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RECTANGULAR SCHLUMBERGER RESISTIVITY ARRAYS FOR DELINEATING VADOSE ZONE CLAY-LINED FRACTURES IN SHALLOW TUFF

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ABSTRACT

Rectangular Schlumberger arrays can be used for 2-dimensional lateral profiling of apparent resistivity at a unique current electrode separation, hence single depth of penetration. Numerous apparent resistivity measurements are collected moving the potential electrodes (fixed MN spacing) within a rectangle of defined dimensions. The method provides a fast, cost-effective means for the collection of dense resistivity data to provide high-resolution information on subsurface hydeogeologic conditions.

Several rectangular Schlumberger resistivity arrays were employed at Los Alamos National Laboratory (LANL) from 1989 through 1995 in an area adjacent to and downhill from an outfall pipe, septic tank, septic drainfield, and sump. Six rectangular arrays with 2 AB spacings were used to delineate lateral low resistivity anomalies that may be related to fractures that contain clay and/or vadose zone water. Duplicate arrays collected over a three year time period exhibited very good data repeatability.

The properties of tritium make it an excellent groundwater tracer. Because tritium was present in discharged water from all of the anthropogenic sources in the vicinity it was used for this purpose. One major low resistivity anomaly correlates with relatively high tritium concentrations in the tuff. This was determined from borehole samples collected within and outside of the anomalous zone. The anomaly is interpreted to be due to fractures that contain clay from the soil profile. The clay was deposited in the fractures by aeolian processes and by surface water infiltration. The fractures likely served as a shallow vadose zone groundwater pathway.

INTRODUCTION

The authors wish to thank the Los Alamos National Laboratory and the Laboratory's Environmental Restoration Project for making the data cited in this report available to them. The Laboratory as an institution does not necessarily endorse the equipment used in this study or the viewpoints of this publication, and does not garantee its technical correctness.

Resistivity methods are used for various purposes related to hydrogeologic, environmental, mining and engineering investigations. Schlumberger and Wenner arrays are commonly used for vertical soundings whereas Wenner and dipole-dipole arrays are commonly used for horizontal profiling. Many of the investigations cover large field areas where vertical soundings are correlated over large distances or psuedosections consist of long transects. Measuring stations are commonly spaced relatively far apart precluding the resolution of small, yet important, subsurface features.

This paper presents the results of a high resolution study using a modification of the Schlumberger array referred to as the Rectangle of Resistivity (Zohdy et al., 1974, Breusse and Astier, 1961; Kunetz, 1966) to delineate a preferred fracture zone that likely served as a vadose zone pathway for groundwater. The surveys were conducted at Los Alamos National Laboratory (LANL) in an area downhill from an outfall pipe, septic tank, septic drainfield, and sump which handled tritium contaminated water. Because tritium is an excellent groundwater tracer, its concentrations were measured in the soil for confirmatory information.

The resistivity survey was first conducted in 1989. The data indicate an anomaly interpreted to represent clay-bearing fractures and/or increased water content in the shallow tuff. A second resistivity survey was conducted at the same location in 1993 and the same anomaly was present in the data. In 1995, a third resistivity survey was conducted in order to extend the area of investigation to the west.

METHODOLOGY

The Schlumberger is the most widely used electrical resistivity array. Traditional Schlumberger soundings consist of two current electrodes (A and B) and two potential electrodes (M and N) placed along a straight line and measurements are obtained as the AB electrodes are successively separated at logrithmic intervals along the linear profile. The MN electrodes, which remain separated a distance no more than 0.1 of the AB spacing, remain in the center of the array. The resulting apparent resistivities may be inverted to produce a vertical distribution of earth resistivity given that there are no major lateral variations in the electrical properties of the local subsurface materials.

The Schlumberger array can be modified to perform horizontal profiling. One modification referred to as the Schlumberger AB profile or the Brant Array (Kunetz, 1966; Lasfargues, 1957) involves moving the MN electrodes along the middle of one-third of the total AB separation (distance) while the current electrodes remain stationary. The Rectangle of Resistivity (rectangular Schlumberger arrays) involves not only moving the MN electrodes along the middle one-third of the AB line but also taking measurements at locations laterally displaced from the linear AB profile (Figure 1).

Rectangular Schlumberger arrays provide a map of apparent resistivity values for a single AB separation (approximately single depth of investigation). Lateral displacement perpendicular to the AB profile should be limited to 0.25 of the AB separation. Apparent resistivity measurements can be obtained at any interval within the defined rectangular area, therefore, small geologic features in the subsurface, such as joints, can be resolved.

RATIONALE

The electrical properties of most earth materials are highly dependent upon the amount of water, the salinity of water and the distribution of water in the soils or rock. Saturated rocks/soil have lower resistivities than unsaturated and dry materials. This is due to electrolytic conduction in which aqueous ions migrate through a three-dimensional pore space matrix (Frangos, 1990).

The presence of clay also reduces the resistivity of earth materials. This is due to surface conduction (Frangos, 1990). The loosely bound layer of ions adsorbed to the surface of clay particles serve as paths for electric current flow. The net effect to surface conduction is to lower intrinsic resistivity and thus produce conductive features in field survey results.

Shallow groundwater pathways or fractures zones can be mapped by employing electrical resistivity measurements. Water may be physically present within the fractures, the fractures may have a higher moisture content, or clay may have been deposited within the fractures at a shallow depth from the overlying soil profile. The clay content decreases with depth and most fractures are open lateral pathways at depths greater than 10 feet. Clay may be present as coatings on fracture surfaces to depths as great as 100 feet. All of these conditions would produce a relative conductive zone in the resistivity data. Rectangular Schlumberger arrays were chosen for the survey because a significant amount of lateral resistivity data can be obtained in a relatively short amount of time.

TRITIUM

Tritium is produced naturally by cosmic-ray bombardment of the atmosphere. It has a half-life of 12.4 years and can be used to date and trace water. The short half-life means that the tritium content in a given water will be below most methods of detection within 40 to 60 years (Davis and DeWeist, 1966).

Tritium is an ideal tracer. It has low adsorption, can be detected in small amounts, has an ideal half-life for experiments lasting several years, and does not occur in large amounts in atmospheric precipitation water. Low levels of tritium pose a low hazard and are generally not considered a risk driver.

At LANL background tritium soil concentrations were evaluated by computing upper tolerance levels (UTLs). UTL for tritium was calculated to be 23.2 pCi/g, which represents the upper confidence bounds for an upper tail percentile of distribution. The LANL [99%, .95] UTL are statistics indicating 95% confidence that not more than 1% of the distribution exceeds 23.2 pCi/g. Calculation of this statistic is based on a linear combination of the sample mean and sample standard deviation.

SITE DESCRIPTION

The geophysical investigation was conducted near the southern boundary of Los Alamos National Laboratory, New Mexico. The field area was located downhill from an outfall, septic tank, septic drainfield, and sump near a tritium processing facility (Figure 2). The operation which discharged water containing tritium ceased to operate in 1990.

The site is located on a mesa top in a Pinion-juniper woodland at an elevation approximately 6,500 of feet. It overlooks Chaquehui Canyon and the Rio Grande River Valley. The surveyed area is characterized by scattered brush. The geology in the area consists of a tuff (hundreds of feet thick) overlying basalt. A thin veneer of soil which appears to consist mainly of weathered tuff and aeolian material is present. The average thickness of the soil is approximately 5 feet over most of the area. Tuff outcrops can be observed at some locations directly outside of the field area. Some fractures can be observed in the outcrops, many of which are subvertical. The groundwater table is several hundred feet deep below the site.

Two types of fractures occur in the tuff, fractures associated with separate cooling events in the tuff and fractures associated with tectonic activity. Cooling fractures are contained to within one cooling event or cooling unit.

FIELD SURVEYS AND RESULTS

Comparison of 1989 and 1993 Resistivity Data

Figures 3 and 4 are comparisons of rectangular Schlumberger data collected in 1989 and 1993. Data were obtained from approximately the same location in both surveys. The only difference between the two surveys is a 2 to 5 degree angle that existed between the AB axes. The same AB/2 and MN/2 spacings were used for both surveys. Both shallow data (AB/2 = 100 feet, MN/2 = 2.15 feet) and deeper data (AB/2 = 215 feet, MN/2 = 5 feet) comparisons are shown. The same resistivity equipment was used for both surveys (ABEM Terrameter). During the 1989 survey the tritium processing operation was still operating. It ceased operation in 1990.

The actual resistivity values for each survey are slightly different. This is likely due to the different field conditions and field season for each survey. However, the important feature of the data is the lateral variations in apparent resistivity. Correlation between both data sets is very good. The same low resistivity (conductive) anomalies occur at the same general location in both data sets. This feature is especially pronounced in the shallower data set (Figure 3).

Borehole Data

In 1990 Boreholes 18 and 19 (Figure 3 through 6) were drilled within resistivity anomalies in the northern and central locations of the rectangular array. Data were reported in pCi/mL of soil water. Samples from Borehole 18, located in the resistivity anomaly adjacent to drainfield and close to the outfall, yielded tritium concentrations generally between 1800 and 82,000 pCi/mL. Samples were obtained to a depth of 170 feet and were generally obtained at 10-foot depth intervals. Near vertical fractures that contain clay are described in the borehole log (continuous core sampling) down to a depth of approximately 100 feet. Samples from Borehole 19 were generally between 17 and 95 pCi/mL for depths up to 150 feet. Fractures containing clay are also reported in the borehole log at approximately the same depths as those reported in Borehole 18.

Borehole 1231 was drilled within the northern anomaly for the 1993 resistivity data (Figure 3 through 6). Soil samples were obtained, at approximately 10-foot intervals, to a depth of 300 feet and elevated tritium concentrations were detected to a depth of 175 feet. Tritium was detected between 140 and 6,900 pCi/g in all soil samples between 10 and 175 feet deep. Below 175 feet tritium generally occurred below LANL UTLs except for one sample at 210 feet (320 pCi/g). Soil water samples were also obtained from the soil samples that yielded tritium between 1,000 and 74,000 pCi/mL in samples obtained from 10 to 175 feet deep. Soil water samples yielded much lower tritium concentrations at depths below 175 feet. Values were generally less than 100 pCi/mL except for four samples where they ranged from 500 to 1,400 pCi/mL.

Borehole 1232 was drilled within the rectangular array outside of an anomaly and Borehole 1230 (not shown) was drilled adjacent to the rectangular array on the north side. Borehole 1230 was located in some reeds in the drainage from the processing outfall. There is no resistivity coverage directly in the region of the borehole. Soil samples collected at approximately 10-foot intervals in these boreholes (0 to 230 feet deep) were analyzed and yielded low tritium concentrations. In Borehole 1230, tritium was detected well below the LANL UTLs (23.2 pCi/g) in a great majority of samples. Only two samples exceeded the UTL where tritium was detected at 34 and 42 pCi/g. In Borehole 1232, soil samples yielded tritium at concentrations well below the LANL UTL.

Moisture content was measured in the samples obtained from Boreholes 1230, 1231, and 1232. The measured moisture content was similar for all three boreholes. In general, the moisture content ranged between 10% and 20% in most of the samples from all three boreholes. However, moisture contents between 5% and 10% were measured in samples from 0 to 100 feet deep in Borehole 1231. This depth interval correlates with high tritium concentrations measured in soil samples.

1995 Resistivity Data

Figures 5 and 6 show rectangular Schlumberger resistivity data obtained in 1995. The same two AB/2 and MN/2 spacings used in the 1989 and 1993 data were used in the 1995 surveys. The 1993 data are also shown on the figures for both AB/2 spacings. The 1995 surveys were conducted in the septic drainfield upgradient from the 1989 and 1993 survey location to determine if either of the previously detected anomalies extends into the area. A Sting resistivty meter was used to conduct the survey.

The actual resistivity values are slightly different than the 1993 data. This is likely due to the different field conditions and different field season for each survey. It may also partially be due to the different equipment used for the surveys. However, the most important feature of the data is the lateral variations in apparent resistivity. It is assumed that anomalies can be correlated from array to array.

The shallow 1995 resistivity data (AB/2 = 100 feet, Figure 5) indicate a prominent low resistivity anomaly trending northwest and making a slight bend through the drainfield area (Figure 5). This anomaly correlates well with the 1993 shallow rectangular Schlumberger data. The anomaly detected in 1995 lines up with the anomaly detected in the middle of the field area in 1993 (Figure 5). The magnitude of the anomalies in both data sets is very similar (approximately 750 Ohm-feet). The anomaly in the northern portion of the field area (1993 data) where elevated tritium concentrations were detected does not appear to extend into the field area.

The anomalies, characterized by relatively lower resistivity values, are interpreted to be due to a relatively higher moisture content (not necessarily saturated) that occurs within a preferred fracture zone. Clay fillings at shallow depths due to surface water infiltration and eolian processes may also contribute to the lower resistivities.

The deeper 1995 resistivity data (AB/2 = 215 feet) also indicate a low resistivity anomaly trending through the field area (Figure 6) at approximately the same location as the anomaly detected in the shallower data. The anomaly is much wider and more poorly defined. This may be partially due to lateral resistivity variations and/or the averaging effect of apparent resistivity data obtained at greater AB/2 separations. It may also be due to geologic conditions. The magnitude of the anomaly is similar to that of the anomaly detected in the northern section of the field area in 1993. Part of the 1995 anomalous zone appears to line up with the previously detected anomaly.

DISCUSSION

The rectangular Schlumberger resistivity arrays conducted in 1989 and 1993 indicate a high degree of correlation. Similar low resistivity anomalies occur at the same location in both data sets that exhibit good data reliability. The anomalies are assumed to be caused by shallow hydrogeologic features.

Percent moisture values generally range between 10% and 20% in all three 1993 boreholes except the samples from the 0 to 100 feet deep in Borehole 1231 where values ranged between 5% and 10%. Therefore, the low resistivity anomalies are interpreted to be caused by a localized zone of clay-lined fractures or jointing rather than a localized increase in moisture. The clay is assumed to have been deposited by surface and/or near-surface water infiltration.

The northern anomaly (interpreted fractures) at Borehole 1231/18 was likely a primary transport pathway in the vadose zone. During discharge periods the fractures may have been saturated with water from the outfall and other structures as suggested by the elevated tritium levels in soil. Because the structures have not operated since 1990, moisture values are similar in all three 1993 boreholes. The slight decrease in moisture from 0 to 100 feet in Borehole 1231 may be due to increased fracturing and, therefore, enhanced drying of the rock profile by atmospheric air.

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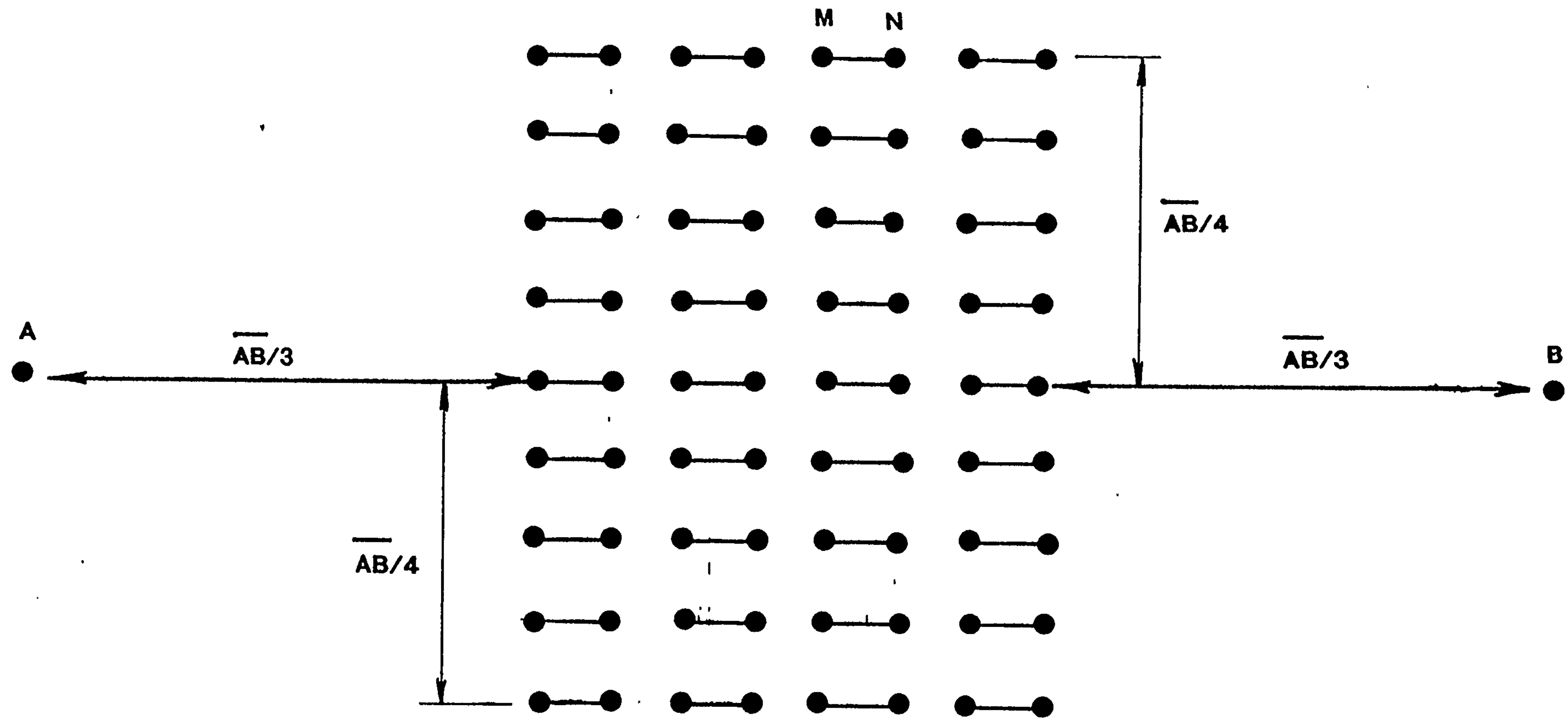

Figure 1: Schematic diagram depicting the electrode array for the Rectangle of Resistivity. Schlumberger AB profile (Brant Array) involves moving the MN electrodes along the middle third of the AB linear axis only. Rectangle of Resistivity (rectangular Schlumberger array) also involves moving the MN electrodes laterally displaced from the axis as shown (adapted from Zohdy et al., 1974).

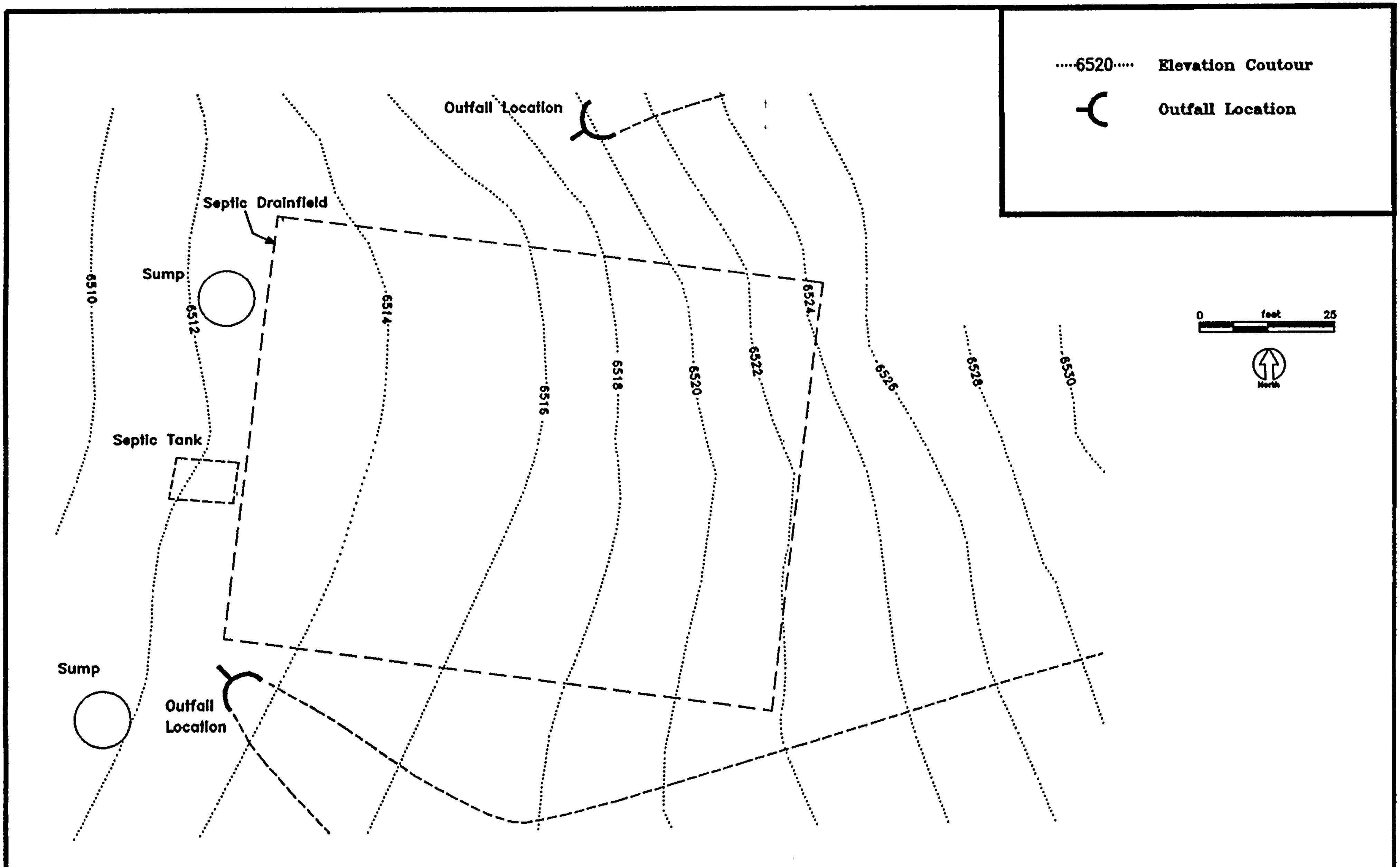

Figure 2: Location map of field investigation area.

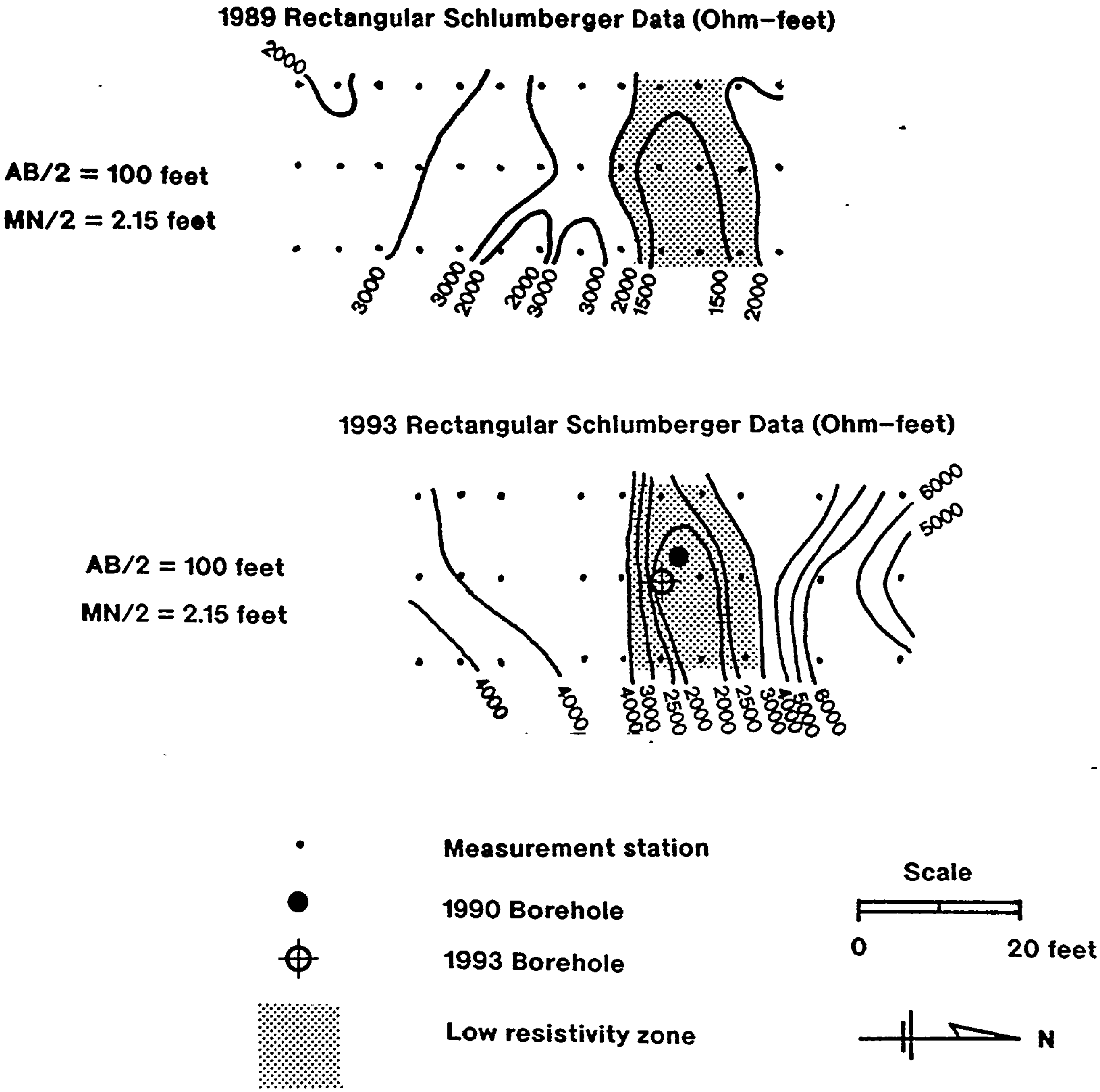

Figure 3: Comparison of 1989 and 1993 rectangular Schlumberger resistivity data obtained from the same location. Maps are aligned to their true relative positions.

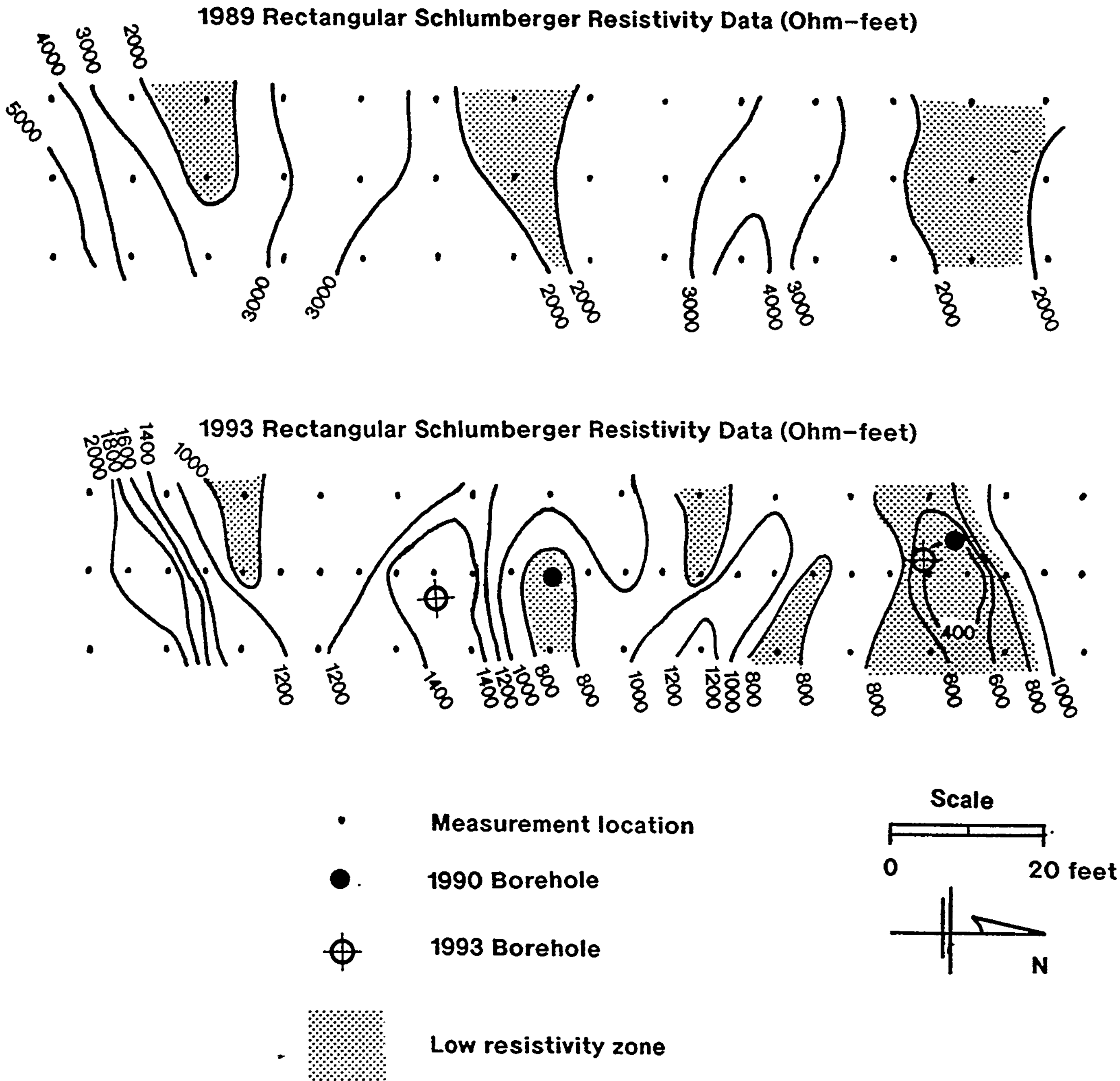

Figure 4: Comparison of 1989 and 1993 rectangular Schlumberger resistivity data obtained from the same location. Maps are aligned to their true relative positions. AB/2 = 215 feet, MN/2 = 5 feet for both arrays.

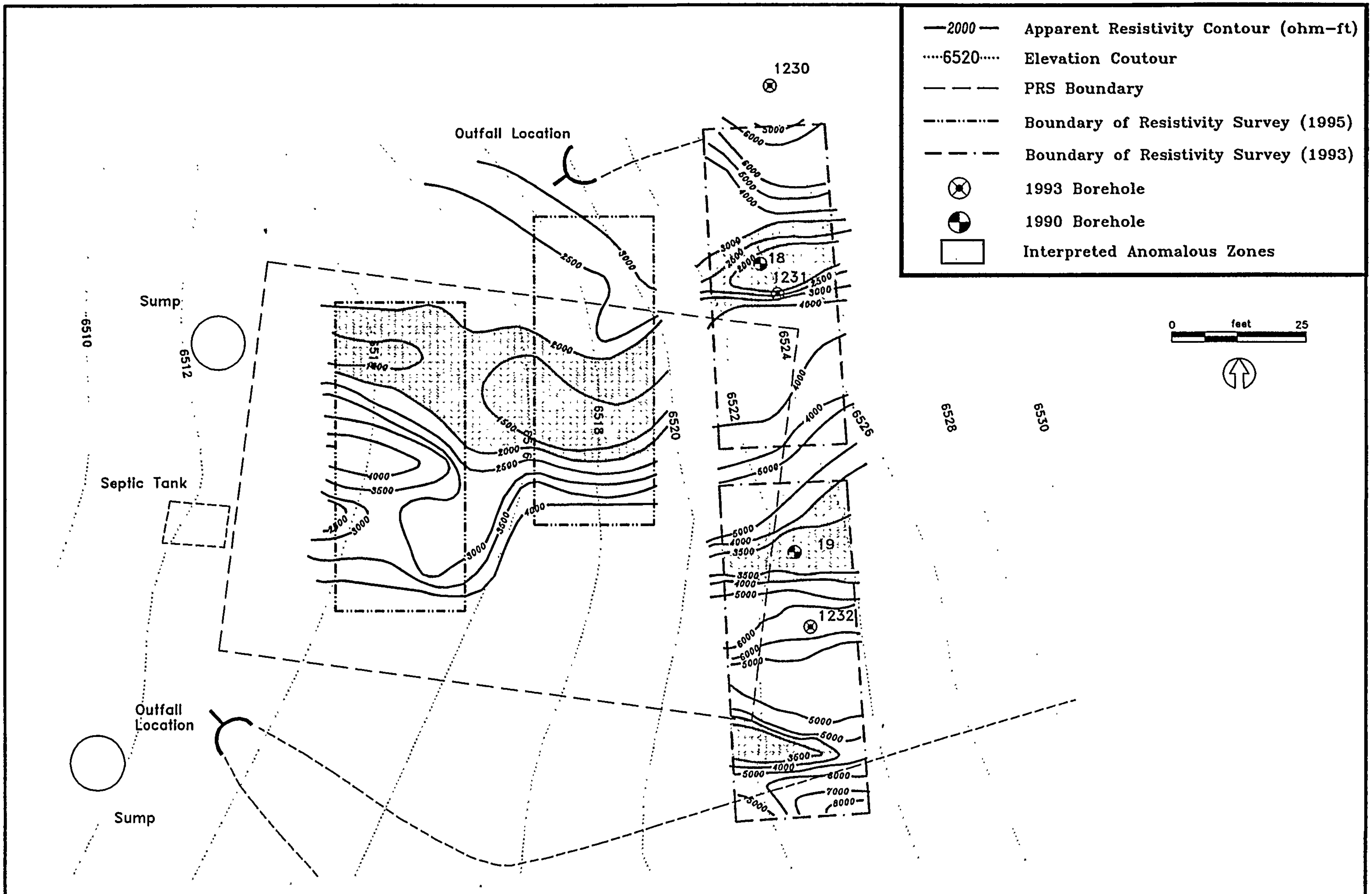

Figure 5: 1993 and 1995 rectangular Schlumberger resistivity data for shallow layer (AB/2 = 100 feet, MN/2 = 2.15 feet)

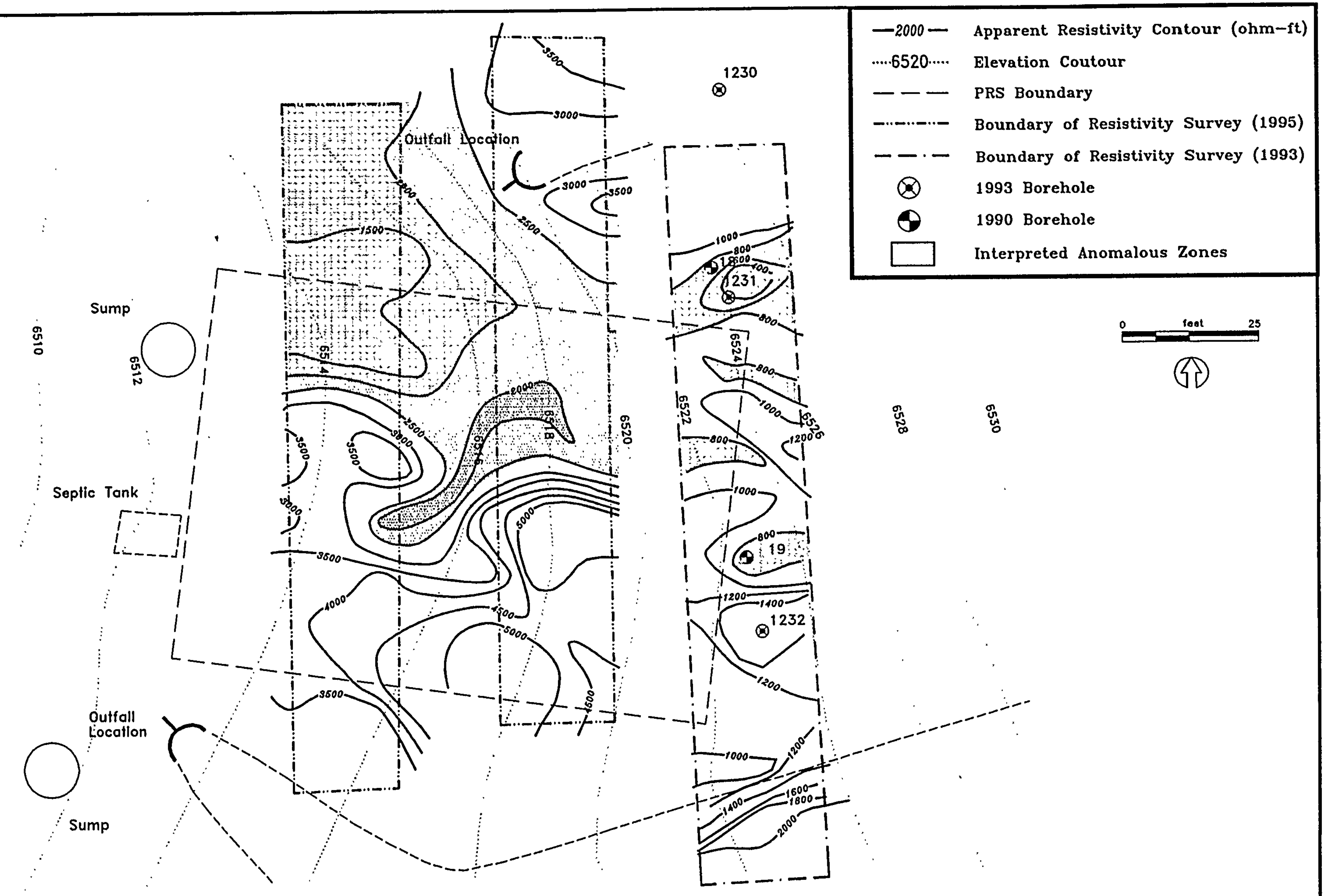

Figure 6: 1993 and 1995 rectangular Schlumberger resistivity data for deeper layer (AB/2 = 215 feet, MN/2 = 5 feet)