UNITED STATES GEOLOGICAL SURVEY DEPARTMENT OF THE INTERIOR

ELECTRICAL CHARACTER OF COLLAPSE BRECCIA PIPES ON THE COCONINO PLATEAU, NORTHERN ARIZONA

by

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This report is preliminary and has not been reviewed for conformity to United States Geological Survey editorial style and nomenclature.

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INTRODUCTION

As part of a Bureau of Indian Affairs (BIA) sponsored mineral assessment program the United States Geological Survey (USGS) has conducted geological, geochemical and geophysical studies on many of the nation's Indian reservations. This report describes geophysical studies conducted on the Hualapai Indian Reservation, northwestern Arizona.

The primary mineral potential found in recent years in northern Arizona is associated with breccia pipes formed in Mississippian to Triassic age rocks. The pipes generally are thought to have originated in the Mississippian Redwall Limestone where dissolution caused large caverns to develop and subsequent stoping of overlying strata continued upward involving strata as young as the Triassic Chinle Formation (Wenrich, 1985; Krewedl and Carisey, 1986). Uranium and associated metals such as copper, arsenic, nickel, lead, zinc, and silver have been recovered from deposits occurring within the brecciated zone.

The breccia pipes are exposed on the walls of the Grand Canyon and its tributaries, but recognition on the undissected plateaus is more difficult. Characteristic common features recognized from the best exposures include the central brecciated zone, or throat, extending upward from the Redwall Limestone to at least the Coconino Sandstone. Above the Coconino Sandstone, a collapse cone surrounds the throat involving the Toroweap and younger rocks. Typical dimensions of the throat may be between 100 to 200 m in diameter and the surrounding cone may be 500 to 1000 m or more in diameter. The attitude of the throat of the pipe is generally vertical but may plunge in any direction from vertical. The EZ-2 breccia pipe (fig. 1) is an example of a vertical throat whose plunge deviates; below the Coconino Sandstone the throat plunges first to the south, then to the southwest (Krewedl and Carisey, 1986).

Many circular to subcircular features have been recognized on the plateaus north and south of the Grand Canyon. These features may show one or more surface manifestations; such as circular depression, vegetation changes, circular drainages, and visible alteration of surface rocks (Wenrich,1985). There appears to be at least two types of dissolution cavities which give rise to the surface features seen today; the first, that occurring in the Redwall Limestone and the second, that which occurs in the upper Toroweap and Kaibab Formations. The second type is a shallow feature and is not mineralized. Of the breccia pipes originating in the Redwall limestone it is unknown what percentage represents mineralized structures.

Geophysical investigations by the USGS have tested a wide variety of methods designed to measure several physical parameters of the rock involved in such a collapse. These geophysical methods measure the density, electrical conductivity (inverse of resistivity), magnetic and seismic character, as well as the ability of the rocks to be electrically polarized (Senterfit and others, 1985). Of the techniques applied, audio-magnetotelluric (AMT) and E-field telluric methods which were able to resolve electrical conductivity to depths of one kilometer, and seem to be the most effective for locating the throat of the breccia pipe (Flanigan and others,1986).

ACKNOWLEDGMENTS

We wish to acknowledge and thank Pathfinder Mines Corp. and Rocky Mountain Energy Corp. for access to, and permission to release data collected on company properties. The acquired data added control for the results of our studies on the Hualapai Indian Reservation. These studies are sponsored by the Bureau of Indian Affairs as part of a Indian lands mineral assessment program.

GEOPHYSICAL METHODS

The primary electromagnetic field data used to compile the interpreted electric cross sections presented here was collected using natural source, scalar audio-magnetotelluric (AMT) equipment developed and built by the USGS. A brief discussion of the methods along with references to more detailed description is included in appendix 1 of this report. Also included in appendix 1 is a discussion of interpretation procedures and estimates of accuracy of the resistivity-depth cross sections used to present the results of this study.

BRECCIA PIPE MODELS

The fifteen structures discussed in this report can be divided into two types based upon common physiographic and electrical features. There are variations within each type due to the physical size and to the stratigraphic exposure level of the pipe. The two types of breccia pipes may be variations of the basic geologic model suggested by Krewedl and Carisey (1986) and are related to pipe formational variations at the Kaibab intersect. For instance, the Mohawk Canyon structure (pipe 494, fig. 1) is exposed at the Kaibab Formation surface. At this level the throat of the pipe consists of a 100 m diameter plug of relatively undisturbed Kaibab surrounded by a 50 m wide zone of highly fractured brecciated rock thought to be ring fractures. The collapse cone surrounding the throat extends for several hundred meters beyond the throat, except at the canyon face where the collapse cone has been eroded. Other structures, as will be discussed later, apparently do not have this plug of Kaibab capping the breccia pipe throat.

Physiographic and electrical features which distinguish the types of breccia pipes are illustrated in figure 2. Model 1 is characterized by a circular hill or hills surrounded by circular topographic lows (fig.2a). Electrically the topographic high is resistive in comparsion to the surrounding topographic lows which are conductive. The second model (fig. 2b) typically is seen as a circular topographic depression. There usually is a distinguishing vegetation anomaly associated with this type. Electrically this model has a conductive central area surrounded by a resistive circular ring of rocks of variable width. Also, there may be a concentric circular conductive zone outside of the resistive ring of rocks.

Breccia pipes exposed above the Kaibab Formation and in particular, in the Moenkopi Formation, do not have surface physiographic features common to either of the models discussed above, but may have electrical features which are similar. The EZ-2 structure, as indicated by Krewedl and Carisey (1986), has very little topographic expression because the Kaibab collapse cone is filled with Moenkopi rocks which draped into the subsiding cone.

In an effort to characterize the electrical nature of a known breccia pipe twenty-two AMT soundings were made at 100 m spacing along two profiles at the EZ-2 breccia pipe (fig.3). The interpreted electric cross sections (figs. 4-5) show a central conductive zone surrounded by more resistive rocks. The upper part of the conductive zone most probably reflects the conductivity of the collapse cone and preserved conductive Moenkopi rocks. At about 200 m depth the conductive zone appears to reflect the south and west plunge of the pipe throat suggested by Krewdl and Carisey (1986). Below 400 m depth, the electrical data suggest the throat of the pipe is nearly vertical.

Another known breccia pipe is exposed in Kaibab Formation rocks on the Coconino Plateau just east of the eastern boundary of the Hualapai Indian Reservation. Topographically the structure is a model 2 type (fig. 2b), that is, it is a conductive circular depression at the center of a small topographic high all of which lies at the center of a larger topographic low. Erosion has removed part of both topographic highs on the eastern side of the structure.

AMT soundings were made along orthognal profiles crossing the central part of the Known breccia pipe. The interpreted data show a central conductive zone within a resistive ring of rocks, a typical model 2 electrical resistivity response (fig. 7-8). A conductive zone outside of the resistive ring of rocks is present on the east and south sides of the profiles and may have been detected on the north and west end of the profiles had they been extended another 100 m or so. The central conductive zone is the electrical resistiviy response of a near vertical breccia pipe throat. The outermost conductive zone probably represents conductivity anomalies within a ring fracture zone.

DISCUSSION OF RESULTS

Interpreted results of electromagnetic measurements across twelve selected sites on the Hualapai Indian Reservation are summerized in table 1 below. Seven sites are thought to definitely reflect breccia pipe orginating in the Redwall Limestone. Of these seven definite pipes, four are model type 2 and three are model type 1 breccia pipes. Four sites are thought to be questionable pipes based on the interpreted electromagnetic data. These four sites display breccia pipes model type 1 characteristics, but because of the overall size of the feature and lack of resolution of the EM data, some question remains as to the authenticity of the feature as a classic breccia pipe. Two sites (571 and 1107a) most probably are not collapse breccia pipes that originated in the Redwall Limestone, but may be shallow dissolution cavities orginating in the Toroweap or Kaibab Formations.

Site 493

Site 493 is located on the east side of Mohawk Canyon, the throat of the structure lies about 75 m from the canyon cliffs (fig.1). The structure is physically a small circular hill (100 m diameter) located within a circular depression that extends 200 m or more from the center. The central area is distinctive in that it is covered with Juniper trees, and the larger depressed area is sagebrush covered. Circular rock outcrops in the central area display increasing dips from 40 degrees to near vertical toward the center.

Table 1 Summary of interpretation of electromagnetic data

Structure designation number	Breccia pipe model type	Breccia pipe designation		
		Definite	Questionable	probably not a breccia pipe
220	1		X	
232	1		X	
493	2	X		
531	1		X	
545	2	X		
569	1		X	
570	2	X		
571	-			X
1102	1	X		
1107A	-			X
1107	1	X		
1108	1	X		
1119	2	X		

Fourteen AMT soundings were made along north-south and east-west profiles (fig. 9). Electrical resistivity data along the north-south traverse (fig.10) indicates a very conductive central zone of about 50 m in diameter surrounded by resistive rocks. Outward from the resistive rocks there is another conductive zone most probably related to ring fracturing.

The east-west profile (fig.11) is seriously affected by the proximity to Mohawk Canyon. The high frequency data are not as seriously affected as is the low frequency data, thus, the upper part of the section is quite similar to the north-south profile but the lower part of the section is seriously distorted. Site 493 is considered to be a type 2 breccia pipe model.

Site 545

Site 545 is located in the National Canyon quadrangle about 13 km north of the Havasupai access road and 1 km west of the eastern Hualapai boundary fence line (fig.1). The area was noted on the topographic quadrangle sheet as a small circular depression in an intermittent stream channel. In detail, site 545 is seen as a small circular hill within a general depression of about 500 m diameter. There is a vegetation anomaly nearly coincident with the small hill where sagebrush is present surrounded by mostly prarie grass cover. Fifteen AMT soundings were made along orthognal traverses crossing the area (fig.12).

The interpreted electrical crossection (figs 13-14) show a 100 m diameter conductive zone located at the center of the topographic low. The structure is thought to be a breccia pipe that extends to the Redwall Limestone Formation. The electrical nature of the pipe is very similar to the classic model 2 type of structures discussed previously, except at the near surface (100-200 m depth) where the rocks are less conductive than at depth.

Site 570

Site 570 lies in the south-central part of the National Canyon quadrangle (fig.1). Physically the structure is a circular depression of about 200 m diameter on the edge of a tree-covered hill (fig. 15). The northeast part of the topographic low forms part of a large valley floor. Kaibab Limestone rocks crop out on three sides of the structure. The central part of the depression is sage brush-covered, as is the broad valley.

An electrically conductive zone of 100 m or more diameter extends to depth (figs 16-17). The conductive zone is complex, in that, at depth it appears to be comprised of two conductive zones. The most conductive part of the breccia pipe throat appears to plunge to the west and south. The telluric data (fig. 16-17) confirms the conductive nature of this type 2 model breccia pipe.

Sites 1107-1108

Sites 1107-1108 are located about 1.5 km northeast of site 570 (fig.1). Site 1107 is located near the base of a small hill, probably part of the collapse cone (fig. 18). Several circular ring fracture zones extend outward from the central part of the structure and form circular benches along the slope of the hill. The central part of the structure is characterized by a small hill several meters high surrounded by circular drainage. About 200 m north and 50 m west, a small circular depression was labeled 1107A. South of site 1107 about 150 m another circular feature was marked site 1108. Site 1108 is distinguished by a 50 m in diameter circular grass covered area surrounded on three sides by bushes and juniper trees.

Nineteen AMT soundings were made along one north-south and two east-west profiles crossing the area (fig. 18). On the north-south traverse (fig. 19) three conductive zones are present. The northernmost conductive zone lies between stations 3 and 4 and is thought to be related to the ring fracture of breccia pipe 1107 to the south. The throat of pipe 1107 lies beneath the small hill mentioned earlier, at AMT station 1. There is a cap of resistive rocks covering the throat of site 1107, a typical model type 1 response. An east-west electric crossection at site 1107 (fig.20) confirms the conductive nature of the throat of breccia pipe 1107.

Further to the south, at station 8 (fig. 18) a third conductive zone is present. This third zone is thought to reflect the electrical nature of site 1108. Whether site 1108 is a true breccia pipe is not clear from these data.

Another east-west traverse was made at the north end of the north-south traverse across a small (50 m) diameter depression. A conductive zone coincident with the first conductive zone discussed on the north-south traverse was detected (fig. 21) beneath station 4. Inasmuch as this conductive zone is offset from the center of the small depression it is thought that the zone is related to ring fracturing of breccia pipe 1107 to the south.

Site 1102

Site 1102 (fig. 1) is similar to site 1107 discussed above in several ways. The central part or throat area of the pipe is seen as a small (50 m, diameter) hill of a few meters height surrounded by circular drainage (fig. 22). At the 1102 site, the normal depression associated with the collapse cone is in evidence only on the west side, the other three sides of the cone have been eroded.

The interpreted AMT crossection (fig.23) indicate that three conductive zones were crossed along the north-south profile. All three conductive areas are covered by a layer of rock of 400 ohm-m or more resistivity. The outermost conductors beneath stations 1 and 7 are most probably due to ring fracture zones surrounding the throat of the pipe, the source of the central or third conductive zone. On the east-west traverse (fig. 24) two conductive zones were detected, one at AMT station 3-4 is thought to be due to ring fracturing. The second conductive zone lies between AMT stations 1-2 and is thought to be the combined response of the west ring fracture and the throat of the pipe. The cap of resistive rocks overlying the conductive zones is similar to other model type 1 breccia pipes.

Site 1119

Site 1119, unlike many of the features previously discussed, does not appear to be a part of pronounced depression. It lies at the summit of a hill of about 30 m height. The central part of the site is sagebrush covered within an area of fairly dense Juniper and fir trees. The sagebrush covered area slopes to the east-northeast and is surrounded by outcropping Kaibab Formation rocks. Circular drainage patterns are present on the north and south sides of the hill. Sixteen AMT soundings were made along two profiles oriented north-south and east-west (fig. 25). The interpreted electrical data indicate that a near vertical conductive zone about 50 m in diameter lies at the center of the sagebrush covered area (figs. 26-7). Electrically, site 1119 is very similar to the classic model type 2 discussed earlier, but the topographic appearence is not the same. Site 1119 is thought to be a breccia pipe that extends to the Redwall Limestone.

Sites 220 and 232

Sites 220 and 232 (fig. 1) are discussed together because they have several common characteristics. First, they have a similar topographic expression, that is, the central part of the feature consists of several small topographic hills several meters high within a topographic basin (figs. 28-9). The topographic features are not that unlike other sites previously discussed, except in the central part of the area and they are larger features. Secondly, sites 220 and 232 have similar electrical features which are quite close to the breccia pipe model type 1, but here again the much larger size of the features in comparision to other type 1 model structures leaves some doubt and should be studied further.

The electrical character of sites 220 and 232 are shown on figures 30-31. At site 220 (fig. 30) three conductive zones were detected, two extend to the surface beneath stations 5 and 7. The third conductive zone is beneath resistive rocks at the center of the small hill at station 6. At site 232 two conductive zones were seen at stations 3 to 4 and at stations 7 to 8 (fig. 31). A suggestion of a third conductive zone beneath resistive rock between stations 5 to 6 was also detected. The single profile data taken on both of these sites are not definitive and are considered questionable breccia pipes which probably should be studied in more detail.

It should be noted that site 220 has generally been considered a strata-bound copper deposit.

Site 531

Site 531 is seen as a circular grass covered area at the center of a gentle topographic high in a generally flat valley bottom. The surface of the small hill dips gently to the northeast. A ring of low bushes and Juniper trees surrounds the central grass-covered area (fig. 32). There is not a pronounced depression at the center of the feature. Interpreted AMT soundings from fourteen soundings crossing the area along orthognal traverses (figs. 33-34) show three conductive zones. On the east-west profile (fig. 33) the vertical conductive areas lie beneath stations 2, 8 and between stations 5 and 6. The outer most conductive zones appear to extend to the surface, but the central conductor at station 8 lies beneath resistive rocks much like other model type 1 structures previously discussed. Because of the subtle nature of the conductive zones, the feature has been classified as questionable (table 1).

Site 569

Site 569 is a sagebrush covered depression (3-4 m-deep) 50 m by 100 m (fig. 35). A single traverse of AMT soundings were made along the long axis of the feature (fig. 36). The interpreted data show a narrow, near vertical conductive zone lying southeast of the center of the depression between stations 5 and 6. A conductive zone was detected near the center of the depression, but, because of its small size, the feature is listed as a questionable breccia pipe (table 1).

Site 571

Site 571 is a small (100 m diameter) depression about 3-4 m deep about one kilometer east of site 569 (fig. 1). The feature is not particularily distinctive either physically or electrically. Five Amt soundings spaced at 50 m intervals were made along an east-west traverse (fig. 37). The data (fig. 38) suggest that a vertical conductive zone lies at the eastern edge of the depression. No conductive rocks were detected near the center of the depression. The feature is not considered to be a breccia pipe originating in the Redwall limestone, but is, perhaps, a shallow karst feature.

SUMMARY

AMT electromagnetic soundings and, in some cases, E-field telluric profiles were made over two known collapse breccia pipes and thirteen structures that were thought to be possible breccia pipes. Of the thirteen unknown structures, seven (sites 493, 570, 1102, 1107, 1108, and 1119) are thought to be collapse breccia pipes extending to the Redwall Limestone. Four structures (sites 220, 232, 531, and 569) may or may not be breccia pipes, but because the data were not definitive, the features are classified as questionable and probably would require additional study for more certain interpretation. Two areas (sites 571 and 1107A) chosen for these studies are thought to be caused by shallow dissolution occurring in the Kaibab Limestone and Toroweap Formations, and as such, probably do not represent areas of potential mineralization.

Two physiographic and electrical models are suggested from these data; some variation of the basic models are seen in the data which is thought to be related to the overall size and erosion level of the pipes.

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APPENDIX I

GEOPHYSICAL METHODS

Electromagnetic field sources

Natural electromagnetic fields are generated virtually everywhere and continously around the world. Low frequency (long period) time-varying changes below several hertz (Hz) generally result from sunspot activity. Solar winds (high energy plasma) interact with the Earth's magnetosphere, which in turn, induces currents to flow in the ionosphere. These induced currents create time-varying magnetic fields that couple with the finitely conductive earth to produce current flow in the Earth. The Earth currents are generally described as "telluric currents".

Electromagnetic energy (from several Hz to about 24,000 Hz) results from world-wide lightning discharges in the lower atmosphere. The principle energy is derived from tropical storms cells that occur most frequently during the Northern Hemisphere summer months. These pulses, or spherics, propagate around the Earth in the earth-ionosphere cavity (wave guide) inducing into the conductive Earth telluric currents in the audio- frequency range, and are, thus generally described as audio-frequency telluric (AMT) currents.

Telluric electric method

Telluric-electric traverse (TT) method, or more exactly, the electric (E) field-ratio telluric profiling method, utilizes the above mentioned telluric currents. The method basically consists of measuring the ratio of the electrical potential developed across two colinear grounded electrode dipoles that share a common reference at the midpoint of the arrays. The ratio of the amplitude of the voltage potential developed across each dipole is related to the resistivity of the earth under the dipole. Thus, if the resistivity of the earth under both dipoles is the same, then the measured voltage potential across the dipoles would be the same and the ratio of the voltages would be in unity.

In practice, the dipole arrays (in this survey 12.5 and 50 m-long each) are moved forward in a straight line at intervals of the dipole length. Each calculated E-field ratio is referenced to the voltage developed in the first dipole setup which is set to 1. The resulting data give a measure of the relative amplitude of the electric field in the direction of the telluric traverse. In general, the technique has been used as a reconnaissance tool to rapidly evaluate large areas with dipole lengths of 500 m or more long. Examples of field studies and detailed explanation of the method are given in Hoover and others (1981) and Beyer (1977).

Audio-magnetotelluric method

Magnetotellurics is an electromagnetic method by which variations in Earth resistivity may be measured as a function of depth (Keller and Frischknecht, 1966). Magnetotelluric soundings are obtained by making surface measurements of natural electromagnetic fields propagating into the earth. The depth to which these fields penetrate the earth is a function of their frequency and the local resistivity of the earth, thus, measurement of these fields at a broad range of frequencies gives information on crustal resistivity with depth. If these measurements are made in the audio-frequency range the technique is generally known as audio-magnetotellurics (AMT). The method is discussed in detail by Strangway and others (1973) and examples of field studies are given in Hoover and Long (1976), and Hoover and others (1978).

The method has important advantages over galvanic resistivity techniques because very resistive surface layers, which limit the amount of source current necessary for deep penetration using galvanic methods, are not a problem to the AMT method. Also, long lengths of wire are not necessary to deliver the source currents into the ground, an important consideration when making field measurements in very rugged terrain.

The exploration depth of the AMT method or skin depth (sd) is related to the frequency (f) of the incoming signal and the local resistivity of the Earth and can be approximated by:

$$sd = 503 \sqrt{(\rho/f)} \text{ meters}$$

Where ρ is the apparent resistivity (in ohm-m) and f is the frequency (in Hz) of the signal. The frequency range of the equipment used in these studies is from 4.5 Hz to 27 kHz so that the exploration depth may range from a few tens of meters to several kilometers, depending upon the frequency and apparent resistivities involved.

The USGS AMT equipment measures the relative amplitude of the electric (Ex) and magnetic (Hy) field in orthogonal directions. The scalar apparent resistivity (ohm-m) is related to the measured fields by:

$$\rho_a = 0.2/f|Ex/Hy|^2$$

where f is the frequency (in Hz) of the measured fields.

FIELD AND INTERPRETATION PROCEDURES

In practice, the orthogonal electric-field and associated magnetic field (H-field) are measured simultaneously and two orthogonal soundings are produced. Apparent resistivities measured at both of the orthogonal directions are nearly the same in a geologic environment where there are no significant lateral changes in apparent resistivity. However, in areas where there is an electrical lateral inhomogeneity the sounding curves may be quite different. In this study, the most serious examples of this type of error occurs with soundings located at or very close to the outer electrical boundary of the breccia pipe and then the deviation of the two apparent resistivities is greatest in the mid-range frequencies. In these cases a hand-smoothed average of the two soundings is used for interpretation.

Standard computer processing and plane-wave modelling techniques are used to determine layered-earth models of resistivity and thickness that would produce the observed sounding curves (Anderson, 1979, Bostick, 1977). The plane-wave layered-earth assumption used in these inversion techniques is quite obviously not the case with many of the soundings crossing the breccia pipe structures. Thus, the electrical sections presented here should be viewed as only a very rough approximation of the true resistivity-thickness parameters of the Earth. In particular, caution should be used when viewing actual depth to apparent electrical interfaces. In addition, actual true resistivity values shown may be somewhat higher in those areas where the interpretive techniques produce some overshoot. In order to qualitatively evaluate the magnitude of these potential errors theoretical soundings were computed over a two-dimensional (2-D) dike model using realistic electrical parameters. The resultant calculated apparent resistivity sounding data were then subjected to the one-dimensional (1-D) inversion in order to produce an electrical model which would be consistent with the input data. The resultant electrical model was in error particularly in those areas where the sounding was being influenced significantly by a lateral boundary interface. In those areas, the computed resistivity was too high (overshoot) as the sounding location approached the interfaces. Then as the distance past the interface increased, the computed resistivity became too low (undershoot). The most important aspect of these theoretical calculations is that the lateral location of the electrical interface of the input model and the calculated model were the same. Thus, one might view with confidence the actual location of the conductive zone associated with the breccia pipe. Wannamaker and others (1984a and 1985b) discuss in detail EM modelling of 3-D bodies in a layered-earth and compare theoretical results to 1-D and 2-D interpretive techniques.

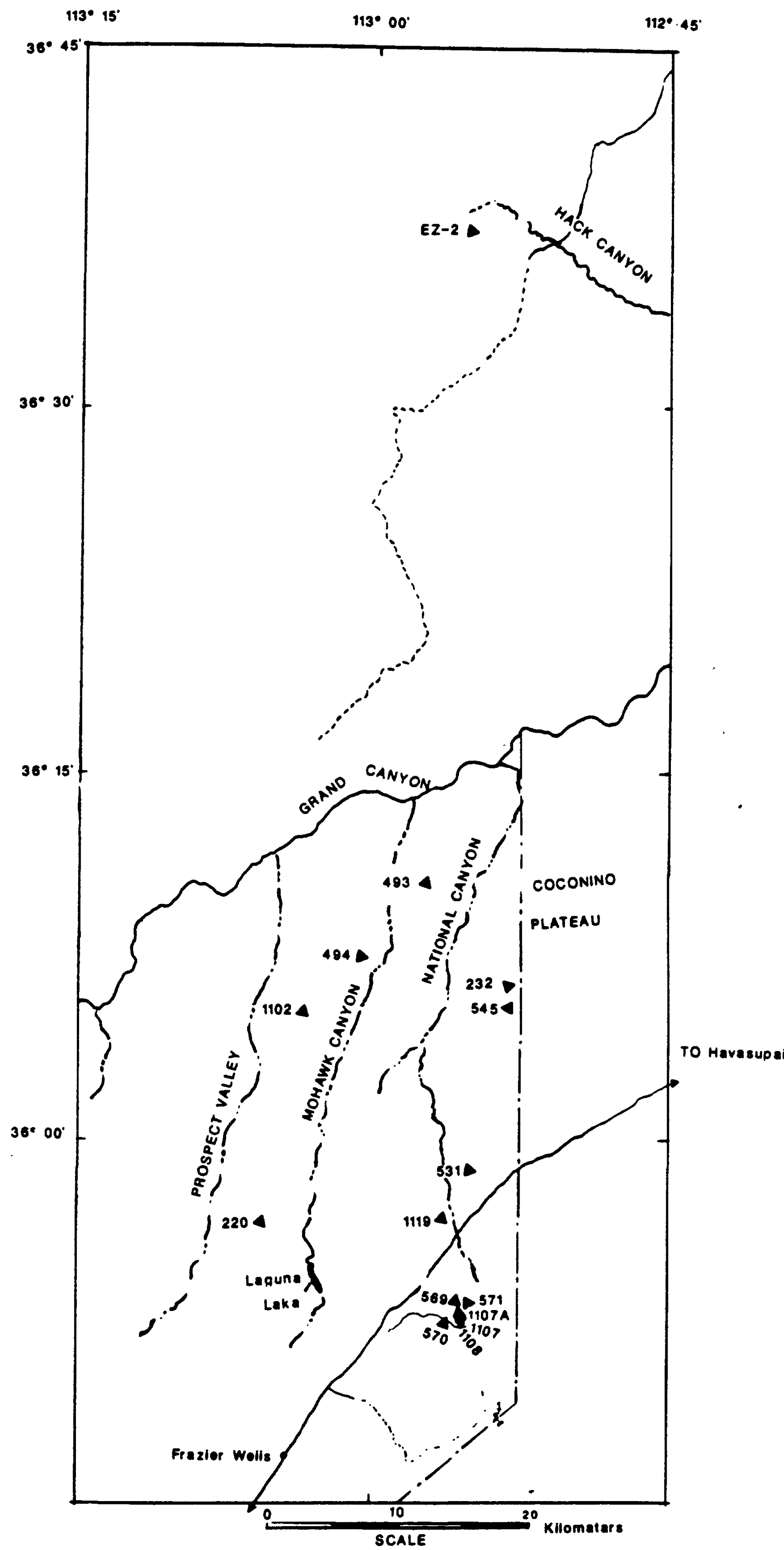
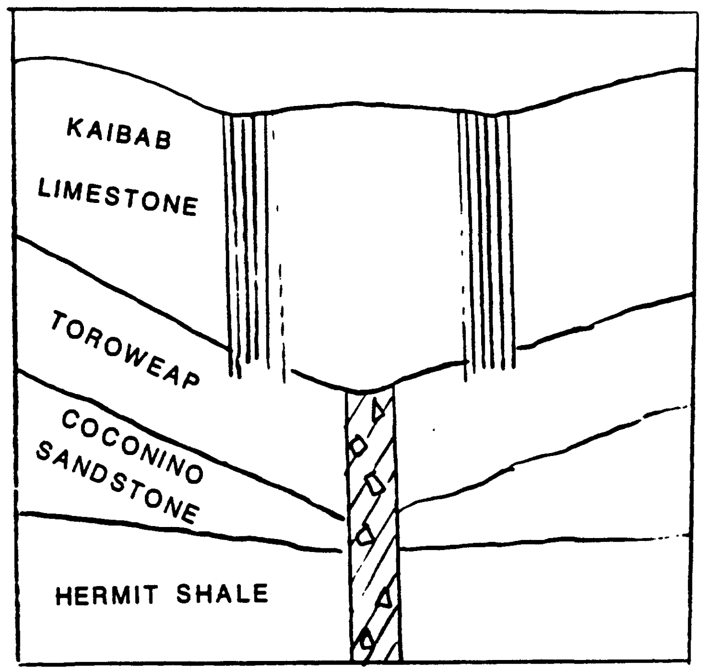
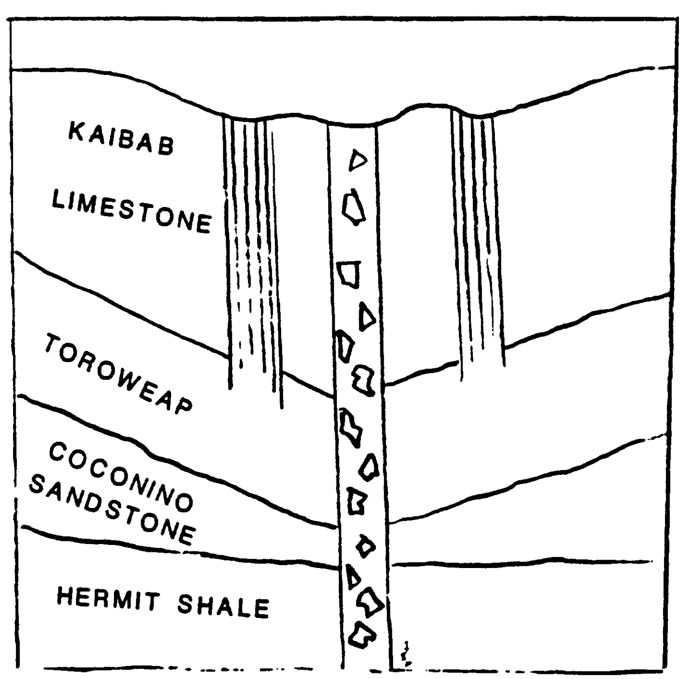


Figure 1 Map showing the location of possible breccia pipes studied by geophysical methods.



MODEL TYPE 1



MODEL TYPE 2

Figure 2 Schematic drawing showing physiographic and electrical breccia pipe models; the shaded area represent zones of rock more conductive than the unshaded areas.

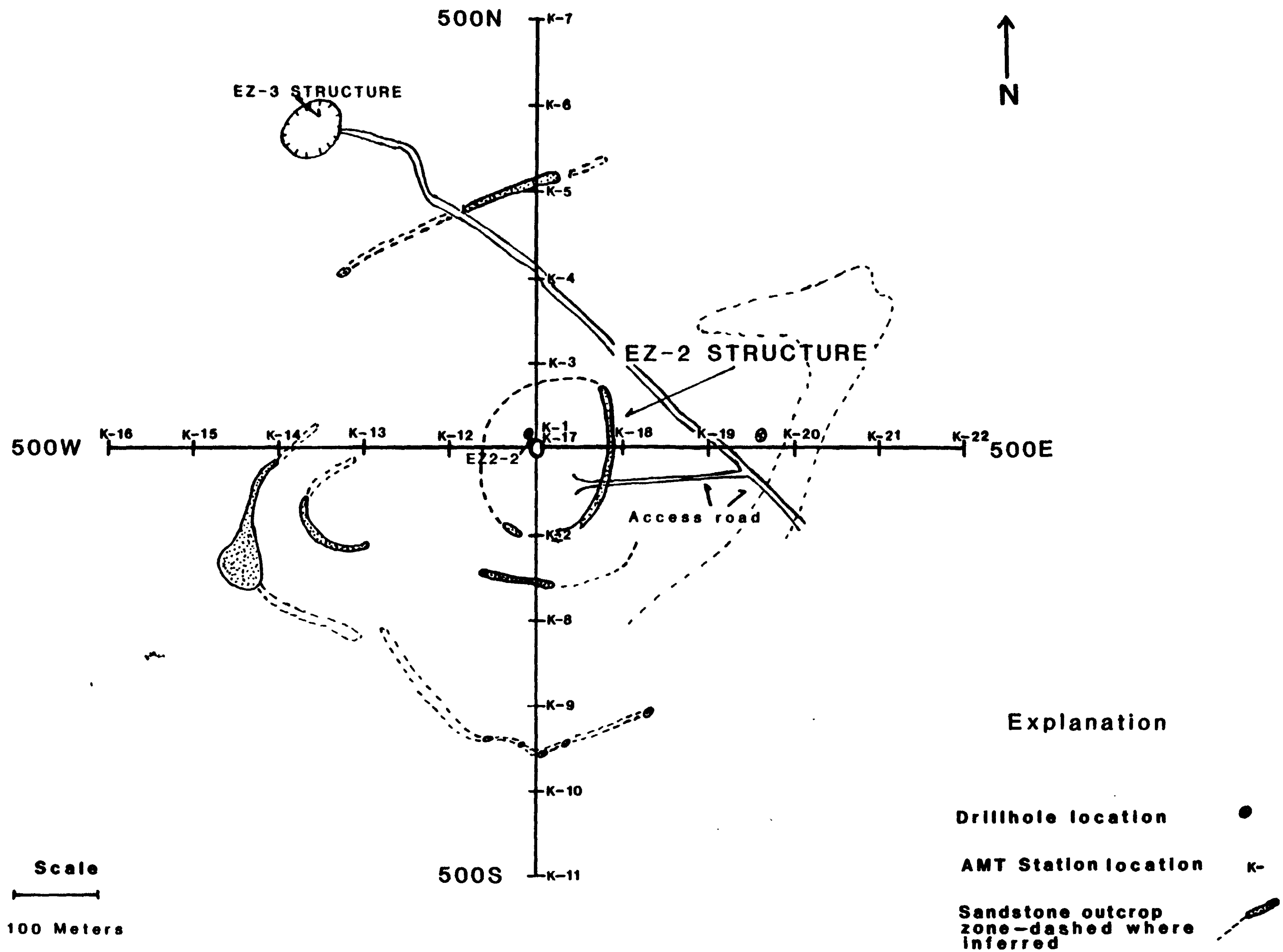


Figure 3 AMT sounding location at the EZ-2 breccia pipe, northern Arizona.

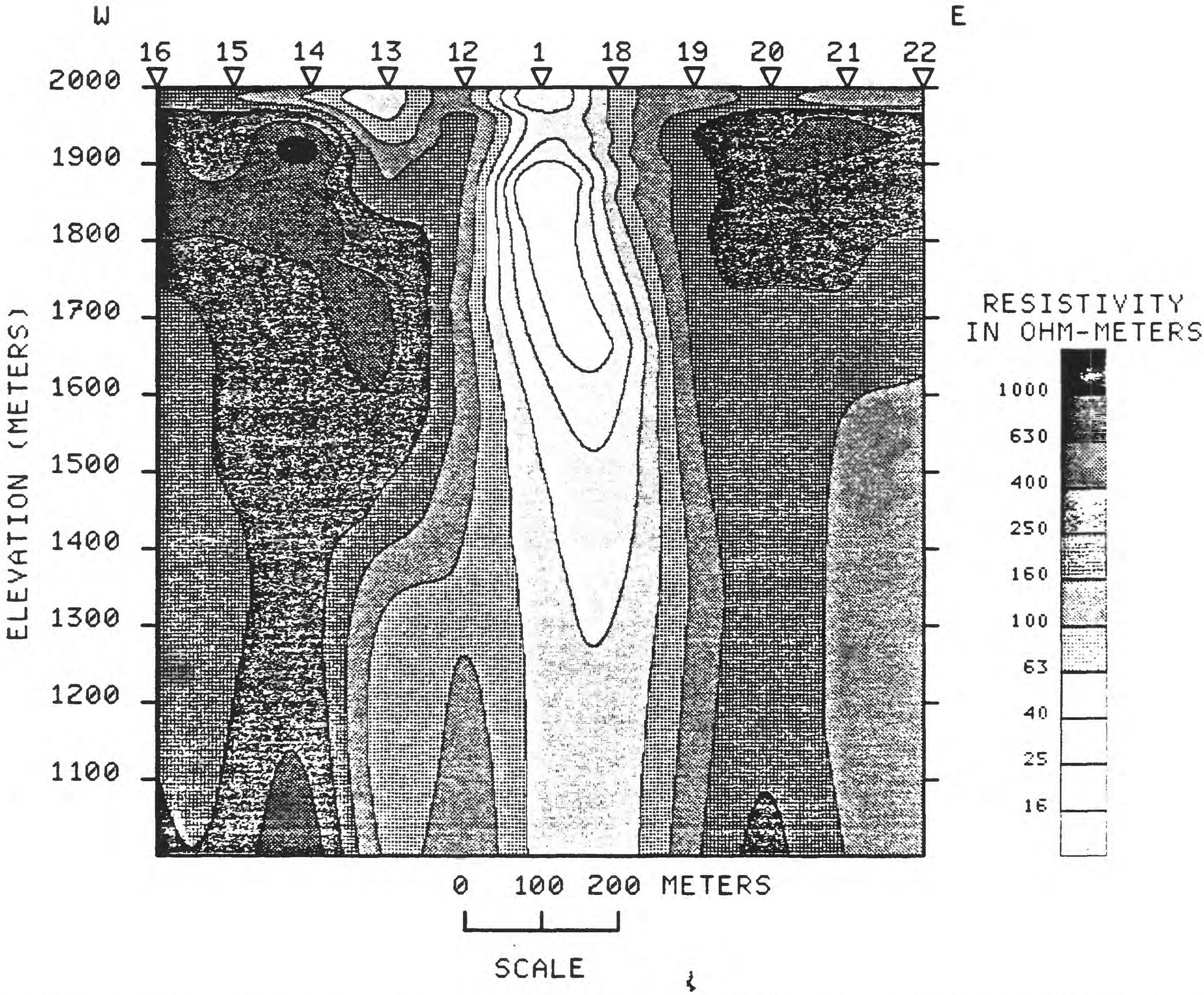
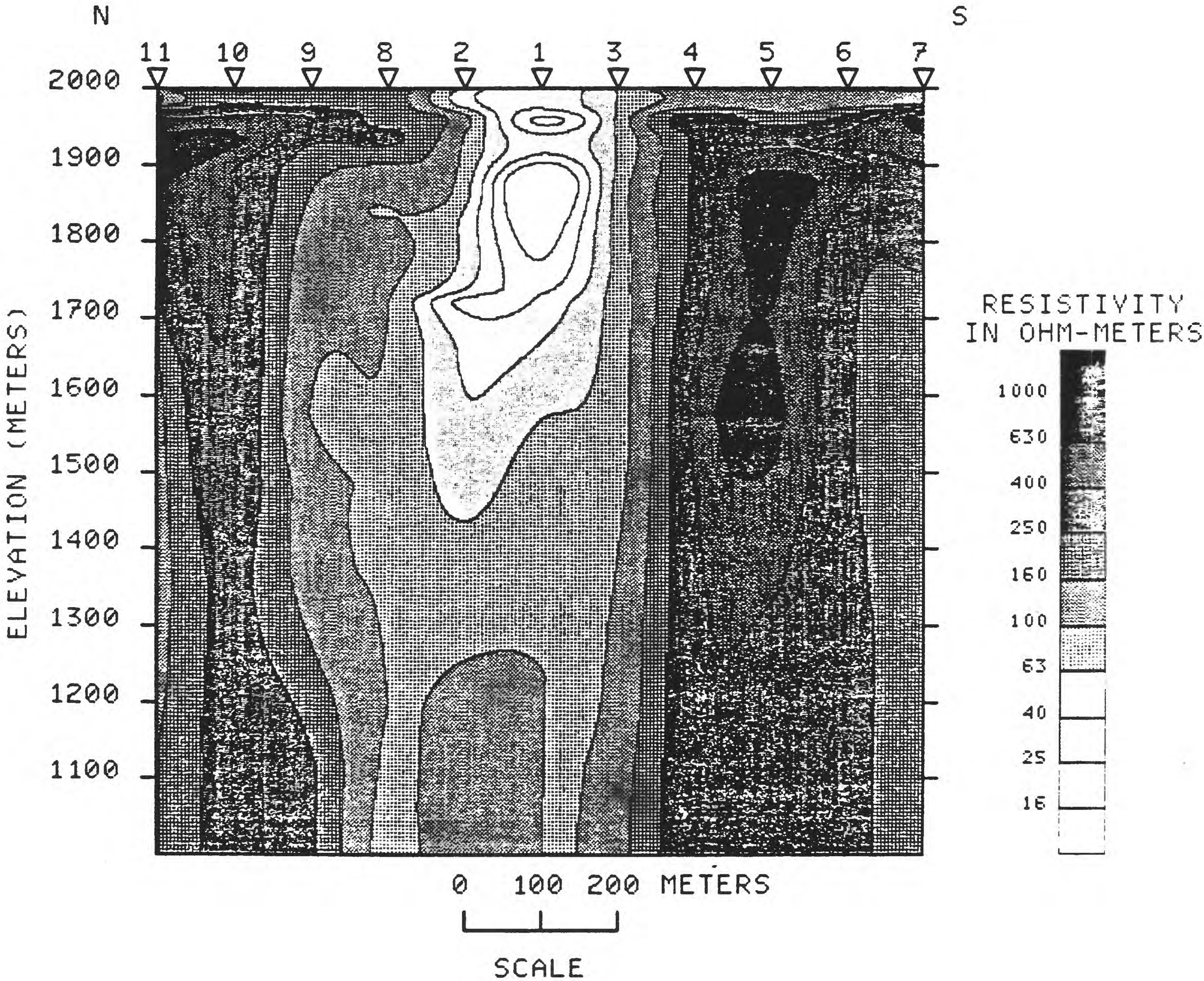


Figure 4 East-west cross section showing resistivity versus depth at site EZ-2.



gure 5 North–south cross section showing resistivity versus depth at site EZ–2.

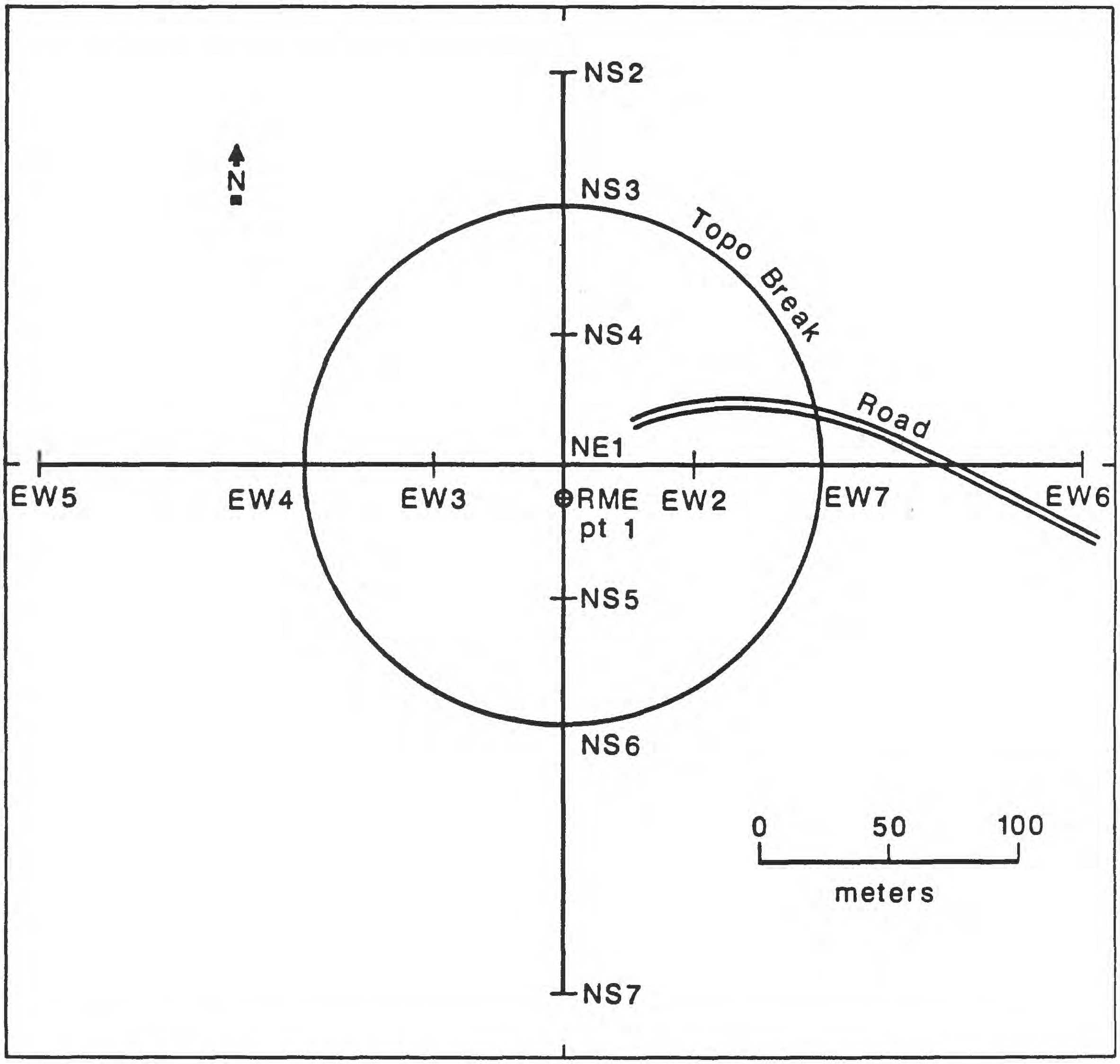


Figure 6 Sketch map of known breccia pipe showing AMT station locations.

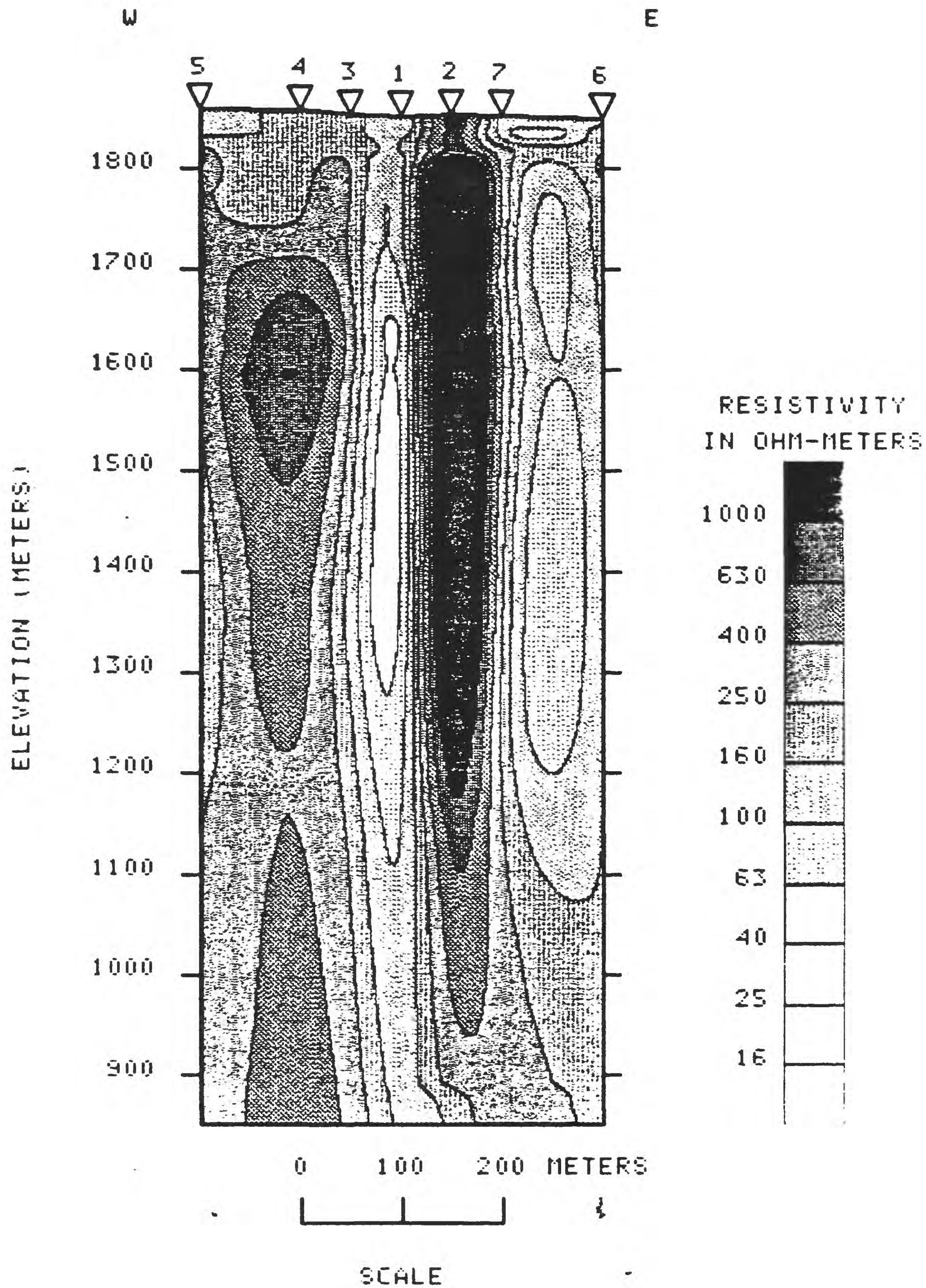


Figure 7 East-west cross section showing resistivity versus depth at known breccia pipe.

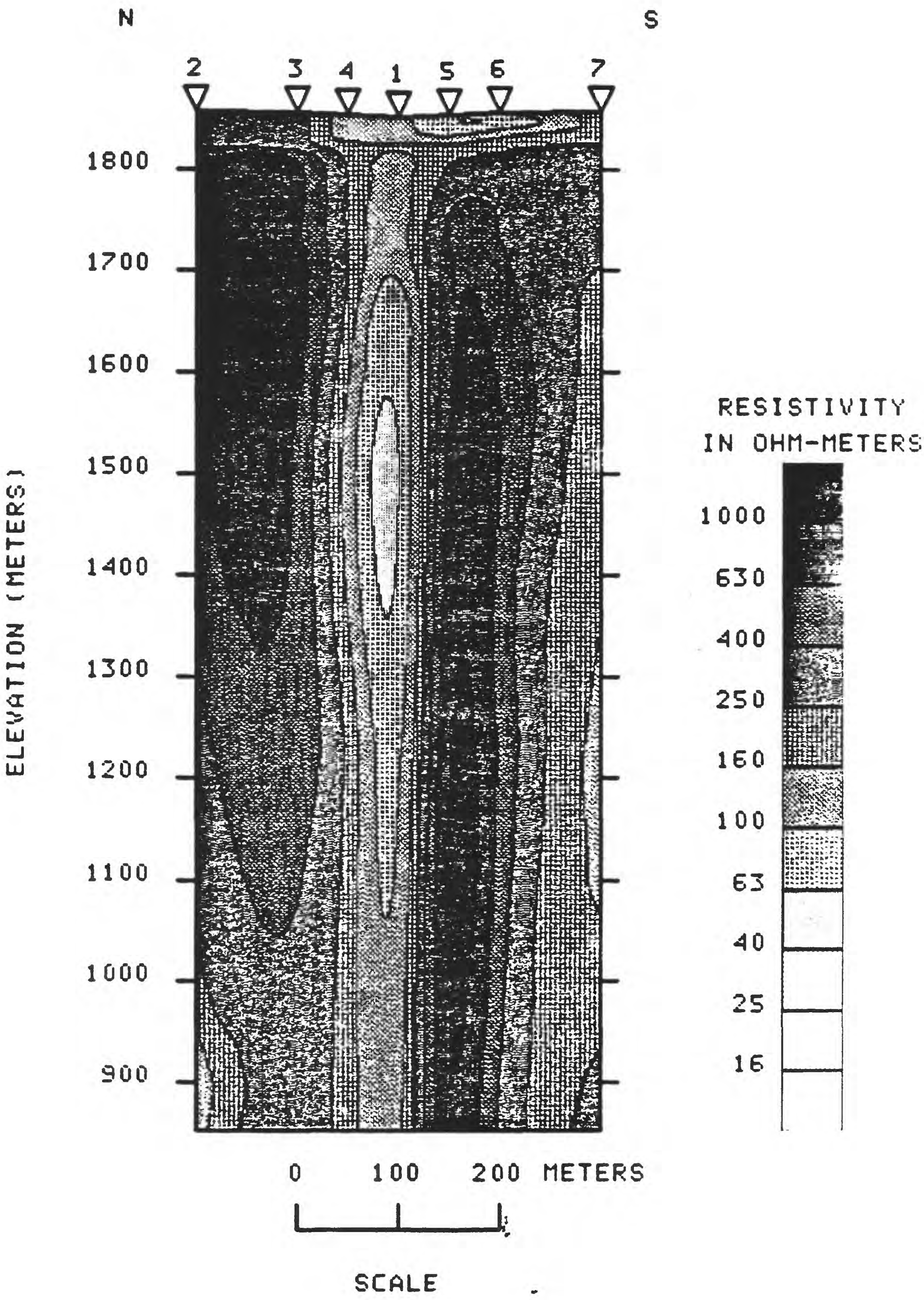


Figure 8 North-south cross section showing resistivity versus depth at known breccia pipe.

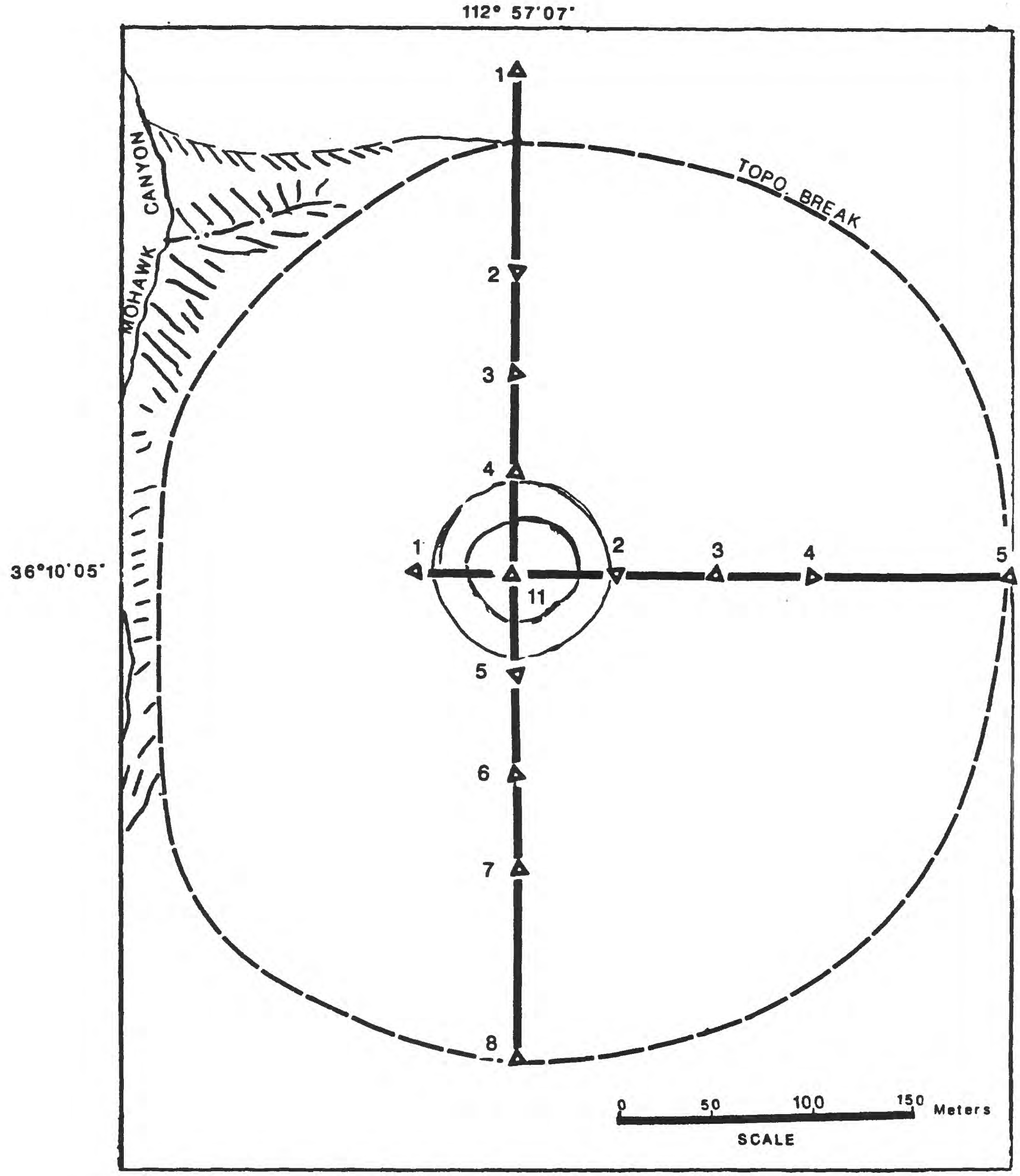


Figure 9 Sketch map showing location of AMT stations at site 493.

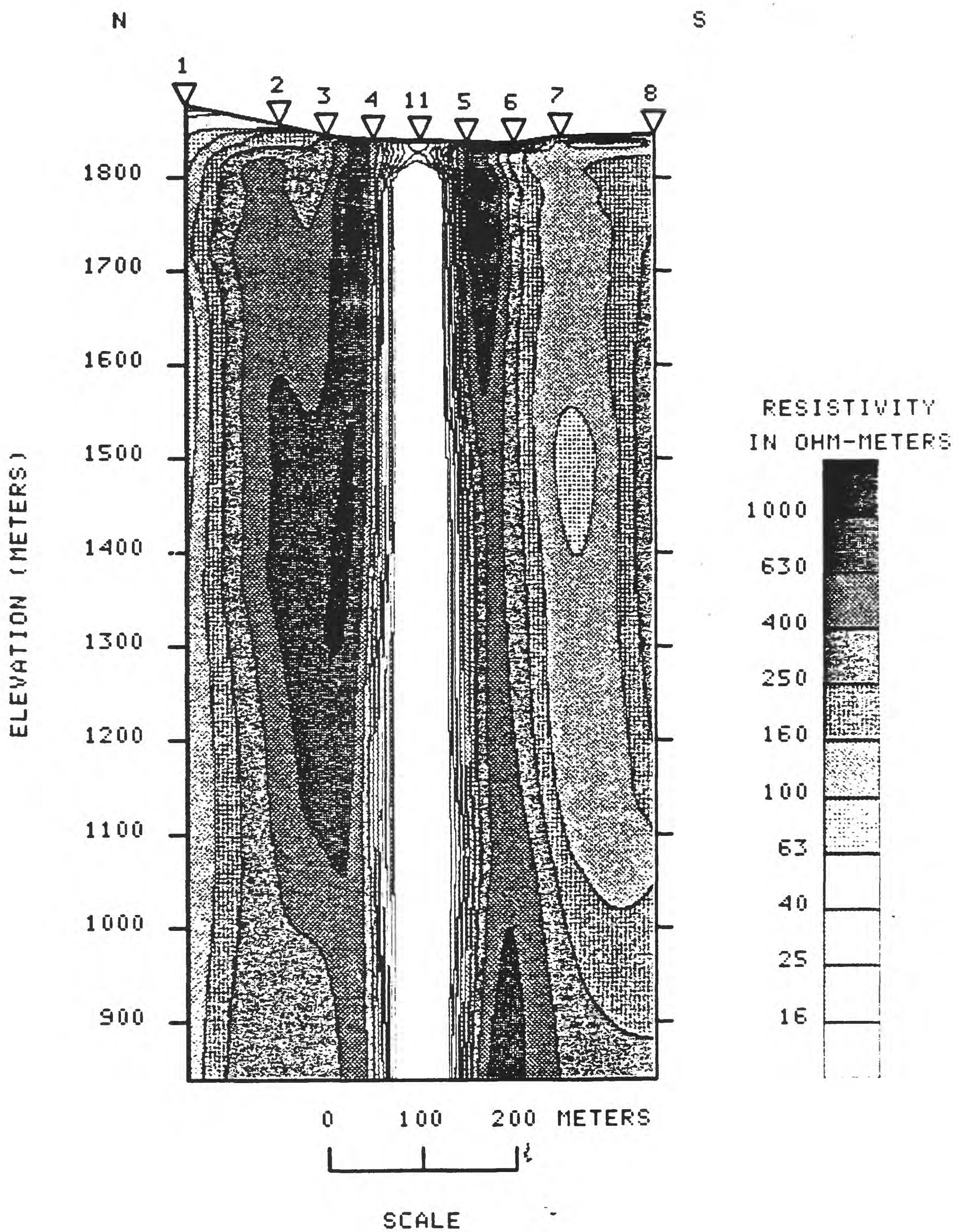


Figure 10 North-south cross section showing resistivity versus depth at site 493.

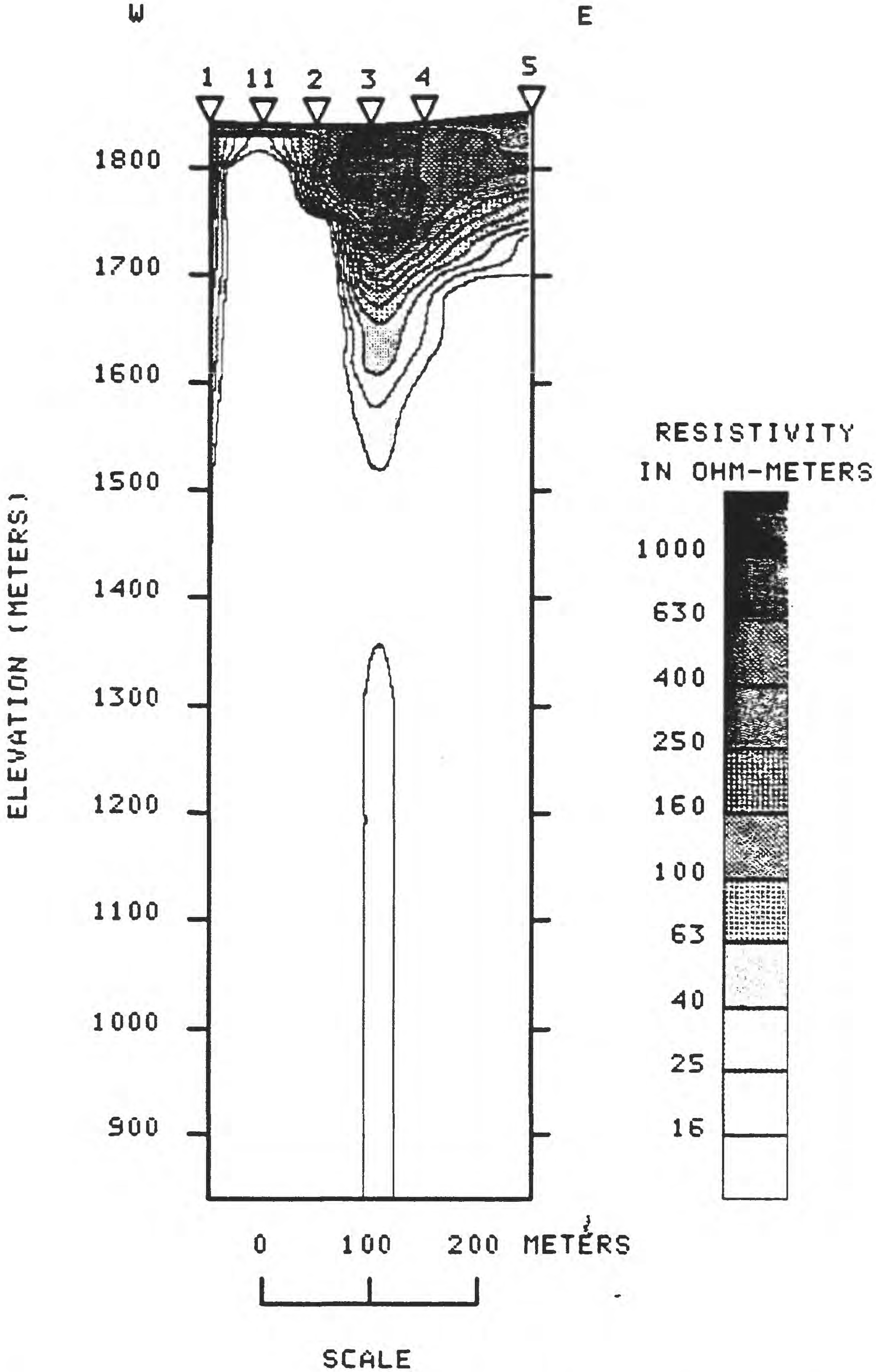


Figure 11 East-west cross section showing resistivity versus depth at site 493.

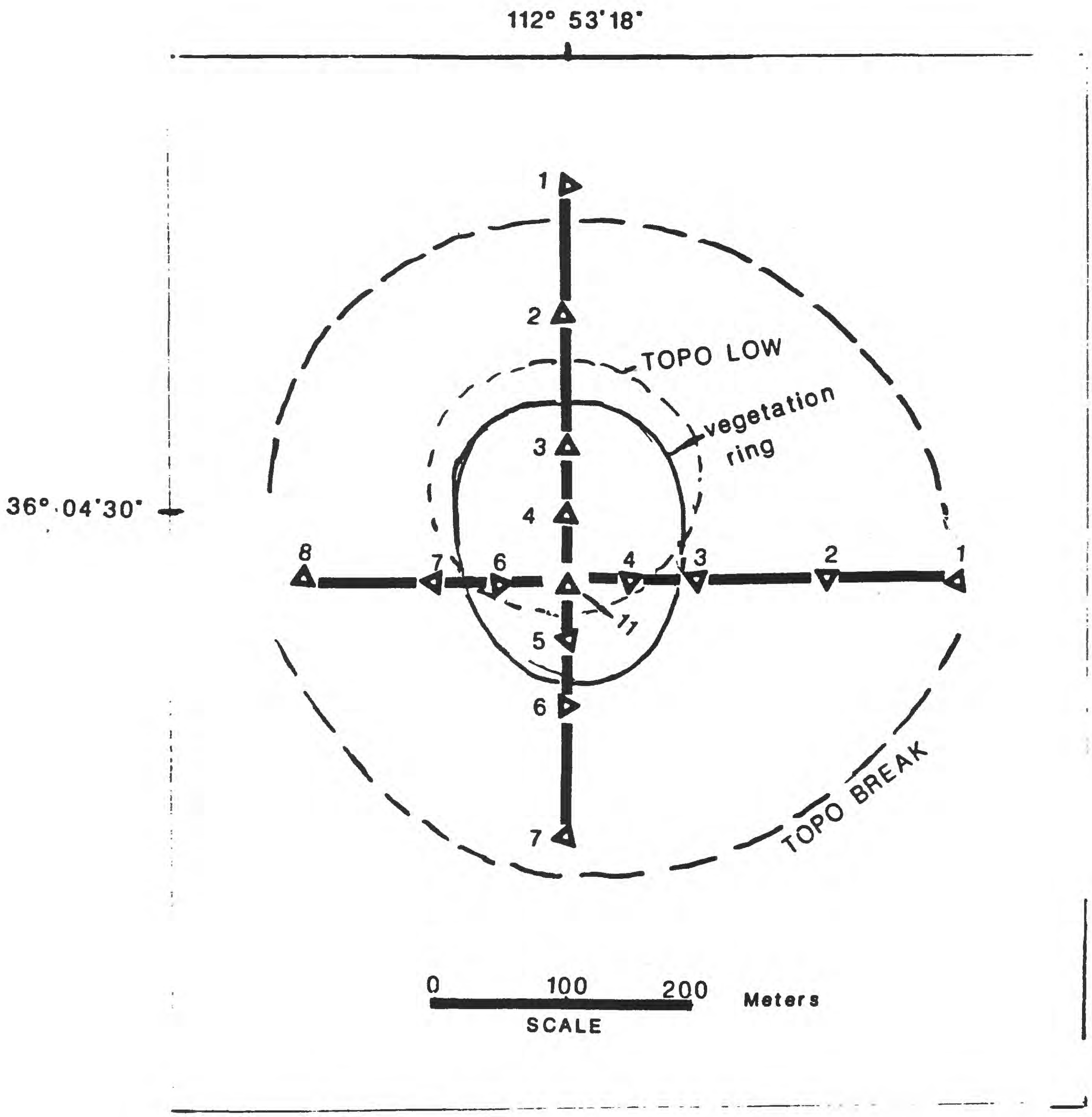


Figure 12 Sketch map of site 545 showing locations of AMT stations.

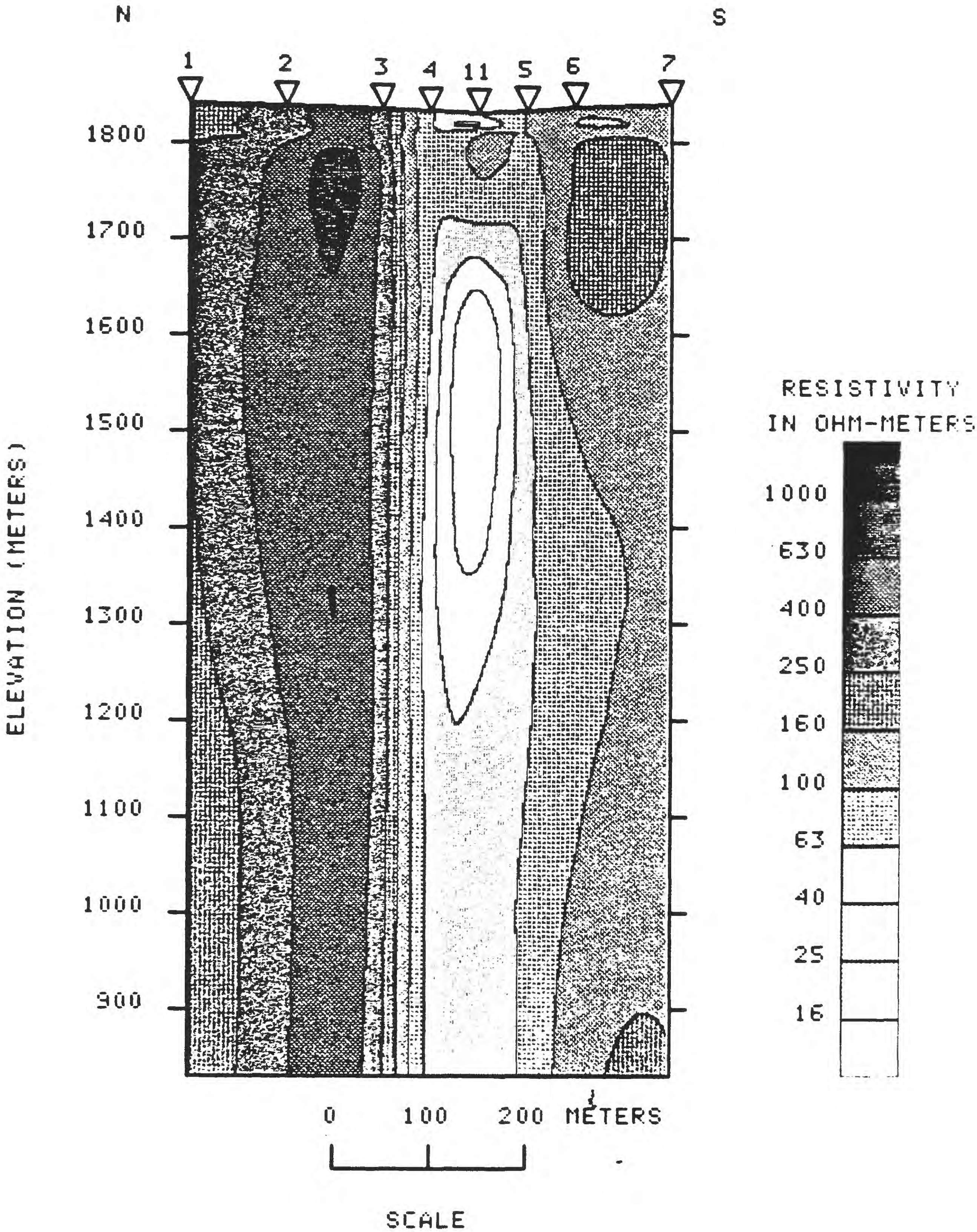


Figure 13 North-south cross section showing resistivity versus depth at site 545

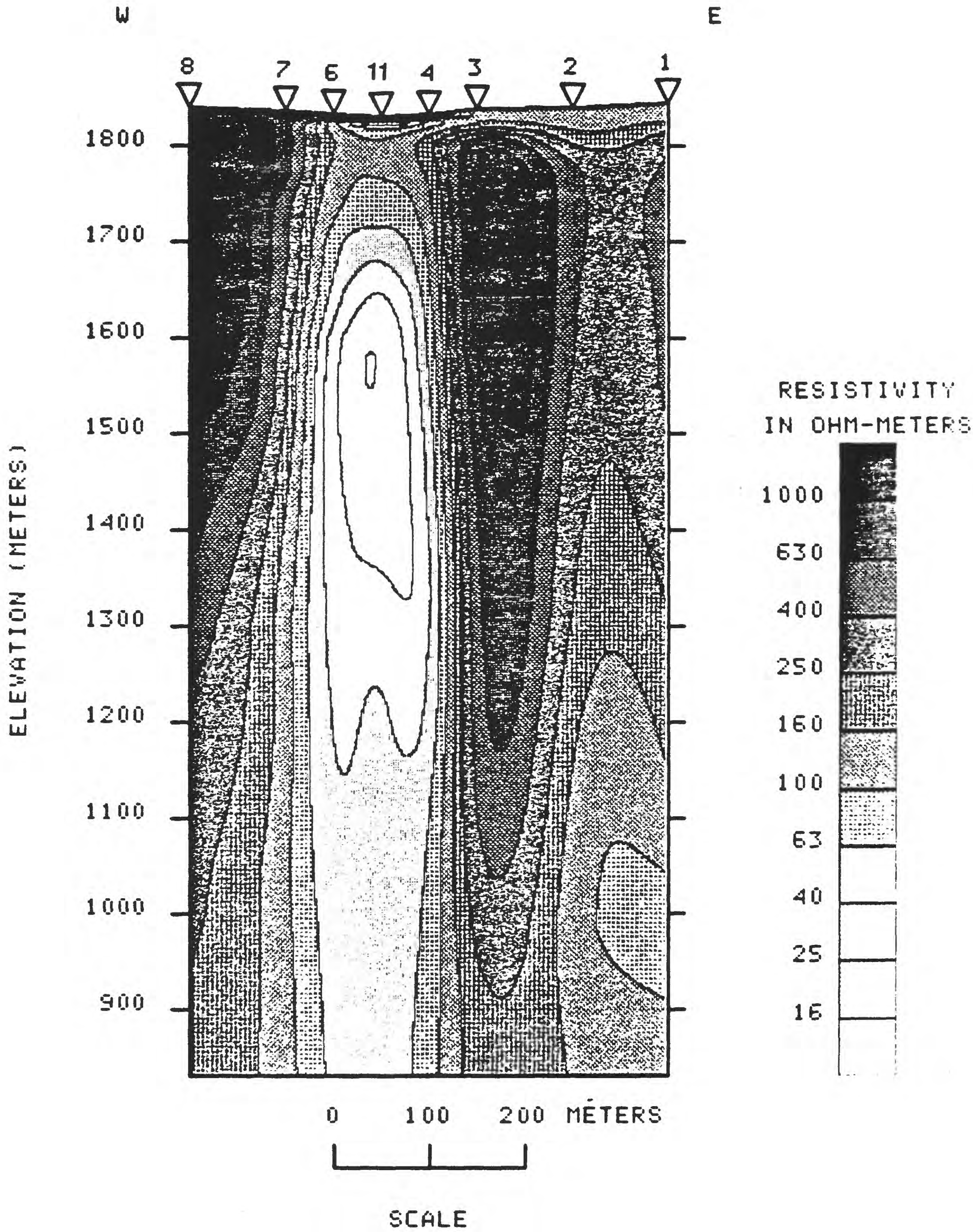


Figure 14 East-west cross section showing resistivity versus depth at site 545.

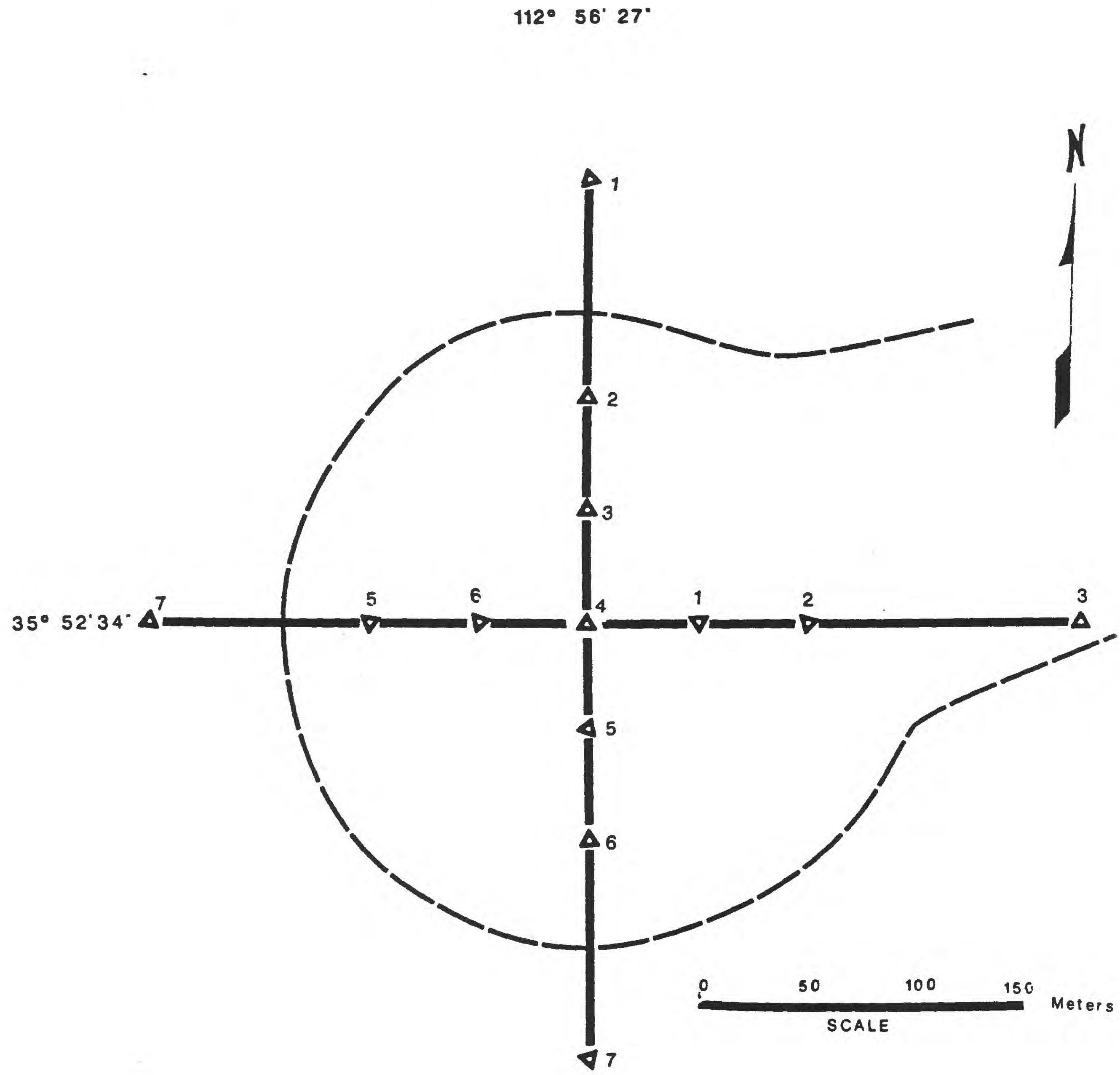


Figure 15 Sketch map of site 570 showing location of AMT stations.

The dashed line indicates the approximate boundry of depression.

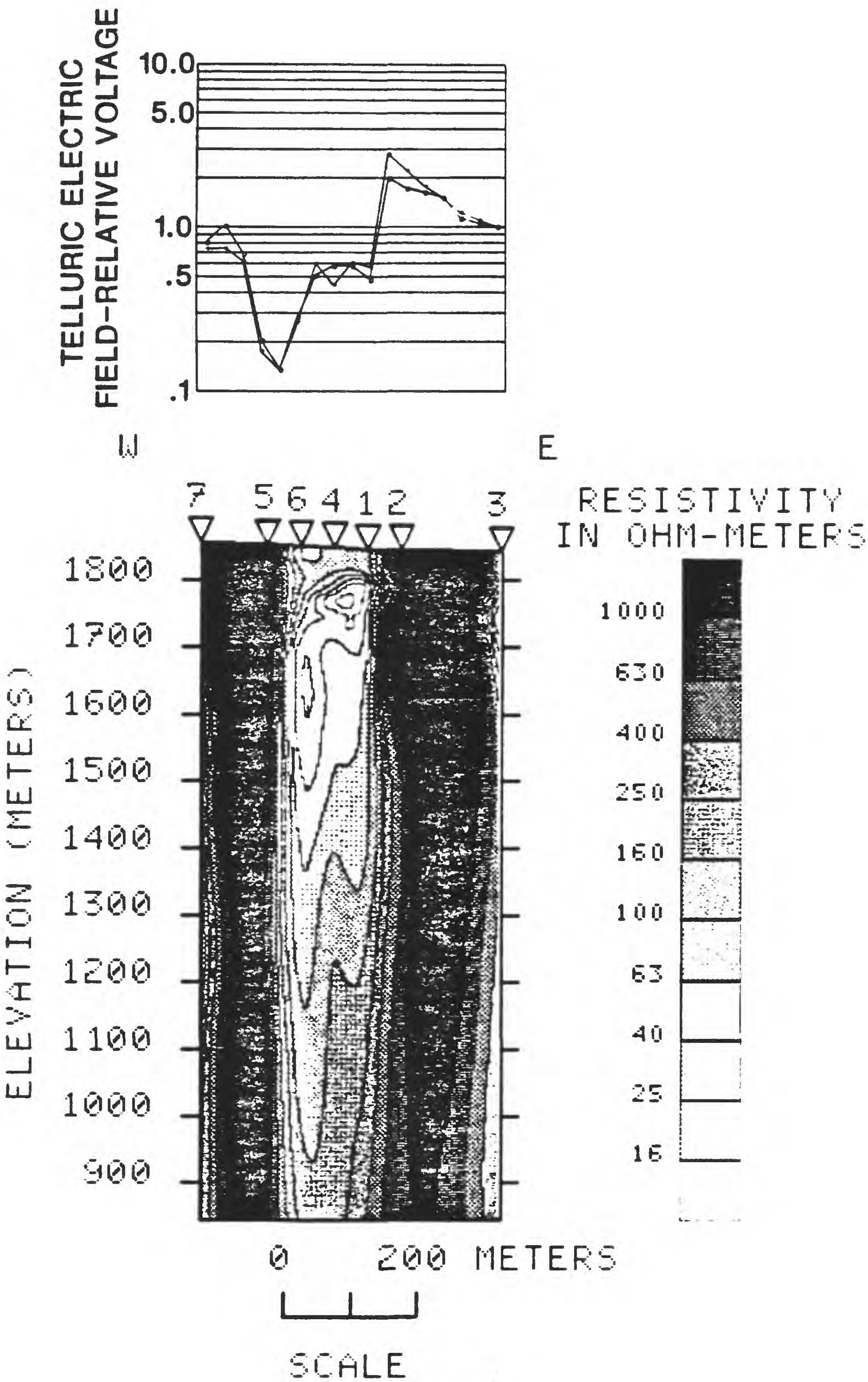


Figure 16 East-west cross section showing resistivity versus depth at site 570.

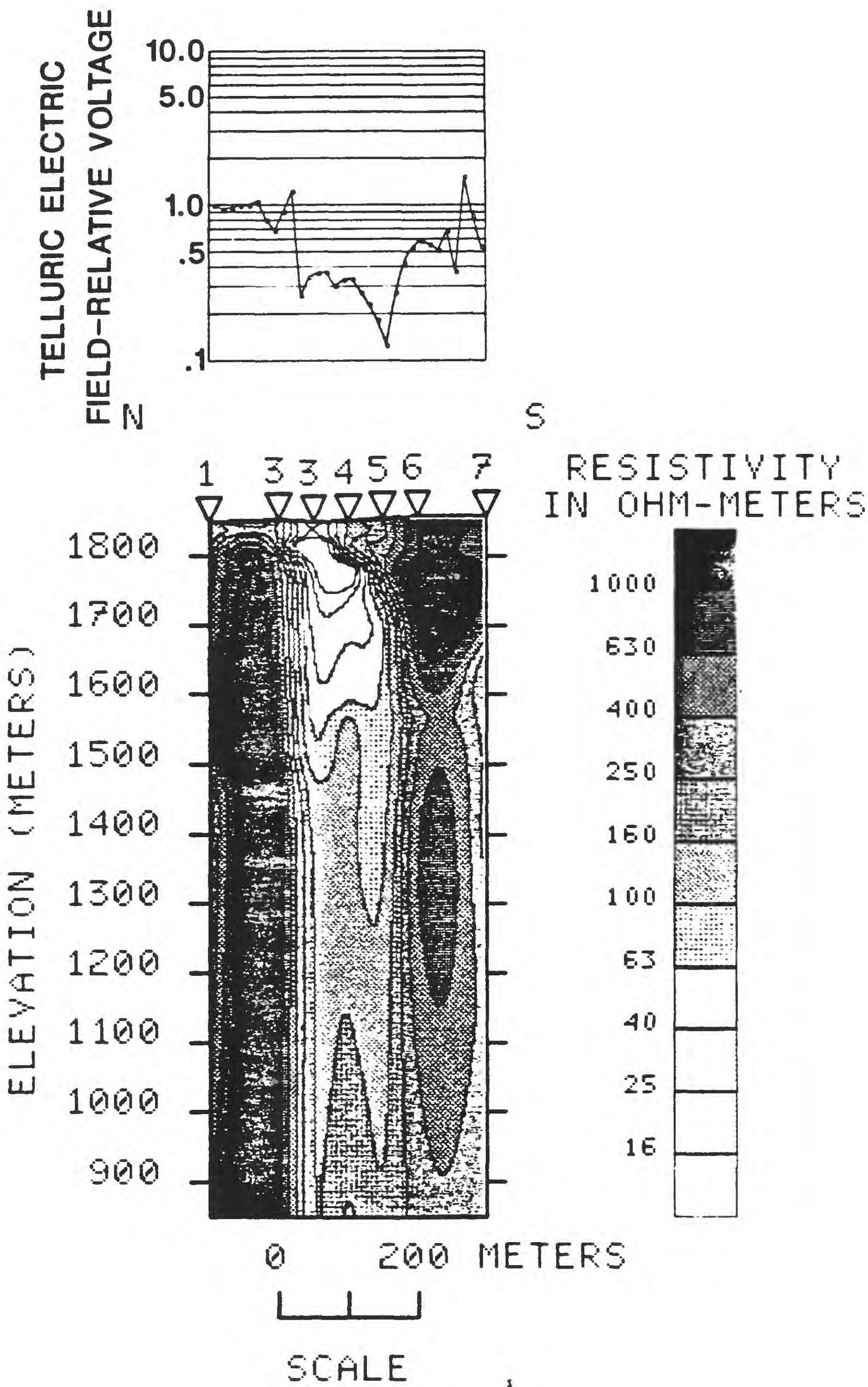


Figure 17 North-south cross section showing resistivity versus depth at site 570.

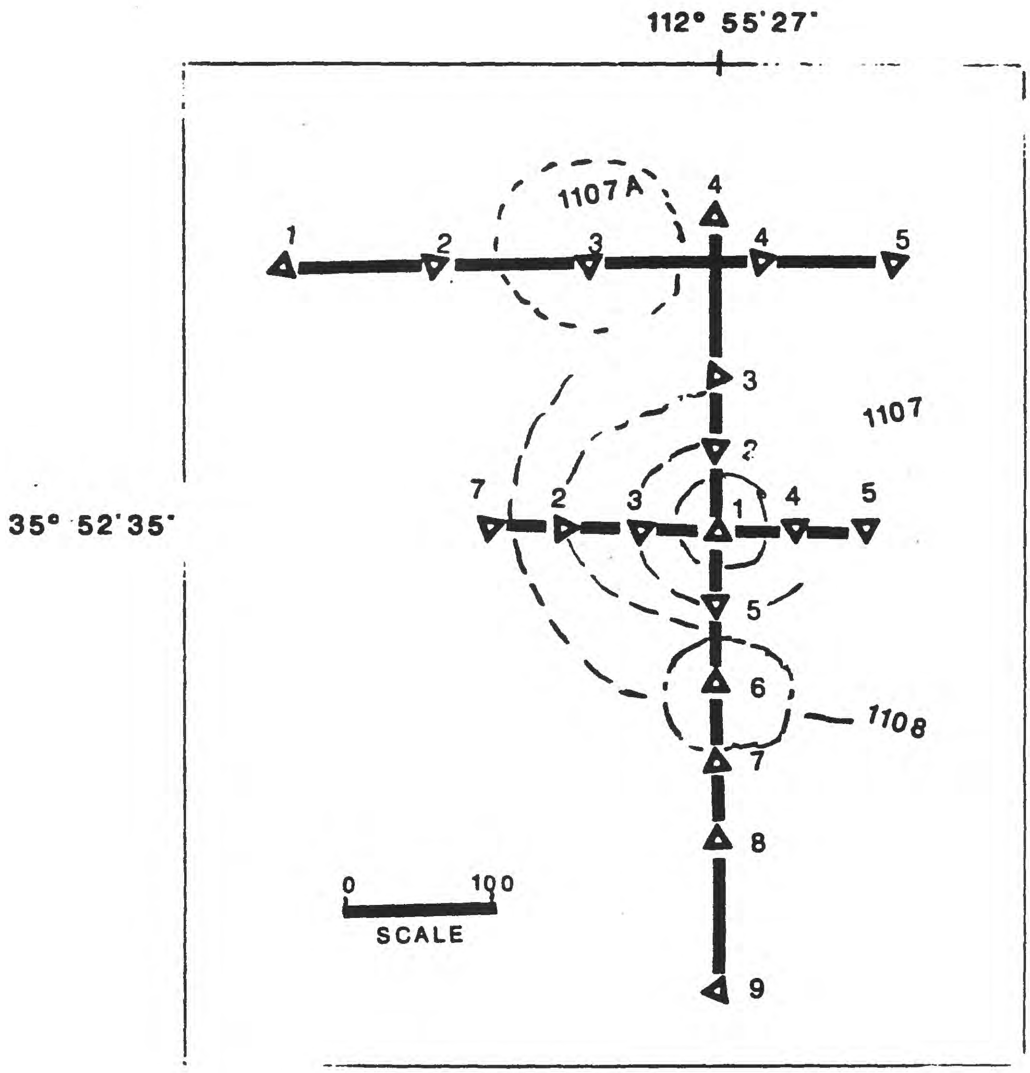


Figure 18 Sketch map of sites 1107 and 1108 showing AMT station locations.

Dashed line indicates approximate location of topography break.

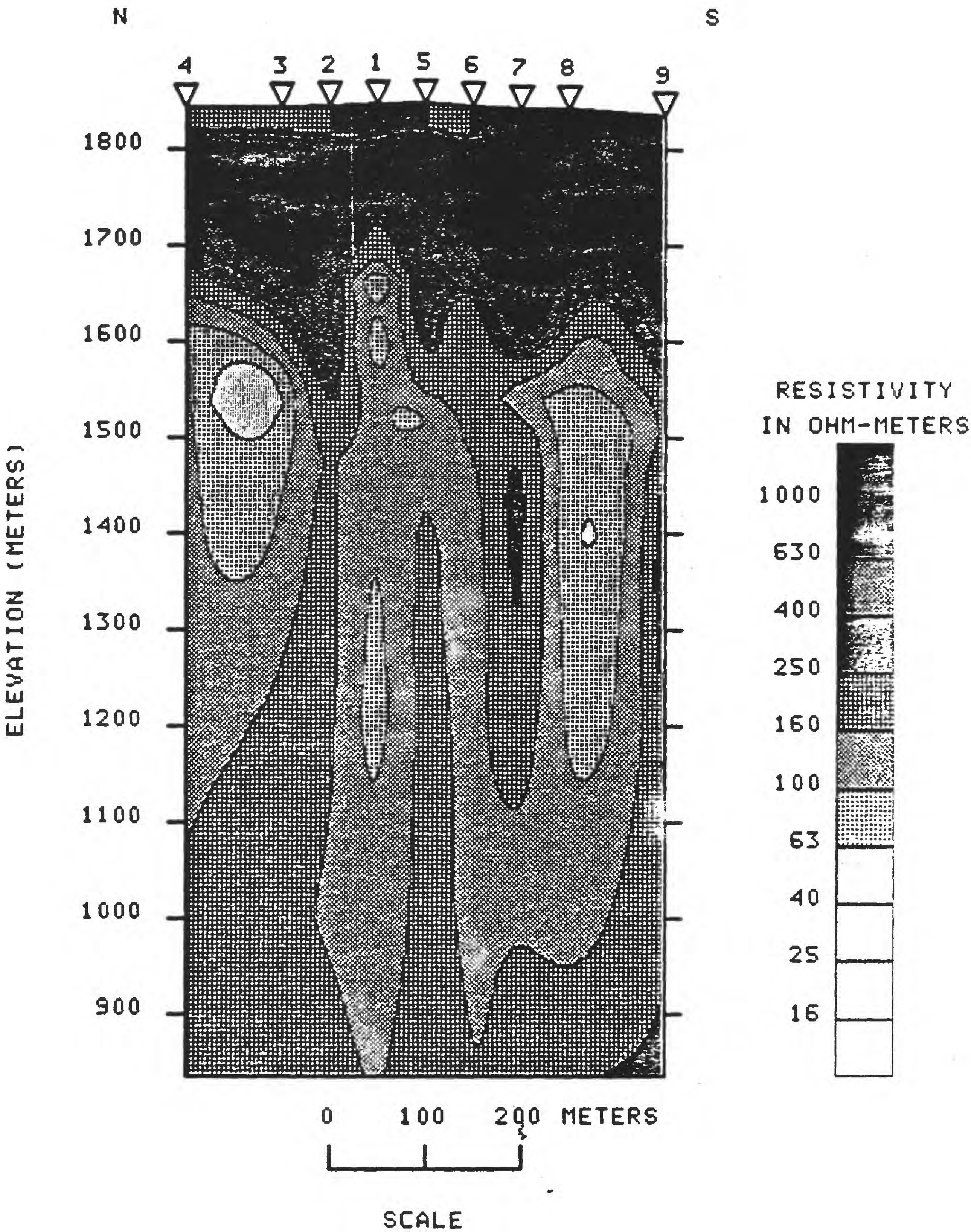


Figure 19 North-south cross section showing resistivity versus depth at site 1107-1108.

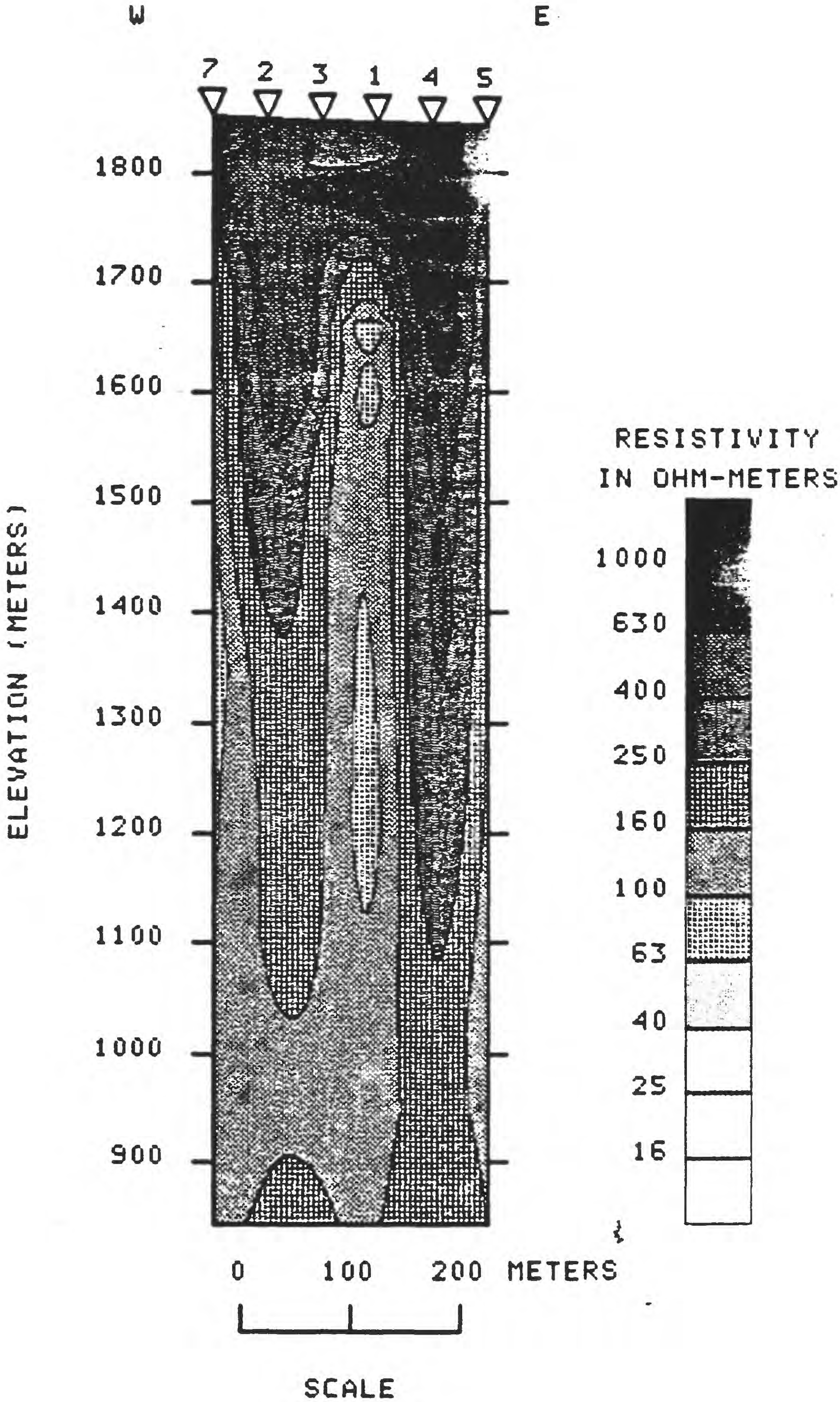


Figure 20 East-west cross section showing resistivity versus depth at site 1107.

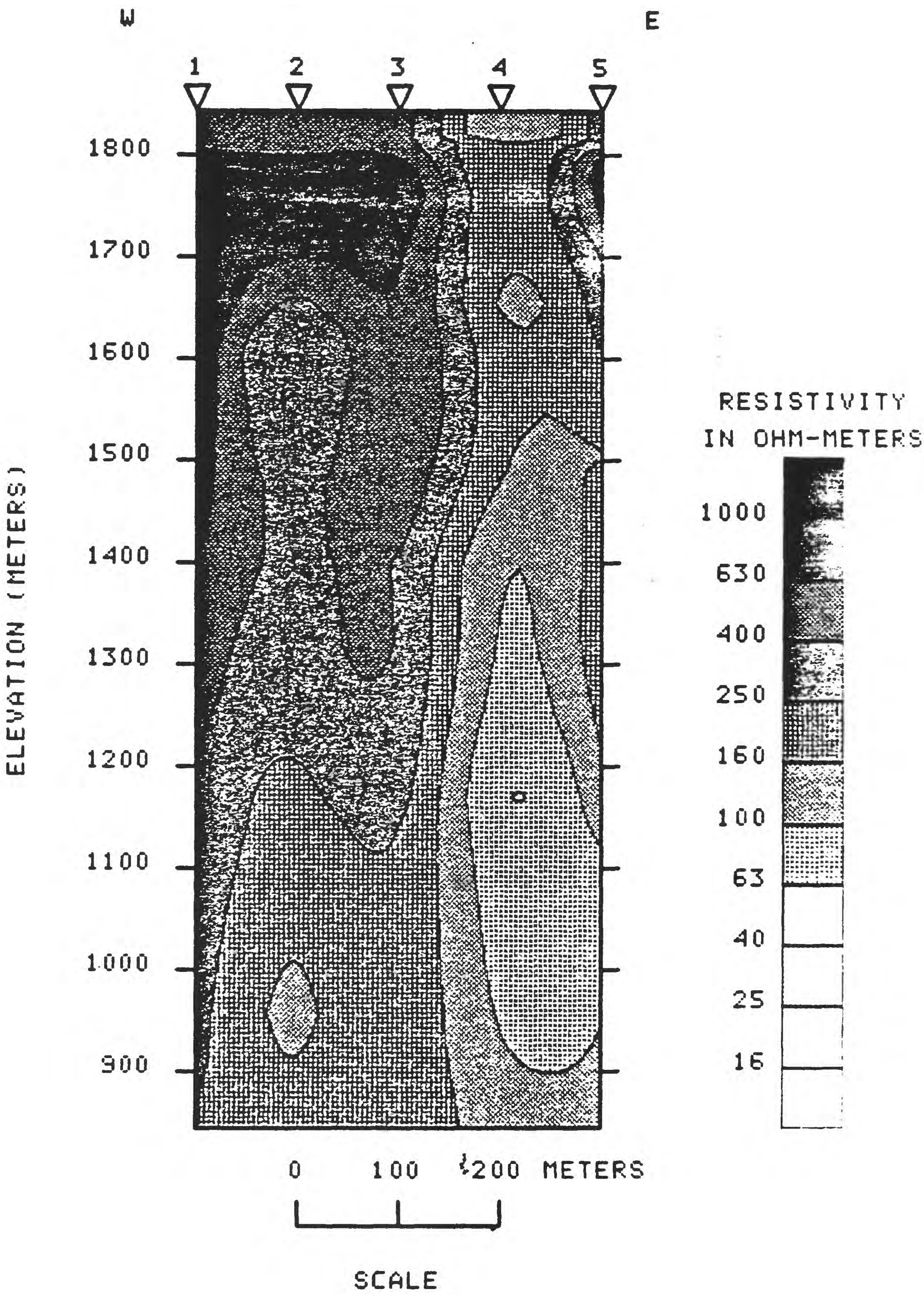


Figure 21 East-west cross section showing resistivity versus depth at site 1107A

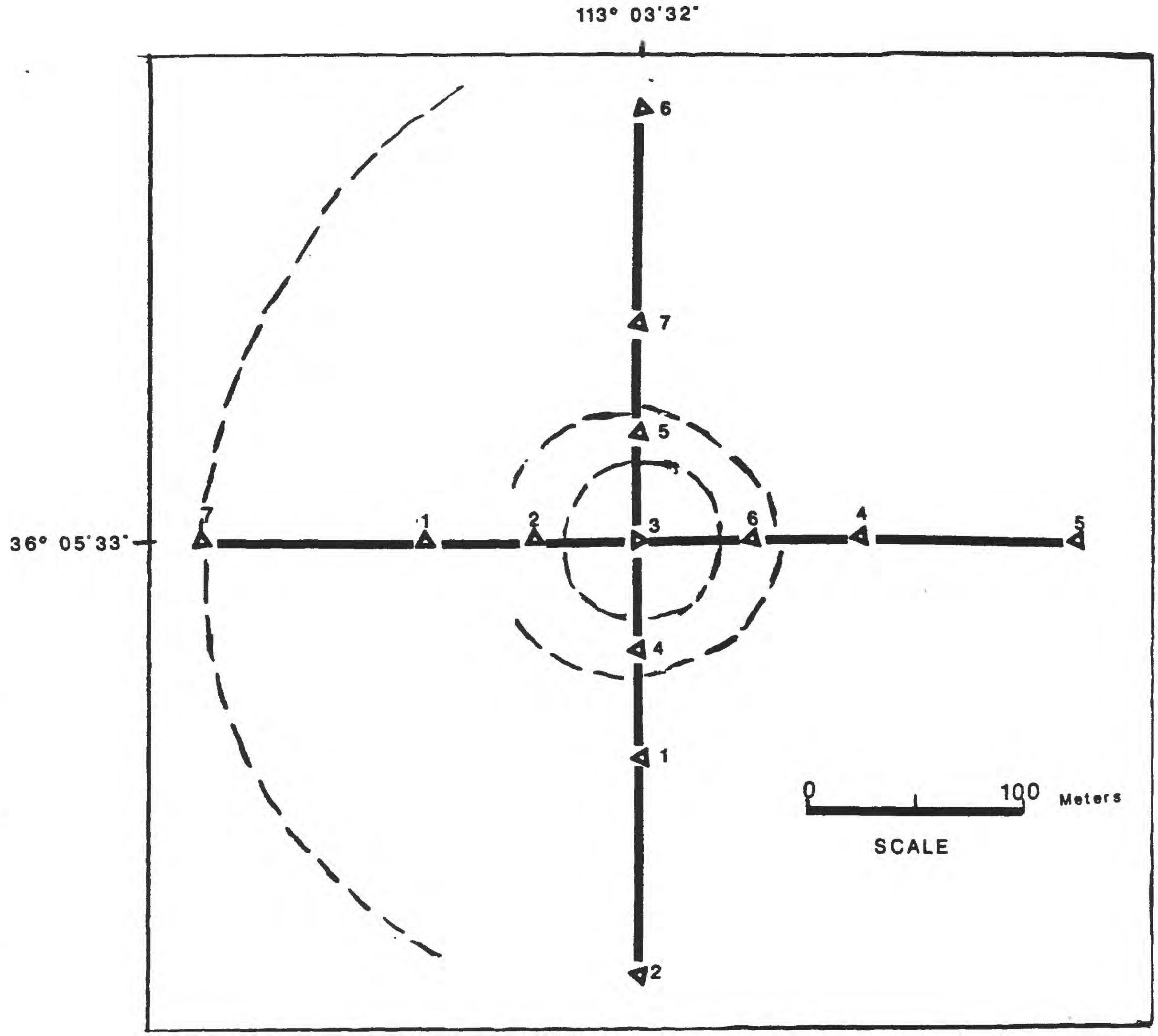


Figure 22 Sketch map showing location of AMT soundings at site 1102.
Dashed line shows the approximate boundry of topographic depression.

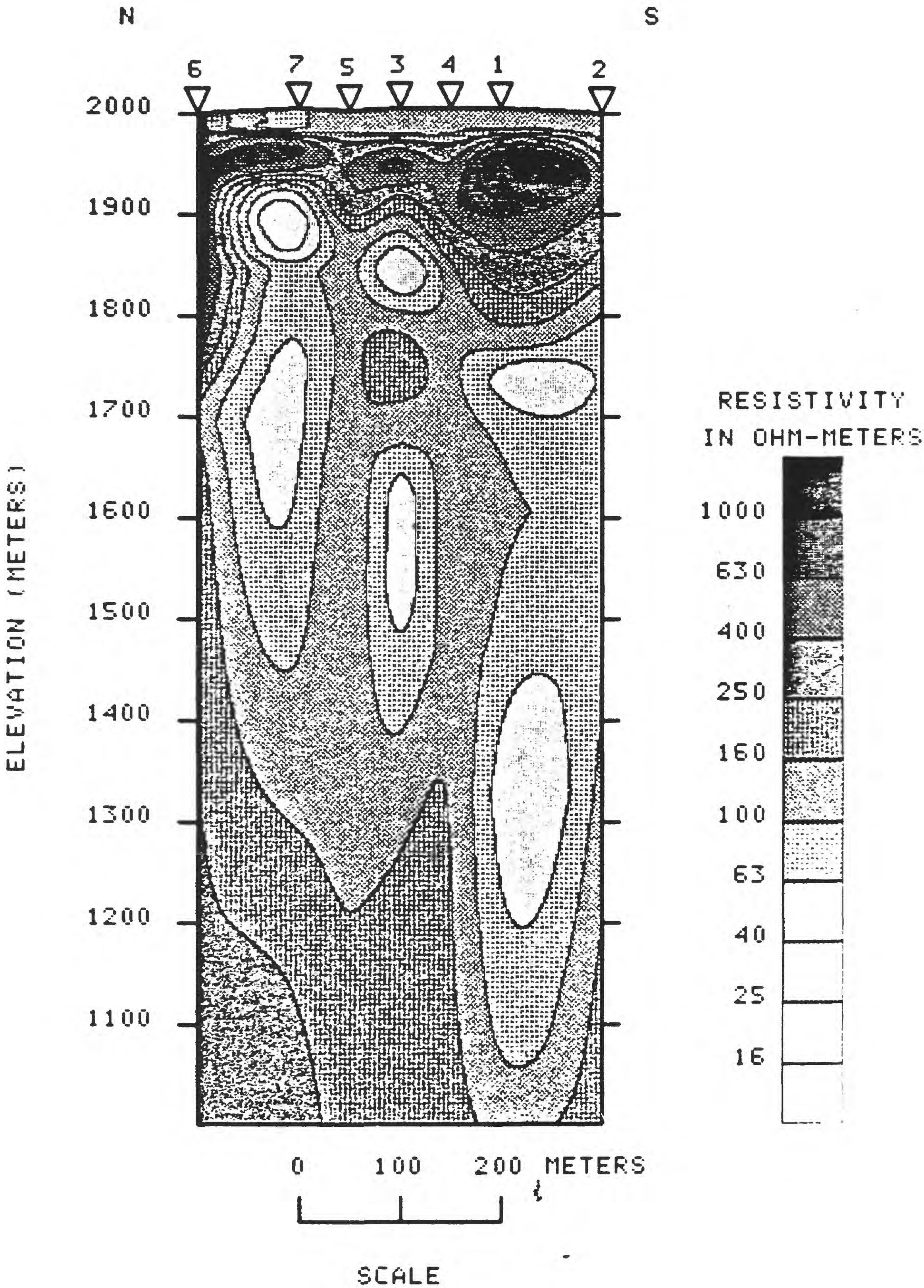


Figure 23 North-south cross section showing resistivity versus depth at site 1102.

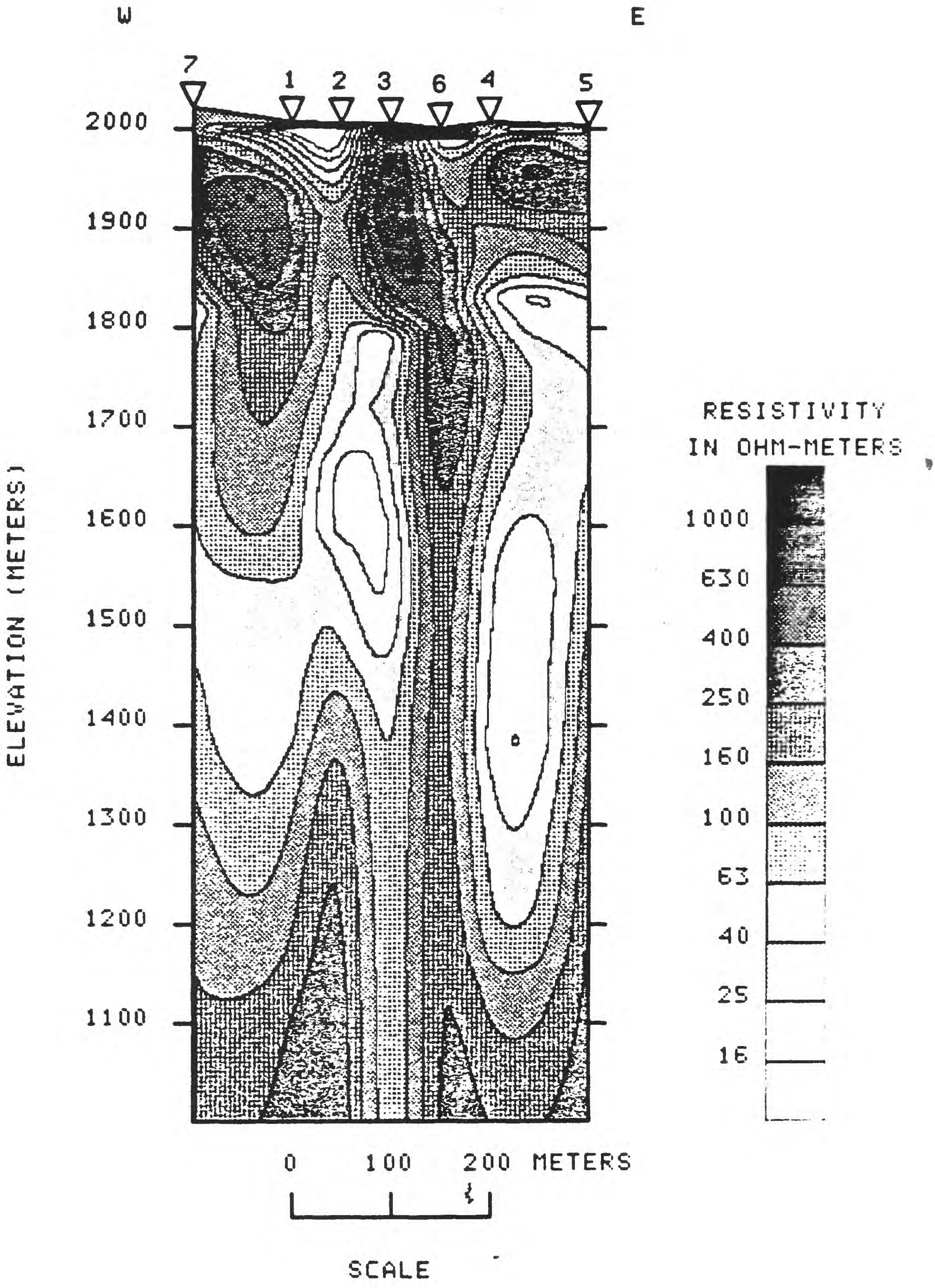


Figure 24 East-west cross section showing resistivity versus depth at site 1102.

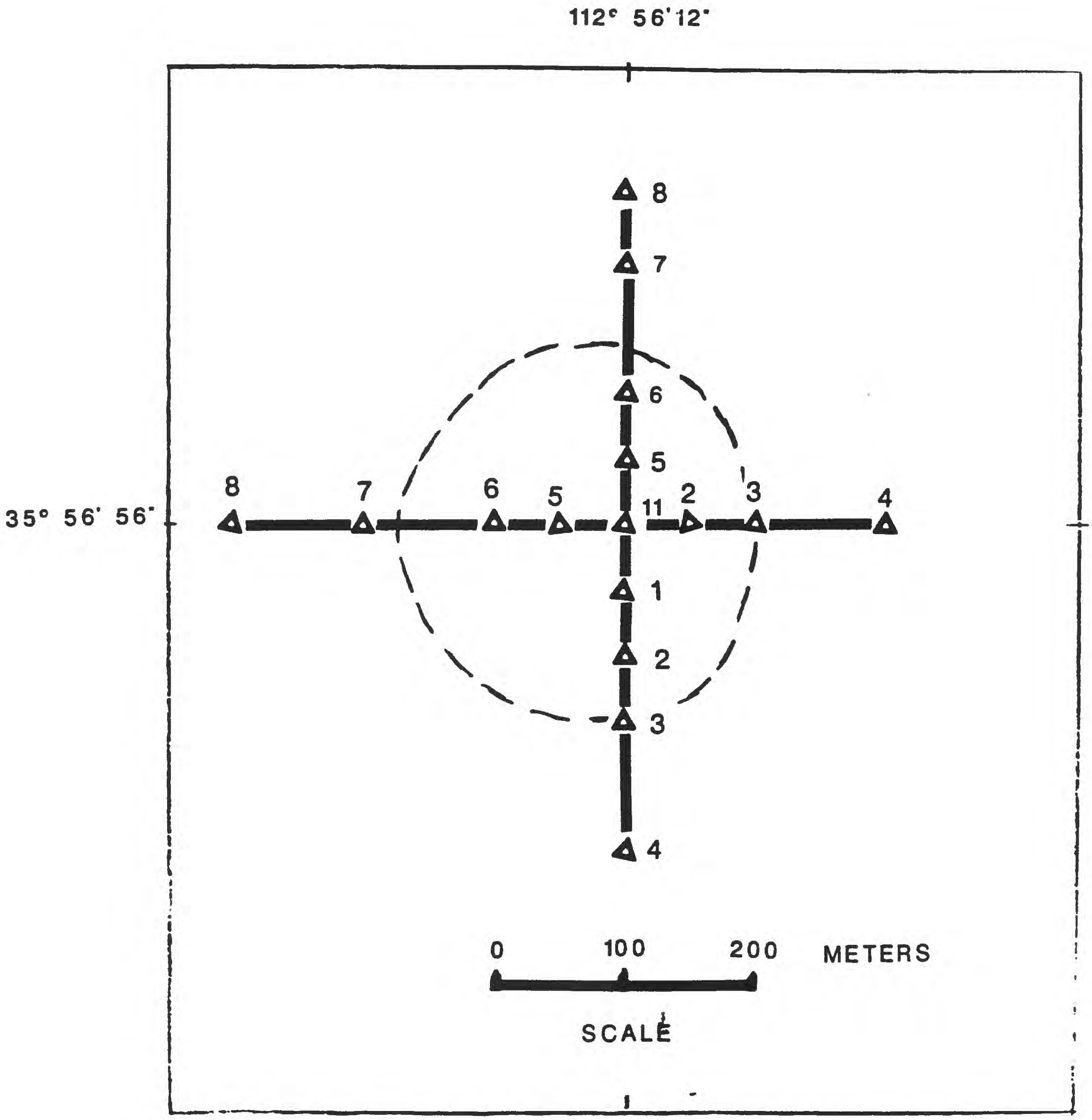


Figure 25 Sketch map showing location of AMT soundings at site 1119.

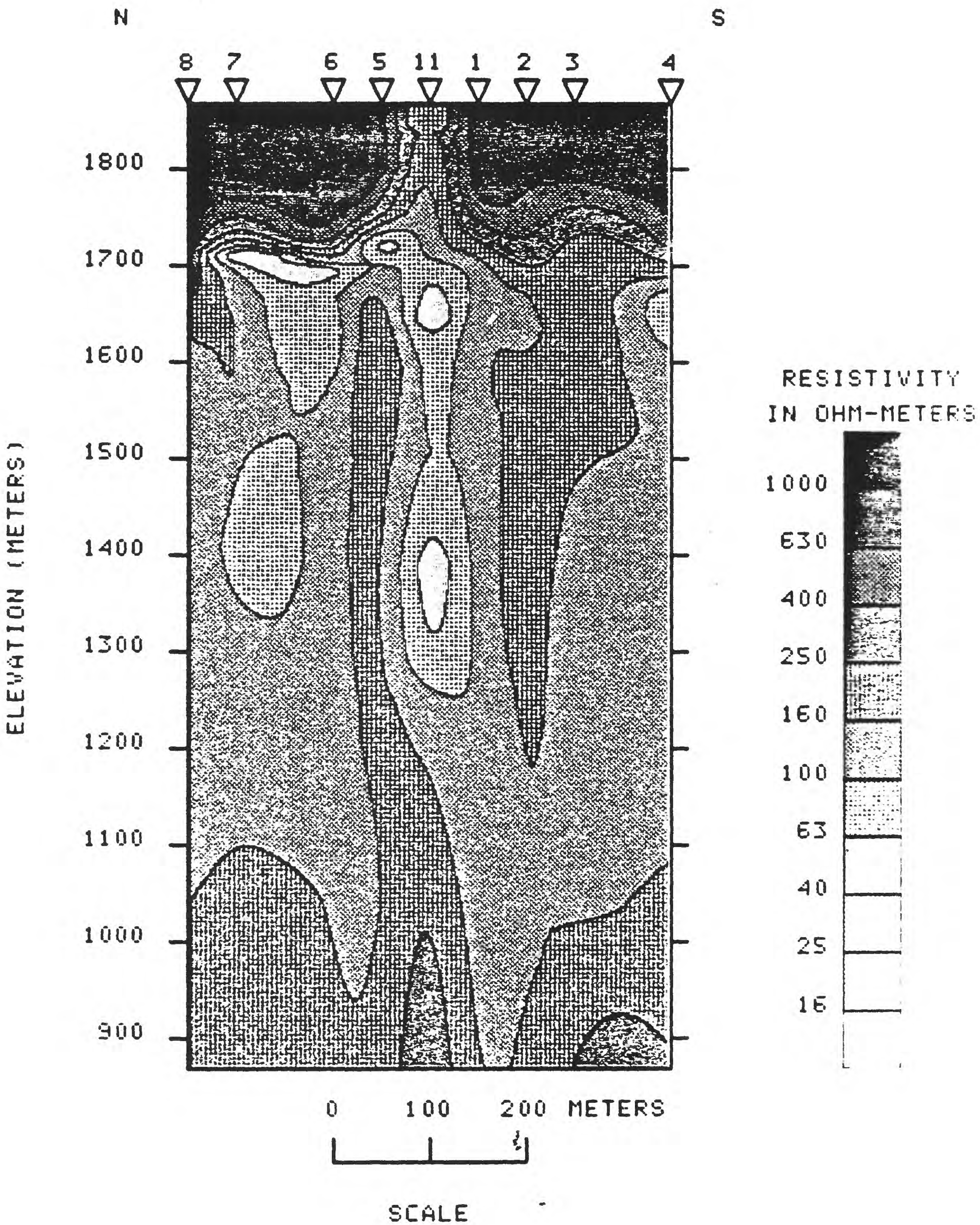


Figure 26 North-south cross section showing resistivity versus depth at site 1119.

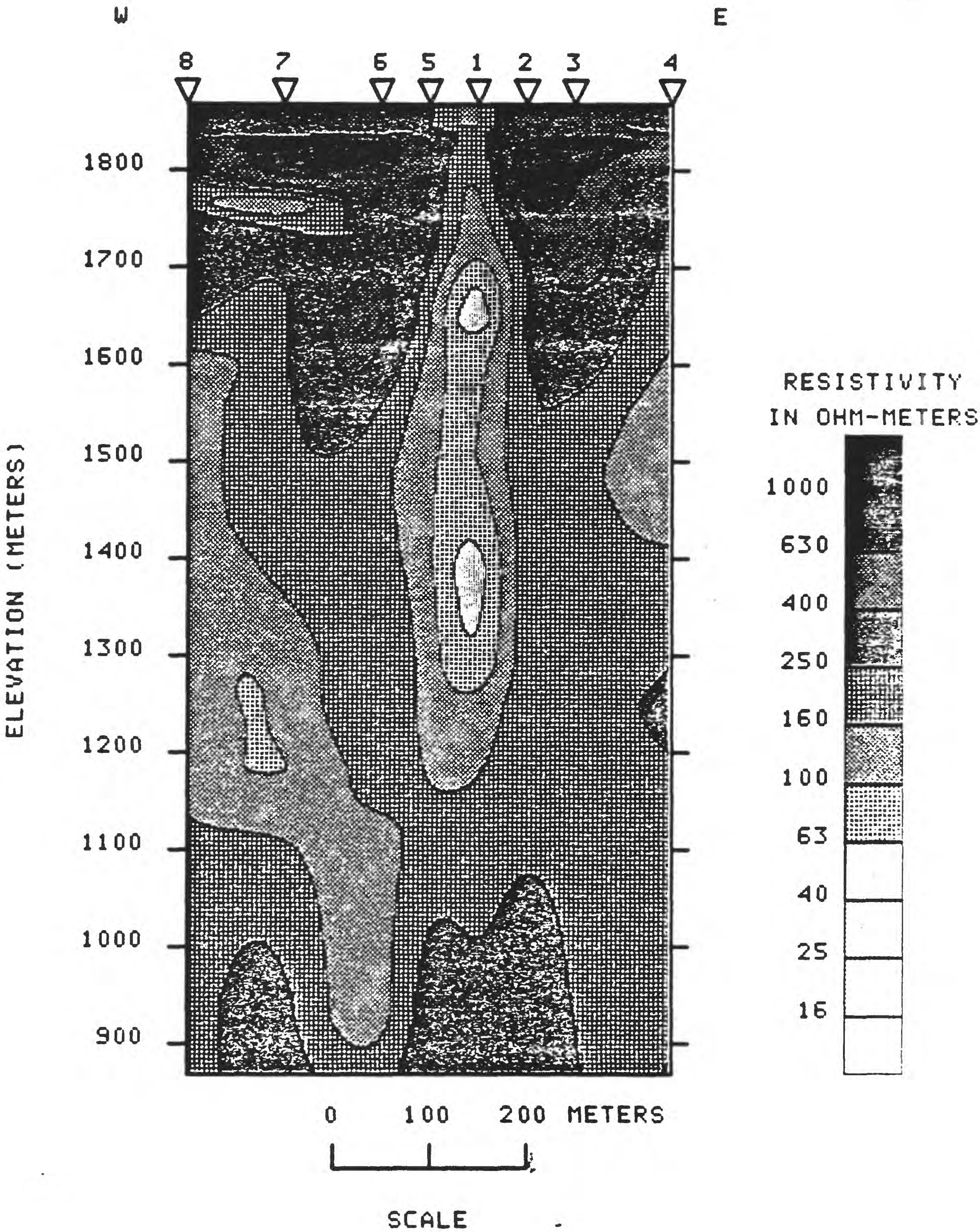


Figure 27 East-west cross section showing resistivity versus depth at site 1119.

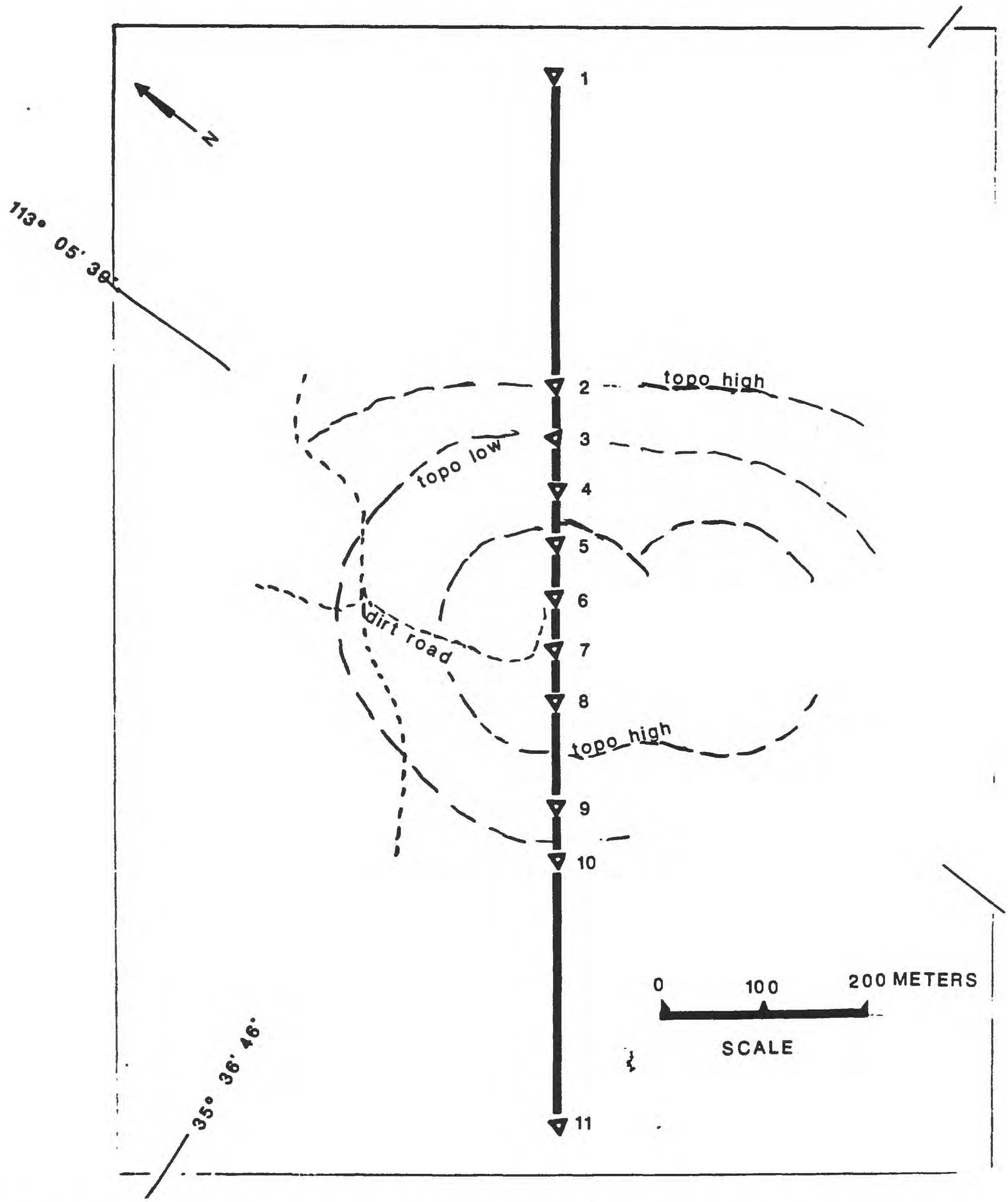


Figure 28 Sketch map of site 220 showing location of AMT soundings along northeast–southwest profile.

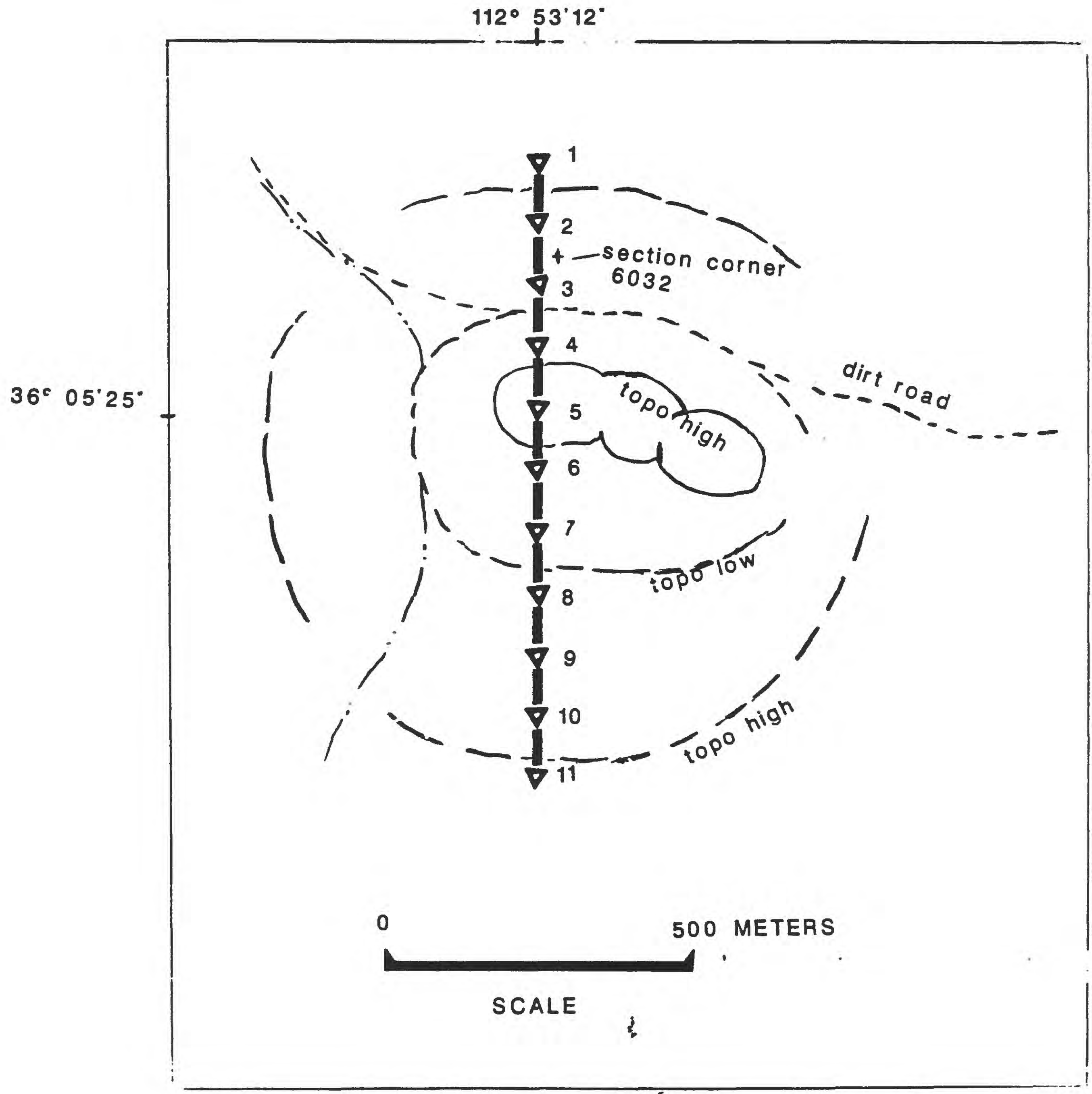


Figure 29 Sketch map of site 232 showing AMT sounding locations.

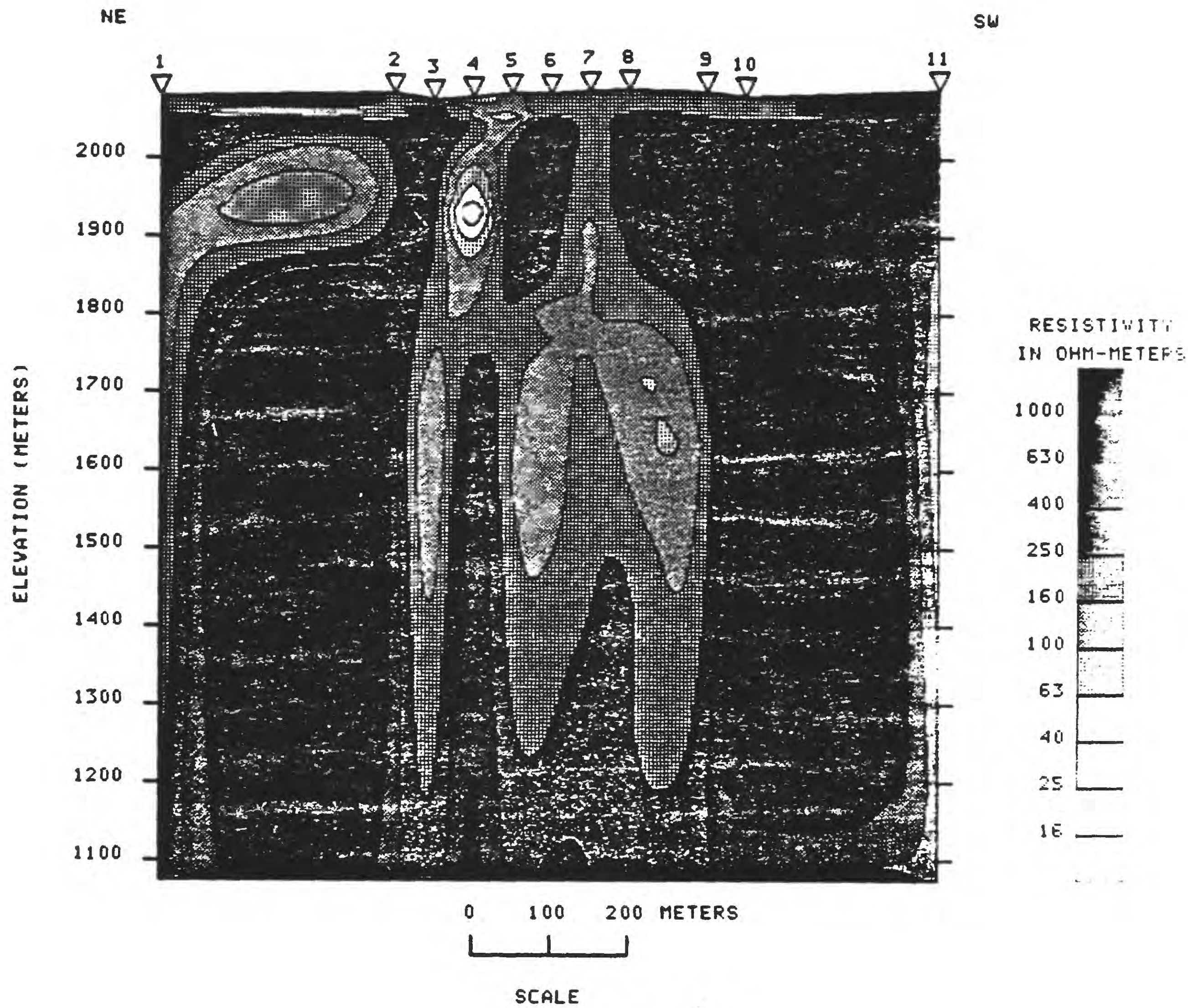


Figure 30 Northeast-southwest cross section showing resistivity versus depth at site 220.

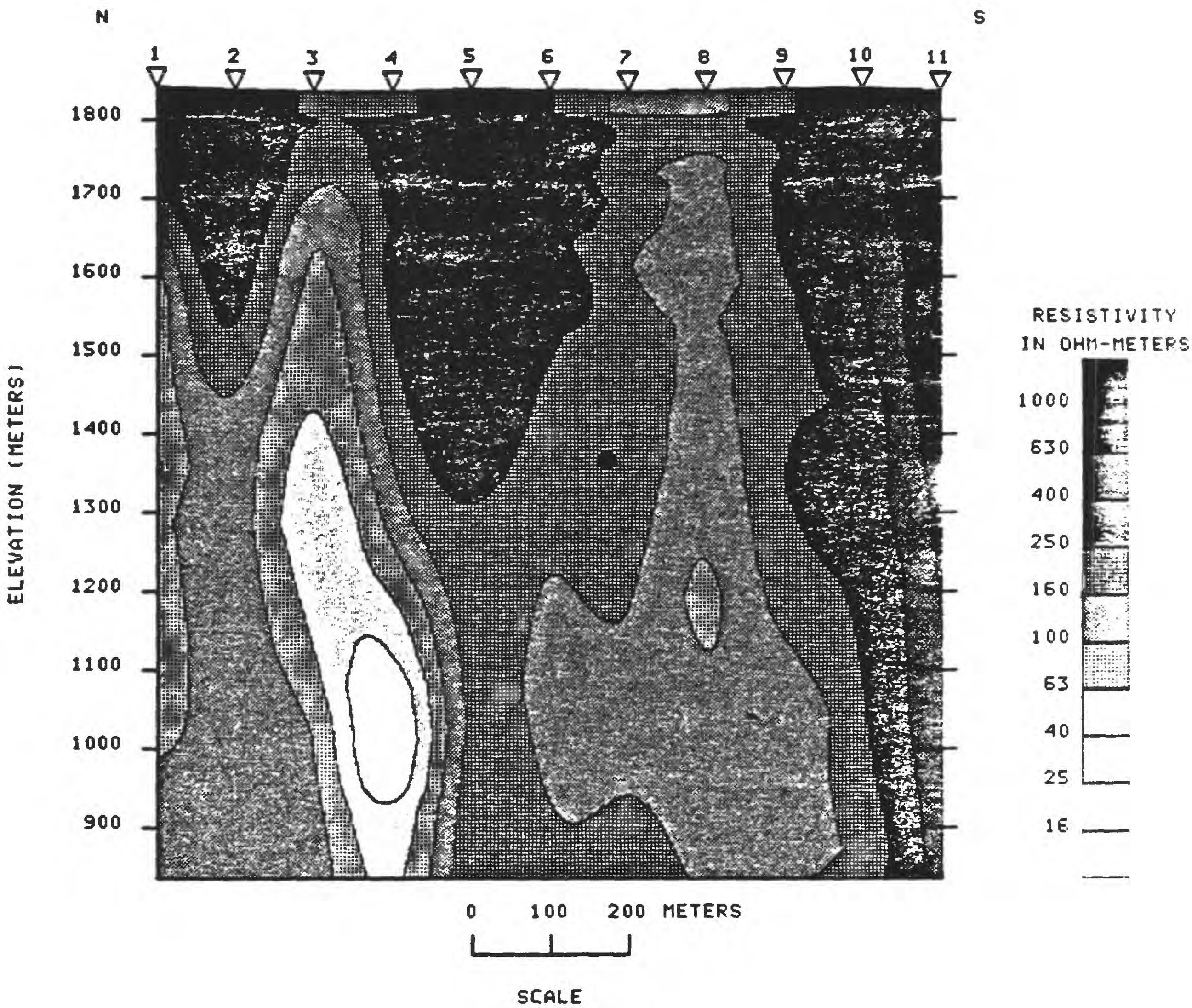


Figure 31 North-south cross section showing resistivity versus depth at site 232.

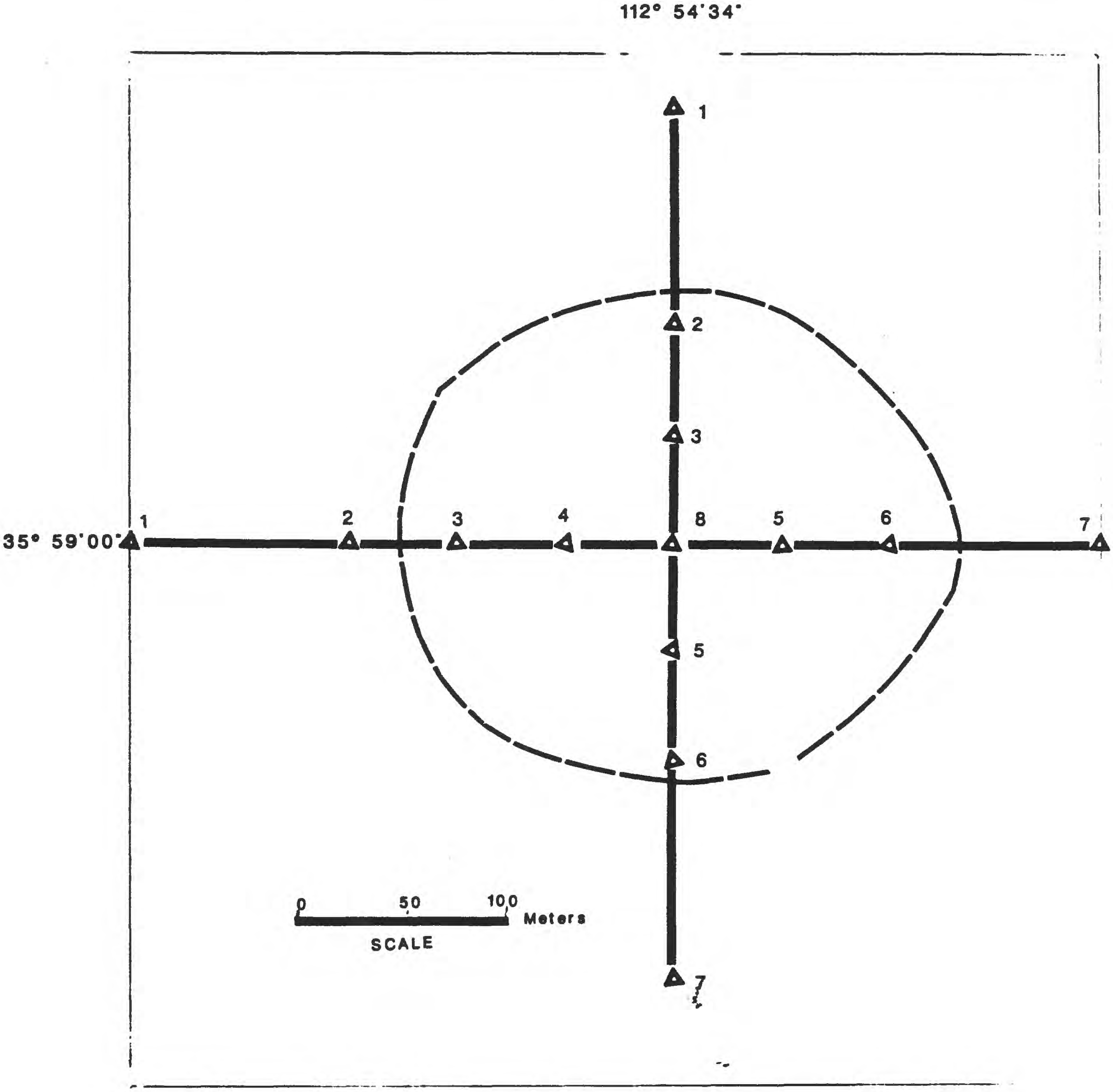


Figure 32 Sketch map showing location of AMT soundings at site 531.

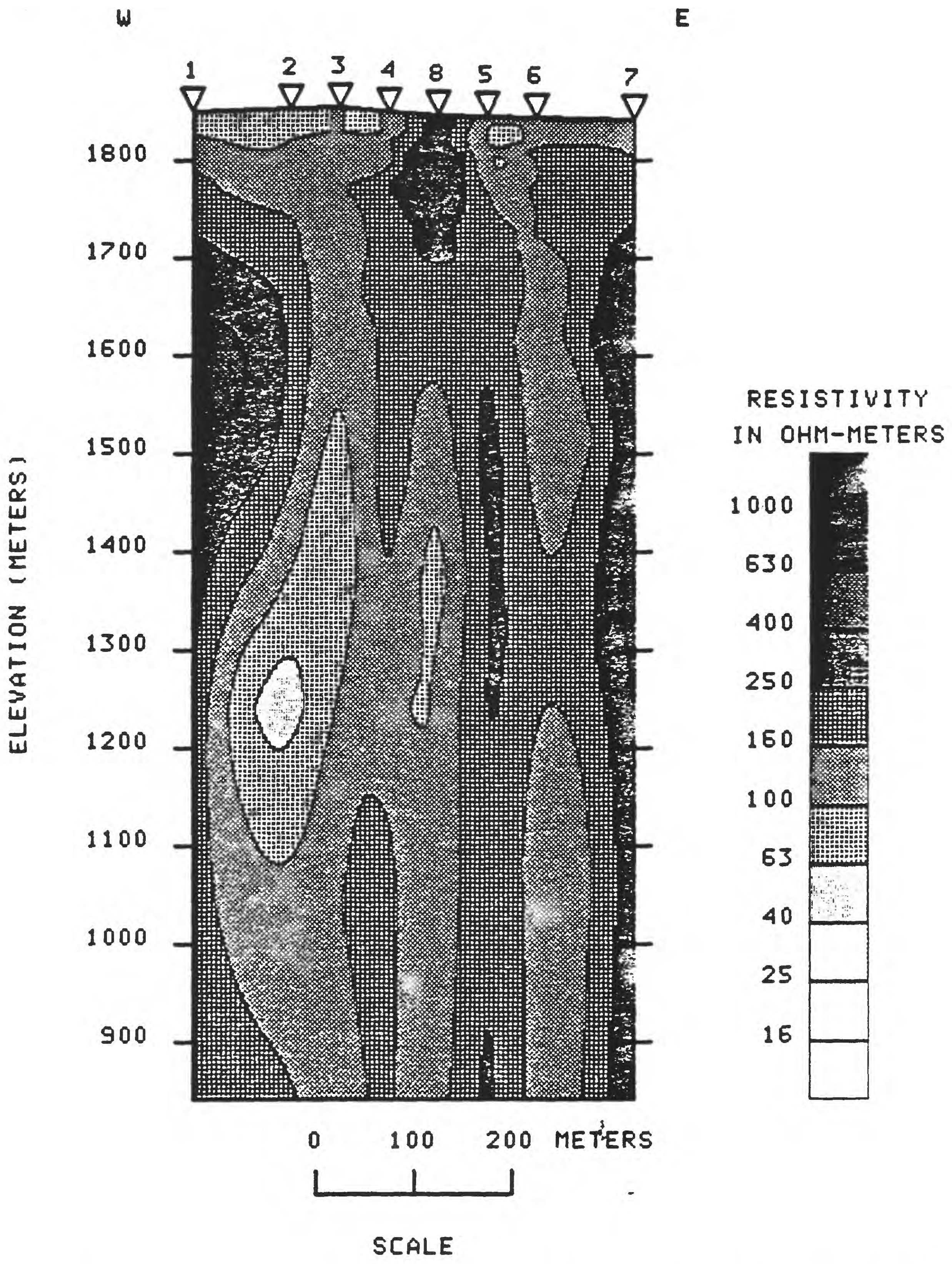


Figure 33 East-west cross section showing resistivity versus depth at site 531.

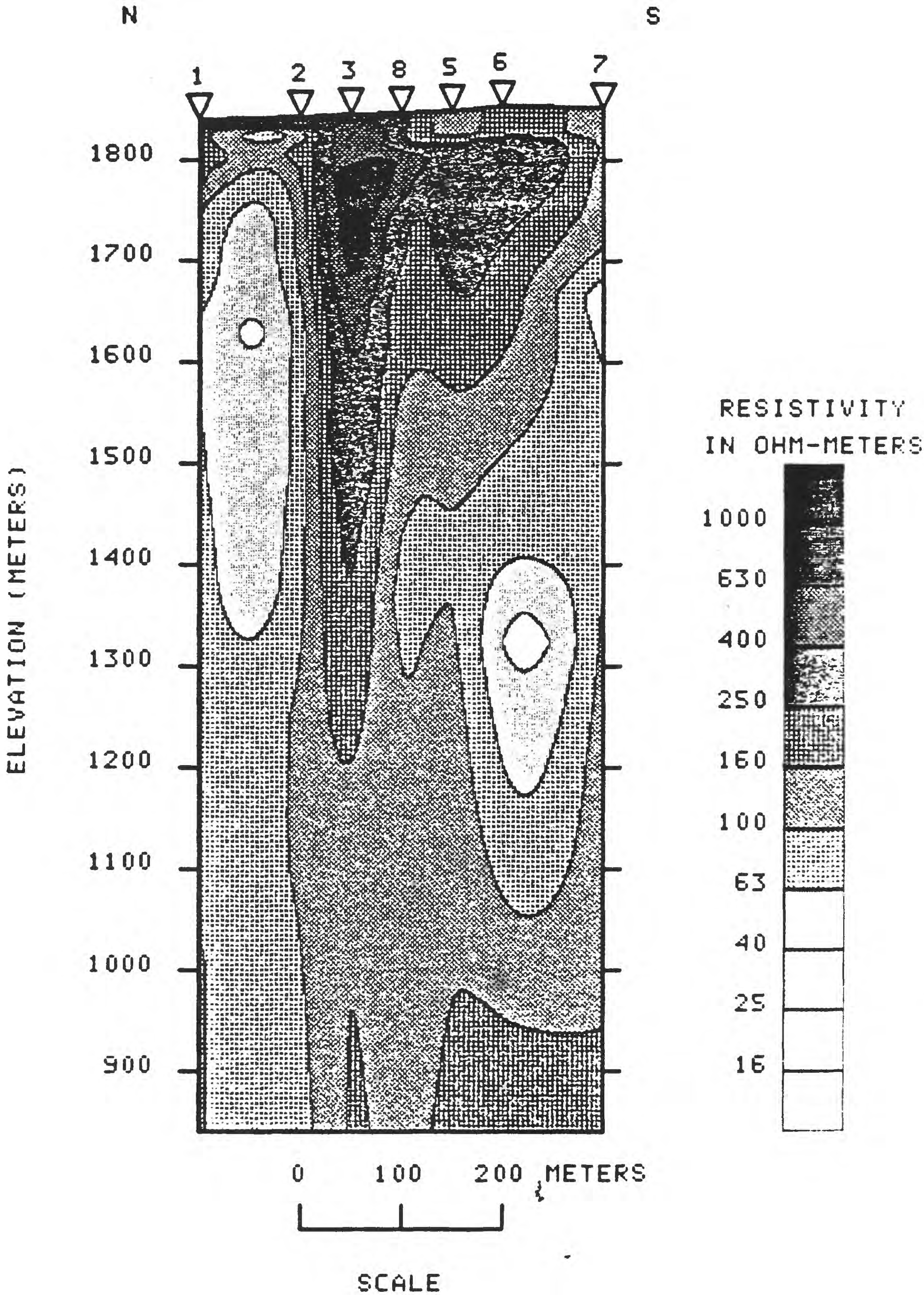


Figure 34 North-south cross section showing resistivity versus depth at site 531.

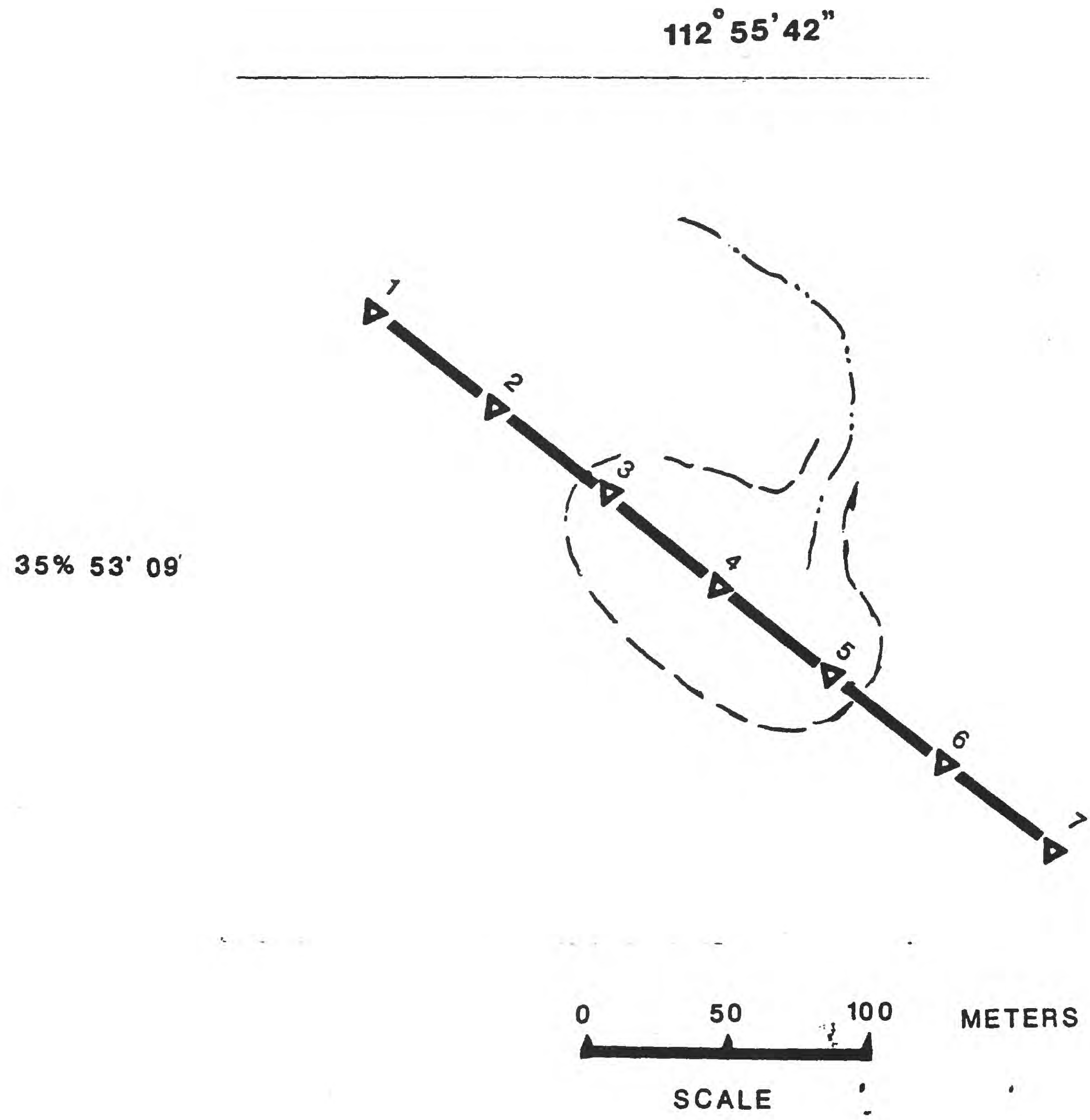


Figure 35 Sketch map showing location of AMT soundings at site 569. Dashed line shows the approximate boundry of topographic depression.

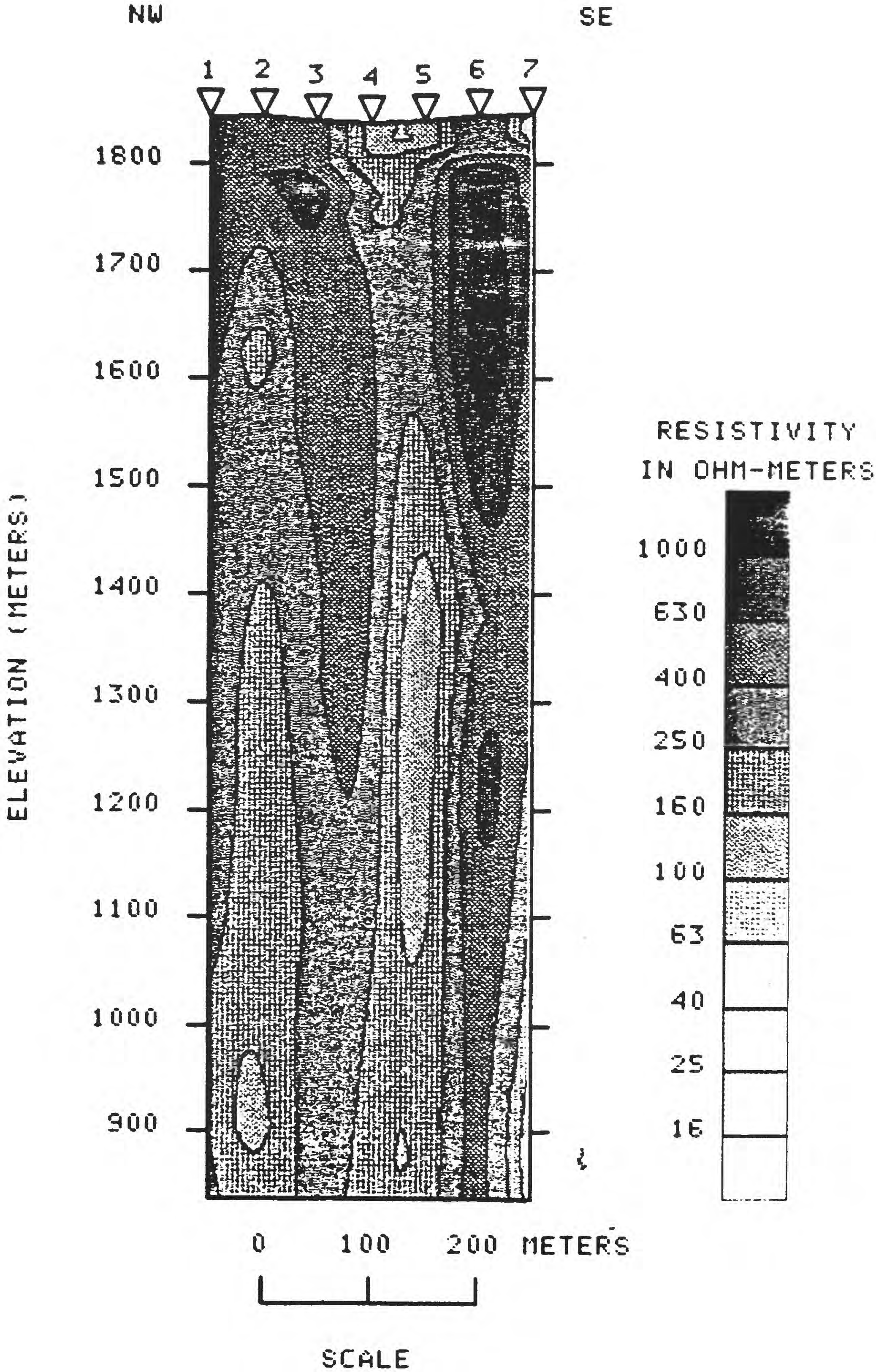


Figure 36 Northwest-southeast cross section showing resistivity versus depth at site 569.

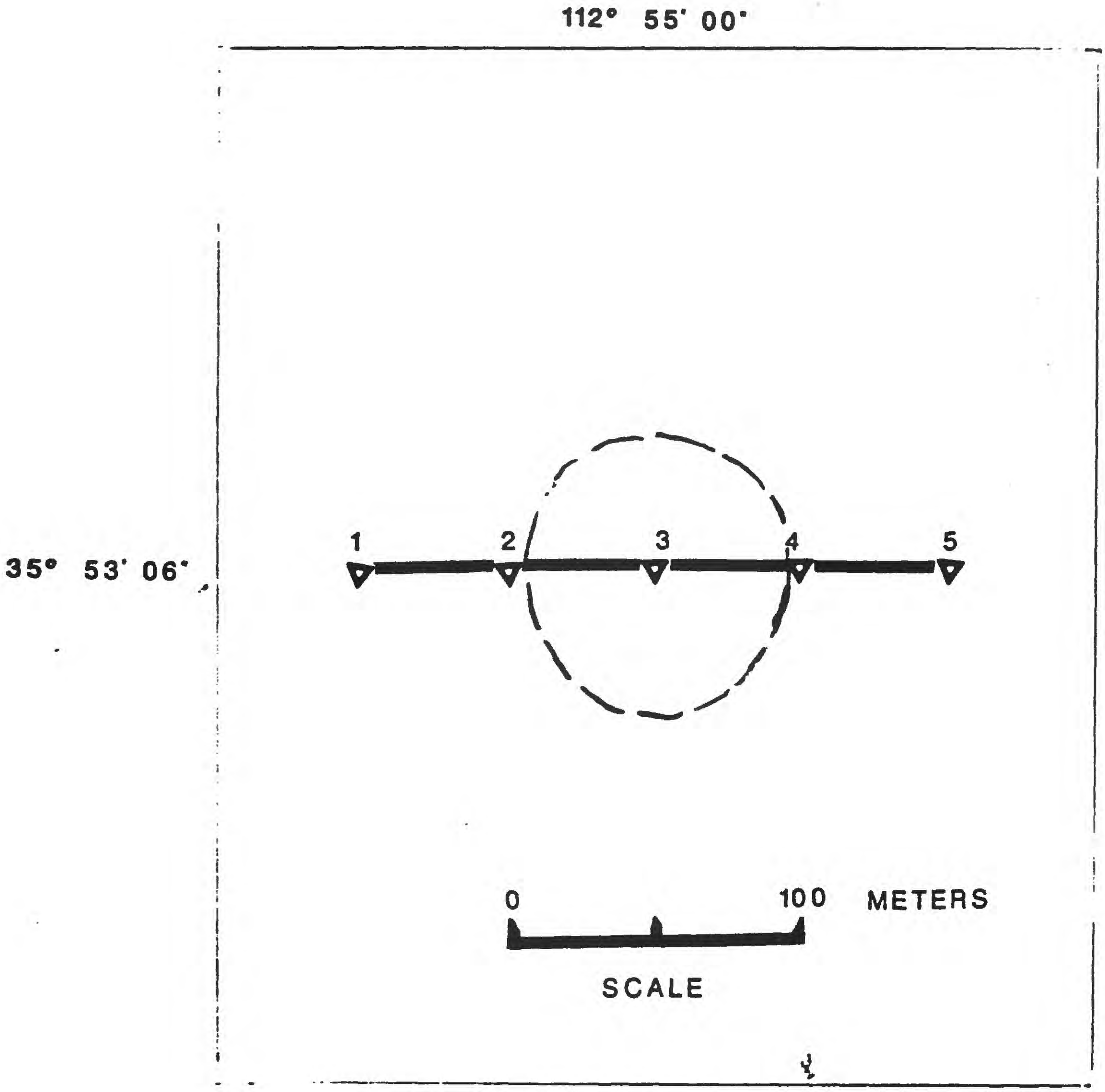


Figure 37 Sketch map of site 571 showing location of AMT soundings. Dashed line shows the approximate boundry of topographic depression.

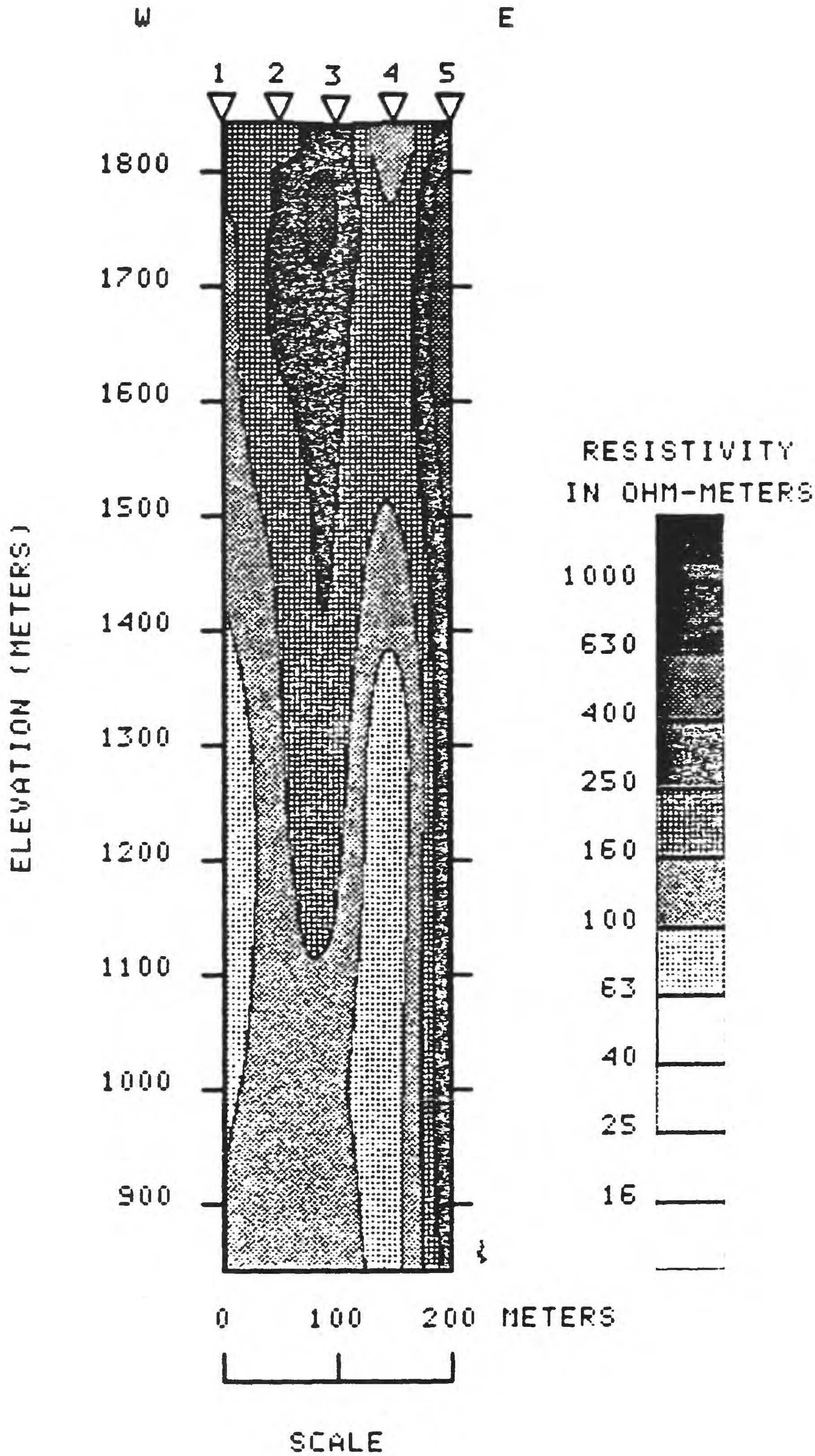


Figure 38 East-west cross section showing resistivity versus depth at site 571.