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Quarterly Report
Geothermal Studies in Montana

by

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Period: February through March, 1983

During February and March of 1983, geophysical investigations consisted primarily of data interpretation. However, additional gravity data was collected in the White Sulphur Springs area during this period.

Geological and hydrochemical work consisted of a double well flow test at Camp Aqua, utilizing a new commercial well and the research well, and data interpretation.

Transmitted as a part of this report is a copy of the manuscript entitled "An analysis of resistivity surveys at Norris Hot Springs", and MBMG Memoir 50, a final report on the Centennial Valley study.

AN ANALYSIS OF RESISTIVITY SURVEYS AT NORRIS HOT SPRINGS

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Butte, Montana

March 1, 1983

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INTRODUCTION

The usefullness of electrical resistivity surveys in delineating geothermal extent and source will be examined by integrating and interpreting data collected in a geothermal area by electrical survey methods. Support is provided by the Department of Energy contract #DE-FC07-701D12033, which funds the collecting, interpreting, and presenting of data.

Electrical surveys were conducted in the Norris Hot Springs area, at about 45 degrees 35 minutes North latitude and 111 degrees 42 minutes West longitude. An index map of Montana, Figure 1, shows the general location of Norris Hot Springs, which lies near the Madison River Valley bounded to the west by the Tobacco Root Mountains and to the east by the Madison Range. Hot Springs Creek, flowing northeast into the Madison River, divides the area of study.

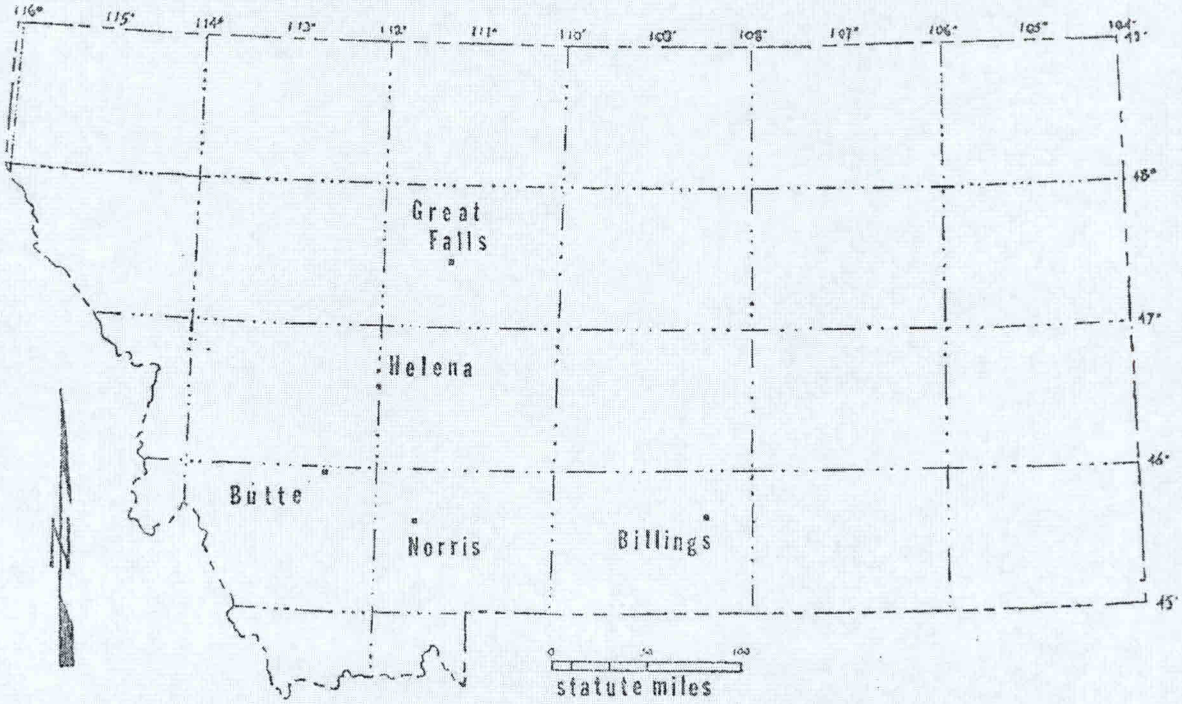

Figure 1. Index Map of Montana

LITHOLOGY

The geology in the area of study, Figure 2, is summarized from a map in the Billings Geological Society Guidebook, Volume 11, Plate 1, by Adretta and Alsup, and from a map by Vitaliano and others published by the Geological Society of America. Lithology consists mainly of quartzofeldspathic gneiss with thin Quaternary alluvium covering the topographic lows. Approximately a mile west of Norris, Tertiary volcanics outcrop about a quarter of a mile south of Hot Springs Creek. Small outcrops of hornblende gneiss and ultramafic intrusives occur near the volcanics. About a mile furthur to the west lies the Tobacco Root Batholith.

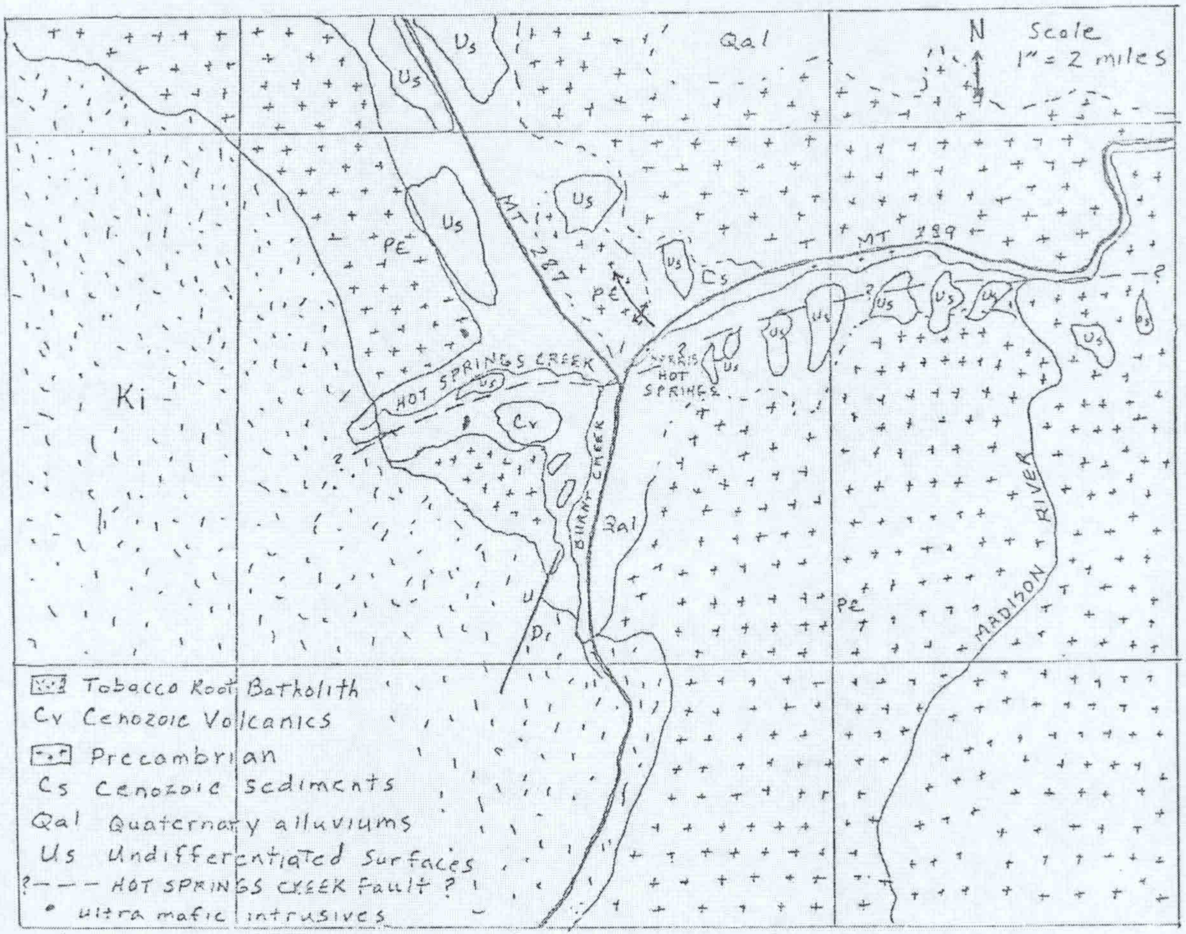

Figure 2. Generalized Geology of Norris Hot Springs area, adapted from Andretta, Vitaliano, and others.

STRUCTURAL GEOLOGY

Structures generally trend north to northwest in the area with Norris Hot Springs lying over a northwesterly plunging anticline (Chadwick and Leonard, 1979). The anticline may be obliquely intersected by a fault, which is speculated to follow Hot Springs Creek (Andretta, ibid.). The fault/anticline contact may be the pathway used by the hot water (Chadwick, ibid.), which forms geothermal seepages at Norris Hot Springs.

A normal fault (Vitaliano, et. al., ibid.) is located about a mile south of the Tertiary volcanics and intersects an arm of the Tobacco Root Batholith's eastern extension into the Madison Valley.

GEOPHYSICAL BACKGROUND

Previous studies of Norris Hot Springs were made by Robert A. Chadwick and others, 1978. A shallow Wenner array electrical sounding was interpreted by Chadwick to delineate a low of 30 ohm-meters at 20 meters of depth roughly circular around Hot Springs Creek. At 100 meters of apparant depth the area lessens in extent, elongates in the northeast direction, and increases in resistivity to 50 ohm-meters.

A hammer seismic survey (Chadwick, ibid.), with penetration to about 70 meters of depth began at a well, which bottoms at 23 meters in granitic gneiss, and was profiled in the east-north-east direction over the low. A resulting seismic pattern of velocities is interpreted by Chadwick to show alluvium up to about 30 meters deep underlain by what is probably granitic and mafic gneiss respectively. The thickest alluvium is at the array center and is directly underlain by the mafic rock.

ELECTRICAL SURVEYS

In the summer of 1982, resistivity measurements in the area were made using a symmetrical Schlumberger array with a portable transmitter and receiver. Figure 3 shows the locations of fourteen soundings in the Norris geothermal area.

Five soundings at half spreads of less than 50 meters will aid in determining resistivities of outcropping rocks for correlation. Six soundings at half spreads of 300 to 1000 meters will help delineate the geographical extent and possibly the depth limit of the geothermal area and may help locate a possible source. Two soundings at half spaces of 100 meters were obtained at desired locations, but were limited in extent because of physical access or restraints. These will be useful in correlation of the data and somewhat in delineation of the area.

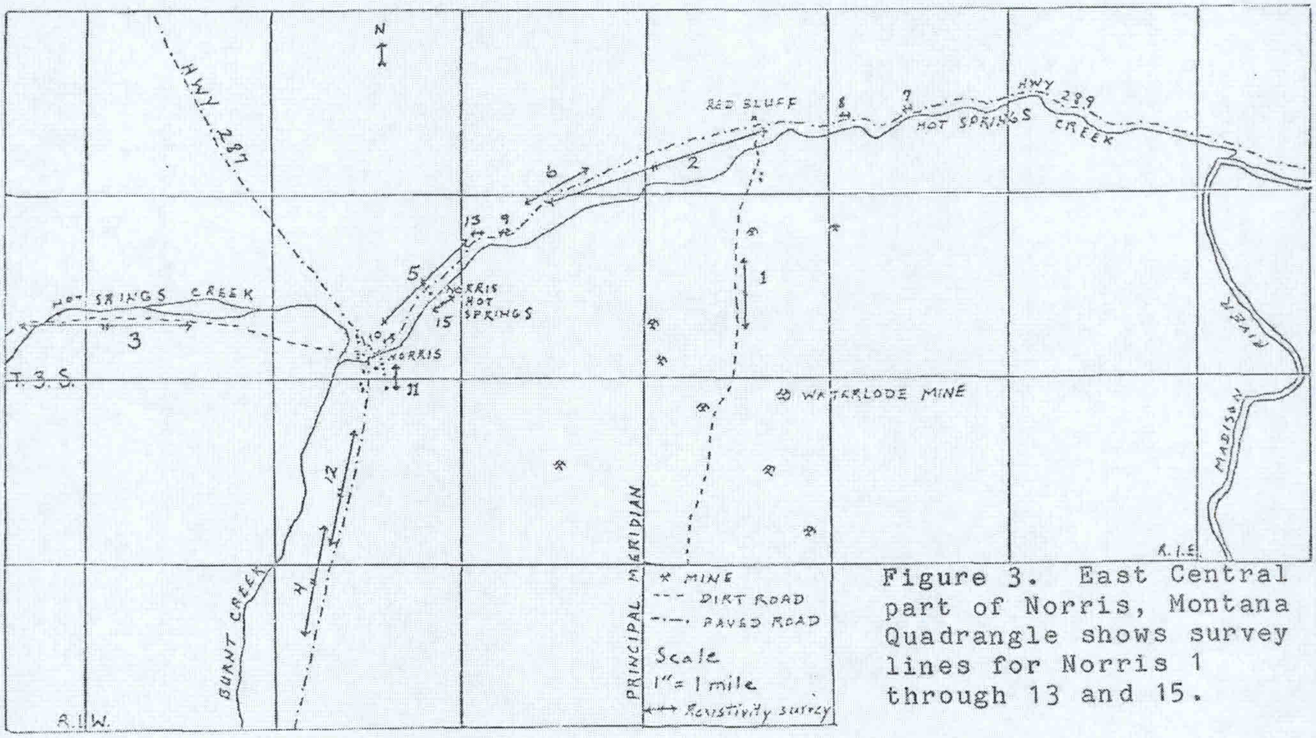

Figure 3. East Central part of Norris, Montana Quadrangle shows survey lines for Norris 1 through 13 and 15.

INTERPRETATION METHODS

Field data was interpreted using forward modeling by computer methods. A resistivity and depth are given for each layer as deduced from a log-log plot of field data. The first two layers are based on curve matching methods, the other layers are estimated. Resistivity and depth are varied until a curve, which best fits the data points, is produced.

Figures 4 through 17 are computer plotted curves of the fourteen resistivity surveys. The x's are the field data points and the curved line is the computer simulated match based on the layer resistivities and thicknesses listed in the upper right hand corner of the graph. Due to the limits of the plotting programs some curves show a basement thickness of 0.00, which means no basement thickness was given to compute the curve and implies an infinite thickness.

Various combinations of resistivities and thicknesses can produce similar curves because the parameter constant used to compute the curve is resistivity times thickness. However, resistivity contrasts, which are evident from the changes in the curve, are relatively valid. There are conductive layers between more resistive layers in most of these curves or a bottoming out of the conductive layer in other curves, due to limited depth probing.

GENERAL INTERPRETATION

Curves one and two are modeled on data taken east of the Hot Springs. Both indicate a high-low-high resistivity pattern, as shown in Figures 4 and 5; Norris one is a north-south array, while Norris two is along the north side of Hot Springs Creek.

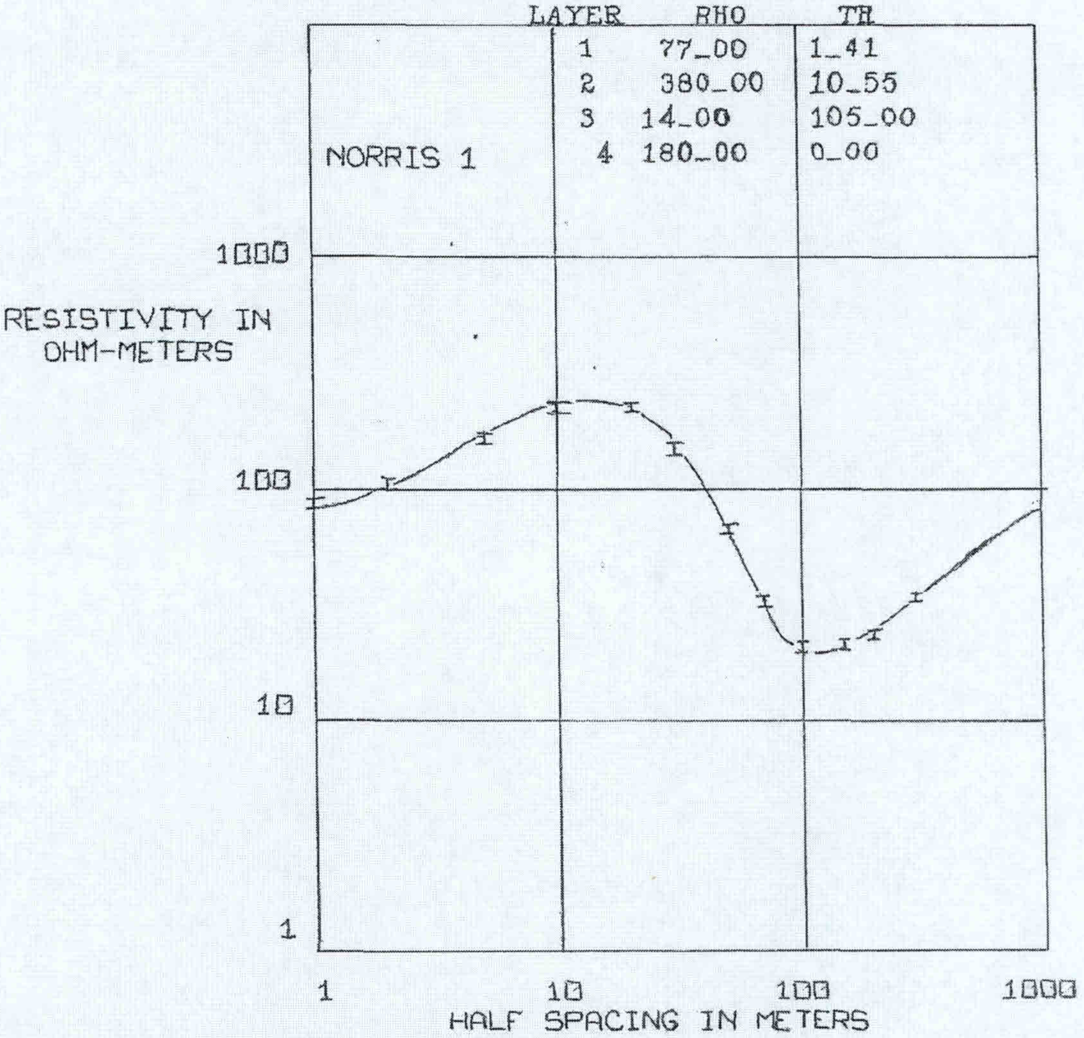

Figure 4. Norris one - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris one shows a thicker but more resistive low than Norris two. The suspected fault (Andretta, ibid.) or shear zone along the Hot Springs creek is possibly a cause of the conductive layer in Norris two. Warm water may ascend along a fracture zone and then percolate laterally through alluvial sediments.

The conductive layer of Norris one is more difficult to explain as Norris one is situated not over alluvium but over highly elevated metamorphic rocks. Norris one lies near inactive mines, an indication of mineral enrichment, which may be the result of hydrothermal alteration due to ascending waters along fracture zones.

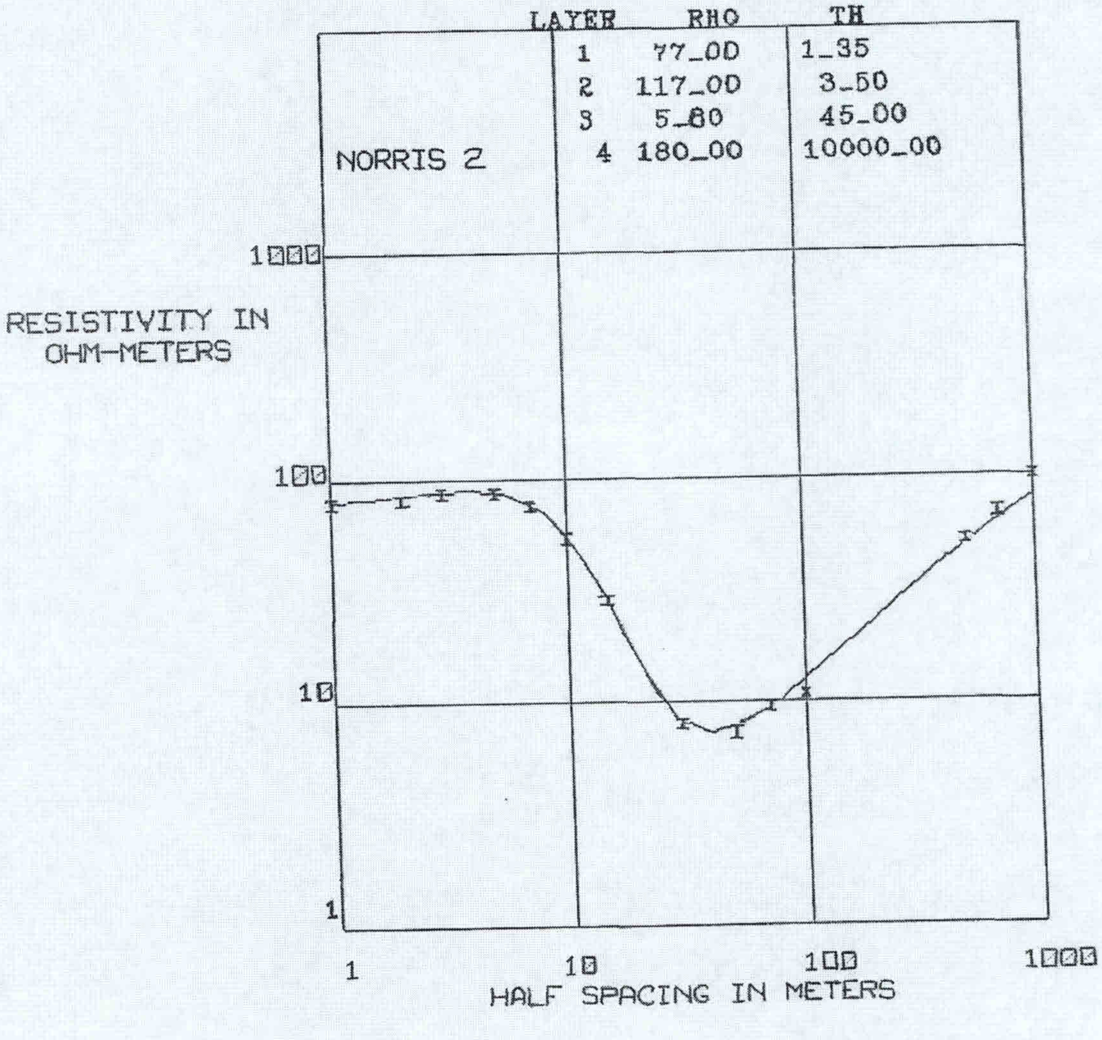

Figure 5. Norris two - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

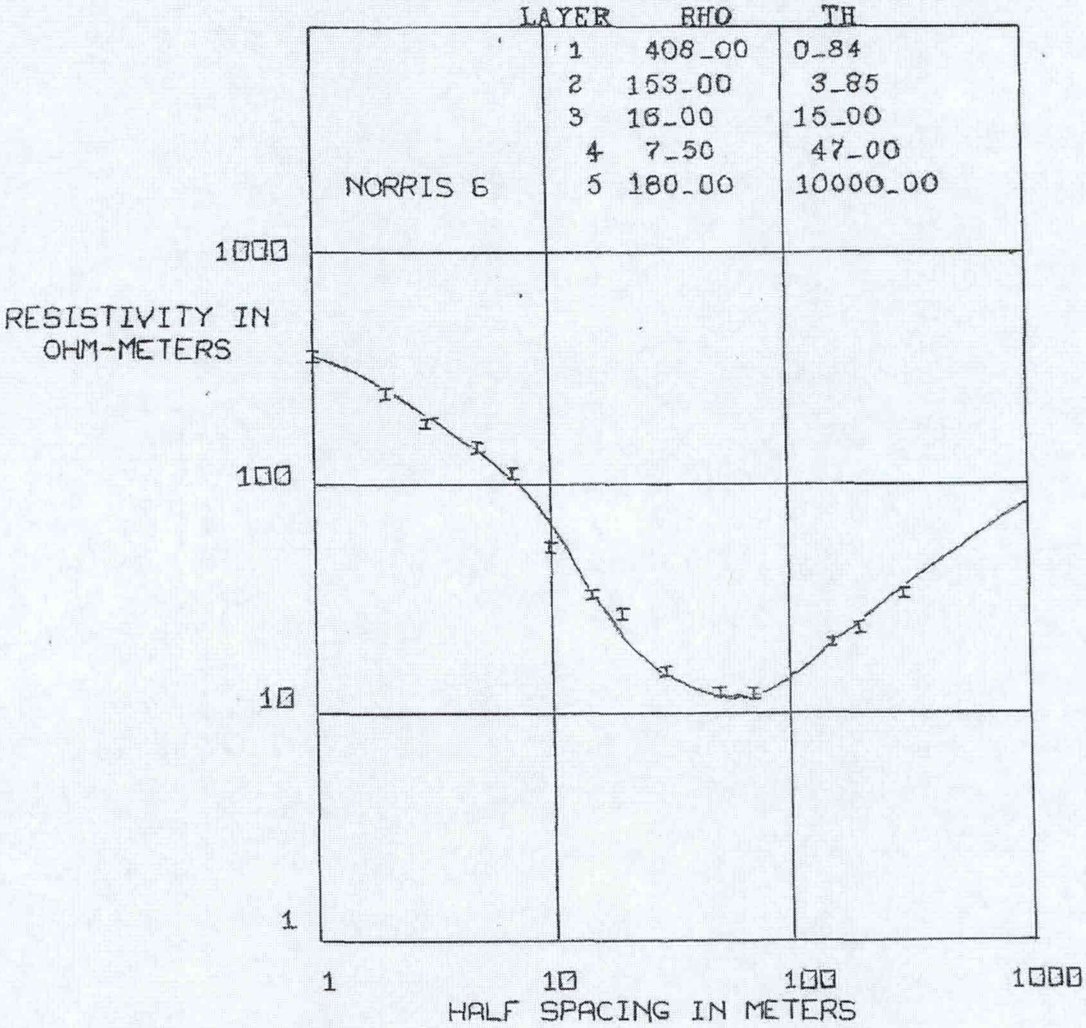

Figure 6. Norris six - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris six, shown in Figure 6, is across Highway 289 from Norris two. The conductive layer is slightly thinner and more resistive than found in Norris two, but definitely exists. The similar low furthur supports a probable shear zone along which hot water may ascend to saturate the alluvium and lower the resistivity.

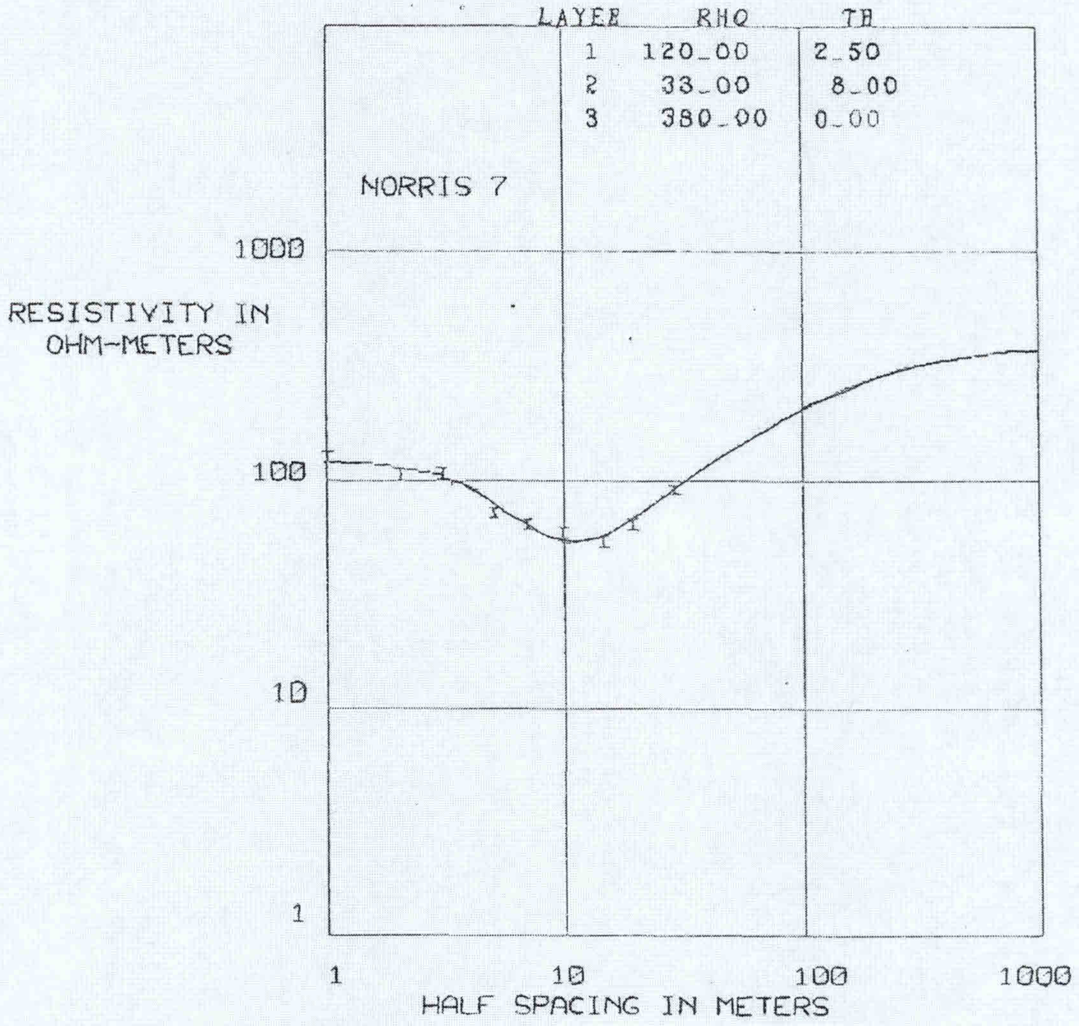

Figure 7. Norris seven - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

The shallow resistivity curves, Figures 7 through 11, indicate three ranges of resistivities. Shallow alluvium, which varies in resistivity, a type layer of about 180 ohm-meters, and a third type layer of about 380 ohm-meters.

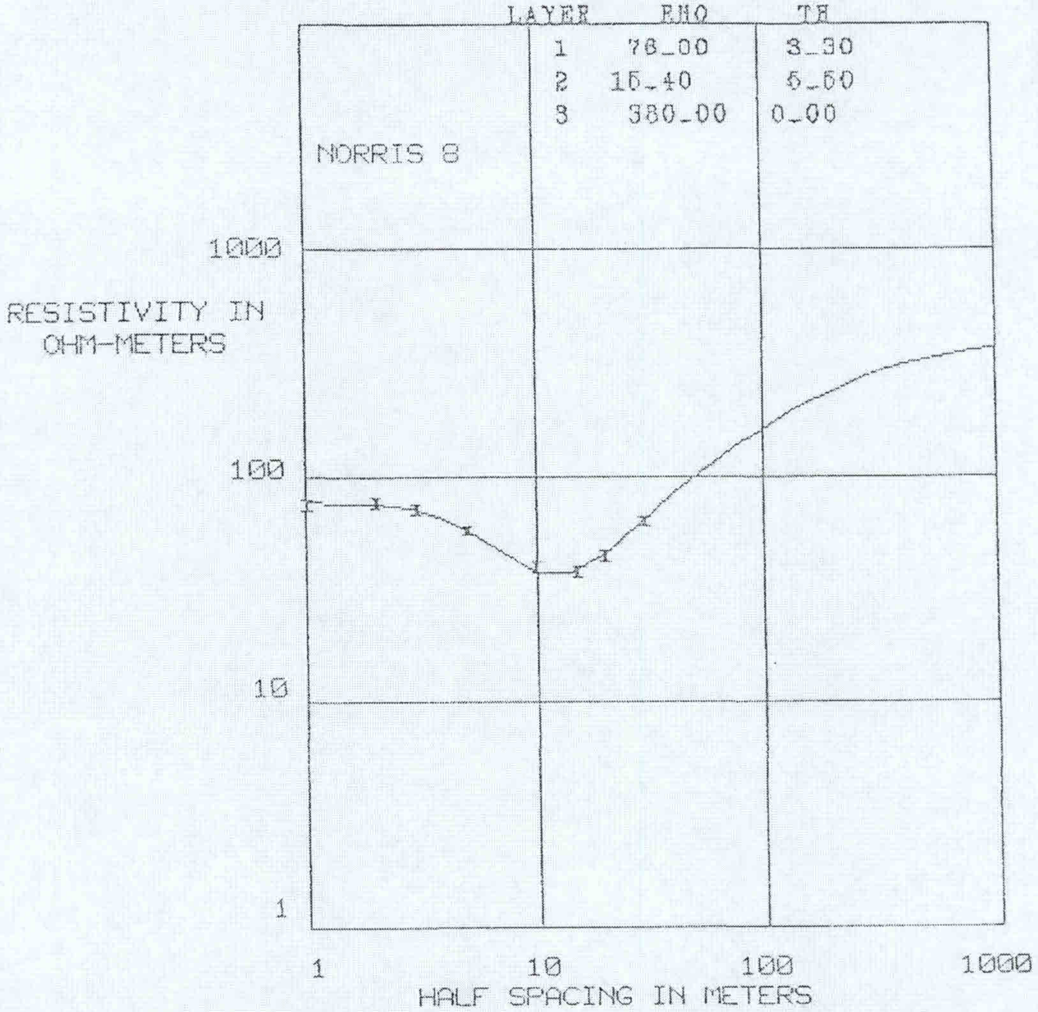

Figure 8. Norris eight - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris seven and eight show a layer about eight meters in thickness of 30 ohm-meter and 15 ohm-meter material respectively, which may be warm water saturated or altered alluvium. Beneath these layers, resistivity increases to around 380 ohm-meters.

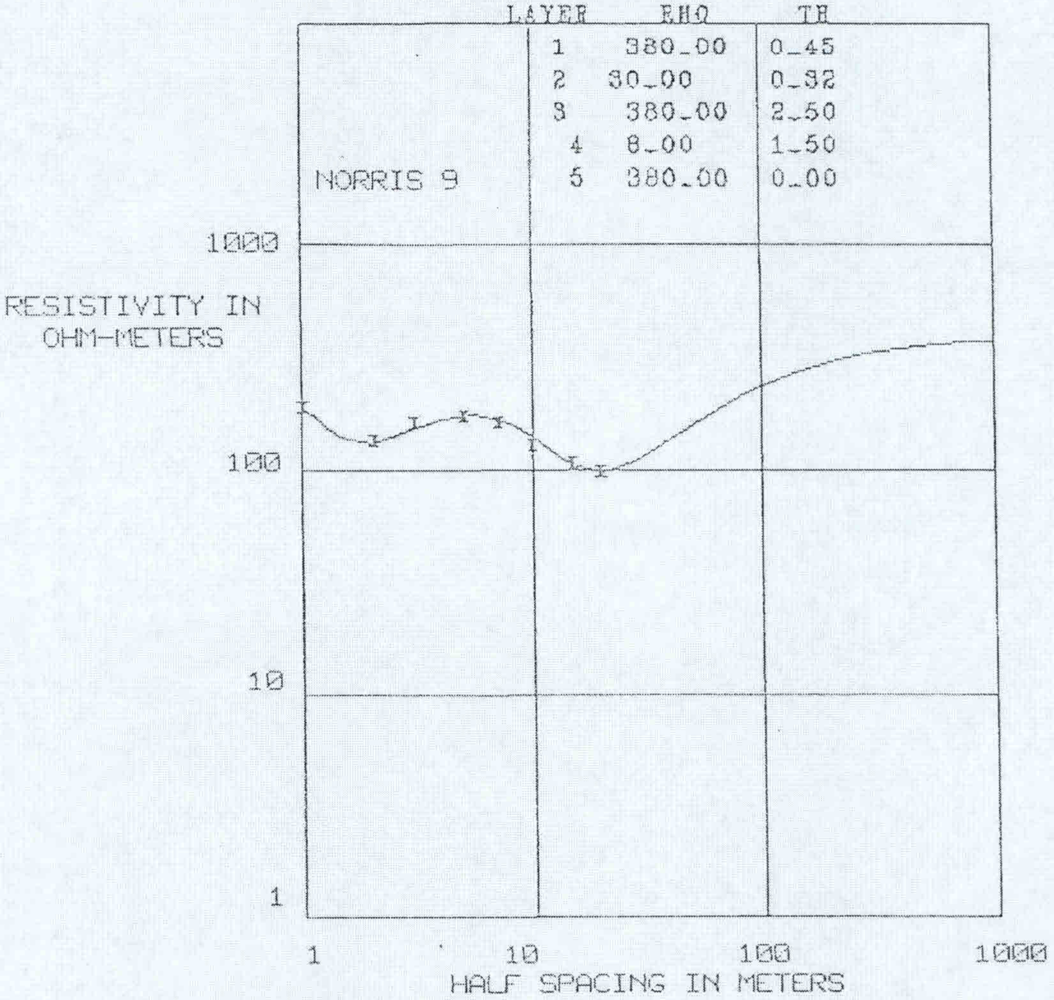

Figure 9. Norris nine - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris nine and thirteen, being next to each other, produce complimentary curves. Norris nine is assumed to turn up, but, because it was measured to a twenty meter depth, the actual data points only show an asymptotic low. A thin conductive layer between the 380 ohm-meter layers may be a localized zone of hydrothermal alteration or possibly a vein or lens.

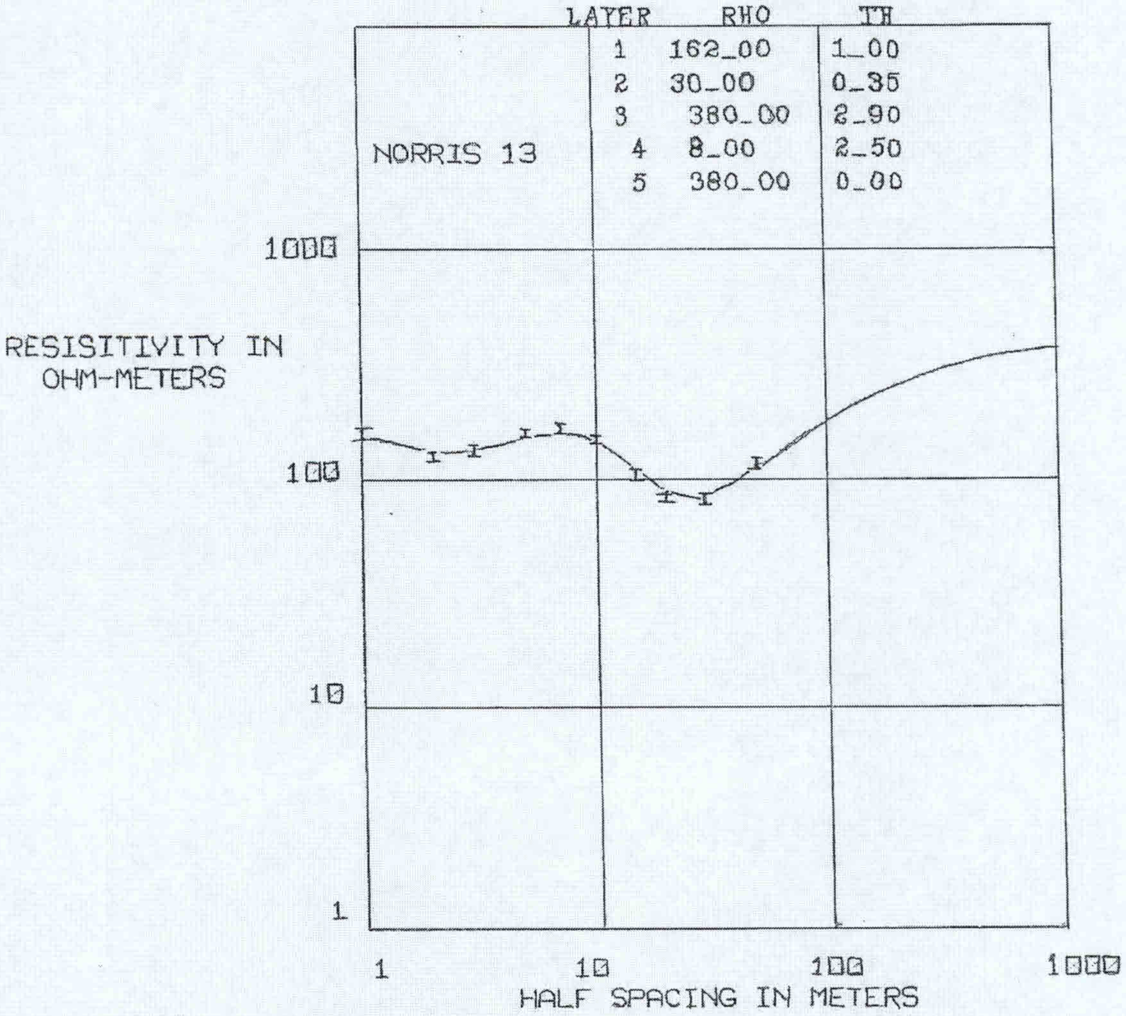

Figure 10. Norris thirteen - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris ten shows a 380 ohm-meter layer with a gradual decline in resistivity to about 160 ohm-meters, which may indicate the contact between the two types of metamorphic rocks interpreted by the seismic velocity findings of Robert A. Chadwick mentioned in the geophysical history section on page 3.

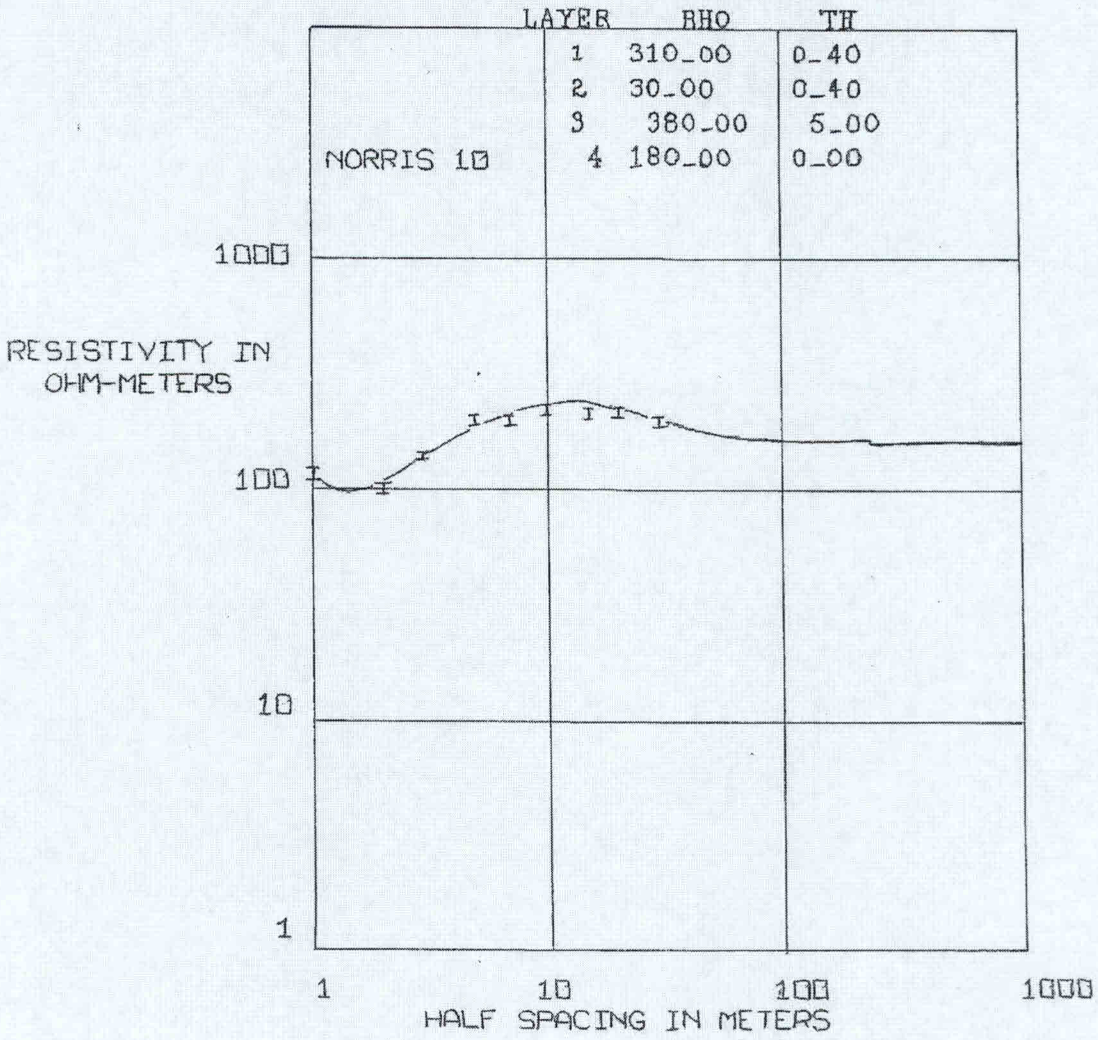

Figure 11. Norris ten - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris five, shown in Figure 3, lies between Norris ten and thirteen directly across Highway 289 from Norris Hot Springs. A matched curve for Norris five (see Figure 12) shows two adjacent layers of intermediate resistance with higher resistivities above and below them. The sounding was centered approximately over the anticlinal feature (Chadwick and Leonard, 1979) shown in Figure two.

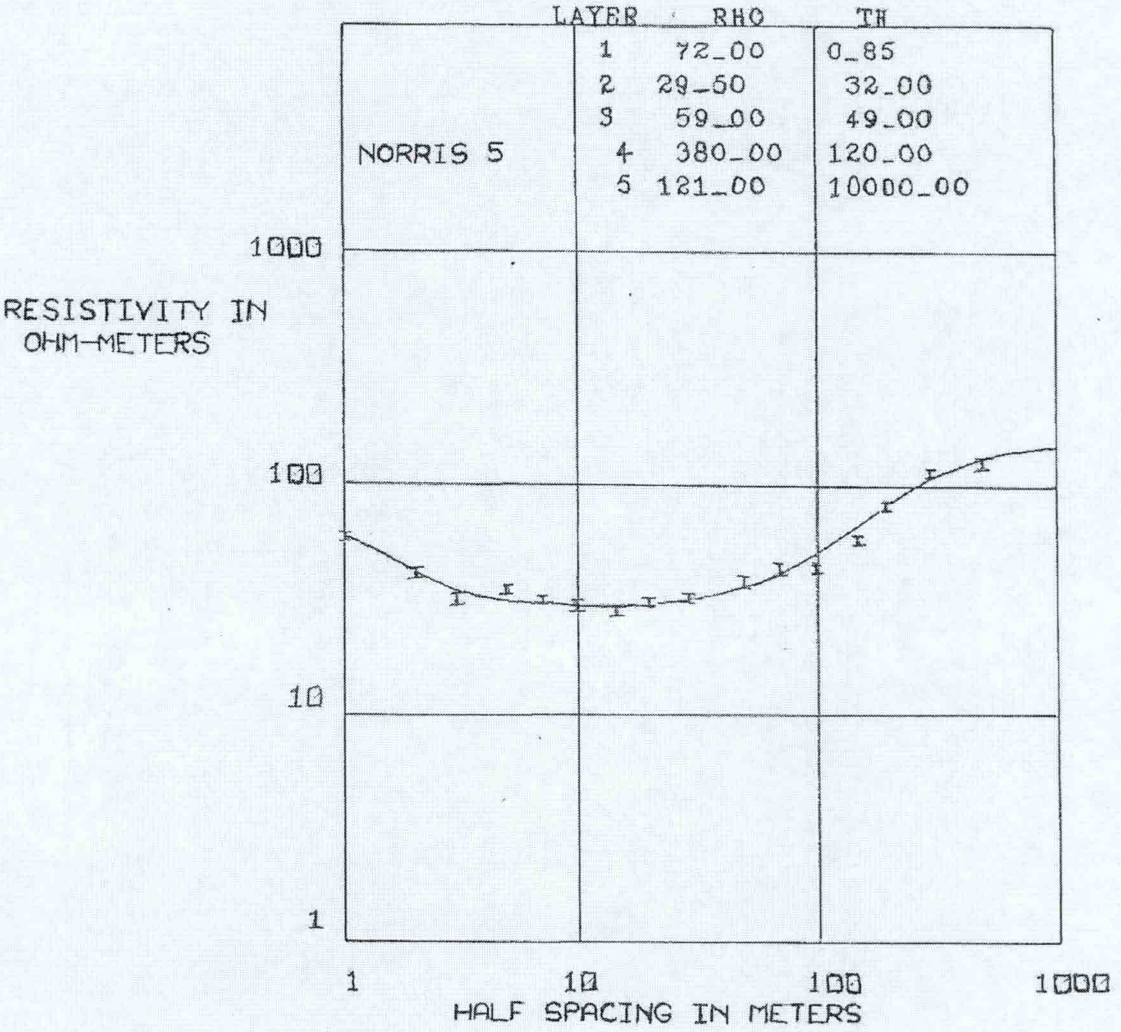

Figure 12. Norris five - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris fifteen sounding, shown in Figure 13, was conducted about a month later than the other surveys due to inaccessibility because of Hot Springs Creek flooding.

Norris fifteen, situated across the creek from the hot springs, shows a shallow layer of 15 ohm-meters and beneath it a layer of about 24 ohm-meters. The sounding is in an area of thickest alluvium, which may act as a reservoire for the ascending hot water.

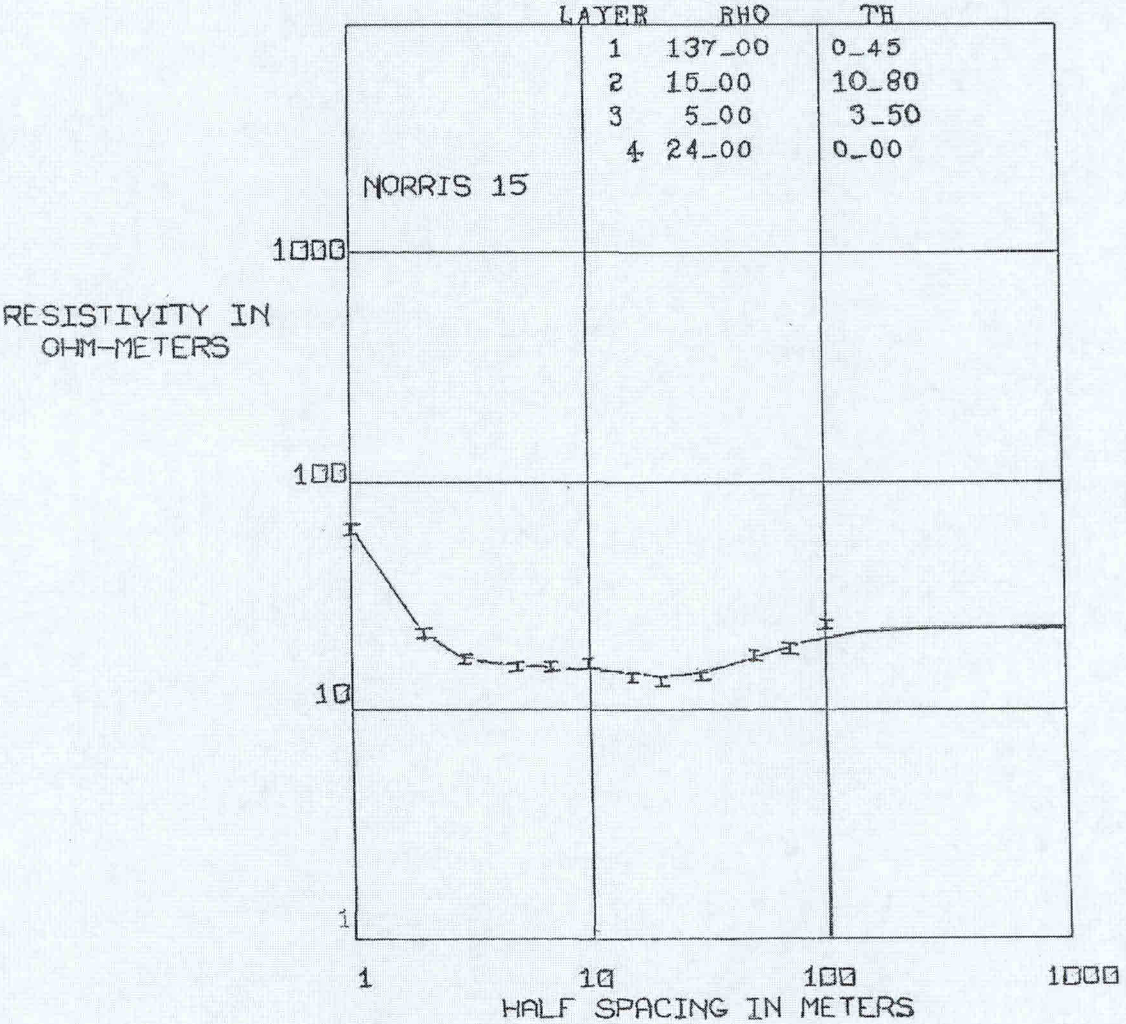

Figure 13. Norris fifteen - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris eleven is a north-south sounding about a half mile southwest of the hot springs, see Figure 14. Though about ten times furthur from the main spring than Norris fifteen, Norris eleven shows a greter low, which may indicate fracturing and shearing extends to the southwest.

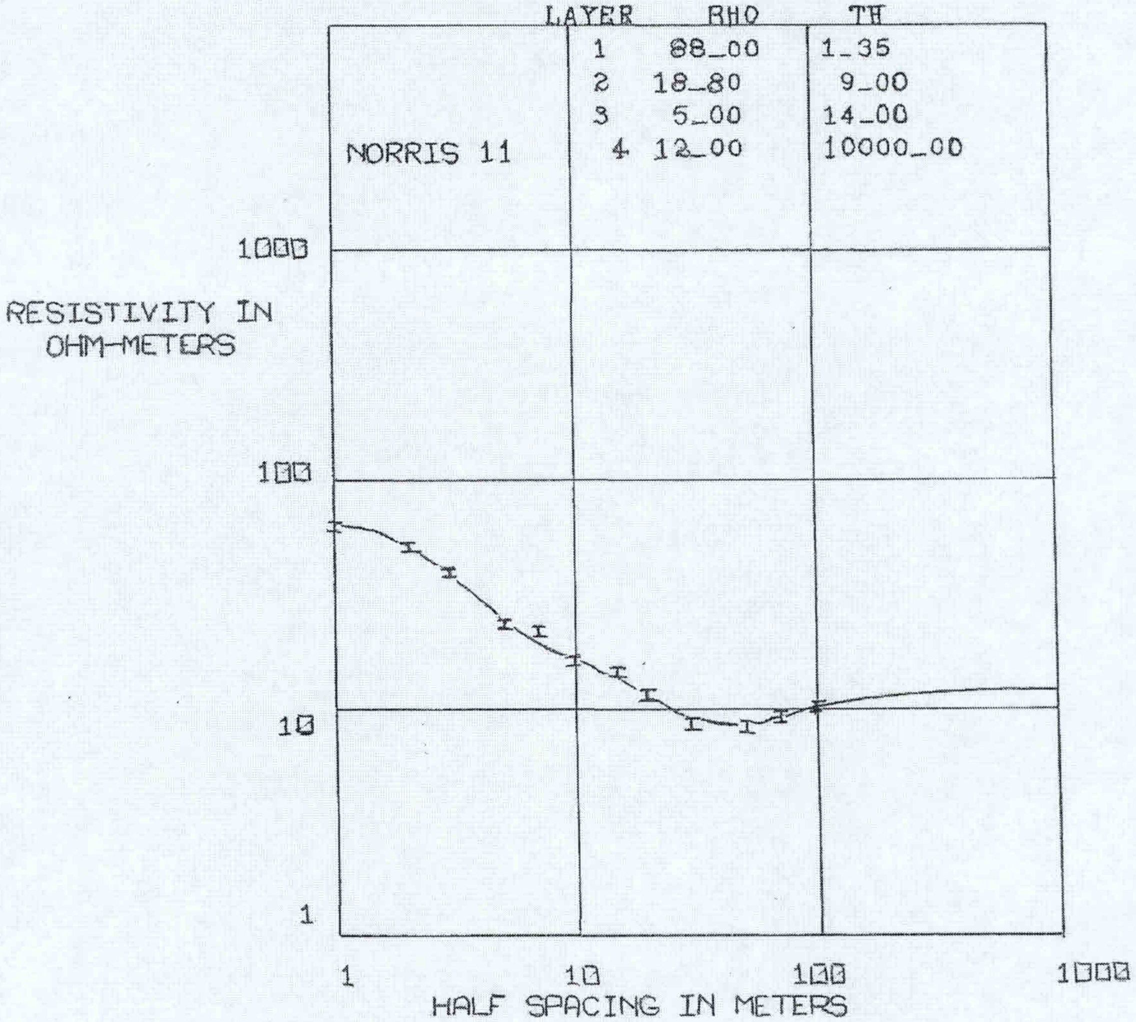

Figure 14. Norris eleven - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

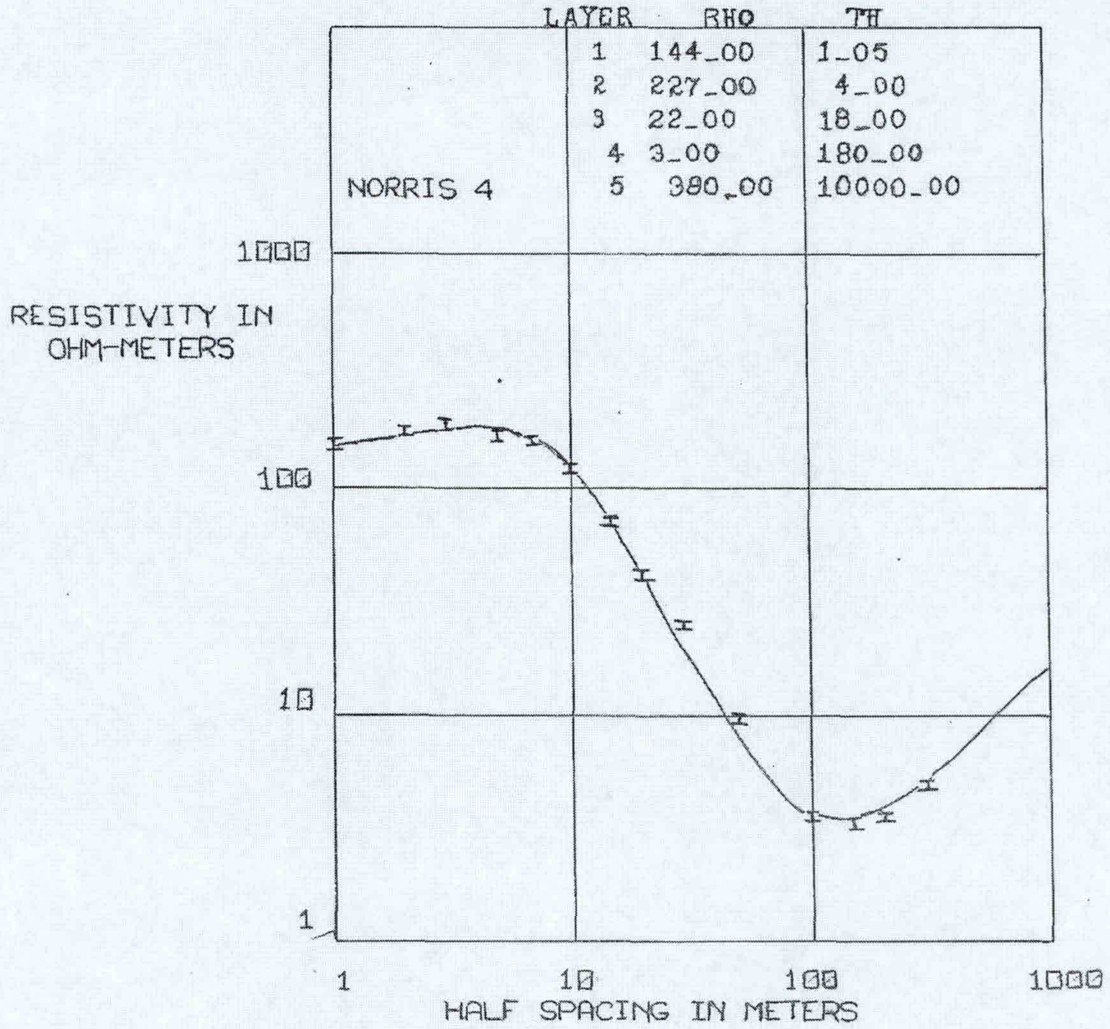

Figure 15. Norris four - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris four and twelve exhibit a thick conductive layer as shown in Figures 15 and 16, respectively. Norris four is west of the normal fault mentioned in the structural geology section. This fault may help control geothermal fluids in the Norris Hot Springs vicinity. Norris four and twelve show the greatest low and propose the interesting possibly of being nearest the source.

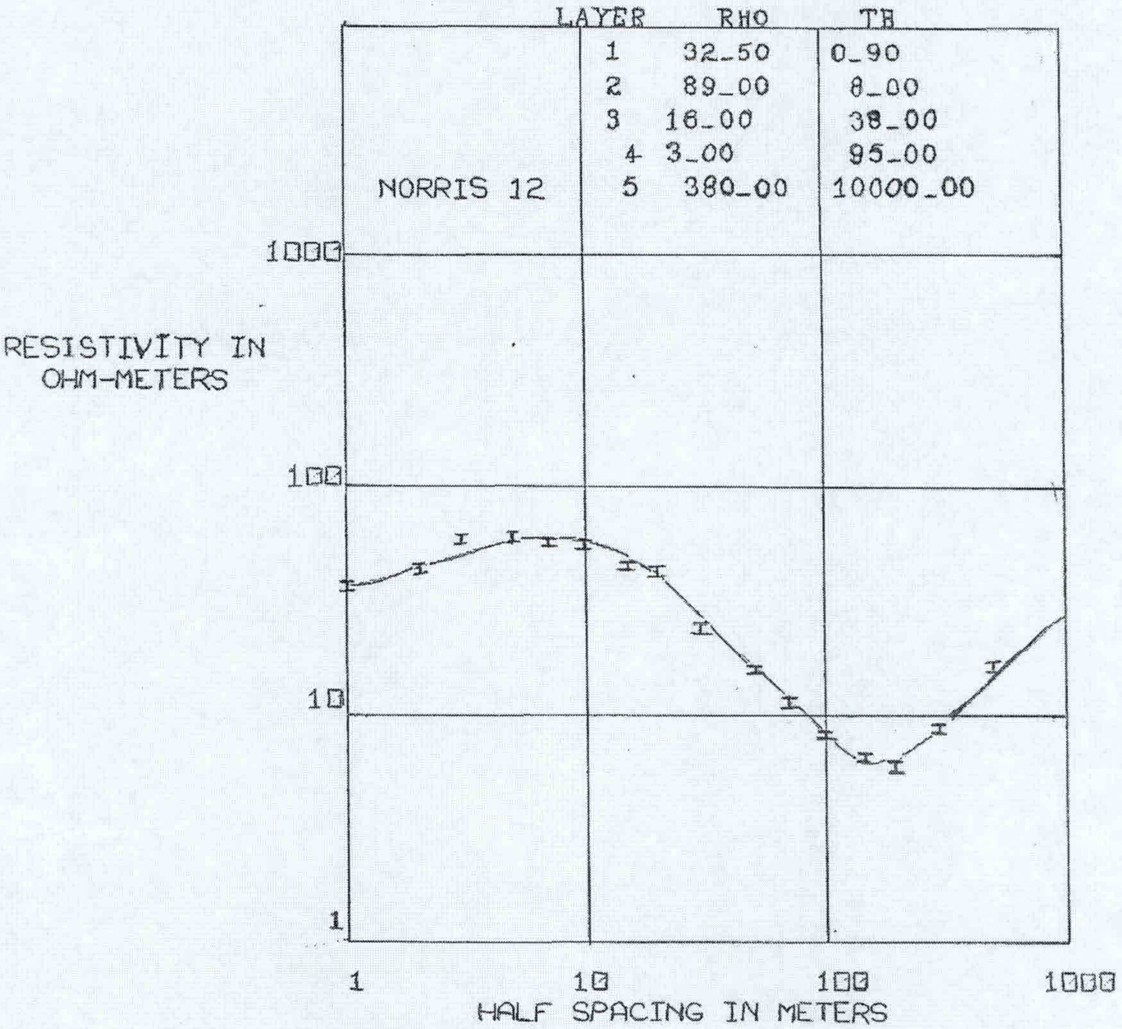

figure 16. Norris twelve - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

It is of interest to note that Norris twelve is about a half mile south of Norris eleven, which also shows a greater low than was measured nearer the hot springs surface manisfestations. A possible southwest trend of a thickening conductive layer will be explored furthur by geoelectric section later in this report.

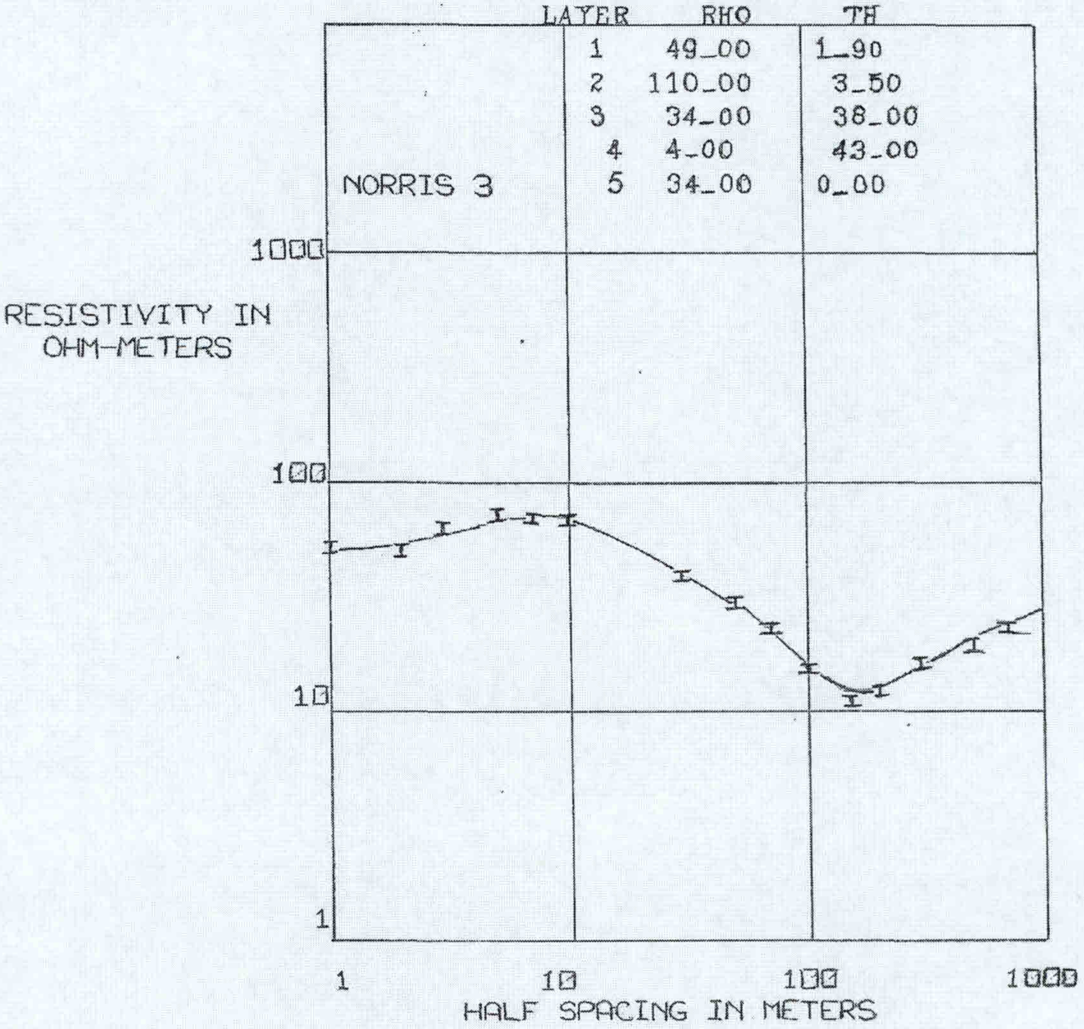

Figure 17. Norris three - the field data points are x's. The smooth curve is simulated by computer using the layer data in the upper right hand corner.

Norris three, in Figure 17, also has a conductive layer at about the same depth as the layer in Norris 12. These last three curves, shown in Figures 15 through 17, make a good case for a nearby source, or possibly water circulation at depth due to a deep seated fault.

GEOELECTRIC SECTION INTERPRETATION

Six geoelectric sections are included as Figures 18 through 23. Figure 18 is a northwest to southeast line which intersects Norris one, two, and six. Because cross-section one does not intersect the centers of the arrays it is assumed there is lateral continuity in each array, which may not be the case.

Cross-section one shows a consistant low beneath Norris two and six, broadening to a much thicker though slightly more resistant layer below Norris one. Basement resistivity is at least 180 ohm-meters and could possibly be higher according to the curve of Norris two, which shows about a 45 degree slope between data points taken at 100 and 1000 meters.

The Hot Springs Creek fault (Andretta, ibid.) is not apparent from the resistivity cross-section. Lateral migration of warm water through alluvium or hydrothermally altered rock may be causes of the low. However, a shear zone or fault can not be precluded from aiding in the spread of warm waters into the wide range they enjoy.

The existance of warm water throughout the area is supported by temperature measurements of discharge water at the Waterlode Mine. Located about a quarter mile southeast of Norris one, it has an anomalous water temperature year round. The mean annual temperature for Montana is about 7 degrees centigrade. The water temperatures of the Waterlode were measured to be 10 degrees centigrade in August, 1976 and about 9.4 degrees centigrade in February, 1978 (Lawson and Sonderegger). More resistivity surveys may help pinpoint the source of warm water.

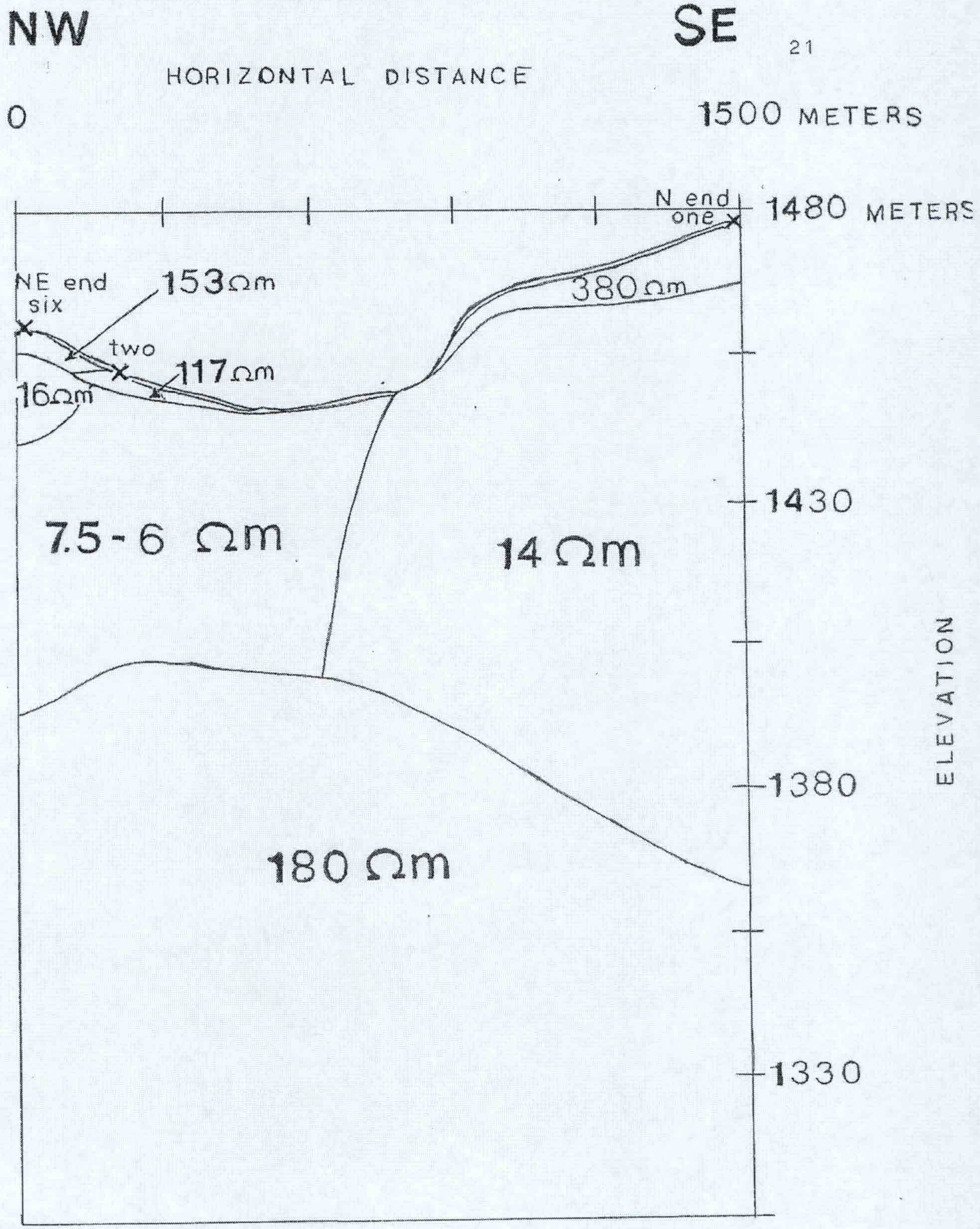

Figure 18. Geoelectric section one, incorporating data from Norris soundings one, two, and six (locations are marked with x's), shows interpreted layer resistivities in ohm-meters. Vertical exaggeration is 12:1.

Figure 19 is a geoelectric section along a line, which lies north and nearly parallel to Hot Springs Creek. Section two intersects Norris six, two, seven and eight. A conductive layer thins to the east and a resistant basement is found at a shallower depth. Soundings seven and eight seem to mark the eastern limit of the Norris geothermal area. The conductive layer's termination may be due to the speculated Hot Springs Creek fault (Andretta, ibid.) or to the natural thinning of warm water saturated or altered alluvium.

Figure 20 shows geoelectric section three, through Norris nine, thirteen, five and ten. The section begins approximately at the western limit of Figure 19. The attitiude is more northeast to southwest, but continues to roughly parallel the north bank of Hot Springs Creek. No conductive layer is evident from this geoelectric section three. The deeper probe, Norris five, approximately in the center of the section, has a broad intermediate low which gradually increases in resistivity at about 75 meters of depth; Then, it rises more steeply (see Figure 12) to an interpreted layer of 380 ohm-meters. At a minimum of 200 meters of depth, resistivity decreases asymptotically to 121 ohm-meters. Inspection of geoelectric section three and the contributing curves (Figures 10 through 13) may indicate a northern limit of the geothermal area or a location at a disadvantage with respect to shear zones and ascending warm water.

Geoelectric section four, shown in Figure 21, lies along a line which is oblique to section three. It crosses the creek passes through Norris Hot Springs, which lies between Norris five and fifteen, and then roughly parallels the creek on its south bank.

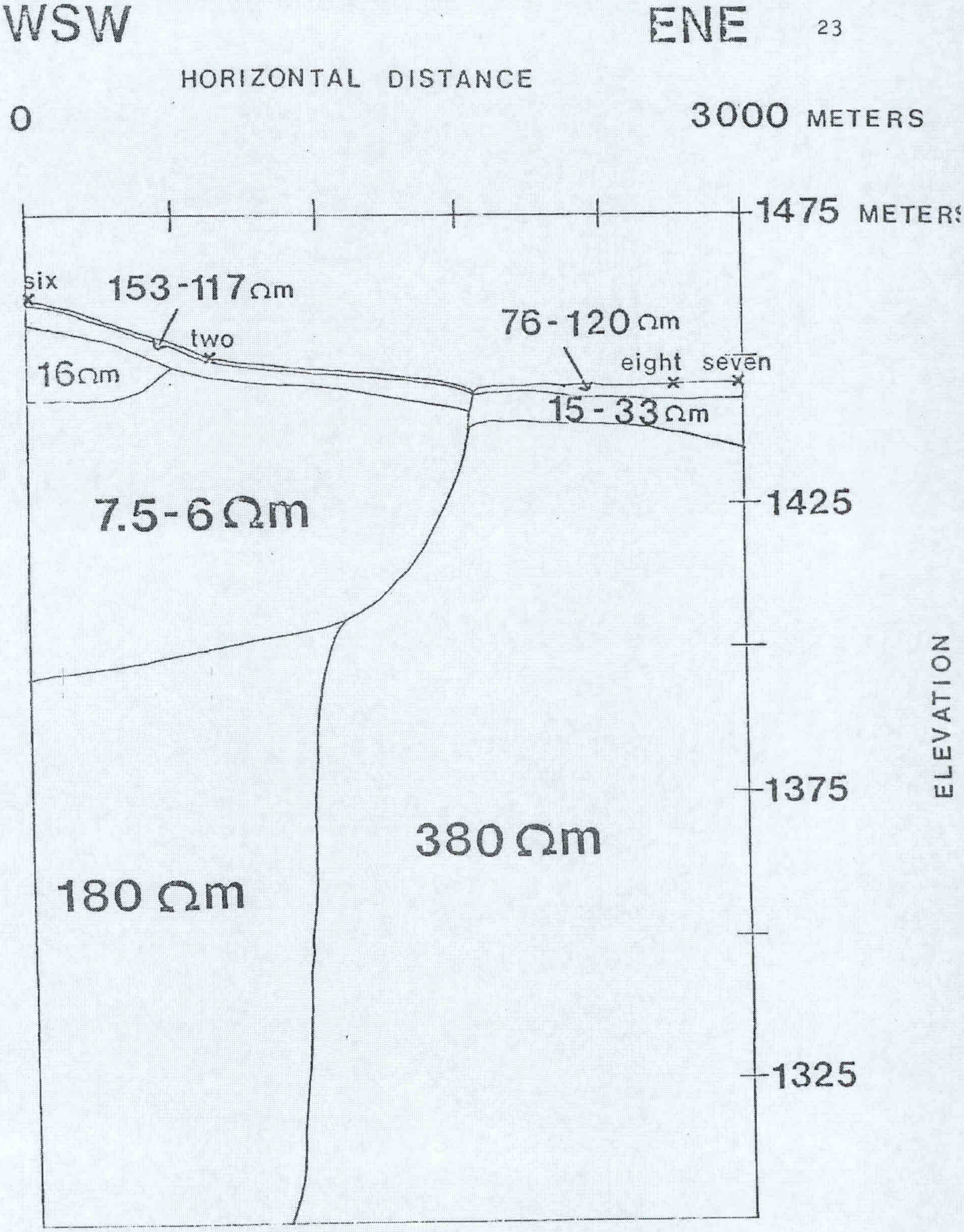

Figure 19. Geoelectric section two, incorporating data from Norris soundings seven, eight, two, and six (locations are marked with an x), shows interpreted layer resistivities in ohm-meters. Vertical exaggeration is 24:1.

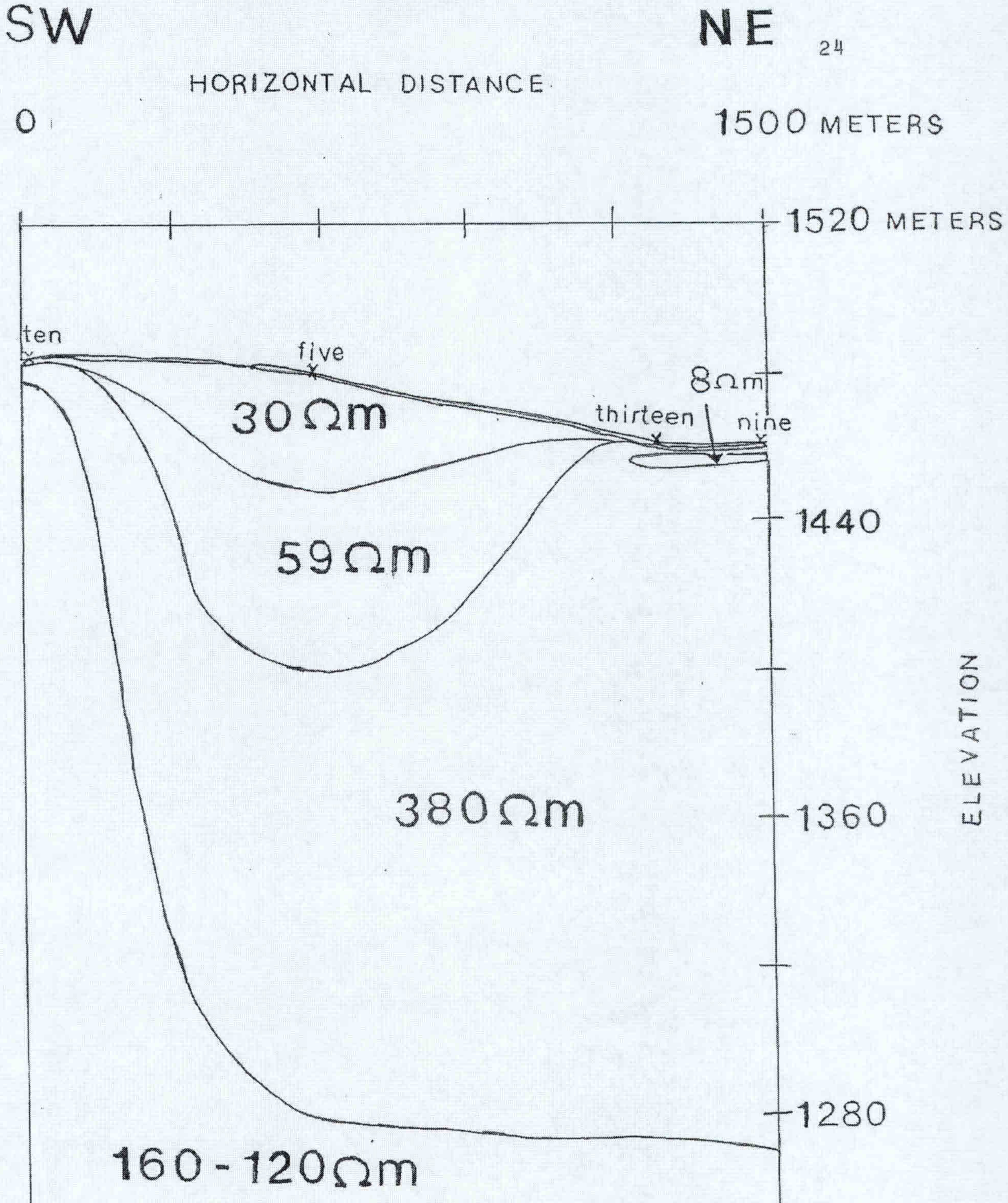

Figure 20. Geoelectric section three, incorporating data from Norris soundings nine, thirteen, five, and ten (locations are marked with an x), shows interpreted layer resistivities in ohm-meters. Vertical exaggeration is 7.5:1.

The inconsistancy between layers in Norris five and fifteen is evident from geoelectric section four. The abrupt break between resistivity layers may be due to the Hot Springs Creek fault, which is inferred by Andretta and others.

The thickness of the conductive layer can only be surmised from the soundings of Norris eleven and fifteen because probing was limited to a half-spacing of 100 meters. The fact that conductance increases to the southwest may indicate a source direction.

Geoelectric section five (Figure 22) extends geoelectric section four (Figure 21) to include Norris twelve, but, because it is slightly offset from section four, it does not intersect Norris fifteen. Again the increase in conductivity and thickness of the conductive layer to the southwest is obvious.

A section through Norris four was not drawn. However, a look at the curves in Figures 15 and 16 indicates a continuing trend towards a thicker and more conductive layer. Because Norris four obliquely crosses a power line, the data is questionable. Norris twelve was obtained along this same stretch, but north of the power line, to substantiate the low resistivities of Norris four. An electric survey south of Norris four would furthur confirm a south to southwestern trending low.

The last geoelectric section connects Norris three and twelve and moves northwest of the previous section. A conductive layer exists, but thins slightly in this direction. The basement is of a much lower resistivity than previously encountered for a sounding with a 1000 meter half spacing. An outcrop of Tertiary basalts, located about a quarter of a mile to the south, may cause the low if they are thick enough to appear as basement rock.

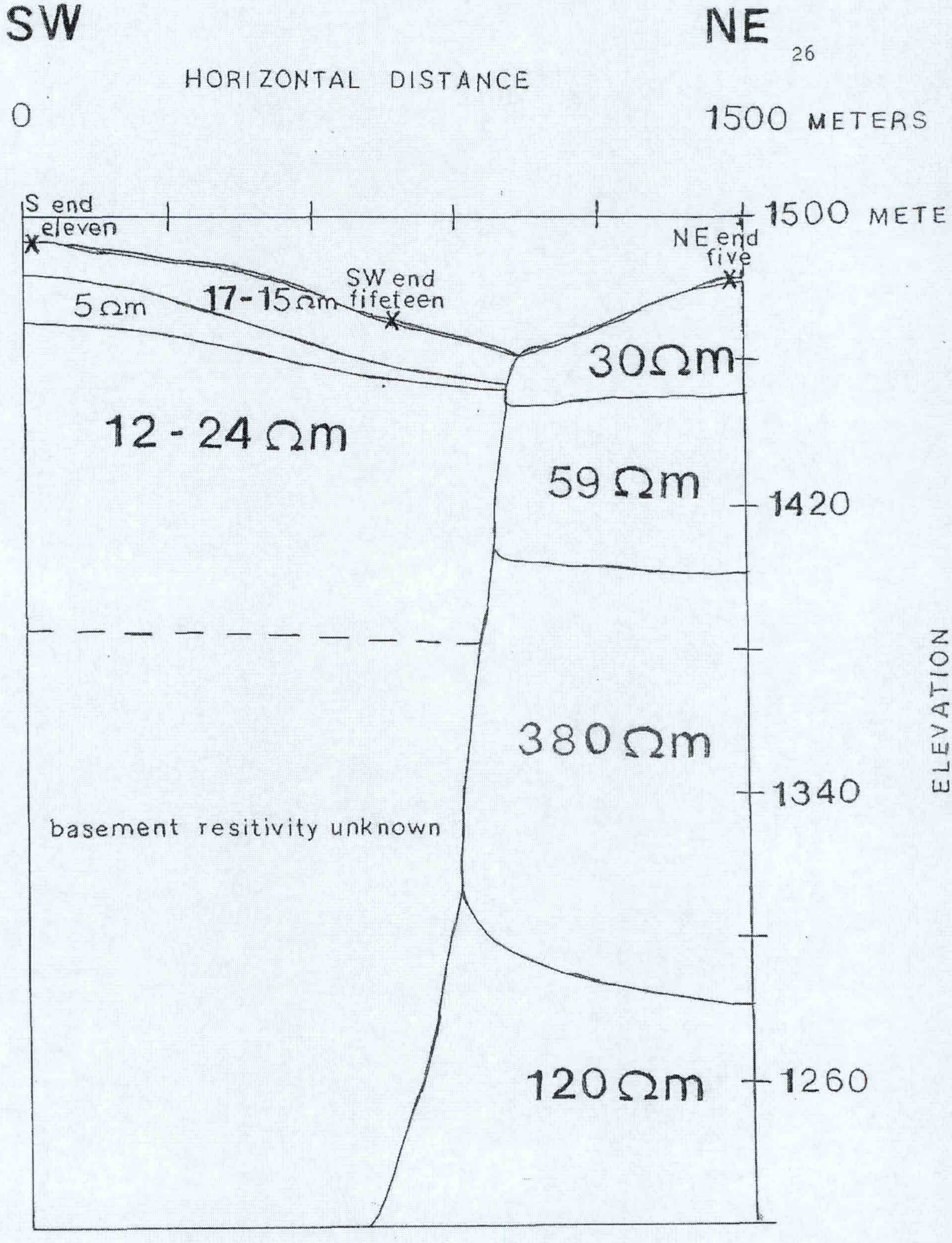

figure 21. Geoelectric section four, incorporating data from Norris soundings five, fifteen, and eleven (locations are marked with an x), shows interpreted layer resistivities in ohm-meters. Vertical exaggeration is 7.5:1.

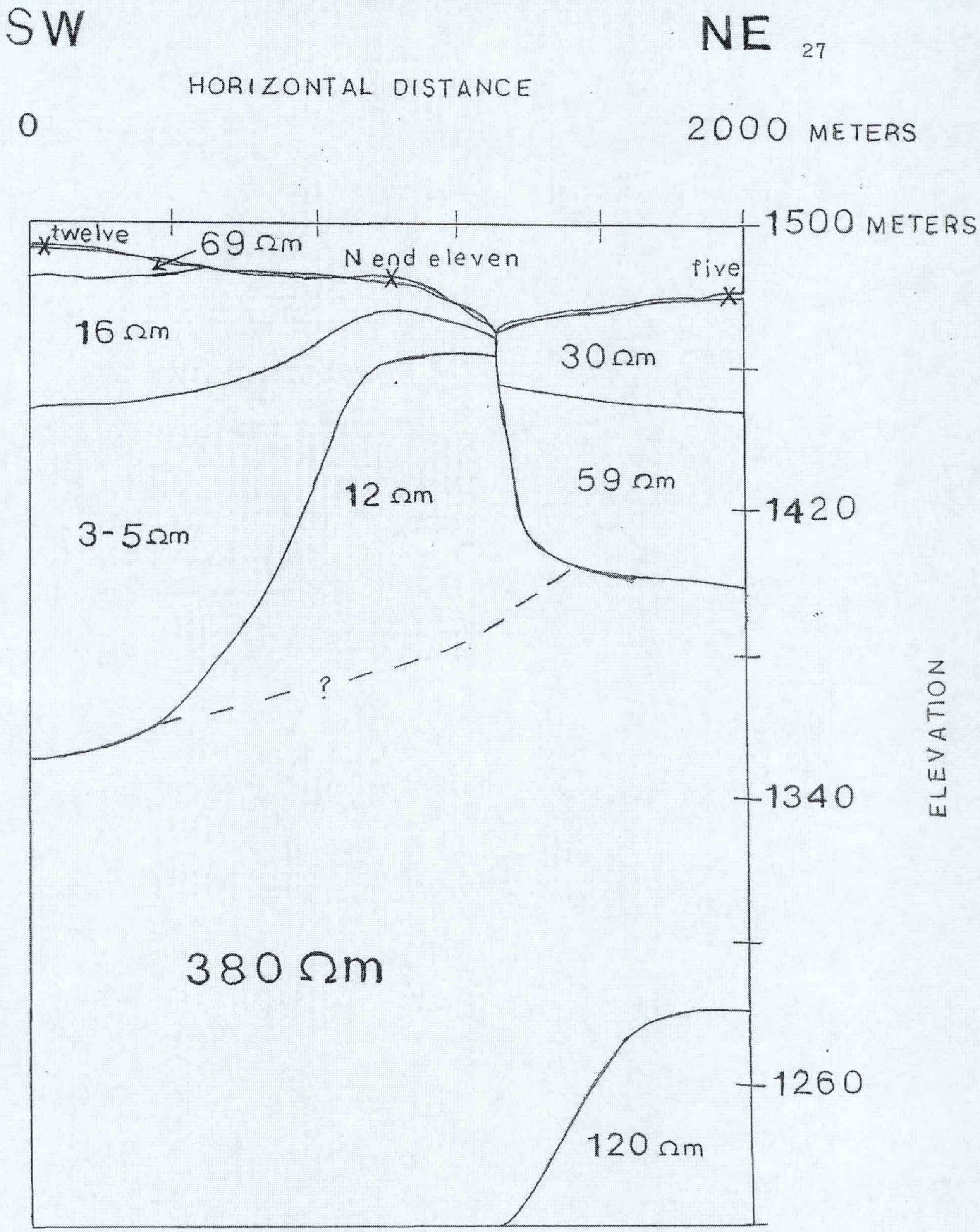

Figure 22. Geoelectric section five, incorporating data from Norris soundings five, eleven, and twelve (locations are marked with an x), shows interpreted layer resistivities in ohm-meters. Vertical exaggeration is 10:1.

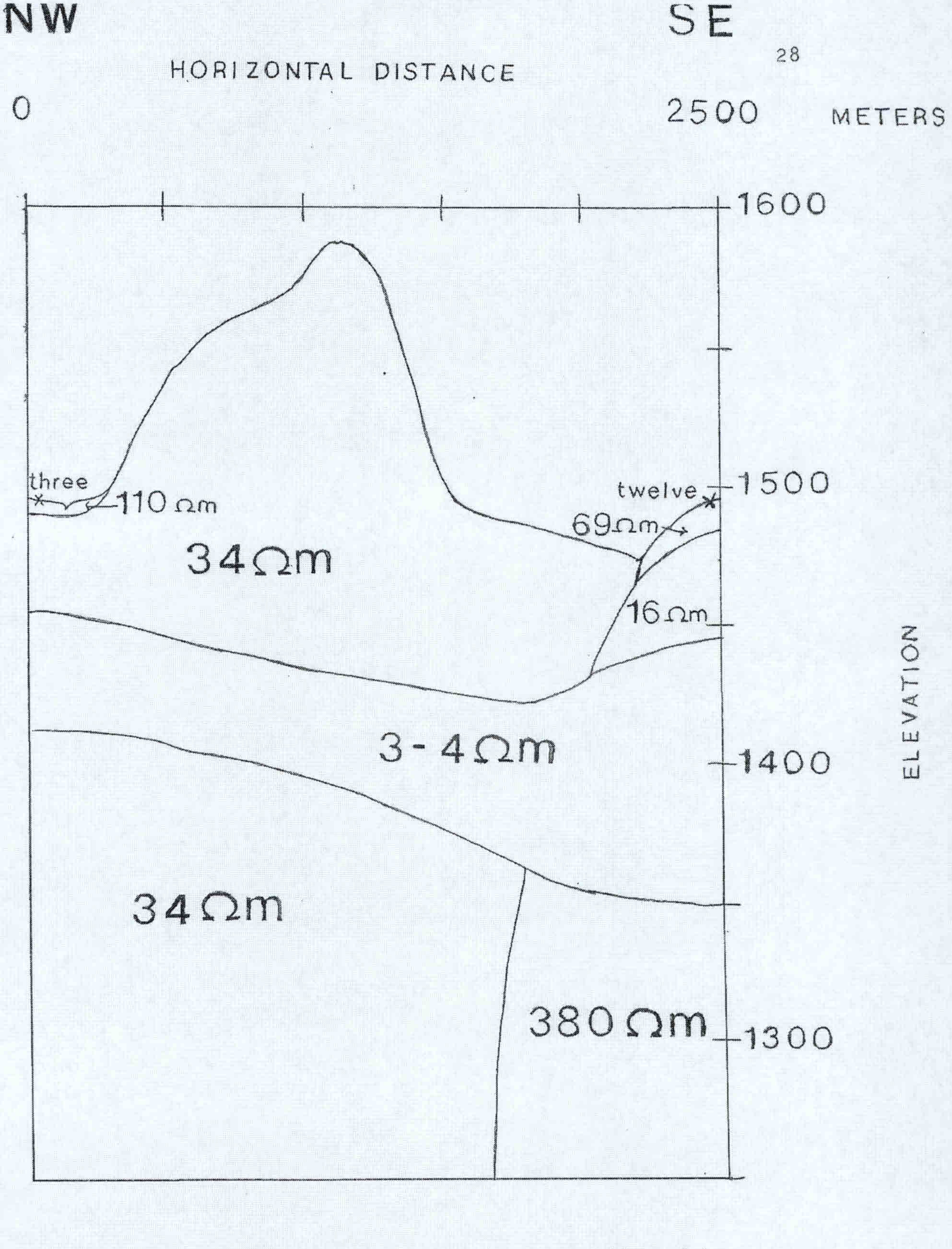

Figure 23. Geoelectric section six, incorporating data from Norris soundings twelve and three (locations are marked with an x), shows interpreted layer resistivity in ohm-meters. Vertical exaggeration is 10:1.

CONCLUSIONS

A conductive anomaly is evident from the electrical surveys and their geoelectric sections. The anomaly extends roughly over an eight square mile area of which the southwestern portion shows the most promise as to source direction. A fault (Vitaliano and others, 1979), shown near Burnt Creek in Figure 2, lies southwest of Norris four and may provide a pathway for thermal waters. Furthur work near Burnt Creek is needed to explore the southwest trending low. Lateral flow into shallow alluvium, which probably acts as a reservoire for the warm water, may be responsible for the wide range of low resistivities, measured throughout the area.

Norris one, though not nearly as anomalous as twelve or four, is interesting because it is not located in a structurally favorable area. Because of the anomalous mine water it would be instructive to do another electrical survey in the area, perhaps nearby the Waterlode Mine, to help determine if a relationship exists between the warm mine water and Norris Hot Springs.

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