structure.

The use of filtering, which is used to remove undesired effects (e.g. noise) on the SP data, also increases the success of the method. Thus, using a simple three-point filter in field applications can be sufficiently effective. A basic filter is shown below, and this can remove many undesired effects from the data

$$0.26\,g_{i-1} + 0.48\,g_i + 0.26\,g_{i+1}$$

where g_i is the observation value for ith point.

Archaeological applications

An Assyrian Trade Colony artificial hill: Acemhöyük

Acemhöyük is an artificial hill from the period of the Assyrian Trade Colony and one of the largest hills in Anatolia (Figure 2), with a length of 700 m in an east–west direction and a width of 600 m in a north–south direction. The highest point of the artificial hill is 20 m, and the surface of this artificial hill is rather flat. Dendrochronology studies ascertained that the Assyrian Colony city was destroyed by fire in approximately 1789 ± 50 BC. As a result, the soil of the artificial hill was altered. Moreover, the physical and chemical properties of the foundation walls, built with sundry brick, were changed. Excavations in Acemhöyük prove that the third archaeological layers were built in an architectural system with NE–SW 45° and NW–SE 45°. Earlier SP studies showed that soils, which have different physical and chemical properties owing to human activities, are an important factor in the creation of self-potential anomalies (Wynn and Sherwood, 1984; Drahor *et al*., 1996). The aim of this study was to determine whether or not an SP anomaly might be generated by the buried archaeological materials and/or variable soil distribution. Therefore, SP studies were carried out in July and August of 1992 and 1993 on the Acemhöyük. In the first step of the survey, a test profile was chosen to determine the visible structures using gradient self potential and other geophysical techniques such as resistivity and magnetic. These data produced some important anomalies over the burnt materials along the test profile (Drahor *et al*., 1996; Drahor and Kaya, 2000). Therefore, the SP surveys were extended to investigate larger areas on the Acemhöyük, and the studies were continued up to the artificial hill (areas A and E in Figure 3c) and down to the

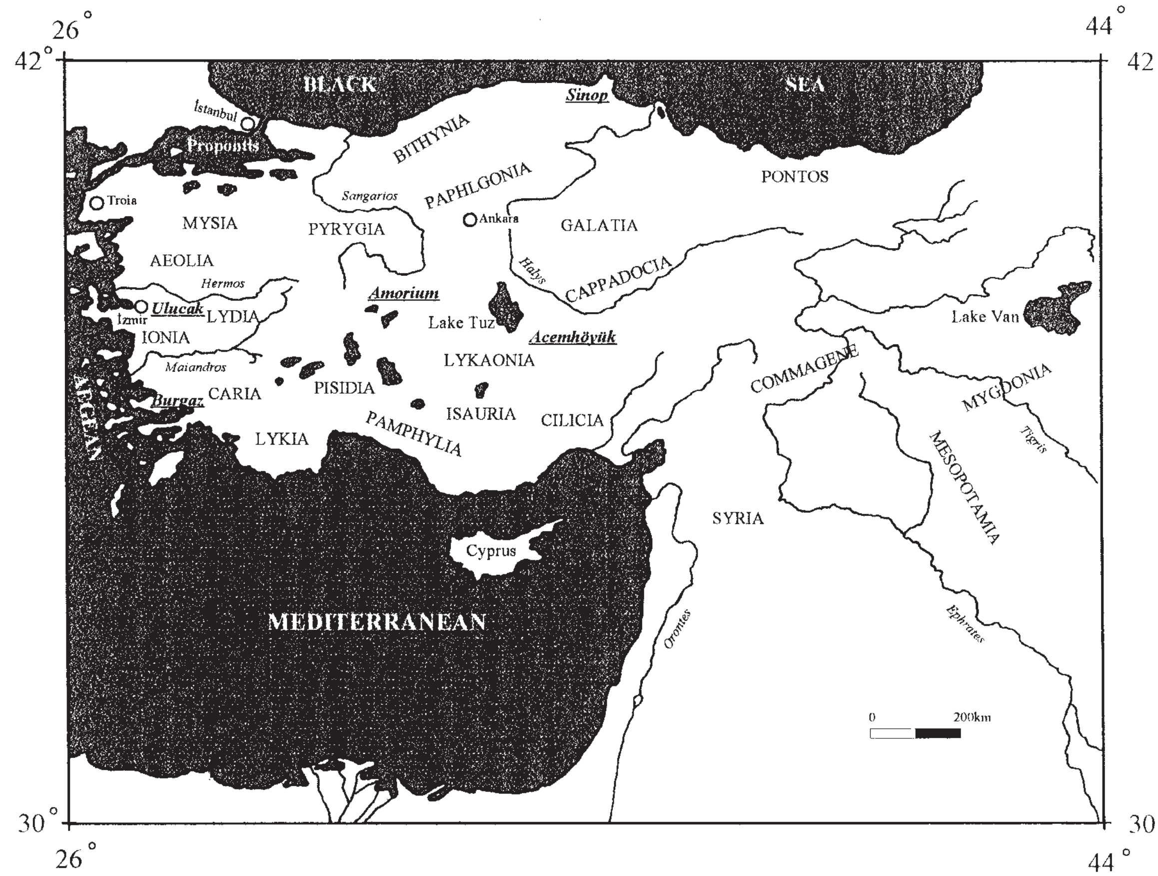

Figure 2. The archaeological sites investigated by SP method (underlined) of Asia Minor.

Acemhöyük Karum area, which was a trade settlement, and had been settled around the artificial hill in the Assyrian era. In the SP surveys, electrode and grid intervals were chosen as 2 m and 1×1 m, respectively. Data were collected by gradient measurement technique, and non-polarizable Cu–$CuSO_4$ electrodes were used in this study. The SP data have a relatively small noise envelope of about 5 mV. Resistivity measurements were also taken at 1 m grid intervals and for 1 and 3 m probe intervals by using a twin probe array. As can be seen from Figure 3b, positive and negative anomalies were in agreement with the directions of burial archaeological structures in the höyük. The amplitudes of the anomaly of the gradient change between 39 and −36 mV/m in the area, and this is an important result in application of the self-potential method in archaeological prospection, with regard to the magnitude of the anomaly. In the western part of the map, the anomalies were in the same locations as the anomalies on the 3 m apparent resistivity map. The high resistive anomalies are observed in the western part of the apparent resistivity image, and they are generally in the direction of N–S and NE–SW and NW–SE (Figure 3a). Furthermore, the anomalies observed in the N–S direction in the western part of the map correspond to deposits from earlier excavations (Figure 3a, shown between arrows). Thus, on the SP gradient map, several anomaly groups with NE–SW and NW–SE directions were observed and this result is very similar to archaeological excavation results indicating many buried structures with NE–SW and NW–SE directions in the höyük. After processing the SP data for the areas A and E with forward and inversion techniques, source parameters such as depth, polarization angle and distance of the origin from the reference point were estimated and shown as a

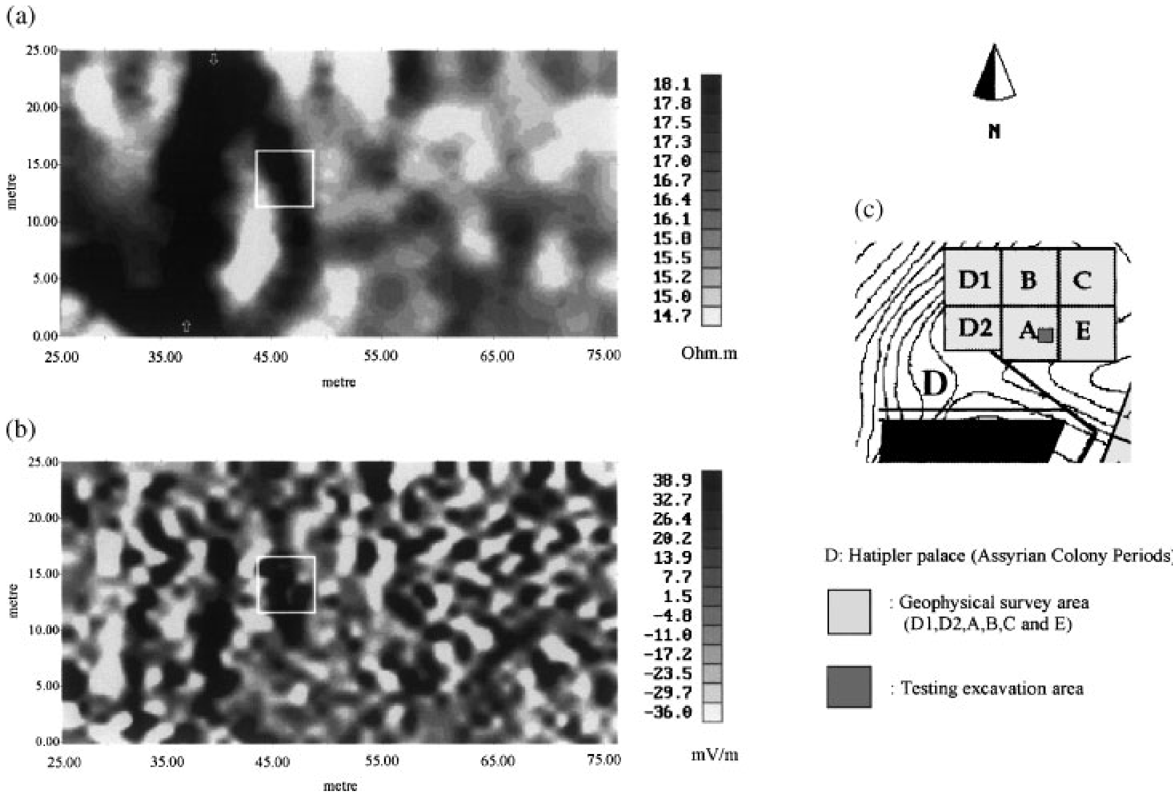

Figure 3. The resistivity and SP images obtained at Acemhöyük archaeological site: (a) apparent resistivity image of area AE; (b) gradient SP image of area AE; (c) geophysical survey plan of north of Hatipler Palace.

horizontal projection of the polarization centres. The horizontal projection representations showed that the results of SP were very similar to those of results from former excavations, and this result pointed out that the SP data could be very important for determining the archaeological structures (Drahor *et al.*, 1996; Drahor and Kaya, 2000) (Figure 3b). Following the geophysical research, the first archaeological excavation was made on the area at Acemhöyük in 1992, and the excavation area was chosen as 5×5 m (shown as a square on Figure 3a–c) and two kilns and bases of several structures (wall, pit, oven, oxidized copper fragments, etc.) were found (Figure 4). The SP studies at Acemhöyük showed that the anomalies were created by the burnt walls and pits, kilns and soils in the locations where physical variations were high, and these results were verified by the archaeological excavations.

Sinop amphorae workshop sites

The archaeological research of the Sinop pottery workshop sites in 1993 showed that Sinop may have been one of the important production and export centres of ceramics in the Black Sea region during antiquity (Figure 2). This research also showed that widespread pottery materials were found at the surface around Demirci Village (Figure 5). As known from previous geophysical studies, magnetic investigation is an important method to detect buried burned materials such as amphorae workshop sites (Hesse, 1991, 1992; Drahor *et al.*, 1995). Therefore, large-scale magnetic investigations were carried out using a Geometrics G-856 proton magnetometer to detect buried kilns and other magnetic materials near Demirci village in May 1994 and August 1994 (Figure 5). The data were collected in 2×2 m grid intervals by gradient measurements.

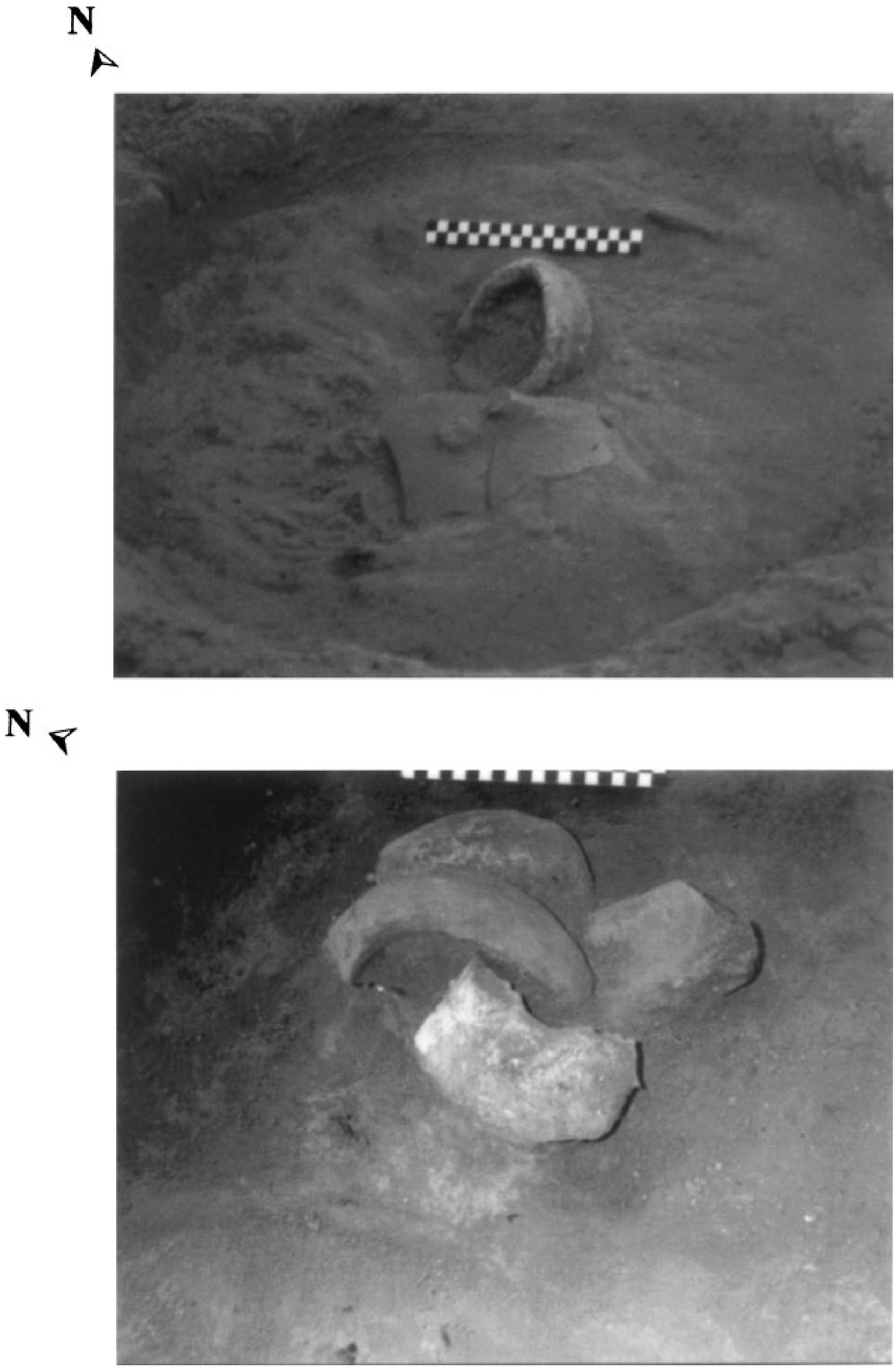

Figure 4. The kiln and small copper fragments (diameter is 0.5–1 cm), which were extremely oxidized, were found during archaeological excavation following the geophysical SP investigation.

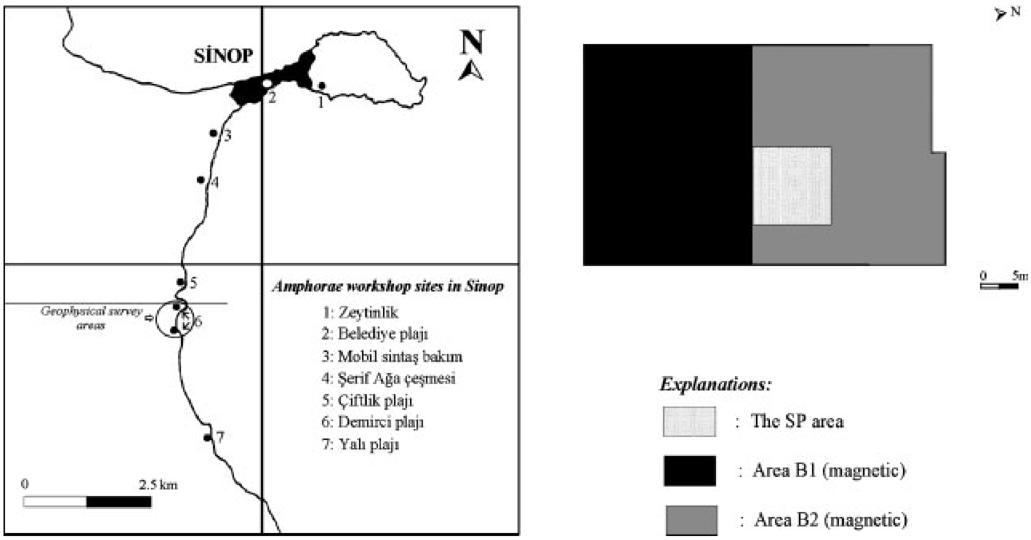

Figure 5. The location map of amphorae workshop sites in Sinop and the plan of magnetic and SP research areas at the Demirci workshop site.

The sensor height was placed at 60 and 180 cm in this study. The data were corrected by the base correction method. Magnetic data were collected for eight different areas in Demirci, and clearly show many magnetically anomalous zones indicative of kiln and other burned features. Magnetic images showed strong magnetic anomalies particularly from areas B_1 and B_2. In this study, the strongest magnetic anomaly in the Demirci amphorae workshop site was observed in area B_2 (Figure 6a). An SP survey was carried out in this region. The gradient measurement technique was used for data acquisition. Electrode and grid intervals were chosen as 2 m and 2 m, respectively. In addition, the data were obtained by using non-polarizable Cu–$CuSO_4$ in two directions, perpendicular to each other (east–west and north–south directions). Data were corrected for electrode polarization and drift effects, and the SP data have a relatively small noise envelope of about 2 or 3 mV. Image views of each direction are given in Figure 6c and d. The SP anomaly map in the east–west direction is similar to the total magnetic field anomaly (Figure 6a and c). This might yield an interesting experimental result about the mechanism of SP in these kinds of areas, and SP anomalies are again obtained over burnt material, which were explained by Drahor *et al.* (1996). The negative anomalies on the gradient SP map correspond to low magnetic values, whereas the positive ones correspond to high magnetic values (Figure 6a and c). Further, the total magnetic data were processed by two-dimensional inverse filters obtained by the least square method (Figure 6b). This is an optimum filter operator convolved with the data. The method aims to present the total magnetic field maps over buried structures. Thus, it should give a sketch of the dimensions of buried structures and present their centres at their actual locations (Tsokas and Papazachos, 1992). The two-dimensional inverse filter result of magnetic data corresponds to a negative anomaly in the gradient SP map in Figure 6c. This similarity indicates that the SP anomalies may detect areas consisting of burnt material. However, the SP gradient data in the north–south direction shows that the negative anomalies extend in different perpendicular directions, but they have the same co-ordinates, approximately. Thus, this result shows that the direction of measurement is very effective in the detection of the SP anomaly, and it is very important to use the SP data collected in two different directions for data interpretation in archaeological areas. Unfortunately, it is very difficult to decide the measurement direction in archaeological areas owing to the archaeological context, which can lie in every direction in the area. Therefore, correct results can be obtained by measuring

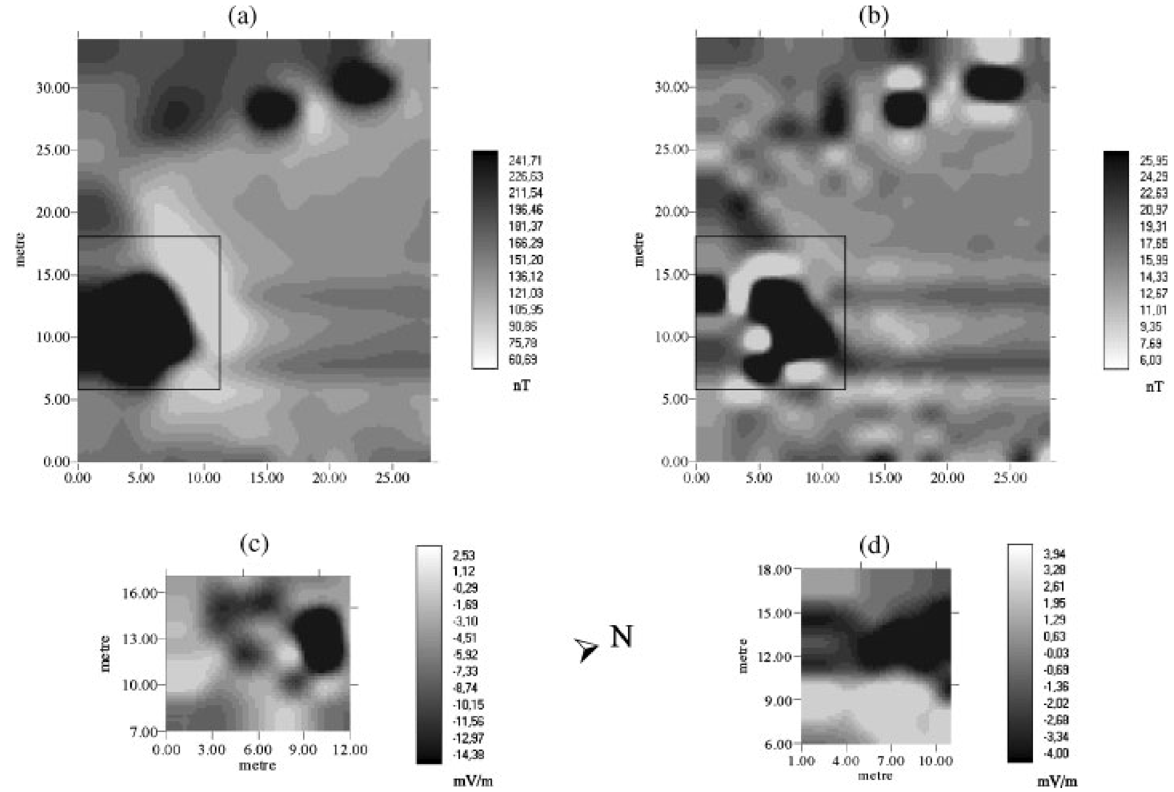

Figure 6. The magnetic and self-potential images obtained from area B2 at Sinop amphorae workshop site: (a) total magnetic field (sensor height = 60 cm); (b) inverse filter result of total magnetic field data; (c) gradient self-potential with east–west direction ($dx = 2$ m); (d) gradient self-potential with north–south direction ($dx = 2$ m).

data in two perpendicular directions and by use of other geophysical methods. The most important result obtained in this area indicated that a detectable SP anomaly could appear in burnt archaeological structures.

Archaeological excavation was performed in area B_2 in the Sinop amphorae workshop sites in 1995. This area was of 10×10 m dimension and the walls and floors, which generally consisted of burnt materials, were found very close to the surface. In addition, it was encouraging to see the similarity between the excavation results and magnetic and SP maps (Figure 7). These results showed that the joint application of the magnetic and SP method would be very useful to get satisfactory results from a geophysical survey.

Burgaz archaeological site

The archaeological site known as Burgaz, which is very near to the district of Datça on the south-western Aegean coast, was a Caria city in antiquity (Figure 2), and the Carian people had inhabited the area from the archaic to classic period. Recently, archaeological excavation results showed that the Burgaz archaeological site could be one of the first settlements of ancient Knidos during the archaic period (Tuna, 1996). Therefore, geophysical studies were carried out in 1995 and 1996 (Drahor and Altay, 1996), and the SP data were collected only in Area B, which is approximately 15 m away from the sea (Figure 8). Archaeologists think that important archaeological remains at the south harbour of early Knidos may be found in this area, and that buried archaeological structures could be very close to surface. The archaeological context might have been affected by seawater intrusion. Thus, electrokinetic or streaming potentials were thought to be the main phenomena for this area. These phenomena can be explained with the archaeological remains between the soil contents, which can be saturated owing to the interference

Figure 7. Confirming magnetic and SP results, the extremely burned walls and floors were found very close to the surface in area B_2 at the Sinop amphorae workshop site.

effect of seawater, and thus diffusion or Nernst potential may occur in this medium. In addition, a resistivity survey was performed in this area using pole–pole array with probe intervals of 1 m and 3 m from the surface and with grid intervals of 1 m (Figure 9a and b).

The signal detection filter found by Mesko (1975) and improved by Drahor (1993a) was used to detect wall-like structures and to increase the signal/noise ratio. The theoretical synthetic resistivity anomaly can be calculated for known size, depth and resistivity values, and this anomaly can be designed as a convolution filter. Thus, this filter may be used to enhance the effects of objects similar to the model. The design of these filters is based on the theory of signal detection filters for single-channel seismic time-series. Figure 9c shows the results of filtering of the resistivity data collected by pole–pole array with a 1 m probe interval. The anomalies thought to be the wall-like structures are observed. After the mapping process, it is observed that there are three anomaly groups with a high resistivity in the eastern, western and southern part of the 1-m array map (Figure 9a and c). It is believed that these anomaly groups were generated by the buried structures very near to the harbour. In addition, Bean (1987) mentions the possibility of such buried structures of the antiquity in the same place.

The main aim of the Burgaz project was to collect resistivity data for this research period. However, we thought that it might be very interesting to observe the SP variations in the coastline areas. The SP data were collected with the gradient technique in one day by using Cu–$CuSO_4$ non-polarizable electrodes. Both the grid and electrode interval of SP measurements were

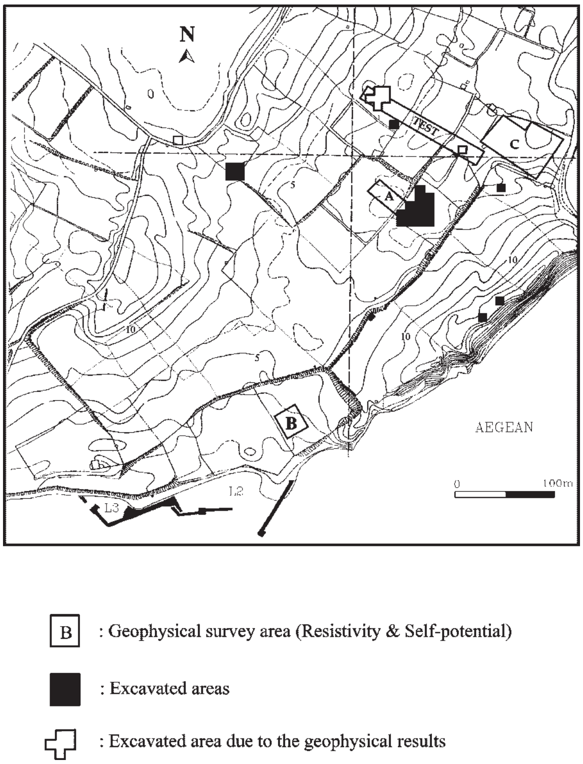

Figure 8. The Burgaz archaeological site and geophysical research plan.

chosen to be 3 m owing to insufficient research time. In this study, the SP data consisted of a relatively small noise envelope of about 2 or 3 mV. Furthermore, gradient SP measurements were carried out in one direction, i.e. NW–NE. After the correction, which was applied to remove the polarization and drift effects, the gradient SP data was imaged (Figure 9d). The magnitude of positive and negative SP anomalies is in the range of 6 and -9 mV/m in the study area. It was observed that the gradient SP anomalies were directed in the northwest–southeast and northeast–southwest directions (Figure 9d), in accordance with the architectural plan of the ancient city, and the resistivity maps (Figure 9a and c). The archaeological excavation, which has been continuing since 1994, showed that the ancient city was planned in a gridded manner, and settlements, which consist of streets, houses, fortification wall, etc., were aligned in the northwest–southeast and northeast–southwest direction. According to these results, the possible phenomena can be explained as follows: the area investigated is located very close to the sea (approximately 15 m). Thus, capillary horizontal water movement by the interference effect of the seawater in the soil could be the main reason for SP anomalies in this area. In addition, another possible source mechanism for SP anomalies could be porosity, moisture and liquid content of the soil and resistivity variations between the buried archaeological structures and the surrounding soil. It can be presumed that these conditions may start an electrokinetic process. As shown in the Figure 9d, the SP anomalies, with negative and positive polarity, and high resistivity anomalies are in good harmony, and geophysical anomaly extents are generally in the same direction as archaeological excavation results. The results at the Burgaz site showed that the SP method might be an effective technique in this type archaeological site.

Archaeological excavation was performed in area B at Burgaz archaeological site in 1999. The excavation area was 5×12 m dimensions and walls and floors were found very close to the surface (Figure 10). As can be seen from Figure 10, the walls were built from small stones and the floor was covered by small gravel. The archaeological structures found after excavation were very similar to resistivity and SP anomaly extents (Figure 9). Thus, these excavation results showed that the SP method would obtain satisfactory results from archaeological sites when used with other geophysical methods.

Amorium archaeological site

The ancient city of Amorium lies in eastern Phrygia (the modern province of Afyon), which is 170 km southwest of Ankara (Figure 2). Part of the site is now occupied by the Turkish village of Hisarköy, which lies within the administrative district of Emirdag. The site of Amorium, which includes a large man-made mound or *höyük*, was perhaps occupied as early as the early Bronze Age (third millennium BC) but was certainly inhabited during the Hittite and Phrygian periods. Although it does not figure prominently in the early history of Anatolia, it may be identified with a Hittite town called Aura. In the seventh century AD, Amorium assumed a major administrative and military role, principally

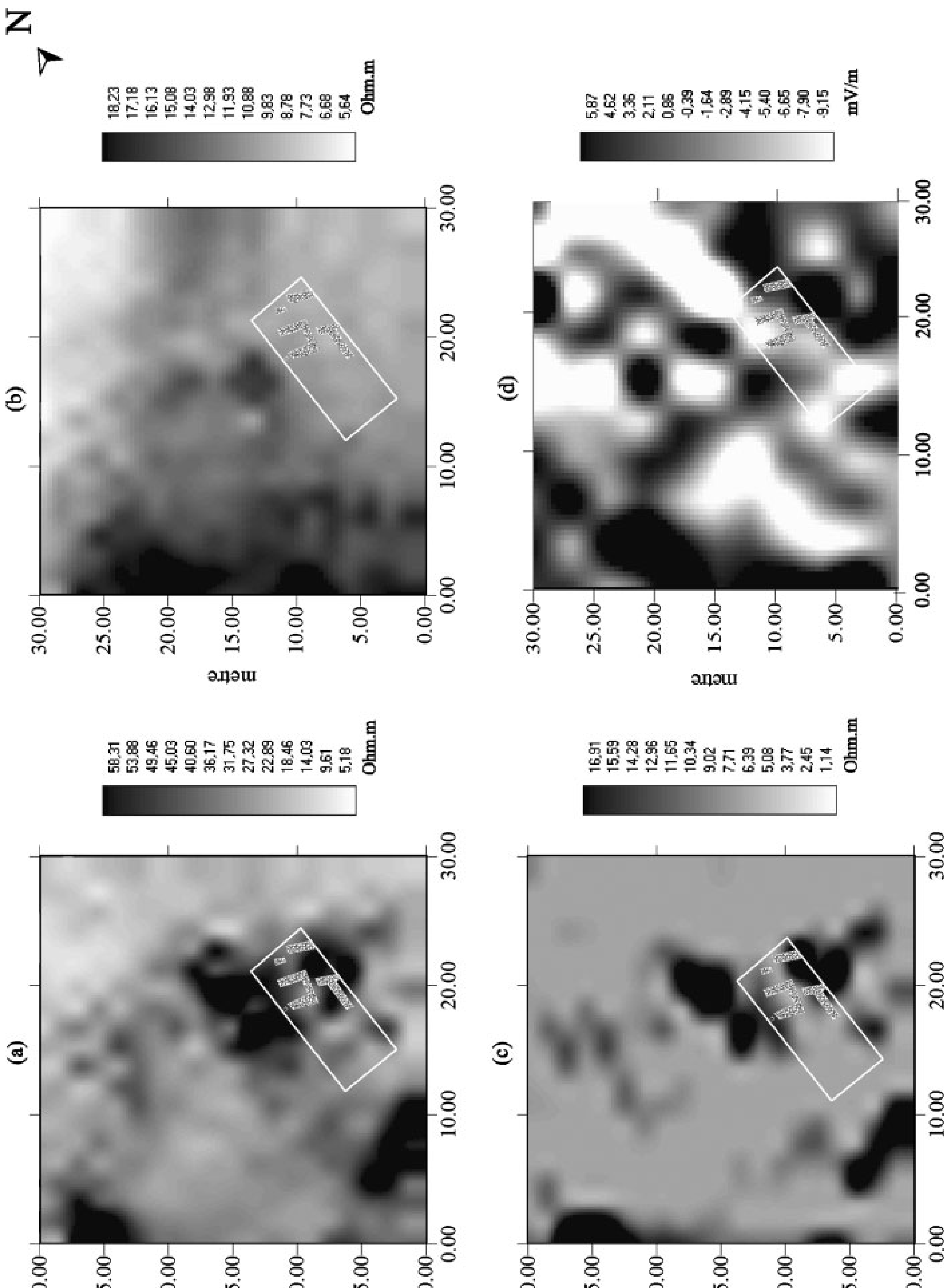

Figure 9. The resistivity and SP images obtained from area B at Burgaz archaeological site: (a) observed resistivity obtained by pole–pole 1 m array; (b) observed resistivity obtained by pole–pole 3 m array; (c) after signal detection filter result of resistivity pole–pole 1 m array; (d) gradient SP.

Figure 10. Structures were found very close to the surface at the south harbour of early Knidos.

because of its strategic position on the main southern land route between Syria and Constantinople. During the 'Dark Ages' (mid-seventh to mid-ninth century), it was the military centre of the Byzantine province or 'theme' of Anatolikon. Amorium's strategic importance meant that it faced repeated attack. Best known of these is the well-documented siege of 838. The siege, although it lasted only 12 days, is famous and received considerable attention from both mediaeval and modern historians (Lightfoot, 1997).

Geophysical explorations were carried out on the large 'Middle Byzantine Military Compound' at Amorium (Figure 11a). In this study, we expected to find important buried Byzantine structures, which might be very close to the surface. The area was surveyed with resistivity, magnetic and self-potential methods in August 1997. The area investigated was divided into 10 square areas each with the dimensions of 20 by 20 m (Figure 11b). The investigation area is flat without any topographic effect. The resistivity survey was carried out using the pole–pole array on eight areas. In this survey, the grid intervals were 1×0.5 m and electrode spacing was 1 m. The magnetic data were also collected by Geometrics G-856 proton magnetometer in nine areas, and grid intervals were 1×1 m. In addition, SP data were obtained from area D, between A_1 and B_1, where resistivity and magnetic values were very high. The SP data were collected by the gradient measurement technique on 21 profiles in 1 day, and this area is indicated with a square frame in the sketch plan of the survey (Figure 11b). In this investigation, the electrode spacing was 3 m, the grid intervals were 0.5×1 m and the measuring direction was NW–SE.

As shown in the image of areas A_1 and B_1 (Figure 12a), very high resistivity values (400–800 $\Omega \cdot$m) generally exist in the middle part of the area investigated. Lower resistivity values (100–300 $\Omega \cdot$m) are observed in the northeastern and southwestern part of the image. These very high resistivity values might be a result of an

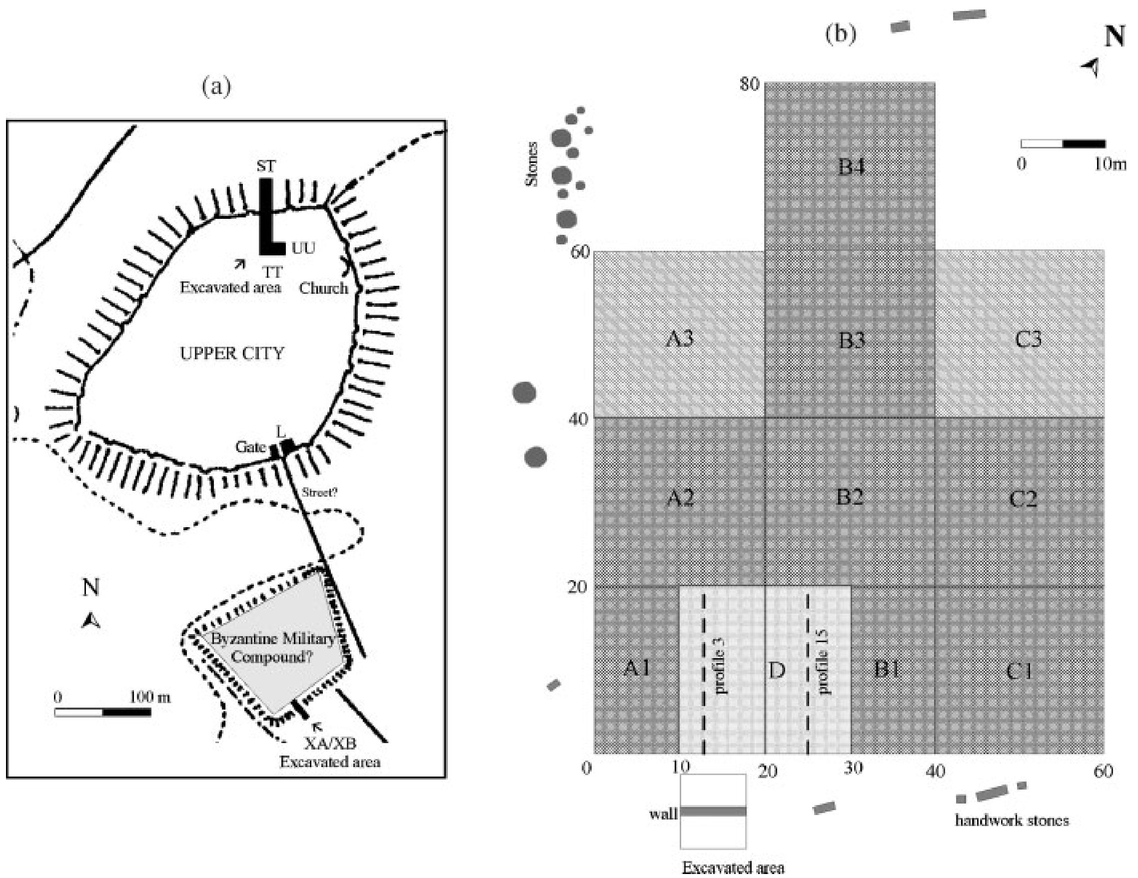

Figure 11. (a) The Amorium archaeological site. Geophysical investigation was conducted in the area of the Byzantine Military Compound. (b) Geophysical research plan of investigation area: resistivity measuring areas — A1, B1, C1, A2, B2, C2, B3 and B4; magnetic measuring areas — A1, B1, C1, A2, B2, C2, A3, B3, and C3; SP measuring area — D.

important buried Byzantine building, which is possibly large and shallow (Figure 12a). We suppose that the burial structures may be built of a mixture of limestones and bricks. The magnetic studies were carried out using the gradient survey technique at the Middle Byzantine Military Compound. The sensor height was placed at 60 and 120 cm in this study. Several magnetic anomalies with high amplitudes (between −32 and 36 nT) were observed along the south, southwestern and northeastern part of the areas A_1 and B_1, and particularly in the centre of area D (Figure 12b). Figure 12a and b show that the resistivity and magnetic anomalies are generally concentrated in the middle part of areas A_1 and B_1, and there is a good agreement between these anomalies. Particularly, the high magnetic anomalies found in the middle part of the investigation area might be caused by buried burnt materials.

According to previous SP case studies at archaeological sites, we know that the SP anomaly might be obtained on burned archaeological materials and in areas that contain physical and chemical changes. The area investigated, 'Middle Byzantine Military Compound', was completely burned in AD 838, according to Byzantine historians. As a result of this fire, the archaeological materials drastically changed compared with previous physical and chemical situations, and this event can create SP anomalies. Therefore, we thought that the SP survey could be useful and give some important information about this area. Before the SP data acquisition, it rained for three

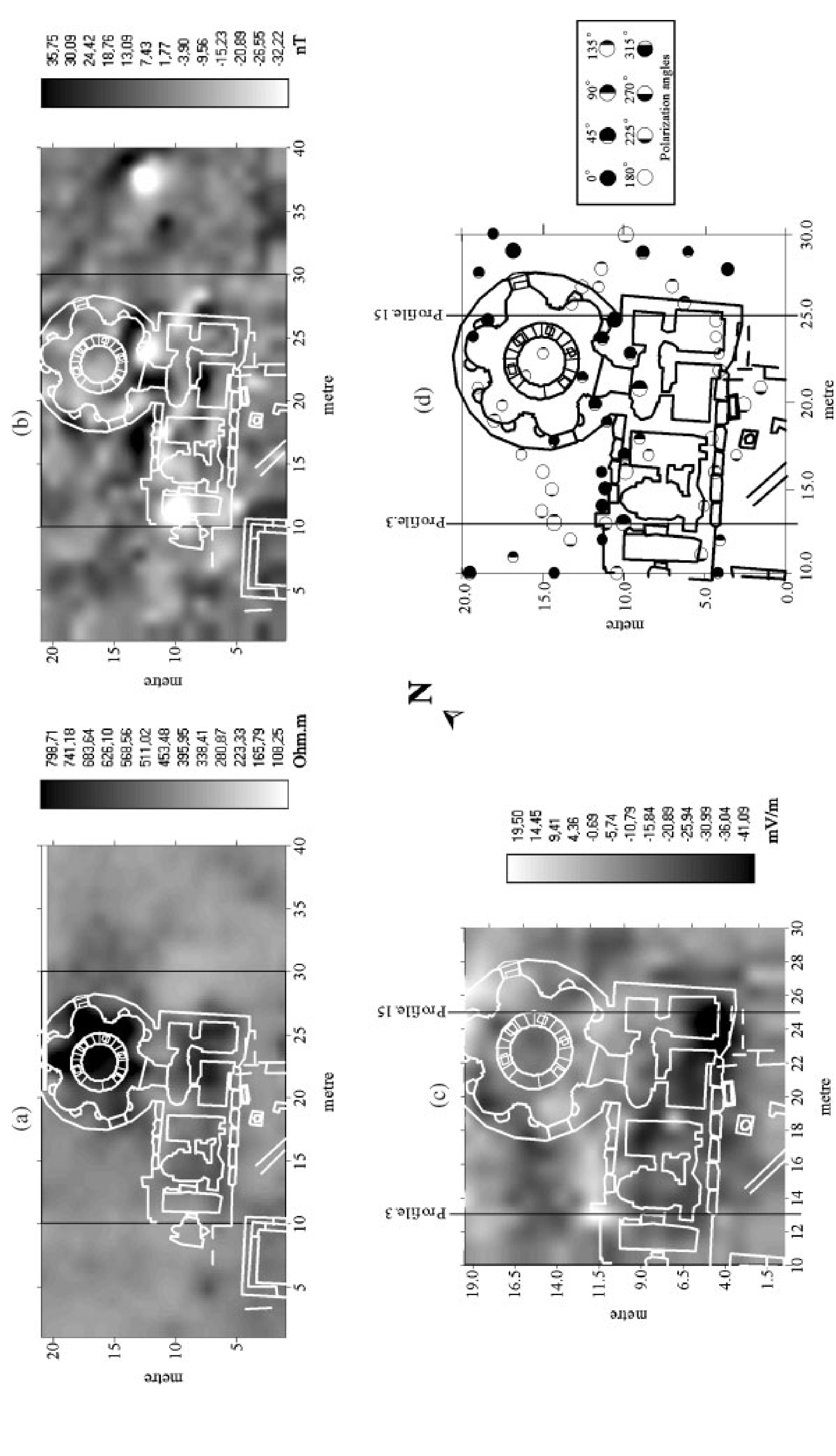

Figure 12. The geophysical images in the A1–B1 and D areas and the architectural plan of the Byzantine bath found by archaeological excavation. (a) Apparent resistivity image of areas A_1 and B_1 (pole–pole 1 m). (b) Magnetic gradient image of areas A_1 and B_1. (c) The gradient self-potential image collected with Cu–$CuSO_4$ electrodes in area D. (d) The horizontal projection of polarization centres in area D (measured using non-polarizable electrodes). Direction: NW–SE 33°. Electrode interval: 3 m. Polarization depth: all depths.

days. Consequently, the soil was saturated and presented suitable conditions for SP measurements. Rainfall was also thought to be an important factor for electrokinetic process owing to the capillary vertical movement of the rainwater. For this reason, SP data were collected using the gradient measurement technique with a pair of non-polarizable copper–copper sulphate electrodes in only the NW–SE direction in 1 day, and the data are shown in Figure 12c. The SP, magnetic and resistivity data obtained from profiles were also graphed and interpreted. The magnetic gradient, resistivity and SP gradient data collected from two different profiles (3 and 15) are given in Figures 13 and 14. As shown in the Figure 13, the gradient SP anomalies are generally in positive and negative forms, and their amplitudes change between -10 and 25 mV/m. A large positive SP gradient anomaly reaches its maximum value at 12 m along profile 3. The resistivity and magnetic gradient values are more or less constant around $x = 12$. The gradient SP values have negative characteristics between 5 and 10 m along profile 3, whereas the resistivity and magnetic values increase. In this profile, the gradient and total SP anomalies are generally opposed to the magnetic and resistivity anomalies (Figure 13). Figure 14 shows four different geophysical profiles obtained along profile 15. The gradient and total SP anomalies show a similar character, and their amplitudes are in the range of 10 and -35 mV/m, 10 and -90 mV for the gradient and total, respectively. Maximum negative gradient SP anomalies are found between 0 and 6 m, and a maximum positive anomaly exists between 8 and 14 m. However, the resistivity anomaly decreases between 8 and 12 m, whereas the magnetic gradient anomaly increases (Figure 11). The physical phenomenon creating these negative anomalies are not known for certain. However, one possibility may be an increase in downward flow of

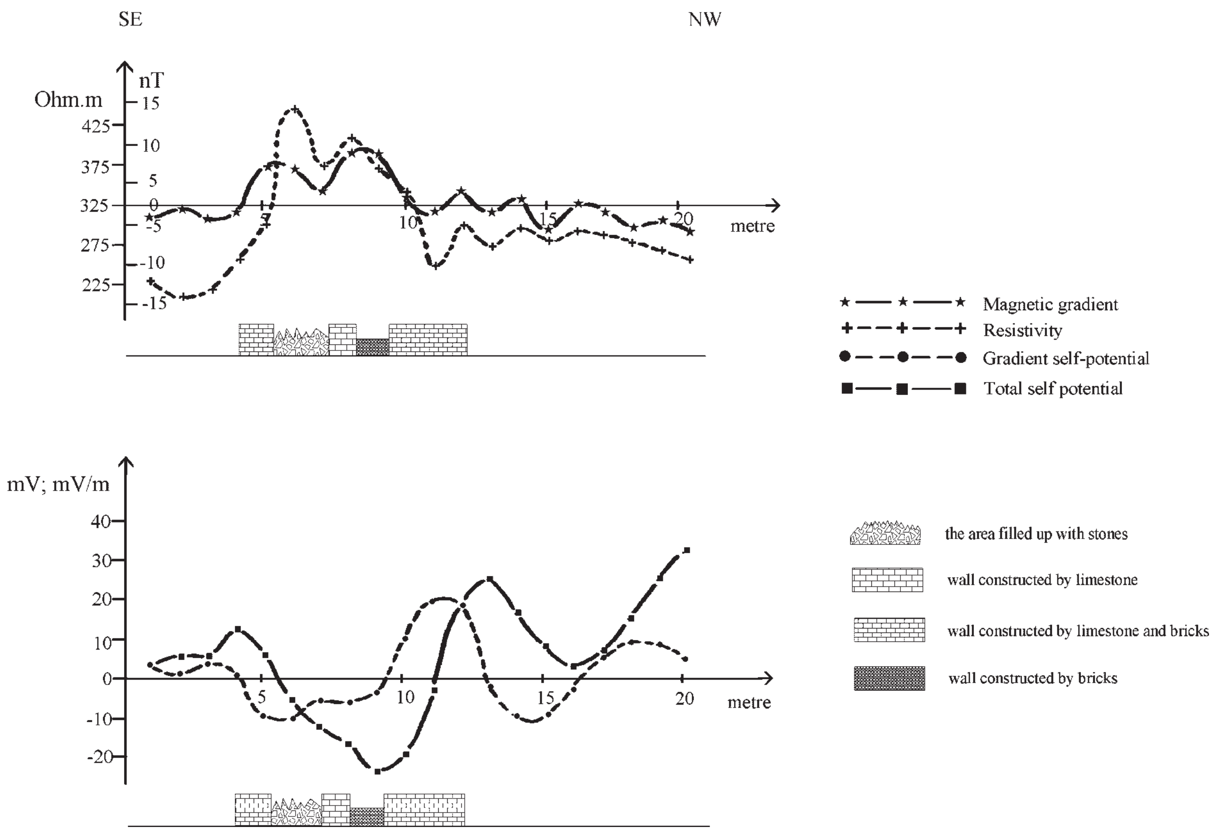

Figure 13. The magnetic gradient, resistivity and self-potential curves for profile 3 in area D and generalized cross-section of the archaeological context revealed by excavation.

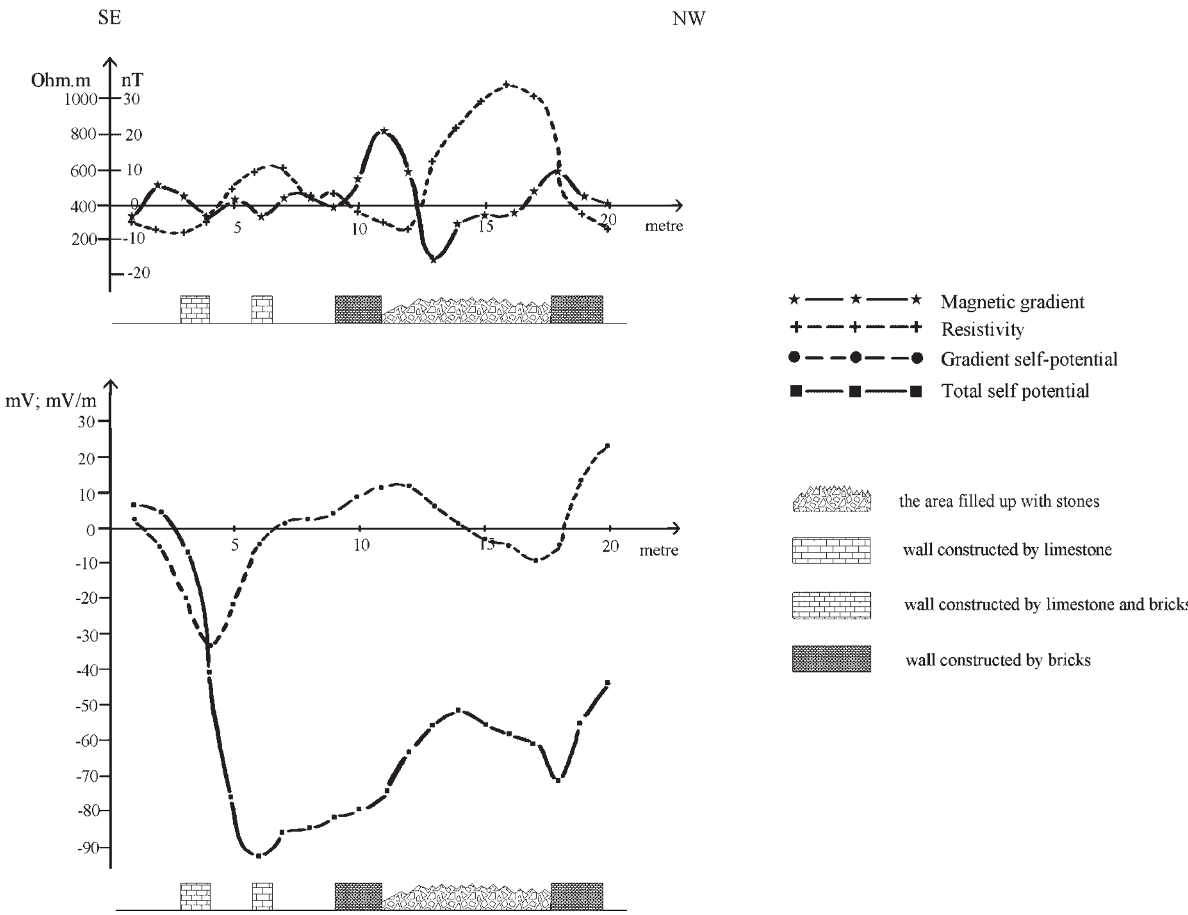

Figure 14. The magnetic gradient resistivity and self-potential curves for profile 15 in area D and the generalized cross-section of the archaeological context revealed by excavation.

rainwater in porous media between the buried walls. A good relationship between the gradient SP and resistivity map is seen, and the negative gradient SP anomalies generally correspond to high resistivity values (Figure 12a and c). The SP data found on each profile were processed with forward and inversion techniques (Ram Babu and Atchuta Rao, 1988; Jaganadha Rao *et al.*, 1993), and the parameters h, Q and x_0 were determined. Then these parameters were placed on a measuring grid with x and y co-ordinates, and representation of the horizontal projection of the polarization centres was obtained. The polarization angles (Q) generally show two different directions in the investigation area (Figure 12d). The first polarization angle (approximately 180°) directions are found mainly in north–south and east–west directions along a rectangular area. The second polarization angle groups (approximately 0°) are present in the central and northern part of the area along north–south and east–west directions. These results correlate well with the architectural plan of the Byzantine city at Amorium. Therefore, archaeological excavations in geophysical investigation areas (between A1 and A2) were carried out in 1998 in Amorium, and the excavation area was chosen with 10×15 m dimensions. The first structural bases constructed from limestone materials were found very close to the surface. The second and third structural bases were built with irregular stones and bricks, and their depths are 0.5 m and 1 m, respectively. Furthermore, burned materials are clearly shown at the bottom of the first structural bases. These excavations continued until 2002, and a Byzantine bath with hypocaust system was found in area D (Figure 15). The bath was built of limestone and Byzantine bricks. The archaeological findings showed that the bath have been constructed in AD 8 or early AD 9, and this building is a unique bath from the Byzantine period (Lightfoot and Arbel, 2003). The archaeologists found that the polygonal structure of this bath and the circular building, which is found inside this structure, were filled with stones. Furthermore, the hypocaust of this bath was found at the southern part of this building, and it contains a thick ash layer and other burnt materials. The architectural plan of the bath was drawn based on resistivity, magnetic and SP images and horizontal projections (Figure 12). As can be seen from the figure, some parts of this building were determined by using geophysical methods for different physical parameters. The resistivity results clearly show the polygonal structure that was found filled with stones. Furthermore, the other structures are obvious in the resistivity image. Thus, we can say that these anomalies with high resistivities strongly masked the other anomaly groups in the image (Figures 12a and 15). The high magnetic anomalies that occurred over the burnt zones and structures appeared in the magnetic image. Excavation revealed burnt materials in those places that contain the high magnetic values (Figures 12b and 15). As can be seen from the SP gradient image, negative gradient anomalies were observed in the tepidarium, caldarium and latrina of the bath, and positive SP gradient anomalies were found over and around the polygonal structures and hypocaust (Figures 12 and 15). Particularly, the SP polarization data showed that their directions and angles are in agreement with walls and burned structures because there are two different polarization angles in this area. This indicates the existence of both burned and unburned materials. The degree of polarization angles is zero on the burned structures, whereas it is 180° on the unburned structures as seen by the results of excavation (Figure 12d). This result may be very interesting with regard to SP studies in archaeological prospection. Thus, positive SP anomalies are observed over burnt materials generally. This is an observational result, and this phenomenon may be explained in the framework of the chemical thermodynamic theory. This phenomenon should definitely be investigated with more detailed experimental and observational studies, which must be further supported by theoretical studies. Self-potential therefore is appearing as a successful method for the investigation of archaeological structures. In addition, it was encouraging to see the similarity between the excavation results and SP, magnetic and resistivity images, which emphasizes the usefulness of the joint application of magnetic, resistivity and SP methods in the study of this archaeological area.

Ulucak höyük archaeological site

Recent archaeological excavations carried out in Ulucak höyük indicated very important archaeological information about Aegean prehistory, and lower horizons were thought to include a proto-Neolithic layer (Figure 2). Archaeological settlements from the Byzantine to the proto-Neolithic eras were found in this artificial hill. Archaeological excavations showed that the Byzantine buildings, which were built with limestone and brick materials, extended in N–S and E–W directions, whereas proto-Neolithic structures, built with brick and limestone materials, extended in NE–SW and NW–SE directions. The diameter of Ulucak höyük is about 90 m, and it is very convenient for geophysical research. The topography of surface of the höyük is flat. Periodic large-scale geophysical investigations were held between different seasons in 1998 and 1999 (Figure 16a and b). The höyük was investigated by magnetic, resistivity and self-potential methods, and buried archaeological structures were clearly detected by large-scale magnetic surveys (e.g. Drahor, 2001). Resistivity investigation was carried out using a METZ SAS 203 resistivity meter. In this study, grid and electrode intervals were 1×1 m and 1 m, respectively, and the twin probe array was used. Large-scale magnetic research was made using a Geoscan FM-36 gradiometer, and the grid interval was 0.5×1 m. In the SP surveys, electrode and grid intervals were chosen as 3 m and 1×1 m, respectively. Data were collected by gradient and total measurement techniques in the N–S direction, and

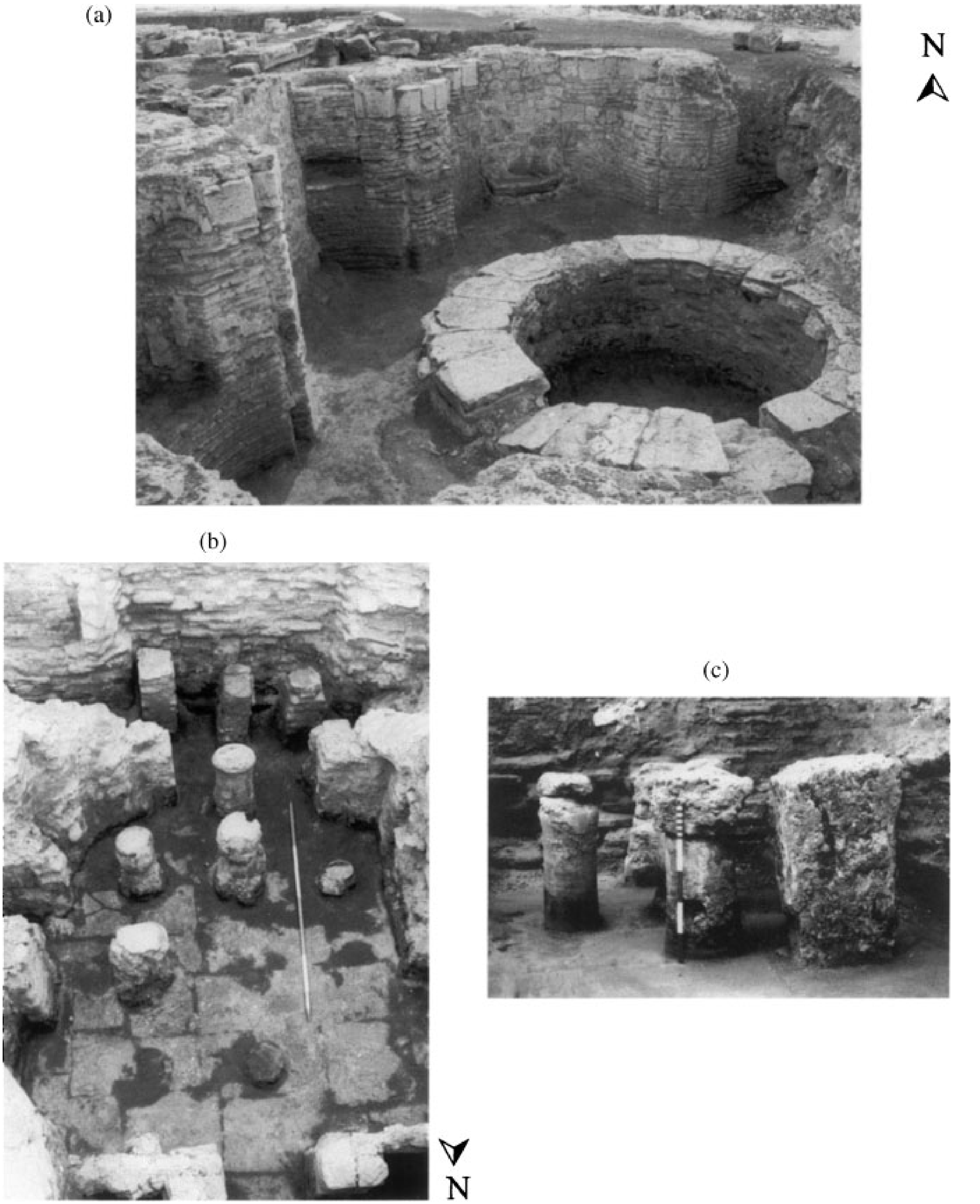

Figure 15. Byzantine bath found by geophysical investigations in area D at the Amorium archaeological site: (a) polygonal structure; (b) caldarium; (c) tepidarium.

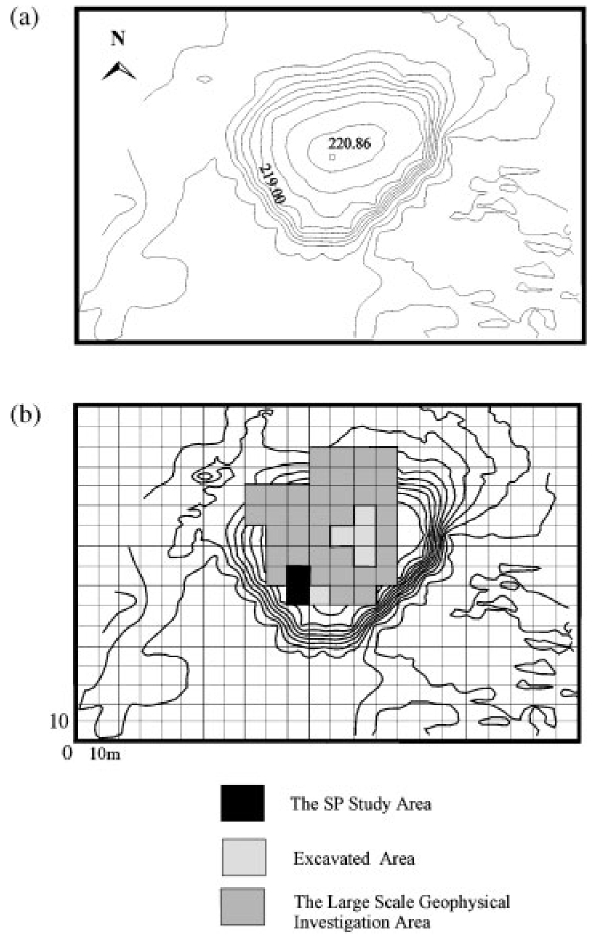

Figure 16. (a) Topographic map of the Ulucakhöyük archaeological site. (b) Geophysical research plan of investigation areas.

non-polarizable Cu–$CuSO_4$ electrodes were used. The SP data have a relatively small noise envelope of about 2–3 mV.

Archaeological sites generally contain burned areas and garbage pits. Thus, the chemical and physical properties of soil change because of human activity, and different soil types are distributed over the area. These properties are a very important factor for geophysical investigations. For example, the magnetic susceptibility values of the burnt soils and materials change with respect to intensity and time of the burning. As known from previous self-potential applications (Drahor *et al.*, 1996), important SP anomalies are obtained over burned archaeological materials. The aim of this study was also to observe the SP anomalies, which can be observed over many burnt or unburnt materials such as höyük type areas. Thus, SP surveys were carried out in an area that was chosen with respect to other geophysical results, such as magnetic and resistivity (Figure 17a and b). The investigation area was selected as 10×20 m, covering two high resistivity and one high magnetic anomaly. Particularly, the anomaly marked by a black arrow was clearly observed in both resistivity and magnetic images (Figure 17a and b).

Both sets of SP data were displayed as greyscale images; however, the correction values were also displayed to observe the difference of undesired polarizations between the electrodes in the area investigated (Figure 18). The correction values were obtained from differences between base point and correction measuring

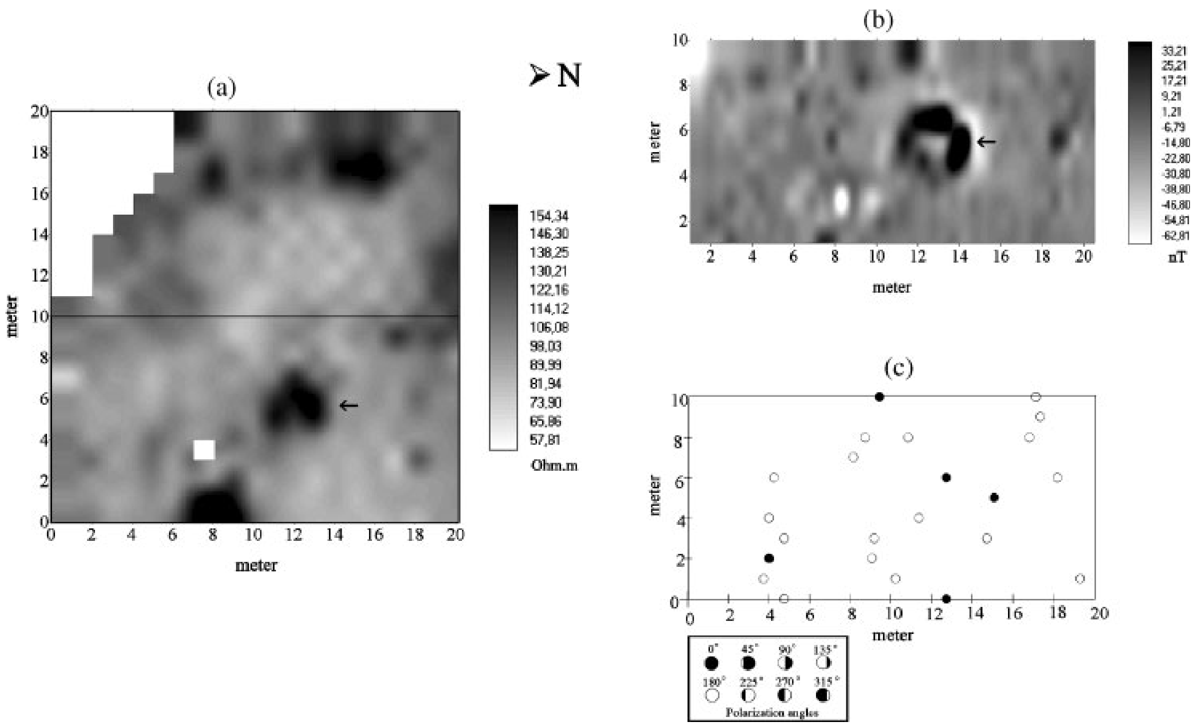

Figure 17. (a) The resistivity image of area A (pole–pole 1 m array). (b) Magnetic gradiometer image of area A. (c) Horizontal projection of polarization centres in area A (measured using non-polarizable electrodes). Direction: N–S. Electrode interval: 3 m. Polarization depth: all depths.

points, which are taken at every four points, by placing both the electrodes side by side ($r = 0$). Both sets of measured SP values were rather low and thus the measuring correction points corrected to the base point were drawn to observe the differences between these points. As can be seen from the correction maps, the correction values are in the range of 13.8–17 mV and the measuring errors are very low with the exception of profile 6 in the gradient measurement. The corrected gradient data are between −3.5 and 6.5 mV/m (Figure 18a and b). The directions of anomalies are generally observed as north–south and east–west in the Figure 18b, and this complies with the buried archaeological structures found in the archaeological excavations in Ulucak höyük. The measuring errors are lower in the total correction map than the gradient correction map. The correction values were between 24.7 and 26.7 mV in the total SP data, and the corrected total data were in the range of 23–31 mV (Figure 18c and d). The anomaly magnitudes had rather low values in both SP images in the investigation area, and generally they include lower values than 10 mV. Therefore is very important to observe the variations between the correction points in such areas, if the difference between maximum and minimum SP values are lower than 10 mV or mV/m. The anomaly directions are N–S and E–W in total image representation. Moreover, the total SP data are represented by lower values in some areas in which resistivity and magnetic anomalies have high amplitudes, whereas gradient anomalies are observed in negative and positive forms in the same place.

The SP data were also interpreted using forward and inversion techniques applied to other archaeological sites. Thus source parameters such as depth (h), polarization angle (Q) and distance values from the reference point to origin (x_0) were determined and shown as a horizontal projection of the polarization centres (Figure 17c). As can be seen in the figure, polarization

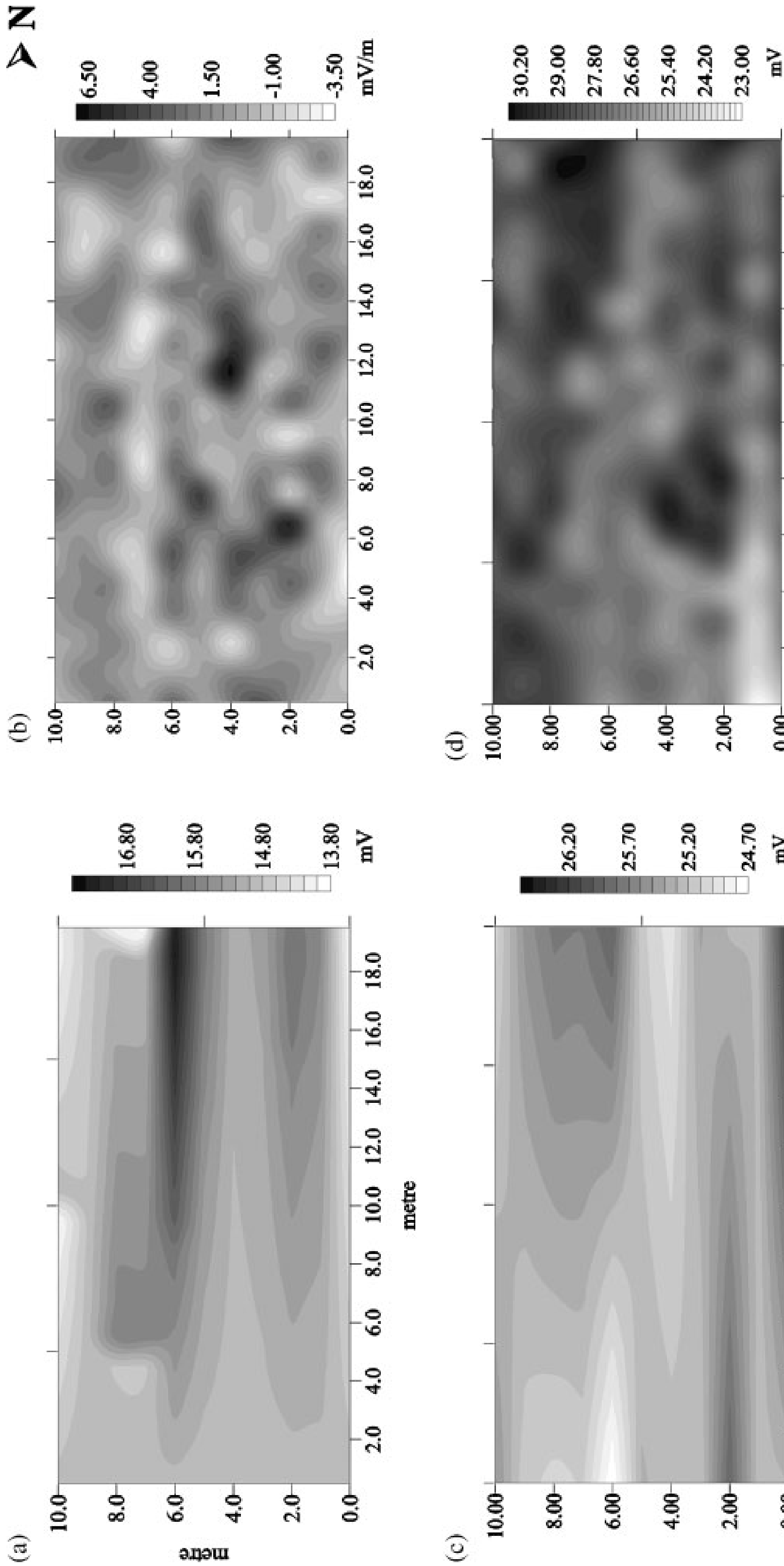

Figure 18. The correction values and corrected gradient and total field SP images: (a) correction values for gradient data; (b) SP gradient map after correction process; (c) correction values for total field data; (d) SP total field map after correction process.

angles generally have a horizontal angle (180°). As a result, the source of SP anomalies may be a resistivity contrast between the soils and buried archaeological structures. The amplitudes of data from each technique (gradient and total) change between 5 and 6 mV, and these values are very low. Therefore, it can be speculated that another cause of SP anomalies might be movement of horizontal capillary liquid between walls.

Unfortunately, no archaeological excavation has been carried out over the geophysical study areas in Ulucak höyük archaeological site. Thus, it is not easy to interpret the SP anomalies without excavation results in Ulucak höyük, and implementation of other geophysical methods is very important for effective interpretation.

Conclusions

Self-potential studies in different archaeological areas indicate that self-potential anomalies might be obtained over burnt materials, such as walls, pits, kilns, etc. This is a new phenomenon in self-potential observed in archaeological areas. Furthermore, the self-potential survey results show that the amplitudes of the gradient anomalies over the burnt materials are higher than those of other SP anomalies. Thus, it could be said that positive SP gradient anomalies are generally observed over burnt materials. This is an observational result, and this phenomenon may be explained by chemical thermodynamics. The SP mechanism involves the redox potentials that occur when buried iron objects or concentrations of ferric minor elements undergo oxidation by porewater in a porous archaeological context. These phenomena definitely should be investigated in the future using detailed experimental and observational studies. In addition, it must be supported by theoretical studies. If a relatively non-porous wall interrupts vertical water flow, positive SP anomalies should occur above it. This result was verified by archaeological excavations (e.g. Burgaz site). This phenomenon can be explained by streaming potentials along the walls. Because the walls behaved as barriers an electrolyte flowing through a capillary or a porous medium could cause an SP anomaly. Moreover, it is noticed that the self-potential anomalies were found over areas with a complex soil distribution and along surfaces with noticeable physical changes. After carrying out self-potential studies at different archaeological sites in Anatolia (Turkey), it is concluded that electrokinetic and electrochemical potentials may be the main cause of SP anomalies observed over buried archaeological structures. Furthermore, redox potential may be the cause of SP anomalies in an oxidized medium where burning has occurred and contain buried iron objects. In these studies, the SP anomalies are generally characterized by both positive and negative values. However, positive SP anomalies were obtained over both burnt and unburned structures, which might indicate streaming or redox potentials. Thus, it is very difficult to define its main origin, and detailed experimental and theoretical studies should be made in the future.

The SP equipment is much cheaper than other geophysical equipments for field practitioners and archaeologists. However, data collection is rather difficult and this process should be applied very systematically during the survey. Gradient measuring technique may be more sensitive to changes along the surface and in lateral irregularities in the subsoil than the total measurement. Nevertheless, it has some disadvantages in terms of data quality. These are: suspicious anomalies generally generated by cumulative errors, electrode polarization, drift effects, time-varying potentials, soil contact effects and reading errors. Therefore, the SP measurement, correction process and interpretation should be done very carefully. The measurement time takes 1 min for every measurement point in gradient and total techniques, approximately. Thus a 20×20 m grid could be measured in half to 1 day in flat surface areas according to the grid intervals. This process time can be shortened by multi-electrode SP measurements, and many undesired effects can be eliminated with this system. The data processing methods are as important as the data collection procedure. Primarily, the data collected should be processed using a low-pass filter to increase the signal-to-noise ratio. Then the known SP parameters should be calculated for every anomaly over the profiles by nomogram and inversion methods. As a result, the parameters calculated may be placed on a measuring grid with *X* and *Y* co-ordinates, and representation of the horizontal projection of the polarization centres drawn to obtain the relationship between the buried structures.

All these results indicate that the SP method might be useful in prehistoric areas that include burnt materials, soils with physical and chemical changes, different moisture content and fluid migration. If the SP survey can be used together with other geophysical techniques such as magnetic, resistivity and magnetic susceptibility, the interpretation will be strengthened. The archaeological excavation results verify that the joint application of geophysical methods is very useful in obtaining satisfactory results.

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