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AUDIO-MAGNETOTELLURIC METHODS IN RECONNAISSANCE GEOTHERMAL EXPLORATION

By

D. B. Hoover* and C. L. Long*

Introduction

About three years ago, at the initiation of a major effort by the U.S. Geological Survey into studies of geothermal systems, a decision was made to evaluate the audio-magnetotelluric, AMT, technique for this application. At that time we had had no real experience with the method nor any equipment. Some prior work by Lebel [1971], and Slankis and others [1972], suggested that field operations might be slow and difficult reducing the advantages of the method. A cautious approach was used in developing equipment and field techniques until some experience was gained with the method. As no commercial equipment was available, design and fabrication of the AMT equipment to cover the frequency range 8 Hz to 18,600 Hz was done in-house. Because of the nature of the method, our approach has been to use AMT surveys for reconnaissance exploration and to follow up with other electrical methods in interesting areas. In this paper some of the results of our research are shown to illustrate the effectiveness of the technique.

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Method

The AMT method utilizes electromagnetic energy from distant sources permitting a plane-wave assumption. While artificial or natural sources may be used, most work has been done with natural sources because of the convenience of not having to provide a strong source field. This is not without its attendant problems however because of the vagaries of natural signals. Our work has used natural sources, with the exception of the upper end of our operating frequency spectrum. The frequency range covered with our system is from the first Schumann resonance at about 8 Hz to 18,600 Hz where a convenient source is available from the Navy broadcast station NLK at Jim Creek, Washington.

The useable natural energy for AMT exploration originates in worldwide lightning storms, with the principal energy coming from tropical storm cells most frequent during the summer months. The method has been well described by Strangway and others [1973], in relation to mineral explorations. The details will not be repeated here. For our purposes it is sufficient to know that the scalar apparent resistivity is given by,

1. $$\rho_a = \frac{1}{5f}\frac{|E_x|^2}{|H_y|^2}$$

ohm metres where f = frequency in Hertz

E_x = horizontal x directed electric field in microvolt/metre

H_y = horizontal y directed magnetic field in gammas.

Hence to determine the apparent resistivity at a given frequency the mutually orthogonal electric and magnetic fields of the distant lightning are measured. The skin depth, , is an approximate measure of exploration depth and is given by,

2. $\delta = 503\sqrt{\frac{\rho}{f}}$ metres if ρ is expressed in ohm metres.

Thus the maximum exploration depth varies with the square root resistivity of the section and with the inverse square root of frequency.

Briefly some characteristics of the method as they relate to geothermal exploration are given below. As this is an electromagnetic technique it is particularly adapted to looking for conductive bodies related to hot saline waters. A disadvantage in a horizontally layered situation is that a resistive layer under a conductive one must be 2 to 3 times as thick in order to be seen in the sounding data. The depth resolution is not as good as in Schlumberger sounding. Equation 2 shows that the depth of exploration is a function of the resistivity so that apparent resistivity maps at a given frequency may represent widely varying depth samples. This must be kept in mind when viewing the maps presented later. The maximum exploration depth in our AMT system is at 8 Hz where the skin depth is from 176 metres in 1 ohm-metre material to 5.6 km in 1000 ohm-metre material.

From our experience and that of Strangway and others [1973], and Strangway and Vozoff [1970], evidence for lateral resistivity changes are common on AMT sounding curves. This raises problems in one dimensional inversion of the scalar resistivities, and suggests that the tensor AMT method is preferable [Strangway and Vozoff 1970; Pound and others 1973]. We now have developed a tensor AMT system but the examples discussed here will be entirely from our scalar system. For reconnaissance exploration the simplicity and general effectiveness of the AMT technique should be evident in the examples that follow.

Equipment and Operations

Our instrument system consists of two matched narrow band, selectively tuned voltmeters. An envelope detector is used on the output with a strip chart recorder providing visual output. While significantly increasing power consumption, the chart recorder was of major help in distinguishing lightning signals from other spurious events particularly in our early development work. The inputs to the voltmeters are from a 100 metre telluric dipole and an orthogonal ferrite-cored coil. Details of the equipment have been described previously [Hoover and others 1974, Hoover and Tippens 1974]. At the present time 12 field frequencies are available to define a sounding curve, 7.5, 10, 14, 27, 76, 285, 685, 1200, 3300, 6700, 10,200 and 18,600 Hz. At the two highest frequencies signals are obtained from convenient VLF broadcast stations in Washington and North Dakota.

Figure 1 shows typical data from several records. Resistivities at each frequency are computed in the field during the recording operation using an Hewlett-Packard HP 65 calculator. The log of the resistivity is plotted against the inverse log of frequency, Fig. 2, to give an AMT sounding curve comparable to a Schlumberger sounding. Generally 10 distinct high amplitude events are read, the apparent resistivity calculated from equation 1, and the average and standard deviation computed. By averaging, some of the problems of varying source direction are minimized and better reproducibility is obtained. Generally, two soundings are made at each site one with the telluric line oriented north-south and another east-west.

Due to poor signal conditions we seldom record at 10 and 1200 Hz. Signals are usually good at 27, 76 and 6700 Hz, and above. The other frequencies exhibit variable signal conditions. Signals have a seasonal peak in the summer particularly for the mid-frequency range. Because of weak signals during the winter season, a question existed as to whether effective operations could be conducted during this time (Pound and others, 1973). We have conducted a survey in December with success at the lower frequencies, although signals from 285 to 3300 Hz were generally absent. The lack of mid-range data is a problem for inversion of the sounding data; however, apparent resistivity maps at the lower frequencies are quite sufficient to define anomalous areas for more definitive follow-up work.

Field operations require two persons operating from a carryall or camper. Typically 4 stations or 8 soundings are obtained per day. Production is expected to be about doubled in our new system giving a very cost-effective reconnaissance operation.

AMT Surveys

In our reconnaissance work the soundings are plotted as the data are recorded and several apparent resistivity maps prepared in the field to guide the surveying and aid in site selection. This has proven to be an important aspect in the effectiveness of AMT surveying. After the field survey has been completed apparent resistivity maps are prepared for all frequencies of interest. As a rule, a map at 7.5 Hz is prepared by averaging values for the two sounding directions because of poorer data quality at this frequency. In addition, two 26 Hz maps are usually prepared to indicate effects of lateral variations which may be present. Often pseudosections will be prepared as aids in understanding resistivity variations and also to indicate the variation in exploration depth.

Due to space limitations only a few of the figures available from each of the geothermal areas will be shown, to illustrate the application of the technique and how it can be used in an exploration program. Further details may be obtained from our open file data. A companion paper by P. Williams and others in this symposium illustrates the integration of AMT data from the Raft River, Idaho, into a complete exploration package.

The Long Valley caldera in eastern California was the first area in which our AMT equipment was tested in conjunction with other geophysical methods. Details of the studies are given by Hoover, Frischknecht and Tippens (1974). Figure 2 shows four soundings taken at two sites in Long Valley. These data are typical. The station-1 sounding shows typical reproducibility of the two sounding orientations where no evidence for lateral effects are present. Station 14 illustrates obvious lateral effects at the lower frequencies. In this case the lateral effect is attributed to a known fault and hot spring about 100 metres east of the sounding station.

Figures 3 and 4 show the two 26-Hz apparent-resistivity maps in Long Valley for the two polarizations. The map showing rock types is adapted from R. Bailey (1974) is also shown in Figure 3. The two maps show a region of low resistivity in the south-central part of the caldera about where the Hilton Creek fault enters and splays north and northwestward. The principal hot spring activity is near, or contained in the area outlined by the 45 ohm-metre contour in Figure 3. There is no obvious correlation between the AMT data and the surficial geology. The leaking of this geothermal system to the surface appears to be along the north to northwest faults within the caldera from a deep source (Stanley, Jackson and Zohdy, 1974). The AMT data appears to reflect the region where the most extensive leakage and alteration has occurred within the upper part of the caldera.

The lower apparent resistivities seen in the data for north-south orientation of the telluric line is probably related to the predominant north to northwest fault trends. The southern edge of the caldera is well defined on the maps by the steep resistivity gradient seen as the Sierra batholith is approached.

Figure 5 shows a comparison between the 26 Hz average AMT resistivity data and a composite total field resistivity map from Stanley, Jackson and Zohdy (1974). There is good agreement between the data sets in the low resistivity zone. This is particularly true when consideration is given to effects of lateral variation and varying depths of exploration of the two techniques. The southern edge of the caldera is more clearly defined by the AMT survey probably due to the greater influence of lateral effects, and a higher resistivity contrast in the upper part of the section.

The Island Park topographic basin in eastern Idaho adjacent to Yellowstone National Park is an area of extensive leasing activity. Current geologic evidence suggests that a Yellowstone-type system does ? not exist at Island Park because the last major rhyolite body was emplaced about one million years ago and subsequent eruptions were of basaltic composition coming from the mantle along fractures in the older caldera (R. L. Christiansen oral communication, 1975). The general absence of hot springs also suggests an old system. AMT and telluric surveys were made in August 1974 to study the possible existence of concealed hydrothermal activity.

The generalized geology of rock types in the caldera is shown in Figure 6 with the 7.5-Hz N-S AMT data. The caldera stands out as an area of high resistivity, generally above 100 ohm-metres, surrounded by a region of intermediate values. Within the caldera local highs around 1000 ohm-metres are associated with small rhyolite domes on the surface, and mostly hidden by later basalt flows. The AMT data shows the possibility of another rhyolite body on the western rim of its caldera which has been covered by tuff and rhyolite flows, and may represent a source for some of these materials.

An east-west cross-section is shown in Fig. 7. Included in the figure is a skin-depth pseudosection obtained by contouring the apparent resistivities at their corresponding skin depths on the section, and a second section obtained by one-dimensional inversion of the same sounding curves. The corresponding gravity and magnetic data showing an edge of the body near station 11. The gravity data shows a high associated with the caldera partly masked by the flanks of the extreme low associated with the Yellowstone region.

The telluric survey data appears in Fig. 8 which shows a high degree of correlation with the AMT data. Telluric data was obtained in the 20 to 30 sec. period range, which would give a skin depth around 25 km in 100 ohm-metre material. The high resistivity material in the southeast part of the caldera is present at depth as indicated on the telluric map, and even the smaller high on the western edge can be seen as well. The telluric data also clearly shows the caldera as a region of high resistivity. This implies that the caldera has cooled, that there is little rock alternation and that the area is not now a very promising exploration target. The high resistivities in Island Park basin clearly support Christiansen's inferences.

A small region near Vale, Oregon, has been classed as a known geothermal resource area (KGRA). Hot spring activity occurs at the town of Vale and at two locations near the neighboring town of Weiser, Idaho. This area is in the Snake River basin [Newton and Corcoran, 1963] which is on the western edge of the Snake River Plain. The basin is underlain by a thick, at least 1.5 km (5000 ft) and possibly 4.6 km (15,000 ft) section of principally nonmarine Cenozoic sediments. The area shown in Figures 9 and 10 is covered almost completely by Idaho Group of Pliocene and Pleistocene age made up of gravel, sand, silt, clay, and ash. In the middle of the basin, which is centered in the mapped area, the Idaho Group is at least 1.2 km (4000) to 1.5 km (5000) feet thick as shown by a number of gas wells drilled within the basin. Older Tertiary rocks crop out around the edges of this region with the principal one being the Columbia River Basalt Group. Structural trends south of Vale are principally north-south, bending more to the northwest in the vicinity of Weiser.

Figures 9 and 10 show the two 27-Hz AMT maps obtained in the basin. As the Crane Creek hot springs northeast of Weiser one of the lowest apparent resistivities was measured, 0.5 ohm-metres, at 8 Hz. The maps in the Weiser region shows rather complex structures and evidence of much lateral change. The higher resistivities in the northern part of the area are associated with older rocks at the edge of the Idaho batholith.

Within the basin proper, the principal trend in the electrical data is northeast. A resistivity low runs through Vale and extends about 20 km to the southwest. Extension of this trend northeast runs into the low at Crane Creek about 20 km northeast of Weiser. A local high of about 16 ohm-metres, just north-east of Vale apparent only in Fig. 10 also is on this same trend. The high is related to the rocks comprising Malheur Butte next to which the sounding was made. This is a small prominent plug in the region whose emplacement may be structurally related to this same northeast trend.

Because of the low resistivities in the basin, the depth of AMT exploration does not in most places extend below the sediments. We attribute the anomalies to hot, saline waters and alteration within the sedimentary section. It is interesting that the electrical trends do not coincide with the surface structural trends. Leakage of the geothermal system to the surface however is probably along faults in the sedimentary section. This same observation has been made in other regions--most clearly in the Surprise Valley, California, KGRA where north-trending basin-and-range faulting is prominent yet the trend of the data relating to the geothermal system implies a northwest direction.

A telluric survey was made in the Vale, Oregon area and the data are shown in Figure 11. The correlation of this map with the AMT data is not as direct as in Island Park which might be expected. The AMT survey is sampling principally the young basin sediments while the telluric data samples a larger part of the crust and may be reflecting basement topography. A low saddle in the telluric data however is seen just north of Vale with a trend to the east and northeast. The lowest values on the telluric map are on the eastern edge near the towns of Ontario and Nyssa.

Summary

A small amount of our AMT data has been shown to illustrate the type of applications to geothermal exploration in which the U.S. Geological Survey is using this method. Several types of data presentations and analyses were also shown. At this time we believe that the principal application is in reconnaissance explorations for shallow to intermediate depth systems. In the reconnaissance phase it is best used in conjunction with standard low-frequency telluric or magnetotelluric techniques which give information at greater depths. AMT exploration is not meant to substitute for more conventional resistivity methods which where applicable can give a more definitive model of resistivity layering in an area. It is intended as a cost-effective tool to delineate areas for more exhaustive follow-up surveys.

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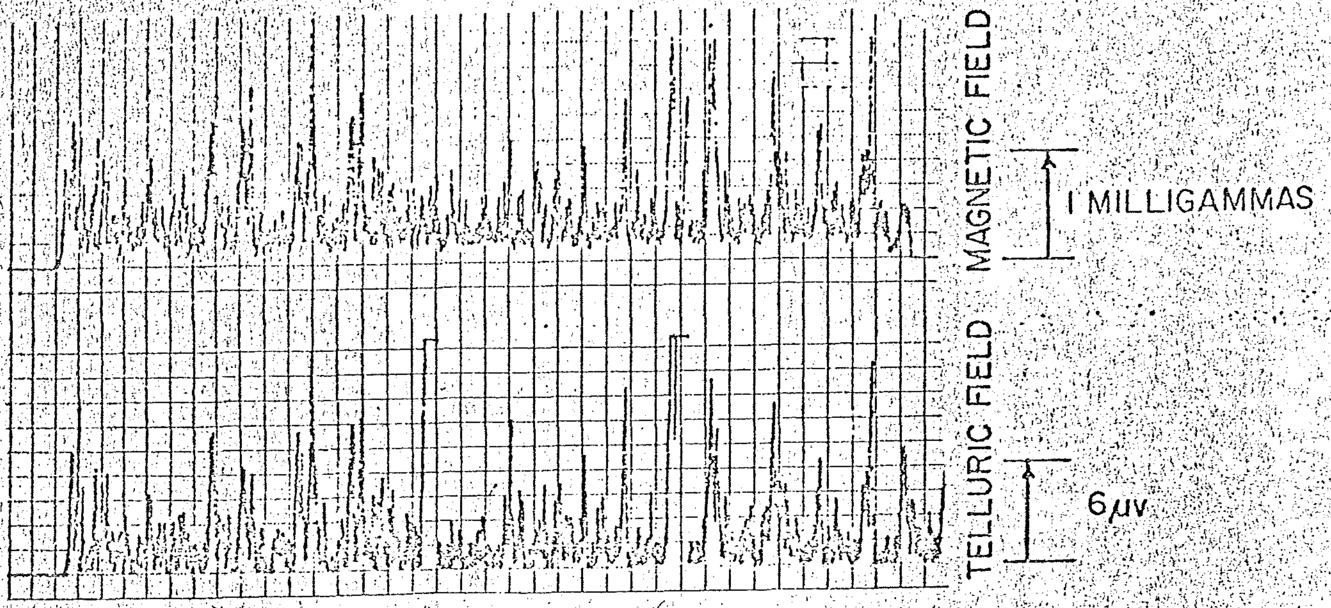
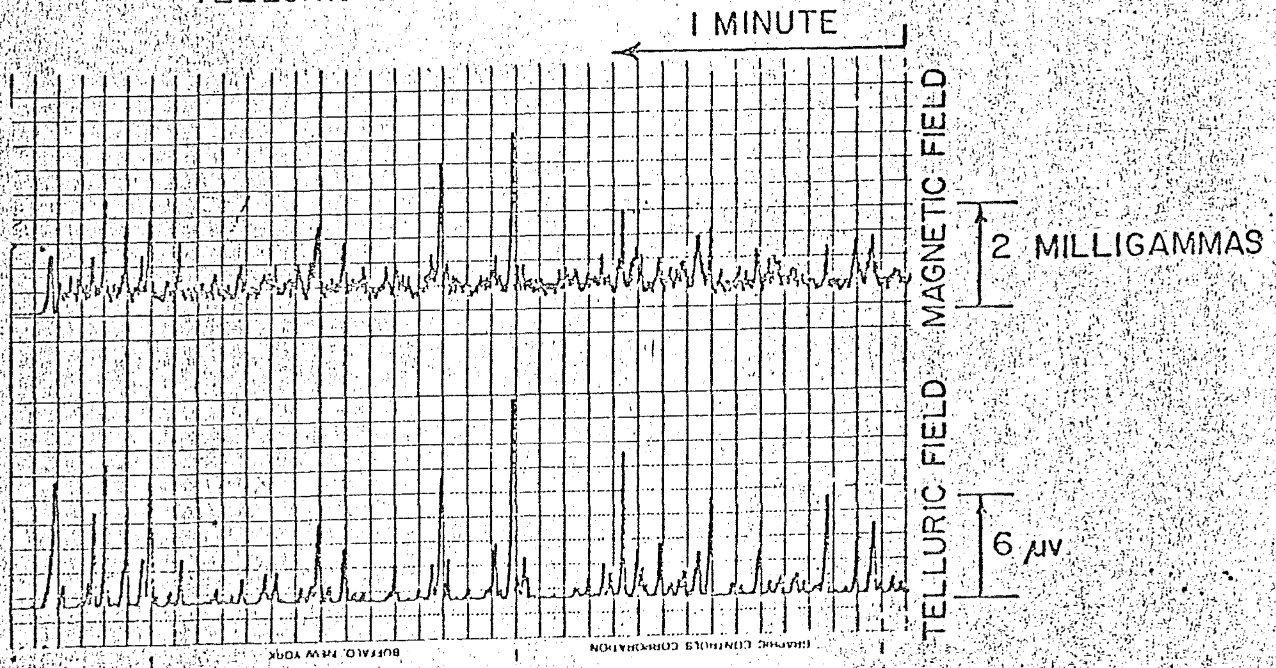


RAFT RIVER, IDAHO-AUG. 10, 1973
TELLURIC LINE NORTH-SOUTH



SURPRISE VALLEY, CALIF.-DEC. 6, 1974
TELLURIC LINE EAST-WEST

Figure 1.--Typical AMT data at 26 Hz.

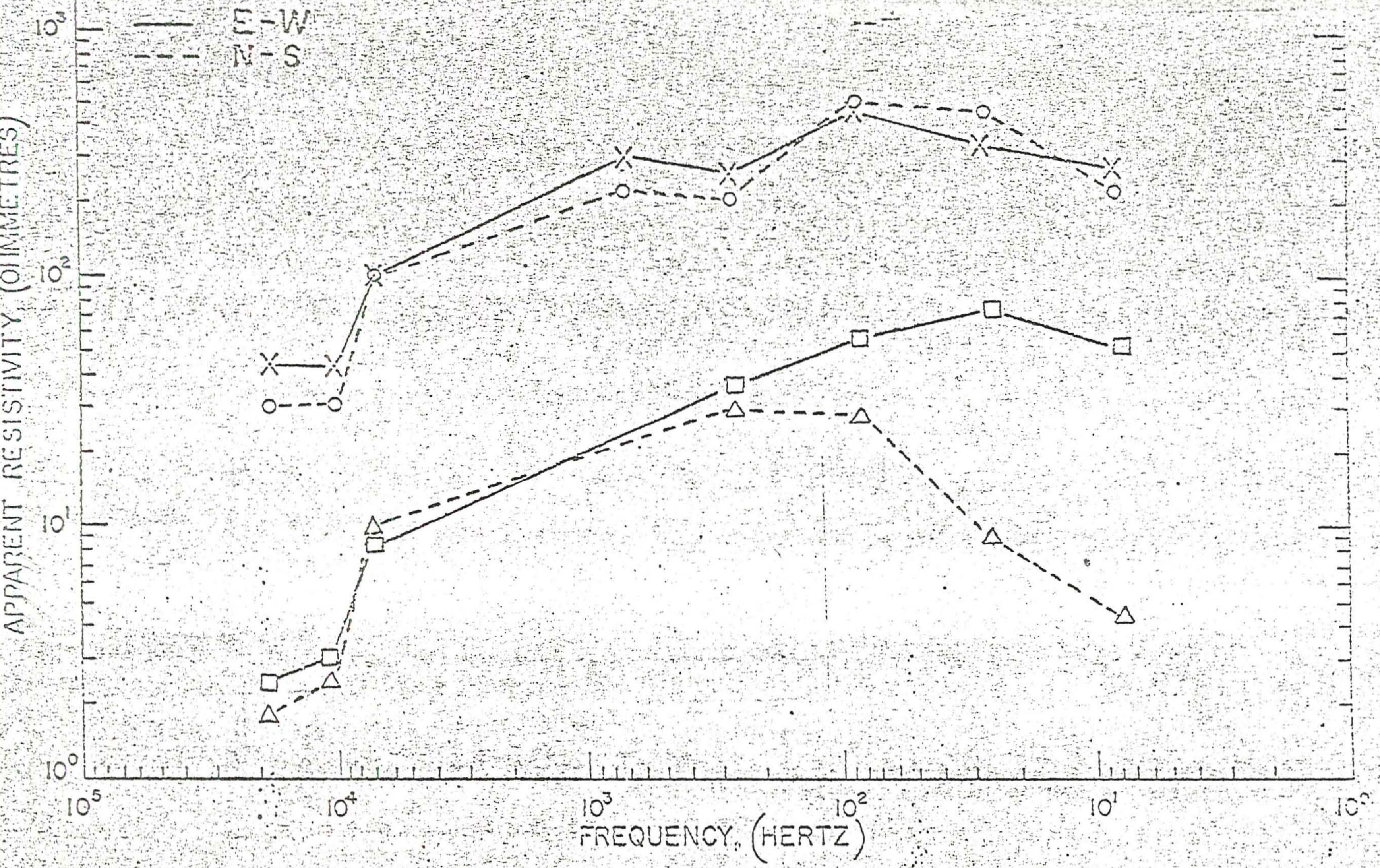


Figure 2.--Long Valley AMT soundings at stations 1 and 14. X, telluric line east-west, station 1; 0, telluric line north-south, station 1; □, telluric line east-west, station 14; △, telluric line north-south, station 14.

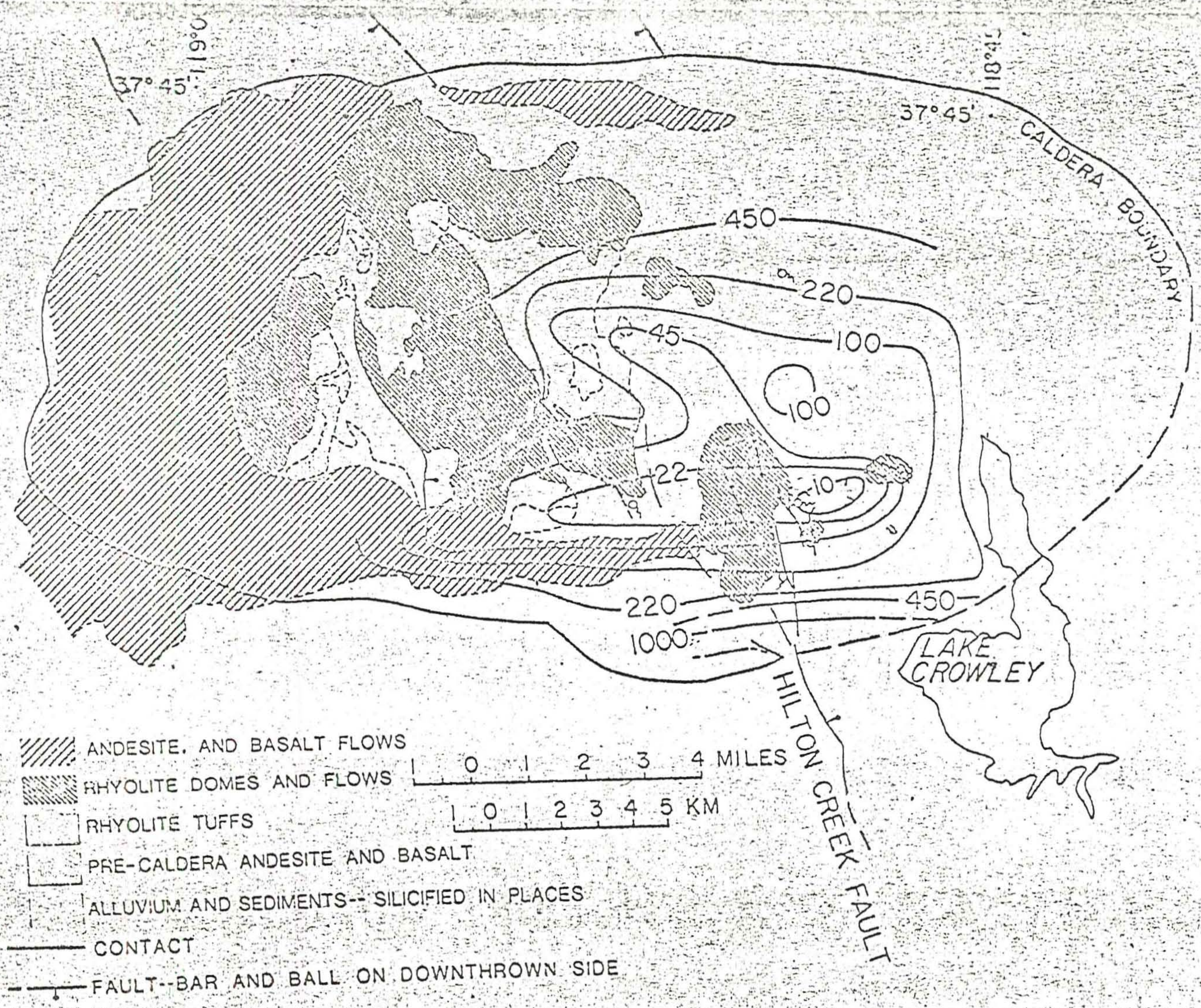


Figure 3.--Rock type and 26-Hz apparent-resistivity map (telluric line north-south), Long Valley, California. Contours in ohm metres; dashed where approximate.

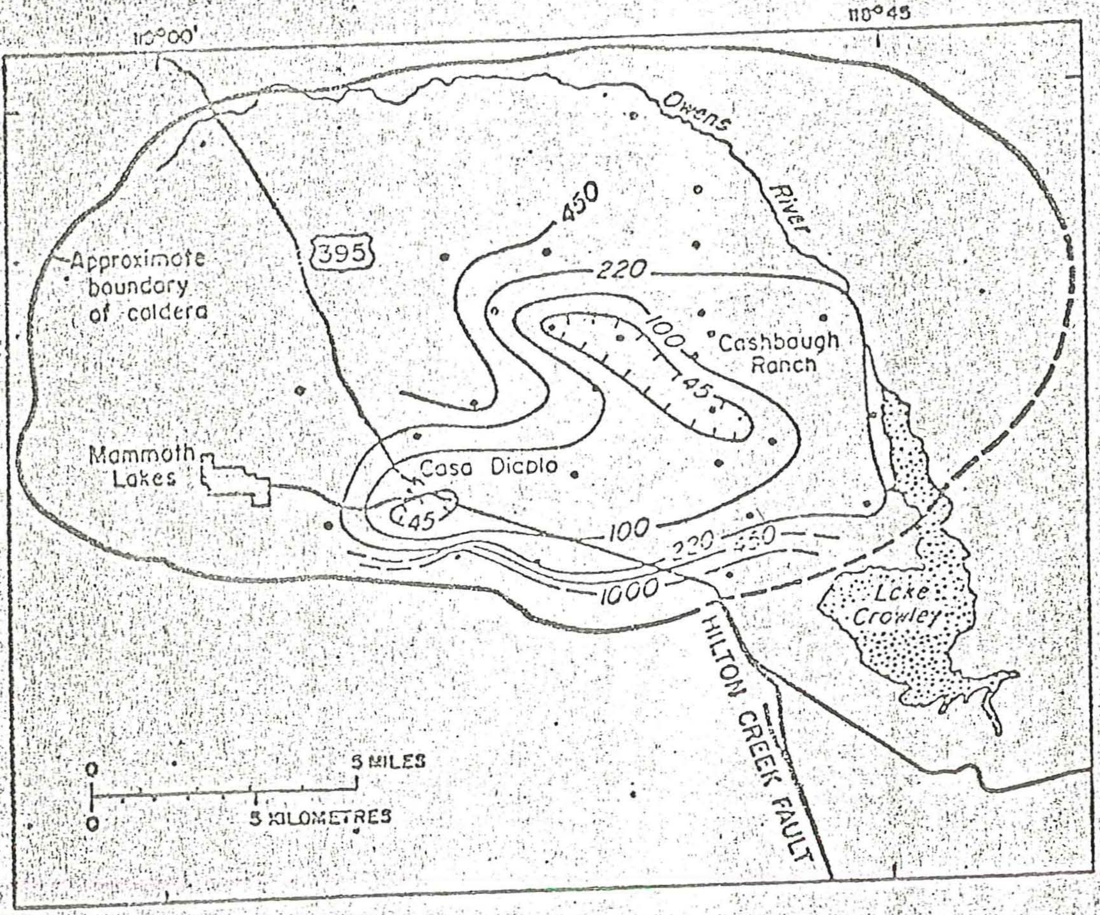


Figure 4.--26-Hz apparent-resistivity map (telluric line east-west), Long Valley, California. Contours in ohm metres; dashed where approximate.

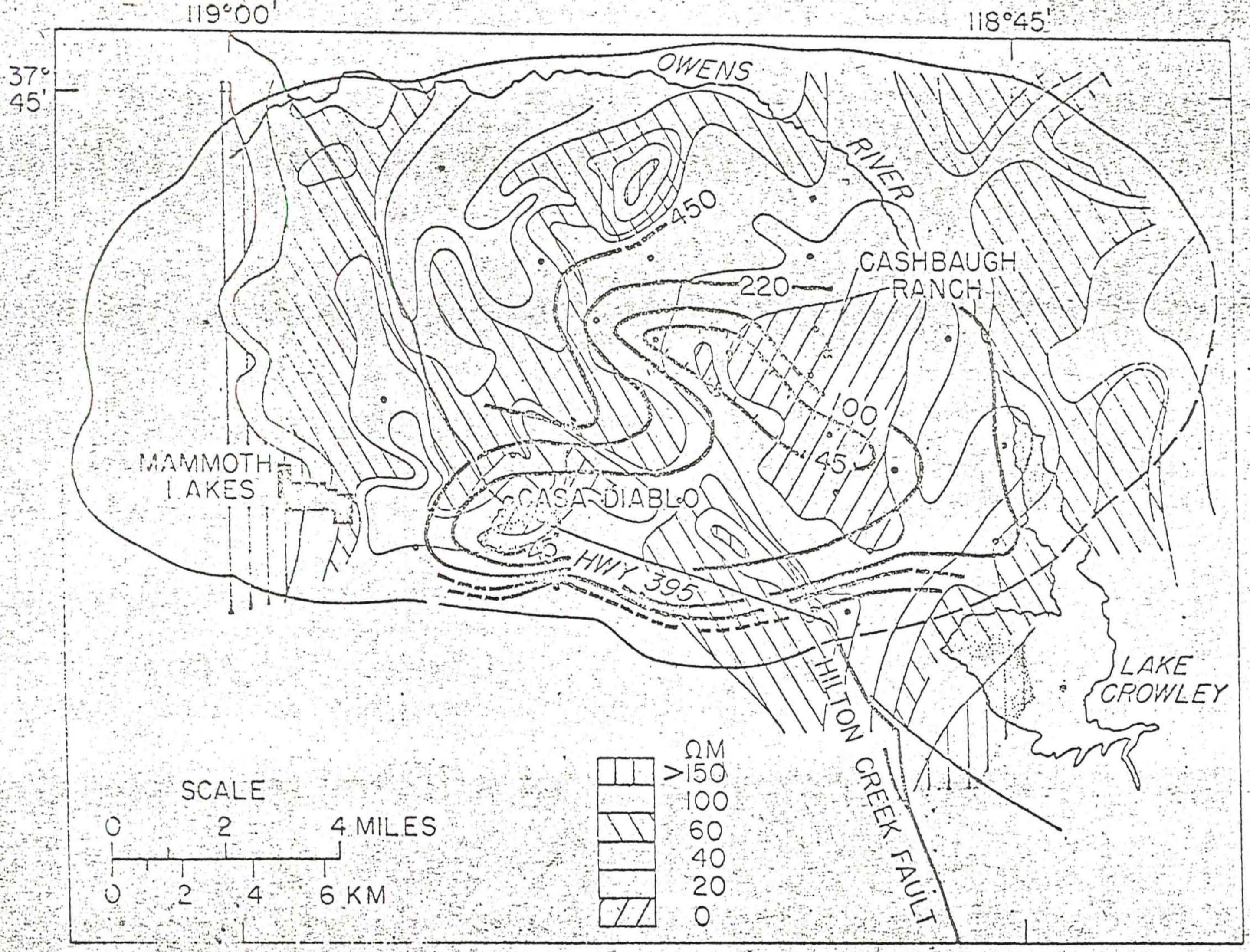


Figure 5.--Comparison of 26-Hz apparent-resistivity data (telluric line east-west AMT data with total field resistivity data, Long Valley, California.

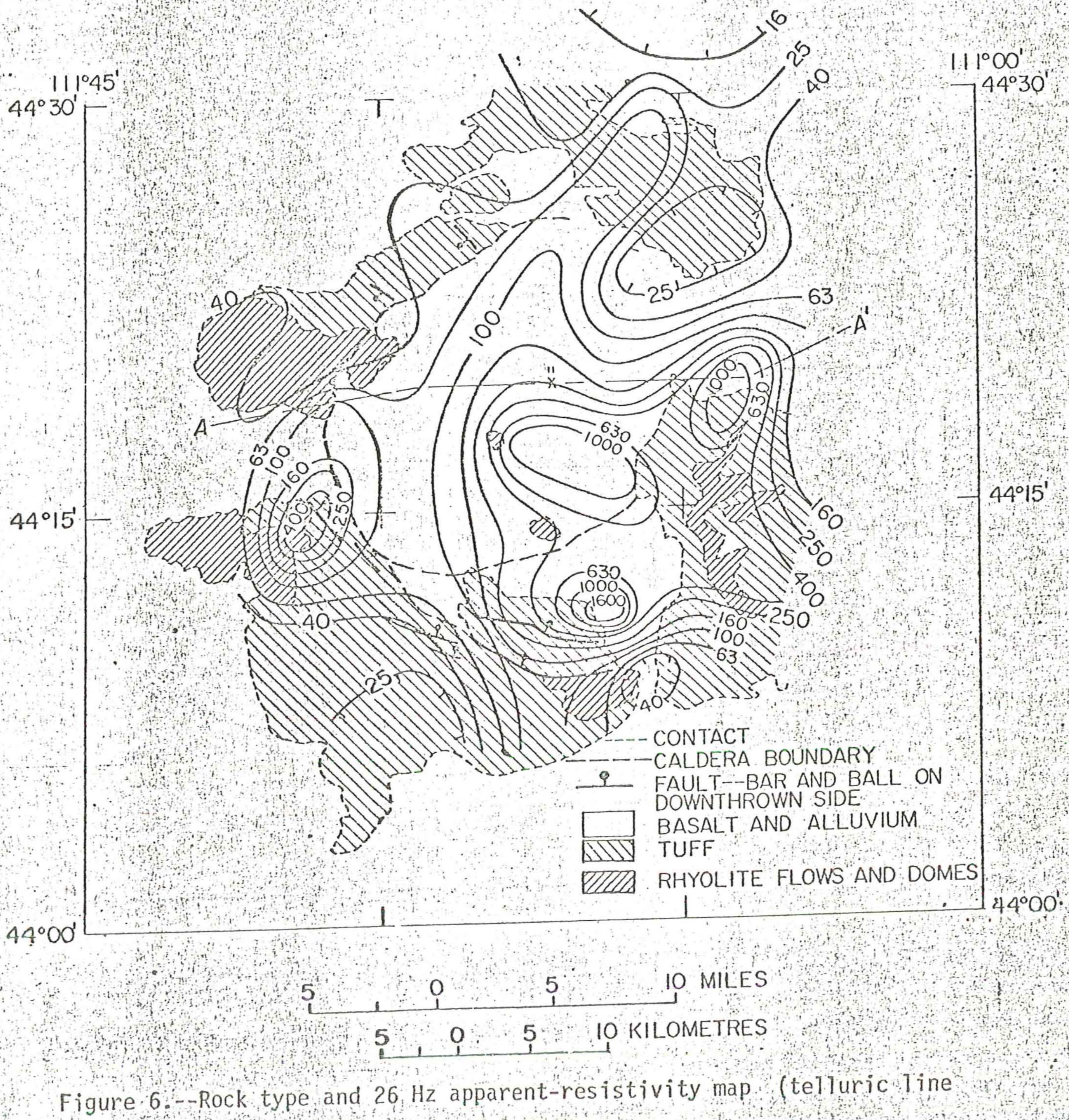


Figure 6.--Rock type and 26 Hz apparent-resistivity map (telluric line north-south), Island Park, Idaho. Contours in ohm metres and logarithmic basis.

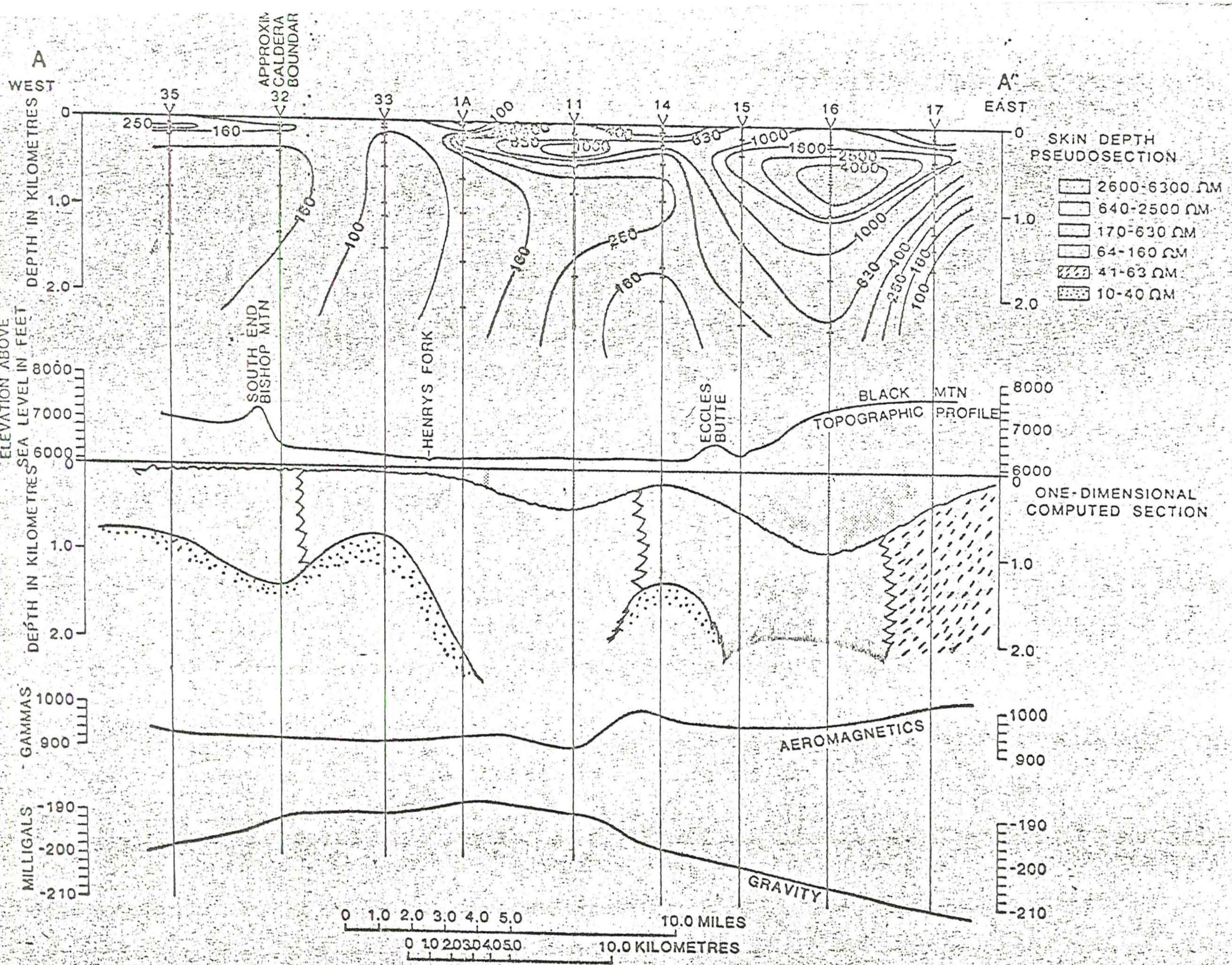


Figure 7.--Comparison of skin depth pseudosections and one-dimension inverted section with gravity and magnetic data across the Island Park area. Line of section shown on figure 6.

Figure 8.--Telluric anomaly map at 20-30 sec period, Island Park, Idaho.

Contour interval 2K = $10\sqrt{J}$.

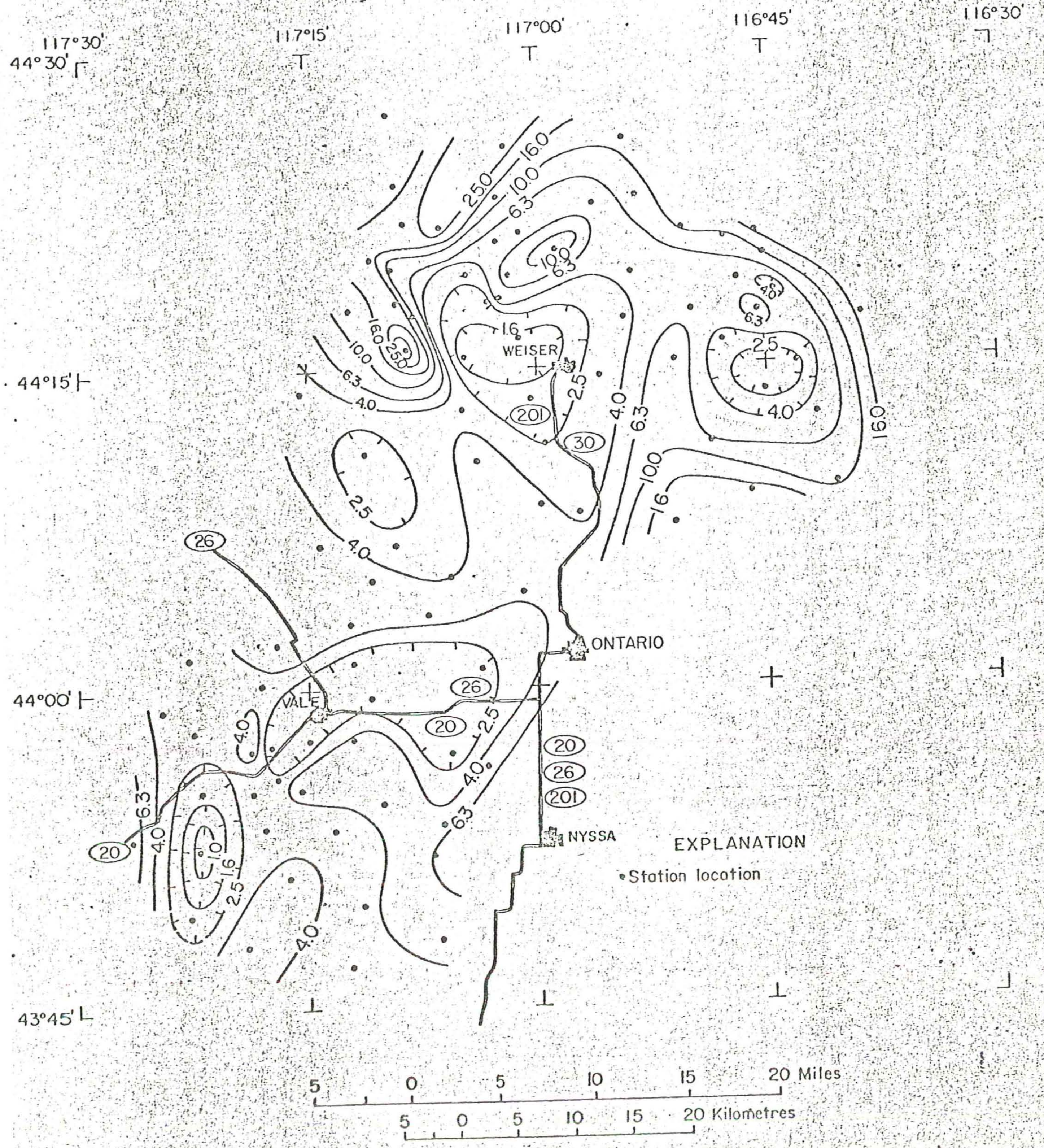


Figure 9.--27-Hz apparent-resistivity map (telluric line north-south), Weiser, Idaho-Vale, Oregon. Contours in ohm metres.

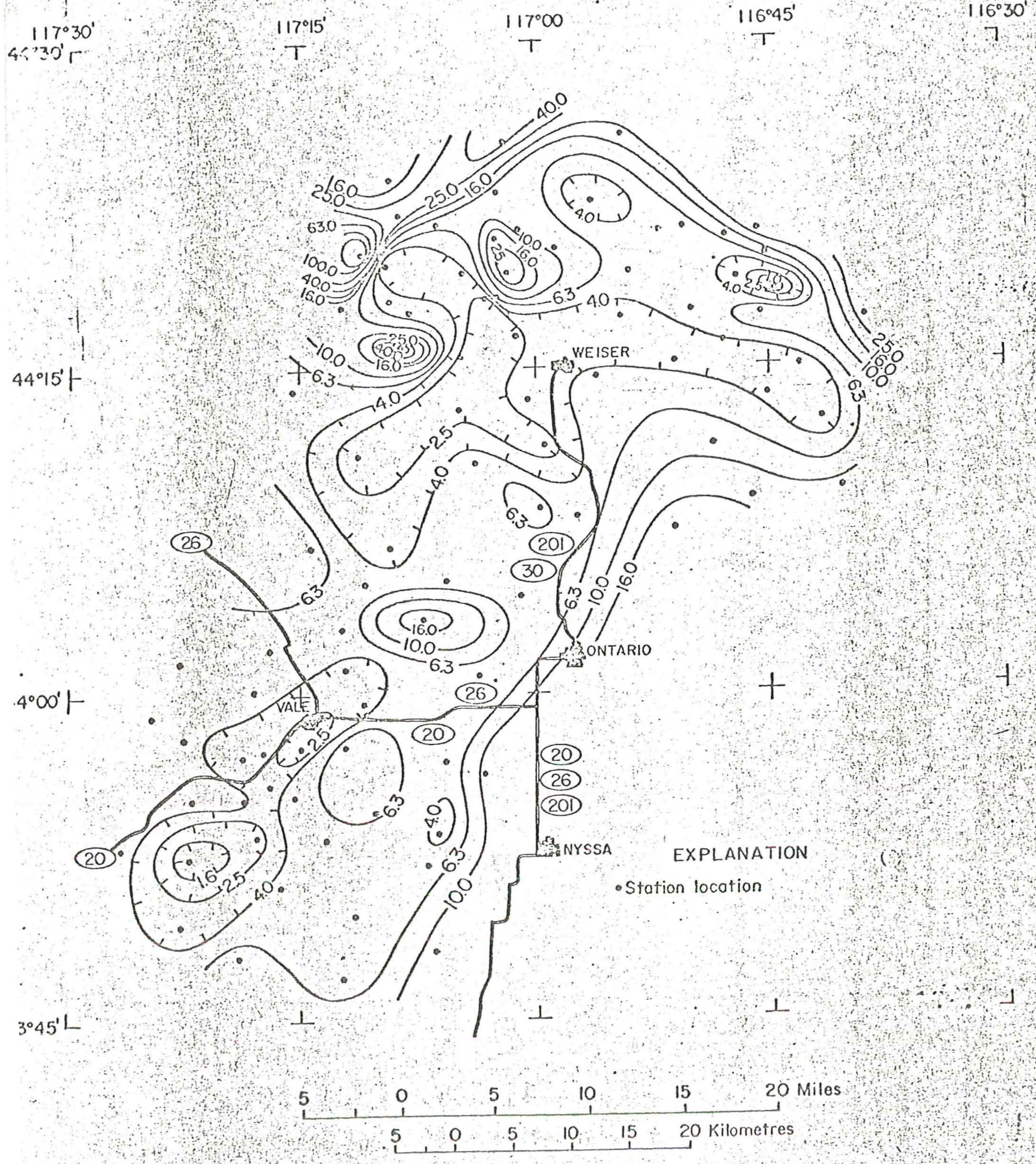


Figure 10.--27-Hz apparent resistivity map (telluric line east-west), Weiser, Idaho-Vale, Oregon. Contours in ohm metres.

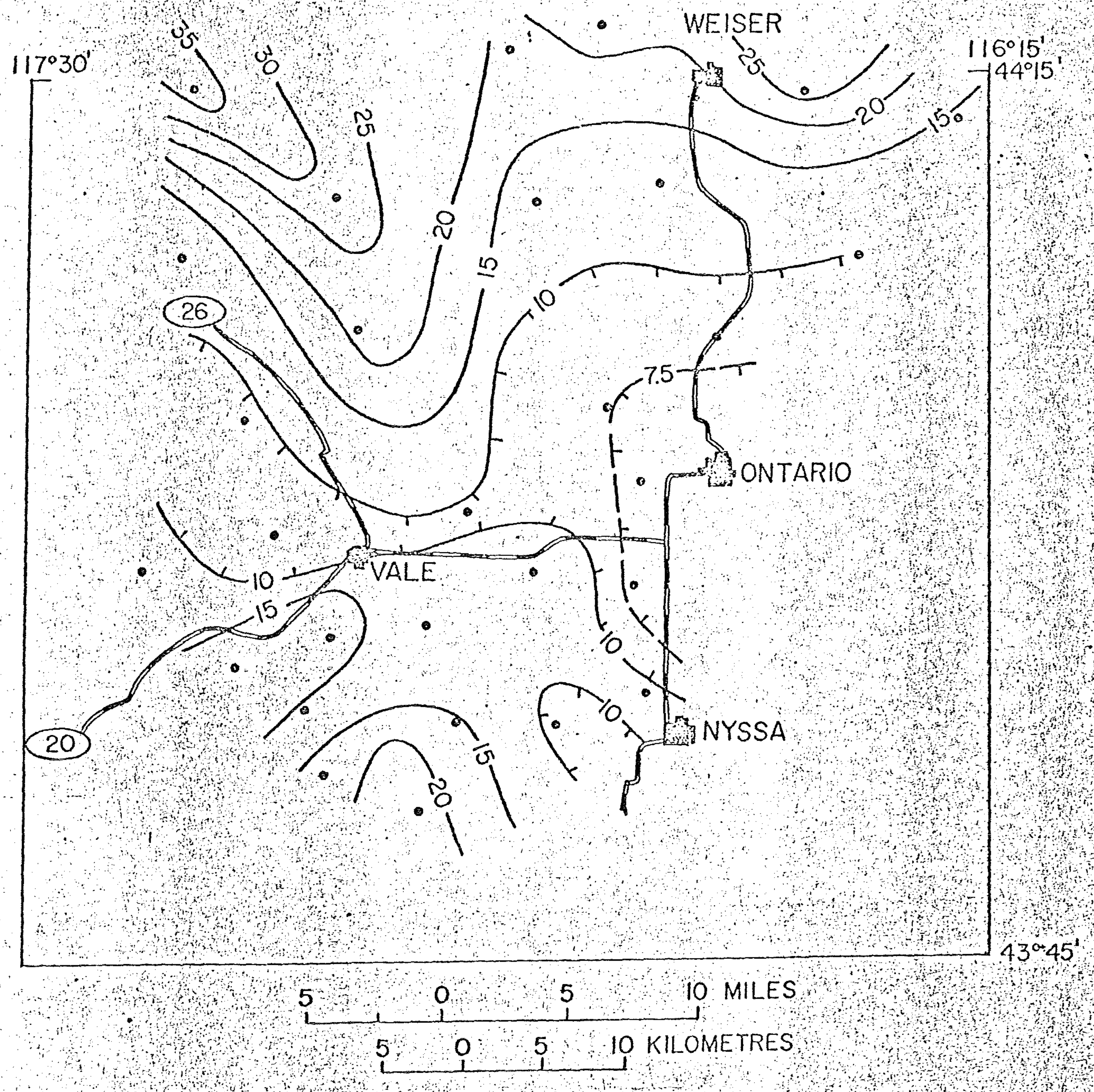


Figure 11.--Telluric anomaly map at 20-30 sec period, Vale, Oregon-Weiser, Idaho. Contour interval $2K = 10\sqrt{J}$