Electromagnetic soundings on the Colville Indian Reservation, Washington

by

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INTRODUCTION

This report presents data from geophysical investigations conducted on the Colville Indian Reservation and is sponsored by the Bureau of Indian Affairs (BIA) as part of an ongoing program of mineral appraisal of Indian lands.

Among the types of mineral deposits known to occur in the Colville Indian Reservation, stockwork copper-molybdenite porphyry deposits similar to the Mount Tolman deposit seem to have the greatest potential for discovery (Rinehart and others, 1975). The literature indicates that a great deal of effort has been made to understand the geologic and geochemical environment of copper-molybdenum systems. The literature is noticeably lacking in geophysical parameters or geophysical case histories from which exploration criteria might be developed for the exploration geophysicist. These geologic and geochemical studies are, however, indirectly valuable in developing some potential geophysical criteria; for instance: Grant (1969) suggests that in the Northern Cascade porphyry systems ore controls include: suitable host pre-mineralization preparation through fracturing and faulting; fault zones and trend direction are often distinguished in potential field data such as magnetics and gravity. He further indicates that pyrite and pyrrhotite are often associated with such deposits; induced polarization would respond to increased sulfide content and magnetics would give an indication of the presence of pyrrhotite. Thomas and Galey (1982), in discussing the discovery of the Mount Emmons, Colorado, molybdenum deposits, indicate that magnetic surveys detected increased magnetite content within the porphyry system, that induced polarization responded well to the Keystone vein system but that detailed gravity measurements were inconclusive in identifying ore bodies.

Lowell and Guilbert (1970) discuss in lateral and vertical alteration zoning associated with porphyry ore deposits. They suggest that hydrothermal alteration in the propylitic and argillic zones causes montmorillonite and kaolin-group clay minerals to develop, and clays normally increase the conductivity of rocks. However, the single most important factor which determines the electrical conductivity of rocks is their water contents (Summer, 1976). The amount of water in rocks is related to the porosity and factors affecting porosity such as fracturing and faulting. Mutschler and others (1981) suggest that during the development of porphyry systems fluid pressures produce massive hydrofracturing characteristic of all porphyry deposits. Kamilli (1978) demonstrated the importance of high salinity (to 60 percent NaCl) fluids in the transportation of molybdenum at the Henderson mine, Colorado. All of the above mentioned factors may also have a direct bearing on the electrical nature of porphyry deposits.

One of the primary objectives of our investigation was to determine if significant changes in the electrical nature of the Mount Tolman porphyry system were introduced during the development of the various alteration zones. This information would then serve as control for interpreting data from mineralized areas.

ELECTROMAGNETIC METHODS

The audio-magnetotelluric (AMT) method can make use of natural or artificial electromagnetic (EM) fields. The natural field energy originates from worldwide atmospheric discharges of storms, with the principle energy produced from tropical storm cells that occur in the northern hemisphere during its summer months. These electrical discharges or lightning strikes often occur at great distances from the measurement site, thus, permitting a plane-wave assumption to be used in relating the measured electric and magnetic fields to the earth's resistivity (Hoover and others, 1978). Inasmuch as the equipment used in these investigations does not use artificial sources of EM fields, our discussions will be confined to natural source methods.

Cagniard (1953) describes the theoretical basis of the magnetotelluric method. Strangway and others (1973, 1979) discuss the application of AMT to mineral exploration and conclude that the method has both advantages and disadvantages compared with other electrical geophysical methods. Briefly, the equipment measures the relative amplitudes of the electric (Ex) and magnetic (Hy) fields in orthogonal directions. The scalar apparent resistivity (in ohm-m) is related to the measured fields by

$$\rho_a = 1/5\ F\ \left|\frac{Ex}{Hy}\right|^2$$

where F is frequency in Hertz (Hz), Ex is the horizontal x-directed electric field component in Mv/km, and Hz is the horizontally directed magnetic field in gammas. Apparent resistivities are calculated from sixteen frequencies spanning several decades, resulting in a form of depth sounding. These soundings can be interpreted using methods described by Anderson (1979) and Bostick (1977) in terms of physical parameters of a layered earth, i.e. conductivity and thickness of the various electrical interfaces present beneath the sounding site.

The skin depth (δ) is an approximation of the effective depth exploration of the AMT method and is given by $\delta(m) = 503\sqrt{\rho/f}$ where (ρ) is the resistivity in ohm-m and f is the frequency of the measured signals. The frequency range of the U.S. Geological Survey (USGS) equipment is from 4.5 Hz to 27 KHz, thus, the exploration depth ranges from a few tens of meters to several kilometers depending upon resistivity and frequency.

Time-domain electromagnetic (TDEM) methods were also tested in two areas in an effort to supplement the frequency-domain data taken with the AMT method. The equipment used (Sirotem) was designed and built in Australia and is described in detail by Buselli (1980). Briefly, the TDEM system used in these tests measures the transient decay of the electromagnetic field from eddy currents which are induced into the earth by a wire loop lying on the ground pulsed by a square wave current source. Inasmuch as the induced eddy currents do not cease to flow the instant the inducing current is switched off, but decay gradually, their presence is indicated by the decaying or transient voltages that are induced in a receiver loop. Hence, the measurement of these transient voltages is a means of detecting geologic conductors. The higher the conductivity of the conductor, the longer the transients persist. The transient decay voltage is measured by up to thirty two channels spaced in time between the cut off of one pulse cycle to the initiating of the next. The TDEM system used, allows for stacking and averaging up to 2048 measurement cycles. Any number of individual stacked measurements also may be averaged to determine to a very high degree of accuracy the transient voltage decay curve.

A variety of transmitter-receiver loop configurations may be used depending on the attitude of the conductors being sought. Characteristics of the received EM field are dependent upon the transmitter-receiver loop configuration, thus, a single wire loop (coincident; where transmitter and receiver use the same physical wire) produces a predominantly vertical local magnetic field which induces a maximum of eddy currents into horizontal conductors. Increasing the size of the transmitter-receiver loop increases the depth of exploration of the method. As a rule of thumb, the exploration depth is considered to be about twice the side dimension of a square transmitter-receiver loop. In practice, measurements are made either in a profile or sounding mode. The purpose of the profile mode is to delineate the horizontal extent, across strike, of an electrical conductor. The purpose of the sounding mode is to evaluate the thickness and electrical resistivity ρ) or conductivity ($1/\rho$) of layers beneath the sounding loop. The operational methods of the two modes do not have to differ significantly, but usually, in the profile mode, fewer time channels are used to sample the transient decay voltage of several successive loop setups, whereas in the sounding mode the full transient decay voltage (within equipment limits) is measured for a single, generally, large loop setup.

Interpretative techniques which allow determination of the layered earth parameters are discussed by Raiche and Spies (1981) and Anderson (1982a, b). As with the frequency-domain AMT data, TDEM data may be inverted to determine layered earth parameters such as conductivity and thickness. The non-unique solutions thus derived are at best, a fair estimate of the geoelectric-section.

DISCUSSION OF RESULTS

AMT soundings were made in six areas on the reservation (fig. 1). They were: 1. Mount Tolman; 2. Keno Trail area; 3. Mineral Ridge; 4. Park City district; 5. Five Lakes area; 6. Stranger Mountain area.

Mount Tolman area

The Mount Tolman copper-molybdenum porphyry deposit is closely associated with the emplacment of the Keller Butte pluton (W. Utterback, 1983, written commun.) Utterback has described the Keller Butte pluton in the vicinity of Mount Tolman as consisting of two distinct zones interpreted as representing in-situ differentiates of the cooling pluton. The border zone, having solidified first, consists of two major phases that are compositionally and texturally similar. Phase 1, the quartz monzonite of Manilla Creek is distinguished from Phase 2, the granodiorite of Mount Tolman (Kgd; fig. 2), by its unzoned potassium feldspar phenocrysts and its coarser grain size. The interior zone, which solidified after the border zone consists of Phase 3 (porphyritic quartz monzonite unit) and Phase 4 (Quartz Porphyry Kqp), which are distinguished from phases 1 and 2 by their lighter color (lower biotite content), their large, zoned, euhedral potassium feldspar phenocrysts, their quartz "eyes", and their automorphic granular texture.

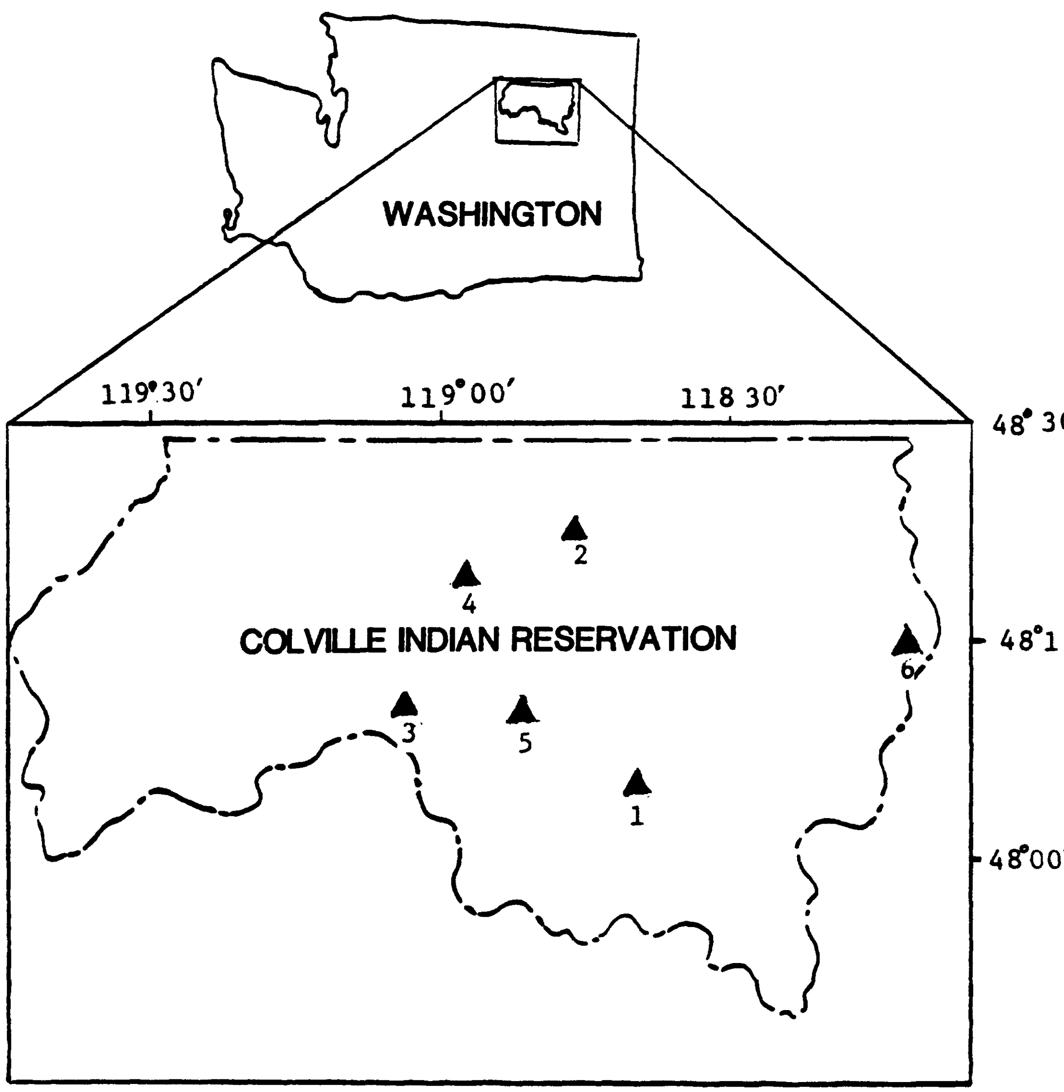
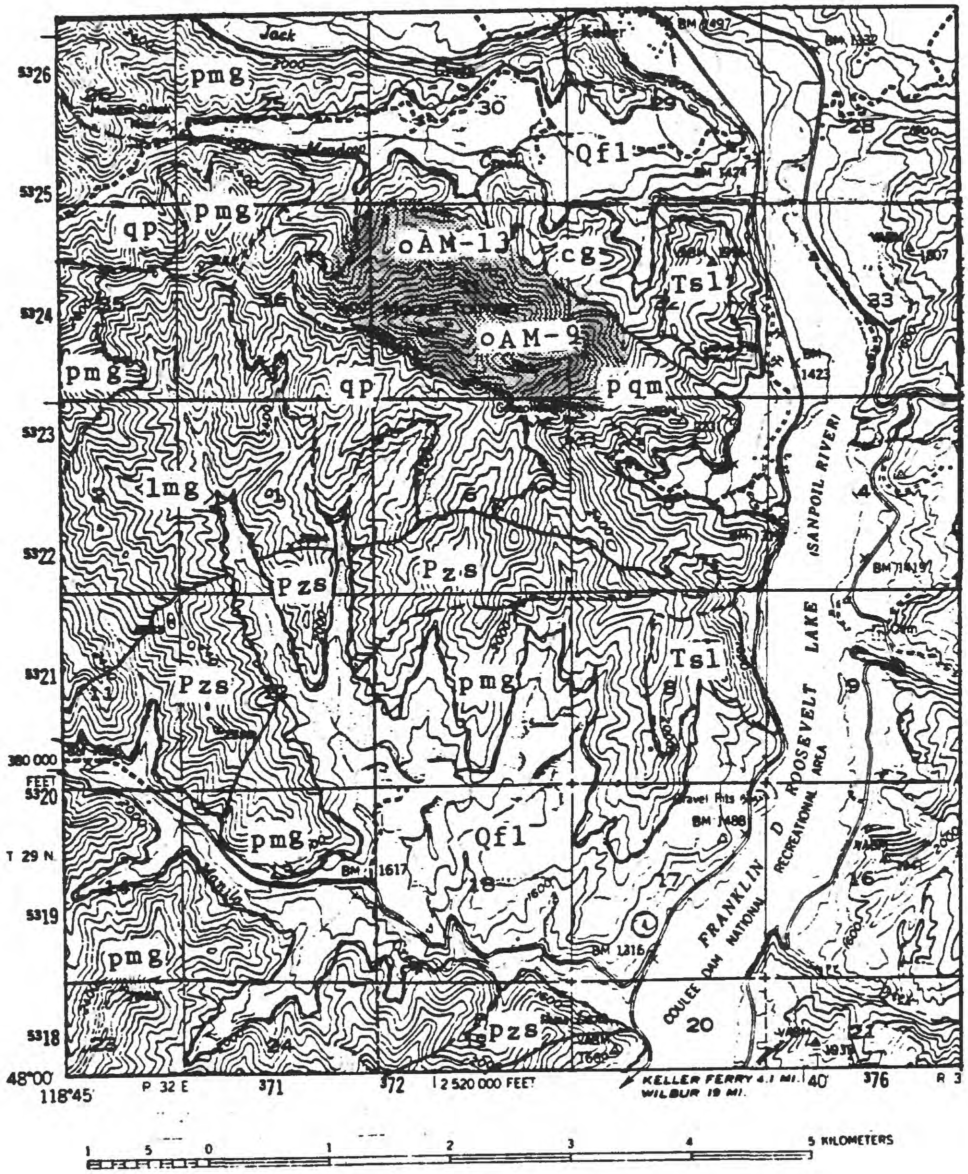


Figure 1. Index map showing the location of the Colville Indian Reservation; shown, also are the approximate locations of the areas discussed in this report. Area 1: is the Mount Tolman area; 2. the Keno Trail Area, 3. The Mineral Ridge area; 4. the Park City District; 5. The Five Lakes area, and 6. the Covada District.



LEGEND

Qfl - FLUVIAL AND LACUSTRINE DEPOSITS

Tsl - LAVA FLOWS

pmg - PORPHYITIC GRANODIORITE

lmg - GRANITE

qp - QUARTZ PORPHYRY

cg - ALTERED GRANITE

Pzs - SCHIST, QUARTZITE, CARBONATE ROCKS

oAMT - AMT station location

Geology from: Preliminary geologic map of the Keller quadrangle, Ferry County, Washington by Atwater and McGroder, 1982; U.S.G.S. unpublished map.

Figure 2. Part of the Keller quadrangle showing the geology in the Mount Tolman area; the shaded area delineates the approximate areal extent of copper molybdenum mineralization.

The Mount Tolman ore body is within the border zone overlying interior quartz porphyry unit. Mineralization followed potassic hydrothermal alteration and explosive brecciation of the border zone in several episodic stages. The ore body has been dislocated by numerous faults associated with post-mineralization movement that has step-faulted the ore body down both to the north and to the east.

In a regional geophysical setting the Mount Tolman deposit lies within rocks of low magnetic character, type 1 granitoid rocks (Roth and Papazian, 1979, Flanigan and Sherrard, 1983). Steep magnetic gradients on both the east and west side of the non-magnetic north trending rocks suggest that they may be faulted at these contacts. Locally, Roth and Papzian (1979) suggest that there may be a modest (20 gammas) magnetic high, the exact cause of which is at present unknown, associated with the mineralized zone. The Mount Tolman deposit lies on the western flank of a gravity high caused by dense granitic rocks immediately to the east. The gravity data suggest that the host rocks of the Mount Tolman deposit are slightly more dense than basement rocks immediately to the west. There is some suggestion of a small (2-3 mgal) gravity low associated with the deposit itself, however, additional detailed gravity measurements will be needed to confirm this hypothesis.

Two AMT electromagnetic soundings (AM-9 and AM-13) were made over the Mount Tolman deposit in order to ascertain the geoelectrical signature of the porphyry as control for EM work in other areas on the Reservation. One sounding (AM-9) is located a few hundred meters east of the summit of Mount Tolman. Three northeast trending faults pass through the area between the summit and the sounding site, the faults have step-faulted the orebody down on the south east side, but the exact amount of offset is unknown. The results of sounding AM-9 are shown in figure 3. The smoothed line drawn through the data point is judged to be a close approximation of the true EM response; the smoothed response was modelled using a one-dimensional modelling program (Bostick, 1977). The resultant layered earth model (fig. 4) indicates that altered rock extends to about 100 m depth; below 100 m, resistivities gradually increase to about 1000 m depth, where the occurrence of unaltered, resistive granitoid rocks is inferred. W. Utterback (1983, written communication) suggests that drilling indicates that the quartz porphyry unit, of the interior zone (phase 4), with a characteristic ground mass, extends to a minimum depth of 3500 feet (1067 m) beneath the lower boundary of the orebody. It is believed that the transition zone from low resistivity to high resistivity rocks is related to the quartz porphyry unit. The orebody lies within the upper 100 m or so of altered rocks of about 200 ohm-m resistivity.

Results of AMT sounding AM-13 (fig. 5) suggest a geologic environment similar to that of the AM-9 site, i.e. border type rocks which contain the orebody (250 ohm-m), extending from the surface to about 150 m depth. At greater depth the the rocks increase in resistivity; at about 600 m depth fresh, unaltered rocks are inferred. Based on these AMT soundings and interpretations, it is concluded that altered granitoid rocks which might be hosts for similar mineralization have resistivities in the range of 100-300 ohm-m and that unaltered intrusive granites have resistivities in the range of 1,000 to 10,000 ohm-m.

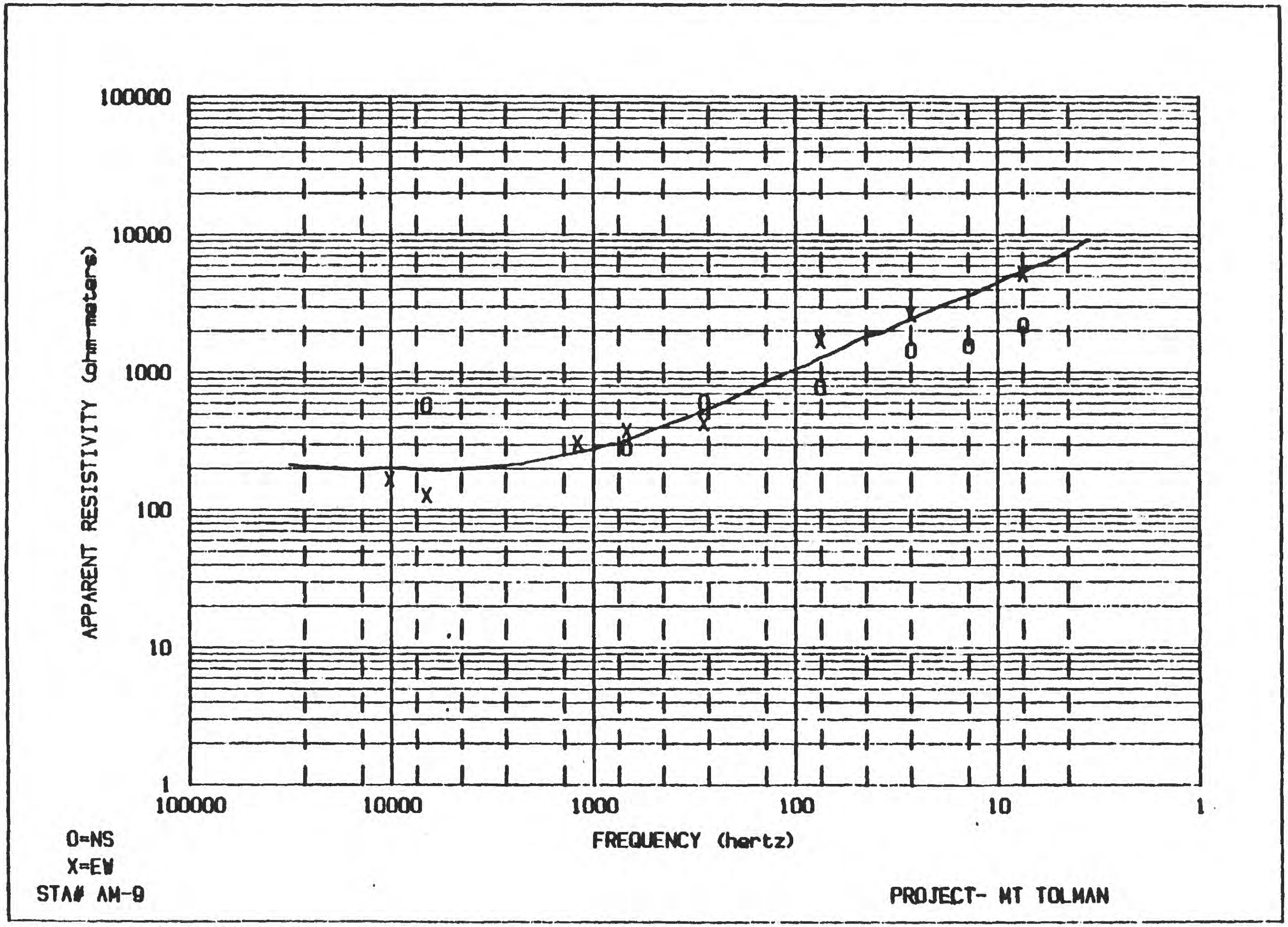


Figure 3. Plot of AMT sounding data from station AM-9, "O" is the east-west E-line orientation, "X" is the north-south E-line orientation, the solid, smoothed line used for modelling, see text.

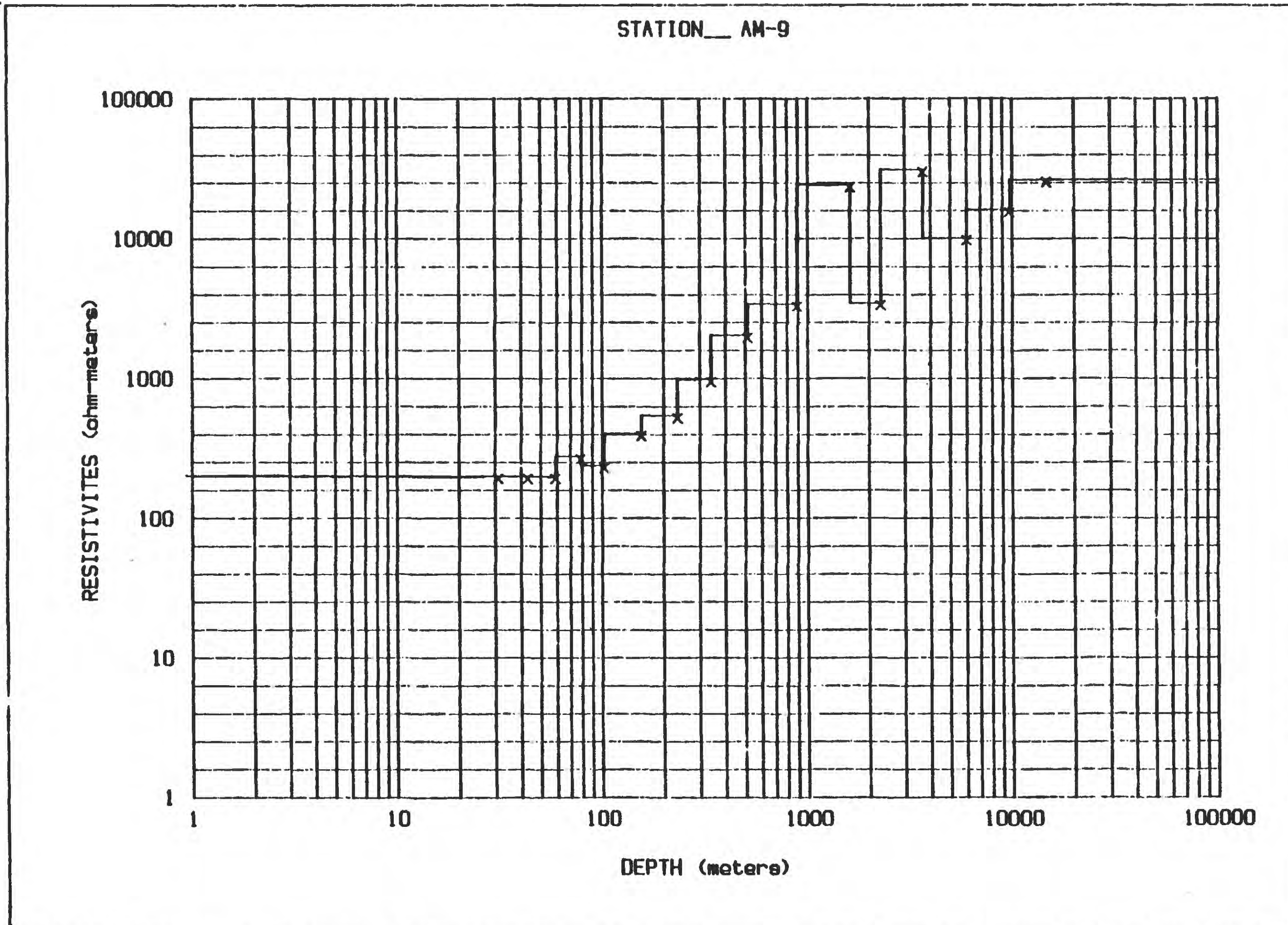


Figure 4. Interpreted geoelectric section of Mount Tolman AMT sounding AM-9 showing the resistivity interfaces versus depth.

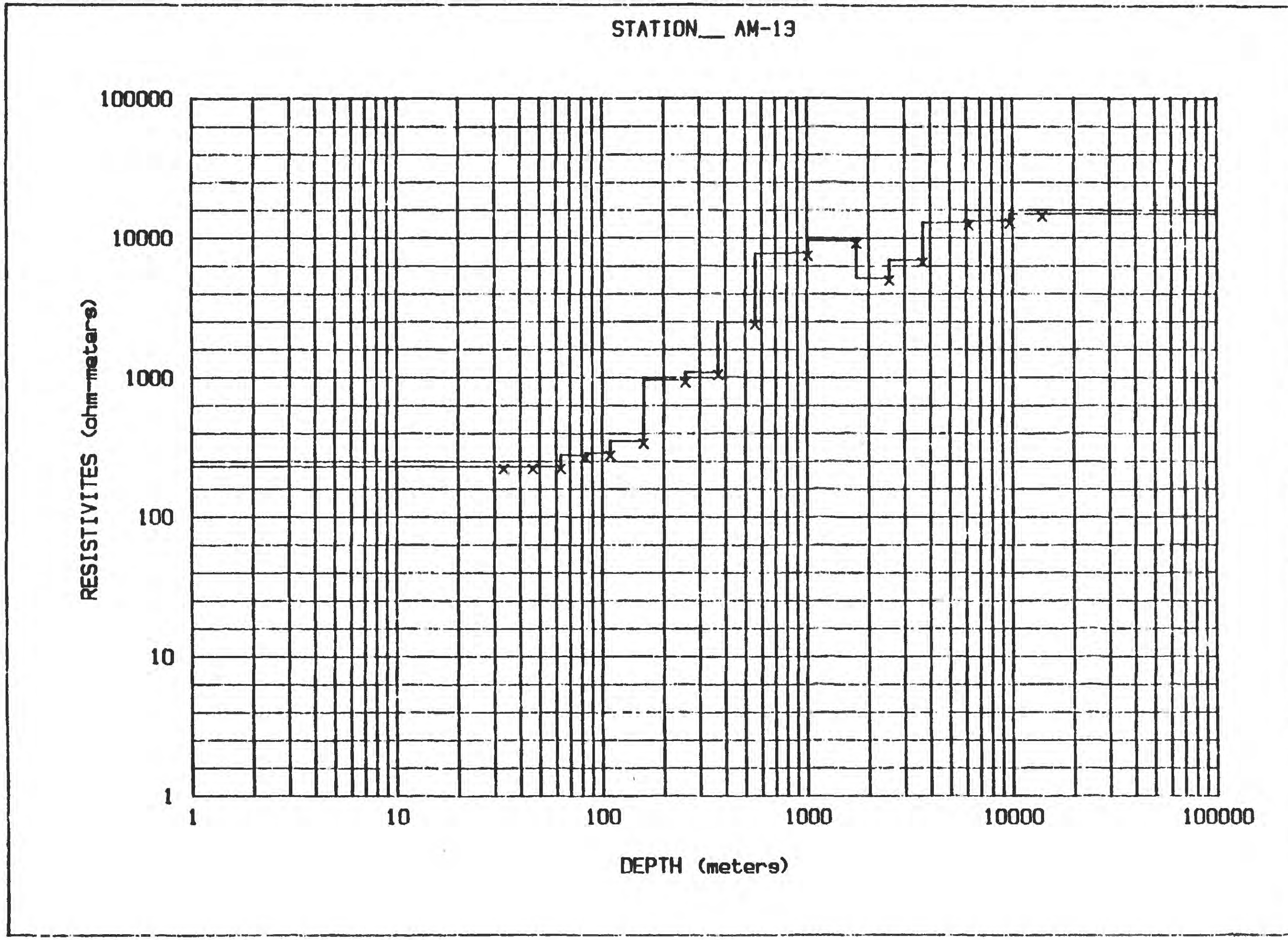


Figure 5. Interpreted vertical distribution of resistivities from Mount Tolman sounding AM-13.

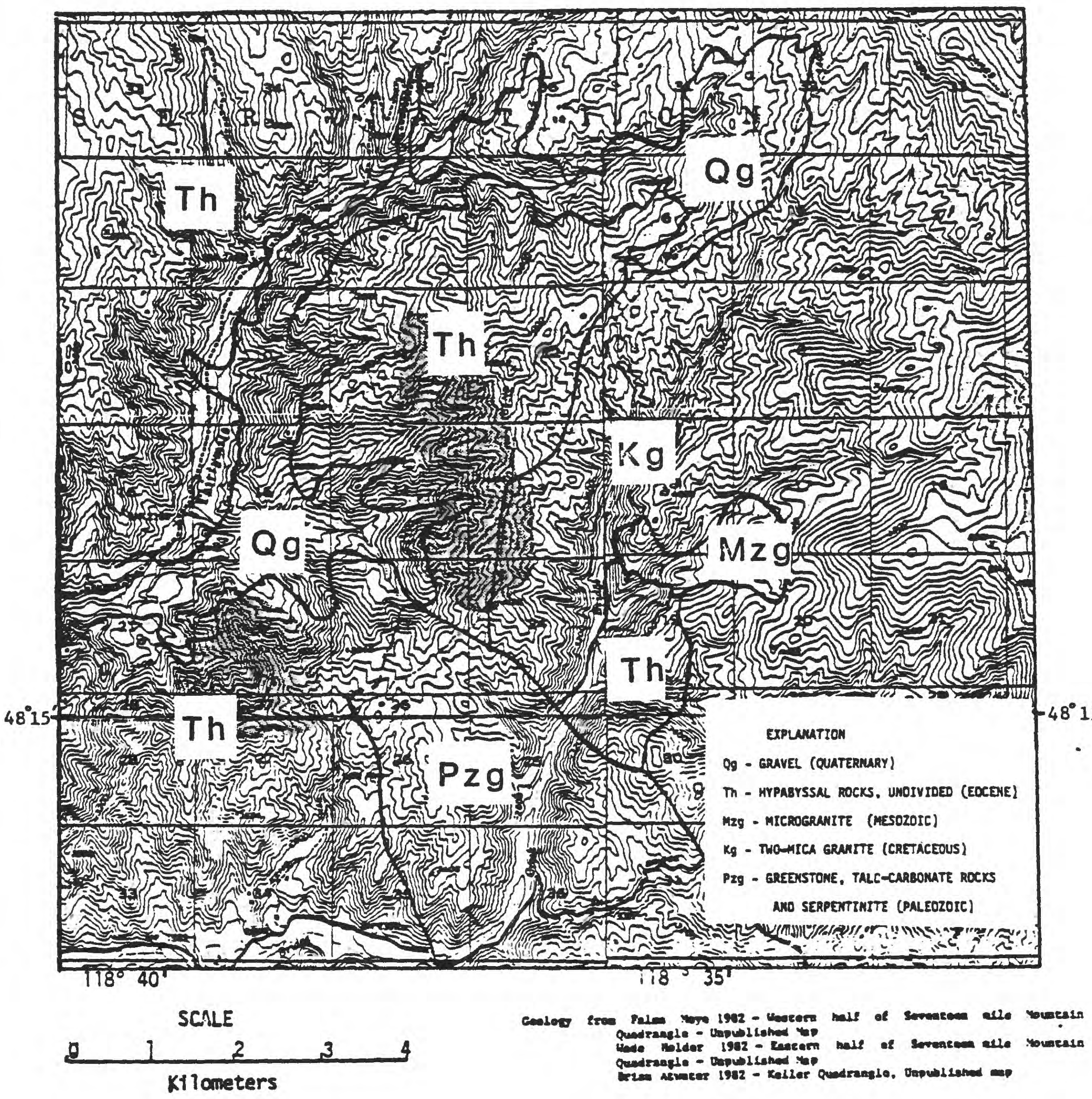


Figure 6. Parts of the Seventeenmile Mountain and Keller quadrangles showing the simplified geology of the Keno Trail area.

KENO TRAIL AREA

The Keno Trail area is located just north of the Bridge Creek highway and east of the San Poil River valley. It covers about 40 km^2 (25 mi^2). The geology of the area (fig. 6) is dominated in the eastern half by a medium grained two-mica granite (Kg), and in the western half by dikes and dike swarms of rhyodacite, dacite, and quartz latite composition (unit Th, fig. 6). These dikes are the intrusive equivalent of extrusive rocks that fill the Republic graben a few kilometers to the west. Metasedimentary rocks composed of greenstone, talc-carbonate rocks, and serpentinite (Pzg) cover a few square kilometers of the southcentral part of the Keno Trail area.

Two areas of hydrothermal alteration were identified by U.S. Geological Survey geologists mapping in the area and have been approximately located by shading on figure 6. The most northern altered area was tested by drilling under the direction of the Tribal Geology Department and while some copper-molybdenum mineralization was intersected, the general conclusion was that the area represented a deep section in the hydrothermal system and as such extensive mineralization is probably not present (J. Erickson, 1982, personal commun.).

During the 1981 and 1982 field seasons twenty-three AMT soundings were made in the Keno Trail Area. The results of these data are presented in figures 7-10. Two apparent resistivity maps (figs. 7 and 8) show the response at 75 and 450 Hertz (Hz), respectively. In general, the lowest frequency (75 Hz, fig. 7) gives a deeper picture of the apparent resistivity than does the 450 Hz response (fig. 8). Both frequencies show similar electrical responses. Apparent resistivities greater than 4000 ohm-meters (Ω-m) define the two-mica granite (unit Kg, fig. 6). The metasedimentary rocks (less than 1000 Ω-m) are most clearly outlined by the 75 Hz map (fig. 6) as are the hydrothermally altered areas.

Geoelectric sections along lines A-A′ and B-B′, (fig. 7) were constructed from AMT soundings that were interpreted using the one-dimensional algorithm (1977), implemented in computer programs by Carl Long (unpublished, 1982). The geoelectric sections show the variation of resistivity with depth. Section A-A′ (fig. 9) clearly shows the hydrothermally altered systems where AMT soundings K-2 and K-5 were located over the altered areas. In the K-2 area, rocks at 400-500 m depth are less than 250 Ω-m and are somewhat less resistive than rocks at the same depth in the K-5 area. Based on the AMT soundings made at the Mount Tolman Site previously discussed, the resistivity of rocks in the K-2 area are similar, although at a greater depth, which suggests that the K-2 area may represent a higher section in the hydrothermally altered system than in the Mount Tolman area. The K-5 area may represent the transition zone of Mount Tolman where resistivities are increasing with depth.

Geoelectric section B-B′ (fig. 10) crosses the contact between the granite pluton (unit Kg, fig. 6) on the east and the metasedimentary rocks and into the hypabyssal rocks on the west. These lithological boundaries can be seen on the geoelectric section B-B′ where resistivities greater than 4000 Ω-m form steep contour gradients between sounding K82-6 and K82-3, typical of the granite-metasedimentary rocks contact. There is a definite break between the metasedimentary rocks beneath sounding K82-3 and the hypabyssal rocks to the west beneath sounding K-1, suggesting an electrical resistivity contrast between the metasedimentary and the hypabyssal rocks.

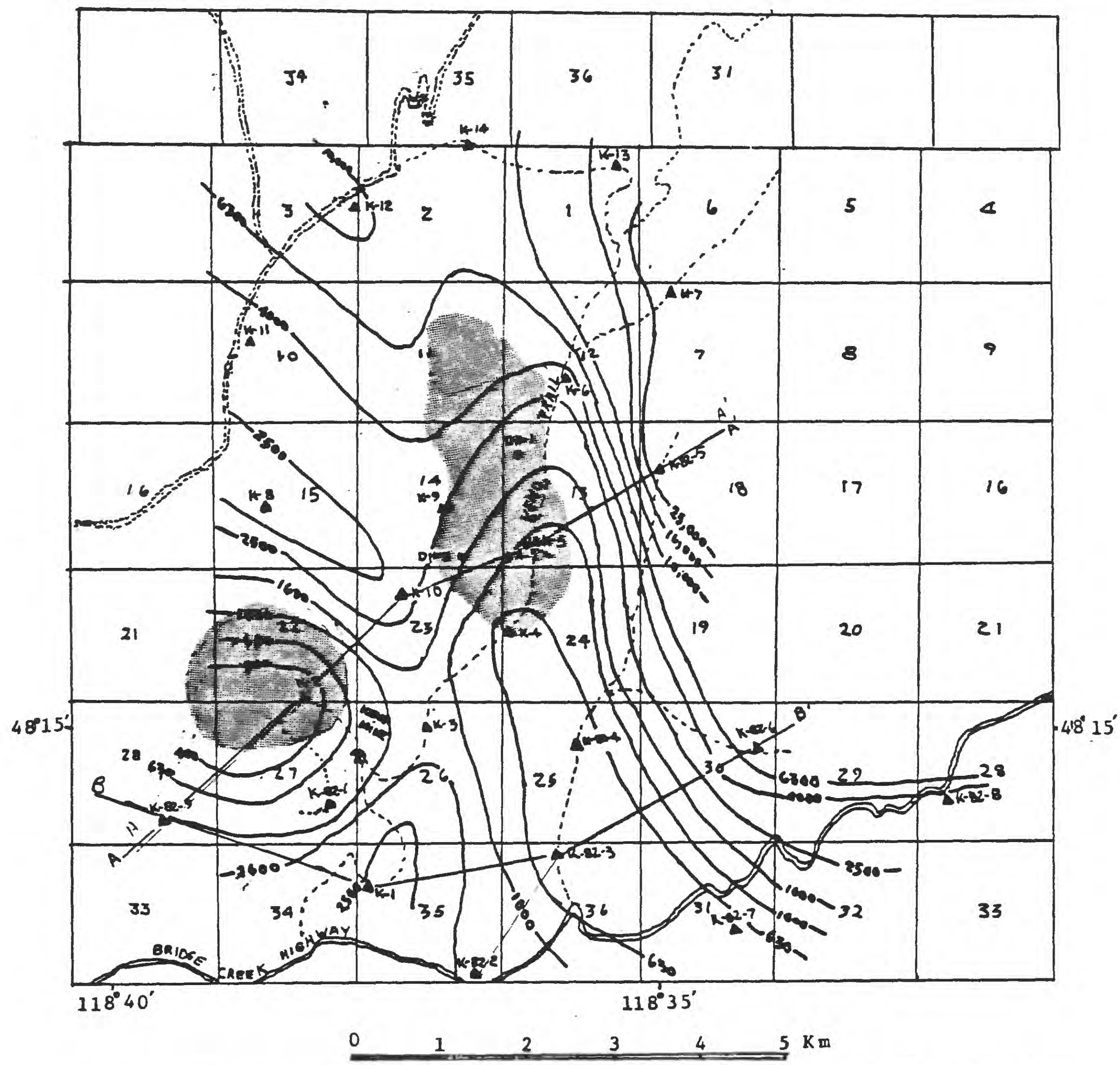


Figure 7. Parts of Seventeenmile Mountain and Keller quadrangles on the Colville Indian Reservation showing AMT station locations in the Keno Trail area, contour lines show the apparent resistivity at 75 Hertz (Hz). The shaded areas are zones of hydrothermal alteration.

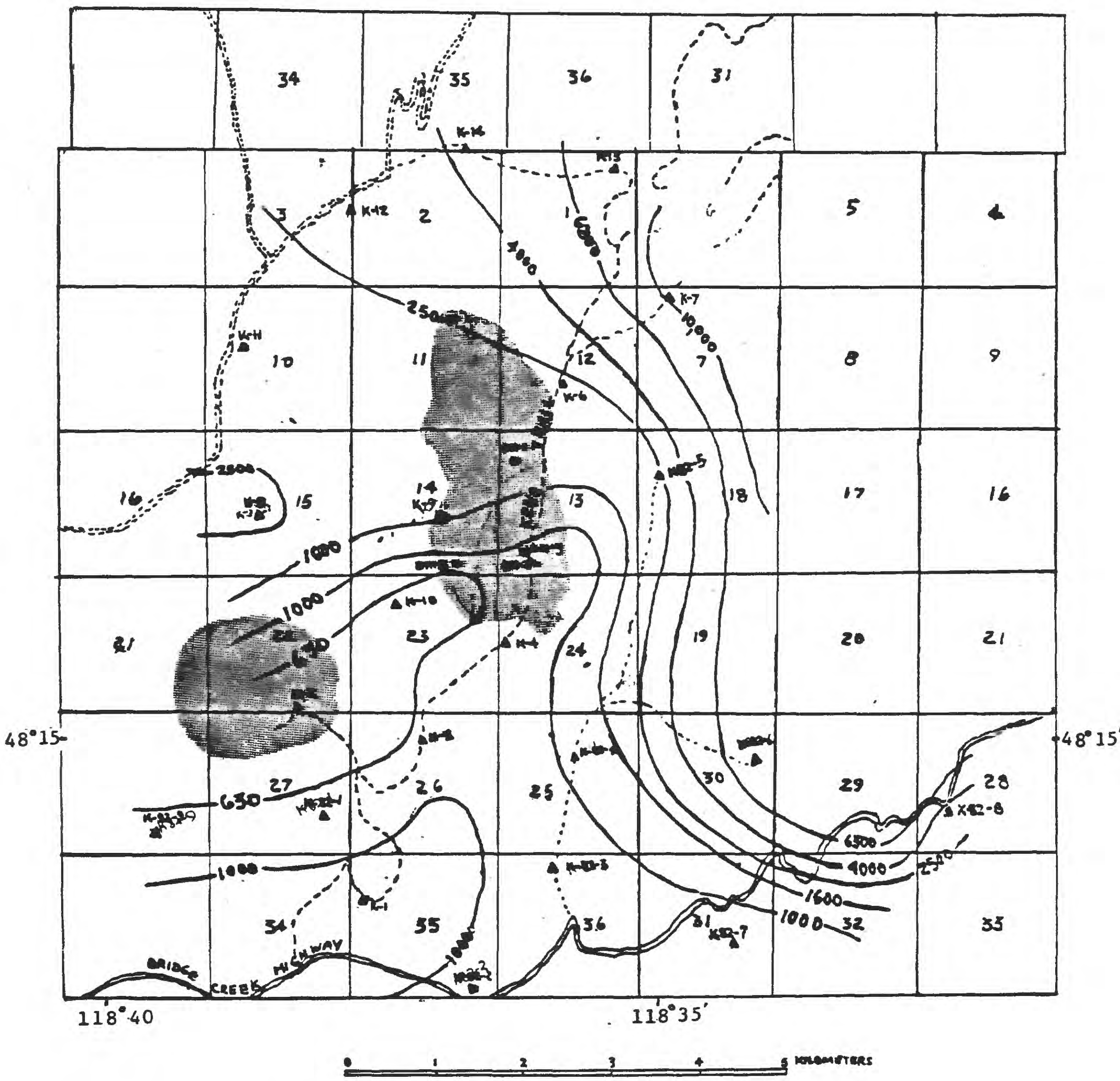


Figure 8. Parts of Seventeenmile Mountain and Keller quadrangles in the Keno Trail area showing AMT, the apparent resistivity at 450 Hz. The shaded areas are zones of hydrothermal alteration.

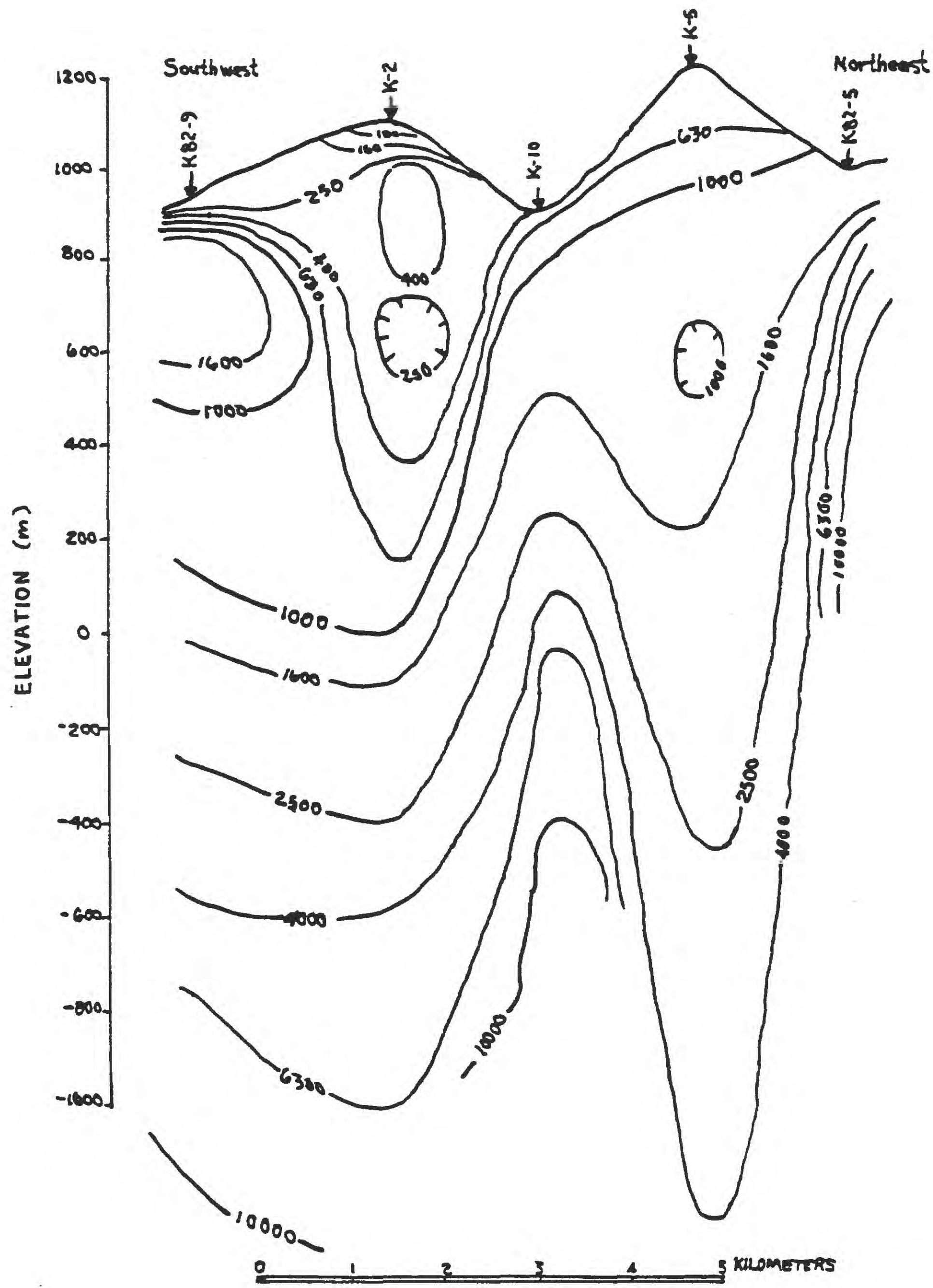


Figure 9. Electrical section A-A' (fig. 7) showing the interpreted vertical distribution of resistivity from AMT soundings.

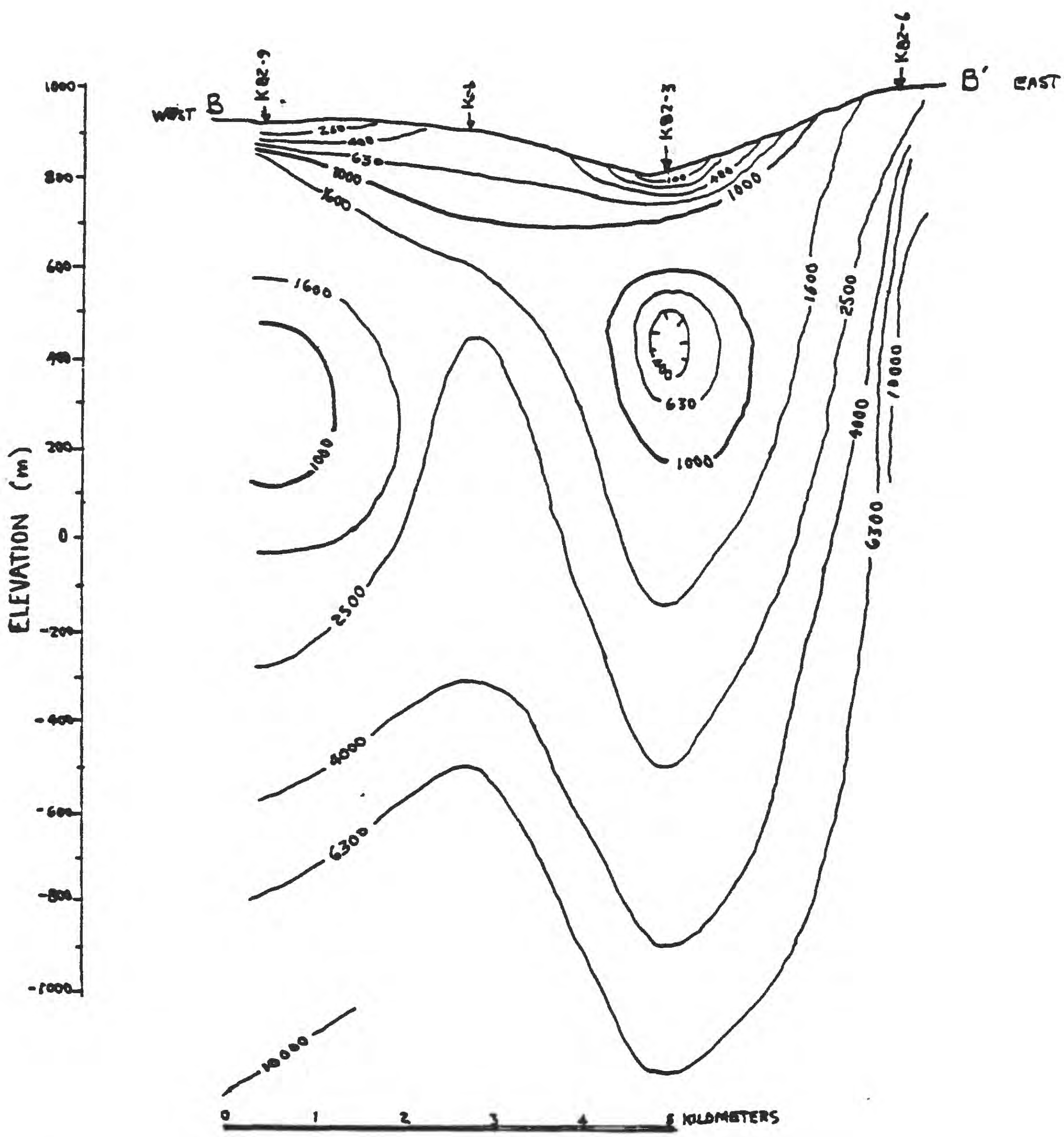


Figure 10. Electrical section B-B' (fig. 7) showing vertical distribution of electrical resistivity interpreted from AMT soundings in the Keno Trail area.

In the Keno Trail area the AMT data generally outlines the major lithologic units, as well as the hydrothermally altered zones. Future exploration should consider detailed exploration in the K-2 area (near the Keno mine) because this altered system appears to be deeper and more intensely altered than the area to the northeast (K-5 area) previously tested by drilling.

MINERAL RIDGE AREA

The Mineral Ridge area lies within the Nespelem District of Rinehart and Greene (1975, fig. 1). The area of these investigations covers about 11.2 km^2 (7 mi^2) and generally surrounds Mineral Ridge.

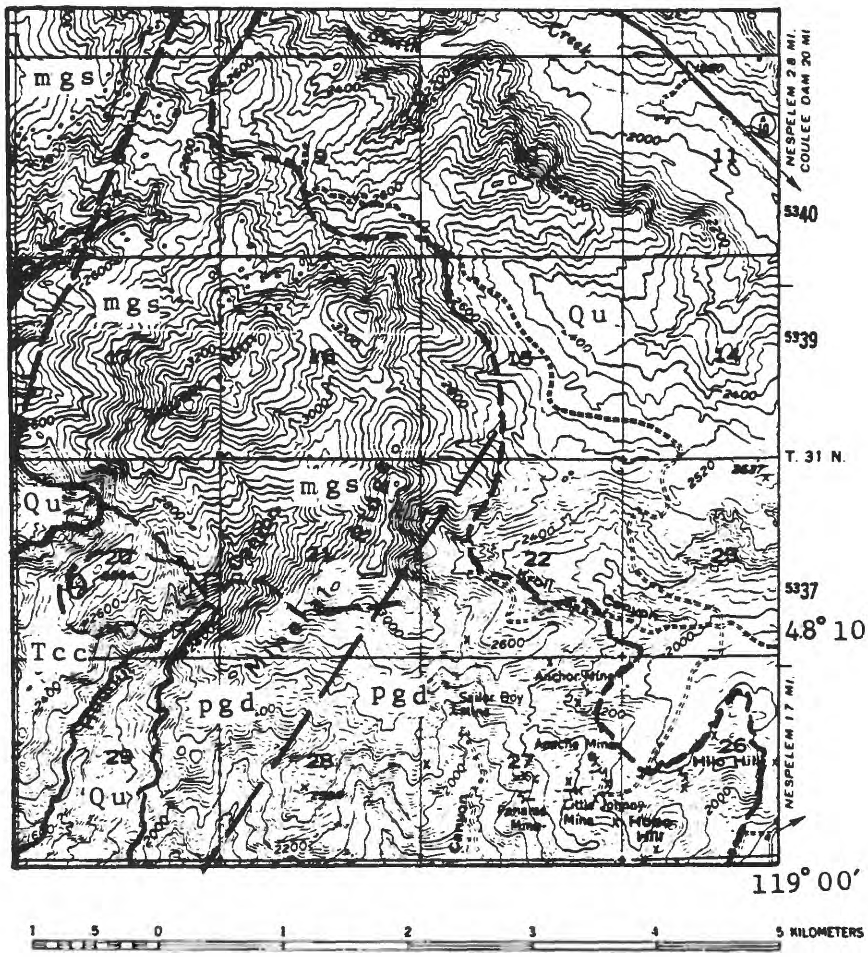
The geology of the area (fig. 11) is dominated by granitic rocks that have intruded older metasedimentary rocks which were nearly completely absorbed so that only small residual masses remain. Younger porphyritic granodiorite dikes trending northeast crosscut the older rocks (Rinehart and Greene, 1975).

Mineralization in the area is related to the intrusive granite, deposits being formed as replacement veins, filled fissures in the granite, and as contact metamorphic deposits in or near the residual masses of metasedimentary rocks. Silver, copper, lead and zinc are the metals of greatest importance. Of the many mines and prospects in the area, the Apache mine in Sec. 27, T. 30N was the area's greatest producer.

The Mineral Ridge area was surveyed in 1981 under contract to the USGS, by an airborne electromagnetic and (AEM) and magnetic, helicopter survey. Results of that survey suggested seven areas in which near surface apparent resistivities were less than 1000 Ω-m. Detailed ground follow-up in one of the areas outlined a subcircular conductive anomaly related to a residual mass of metasedimentary rocks (Flanigan and others, 1982).

Thirteen AMT soundings were conducted in the Mineral Ridge area (fig. 12). The results of the AMT survey are presented as apparent resistivity maps (fig. 12 A, B). The data correlate well with the AEM data (see fig. 2, Flanigan and others, 1982). An east trending conductive zone, most clearly seen on figure 12B, generally follows Kroll Canyon and is thought to be related to a thick section of glacial till and alluvium in the canyon. A conductive anomaly located in Sec. 15, T. 31 N. is most apparent on the 685 Hz apparent resistivity map (fig. 12B). The airborne survey detected a conductive anomaly in the same area. Conductive alluvium may be responsible for or at least contribute to the anomaly source.

A third conductive anomaly, located in Sec. 17, T. 31 N., at the southwest end of Squaw Mountain, confirms the AEM data also. Previous geophysical work in the Squaw Mountain area suggested that pyrite (up to 4 percent) was the cause of a measured induced polarization (IP) anomaly (Amax, 1980, unpublished report). Inasmuch as disseminated pyrite would not contribute significantly to electromagnetic conductivity anomalies such as detected by the AEM and AMT surveys, it is suggested that the Squaw Mountain anomaly may be associated with a hydrothermal system that has lowered the intrinsic resistivity of the granitic rocks through alteration. Further geologic, geochemical and geophysical studies of the Squaw Mountain anomalous area would be required to ascertain the validity of this conclusion.



EXPLANATION

Qu - Unconsolidated sedimentary deposits
Tcc - Coyote Creek Pluton (Eocene)
pgd - Porphyritic granodiorite (age unknown)
mgs - Metamorphic and granitoid rocks of Squaw Mtn.

Geology from Atwater, B.F., 1983, "Reconnaisance geologic maps of the Alameda Flat andBoot Mtn. 15-minute Quadrangles North of the Columbia River, Okanogan County, Washington." unpublished map.

Figure 11 Preliminary geologic map of the Mineral Ridge area, Colville Indian Reservation.

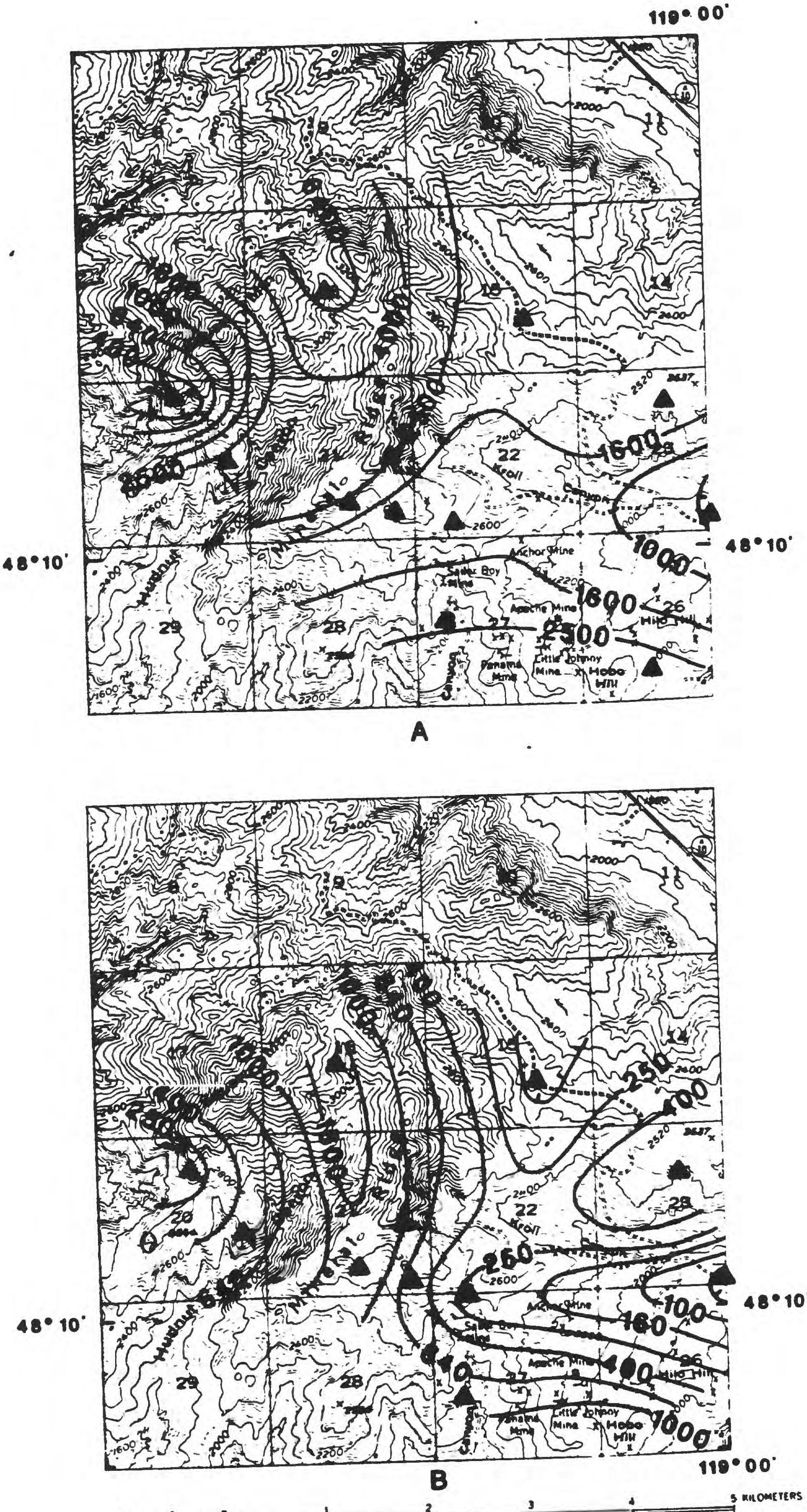


Figure 12. Maps showing apparent resistivity from AMT soundings in the Mineral Ridge area; A: apparent resistivity at 27 Hz; B: apparent resistivity at 685 HZ.

Park City area

Mines and prospects about 14 miles north of Nespelem in the Bald Knob 15' quadrangle comprise the Park City District (fig. 1).

The geology of the district consists of metasedimentary rocks intruded by granite and overlain by volcanic rocks. Major, north trending bounding faults for the Republic graben immediately to the east, and secondary faulting complicates the local geology.

Time restraints did not allow extensive geophysical work in the area beyond the regional gravity and airborne magnetic measurements which cover the entire reservation. However, three AMT soundings were made in 1982 in support of tribal economic geologists who began a limited drilling program in the Park City area (fig. 13). The purpose of the AMT soundings was to determine, if possible, the depth to granitic rocks which had intruded the metasedimentary rocks of the Covada Group.

Sounding data from AMT station PC 82-1 was modelled using a plane-wave inversion program (Anderson, 1982a, 1982b). The results of a three-layer model are shown in figure 14. The open-circles are the observed data logarithmic average of the NS and EW component apparent resistivity data), the solid curve represents a best least-squares fit of the theoretical data computed over a three-layer earth model as shown by the solid line step model. The model suggests that material, probably alluvium and weathered rock of about 60 Ω-m resistivity extends from the surface to about 25 m depth; from 25 m to 50 m depth rock of about 3000 Ω-m resistivity occurs; below 50 m the rock is resistive (25,000 Ω-m). In this area the intrusive body is thought to be at no more than 50 m depth.

The three-layer model which best fit AMT data from sounding PC 82-2 suggest a similar sequence of rock with one notable exception (fig. 15a). Alluvium and weathered rock of 50 Ω-m extends from the surface to about 25 m depth, from 25 m to about 250 m rocks are about 150 Ω-m, at 250 m depth, rocks become more resistive (1400 Ω-m). Intrusive rocks equivalent in resistivity (25,000 Ω-m) to those encountered at the PC 82-1 sounding area was not detected. At sounding site PC 82-3 a very similar sequence of rocks and resistivities as seen at site PC 82-2 seems to occur, except that the second layer is considerably thicker (fig. 15 b).

The lithologic log from diamond drill hole PC 82-2, which was spotted about midway between AMT soundings PC-82-1 and PC-82-2 indicates that alluvium, andesitic rocks, and a Tertiary dike extend from the surface to about 70 m depth. From 70 m to 466 m in depth there is an alternating sequence of black shale, dike rocks, and biotite-hornblend rocks. A quartz monzonite intrusive body was intersected at 466 m depth.

Based on the lithologic drill log and the results of the modelled AMT data, we suggest that the intrusive contact between the quartz monzonite and the overlying metasedimentary rocks deepens from 50 m depth at AMT sounding site PC 82-1 to greater than 250 m depth at AMT site PC 82-2 and greater than 1000 m at AMT sounding site PC 82-3.

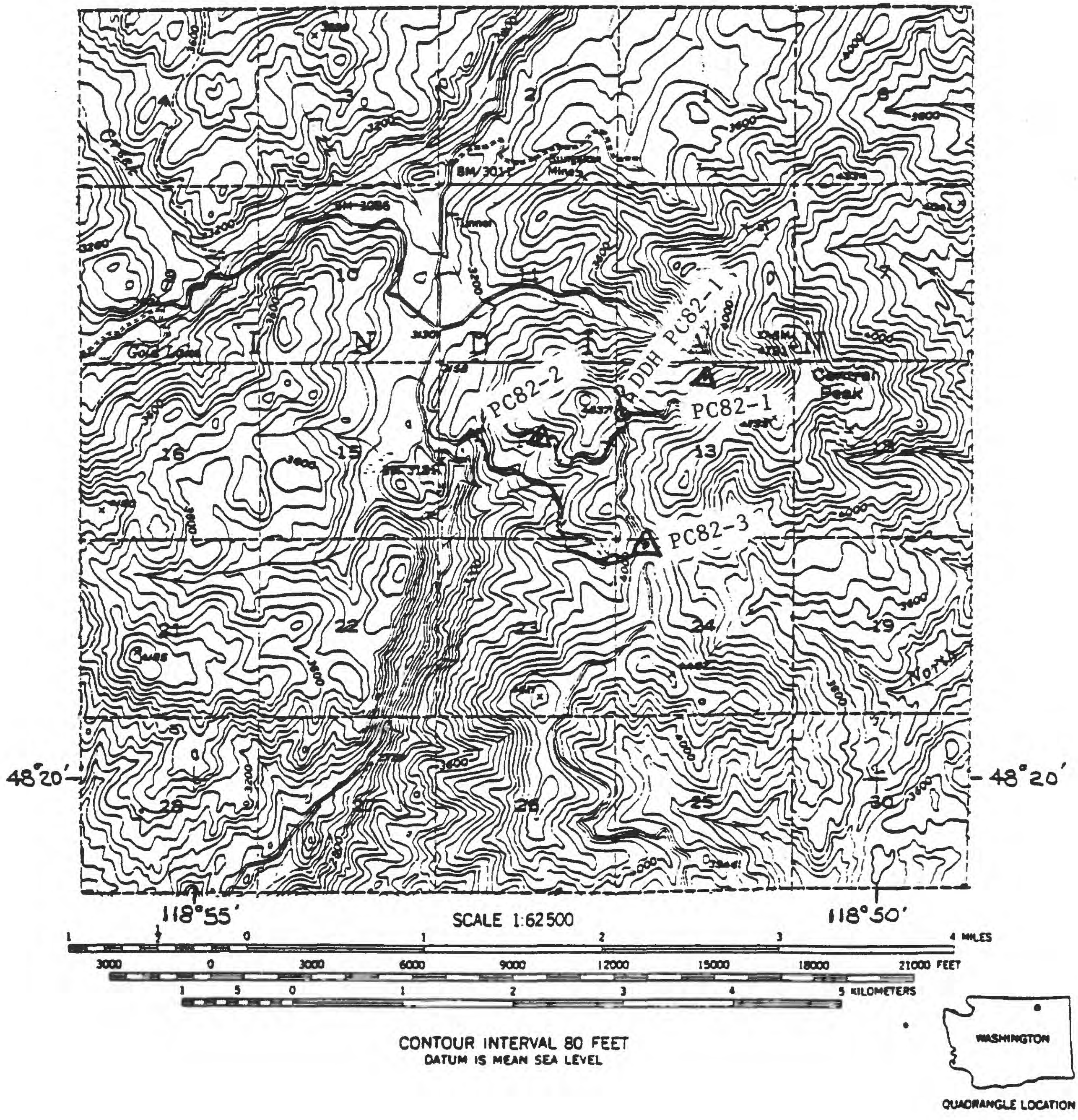


Figure 13. Part of the Bald Knob 15' quadrangle showing the location of AMT soundings in the Park City district; also shown is the location of diamond drill hole PC-82-2 in Sec. 13, T. 33 N.

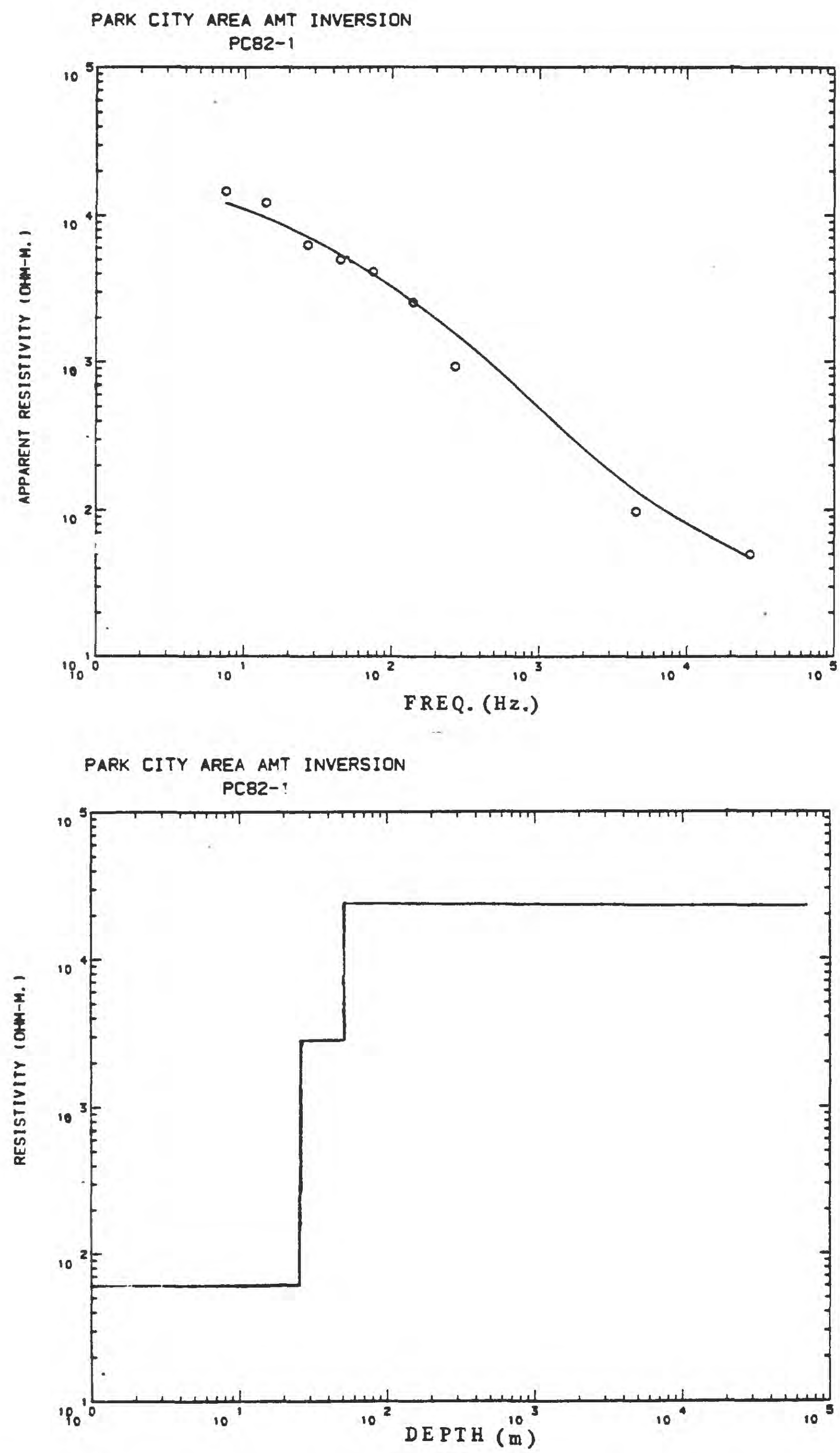


Figure 14. Plot showing apparent resistivity (o) versus frequency for AMT sounding PC-82-1. Also shown is the computed apparent resistivity sounding curve (solid line) from a three-layer model with resistivities and layer thickness as shown by the step model.

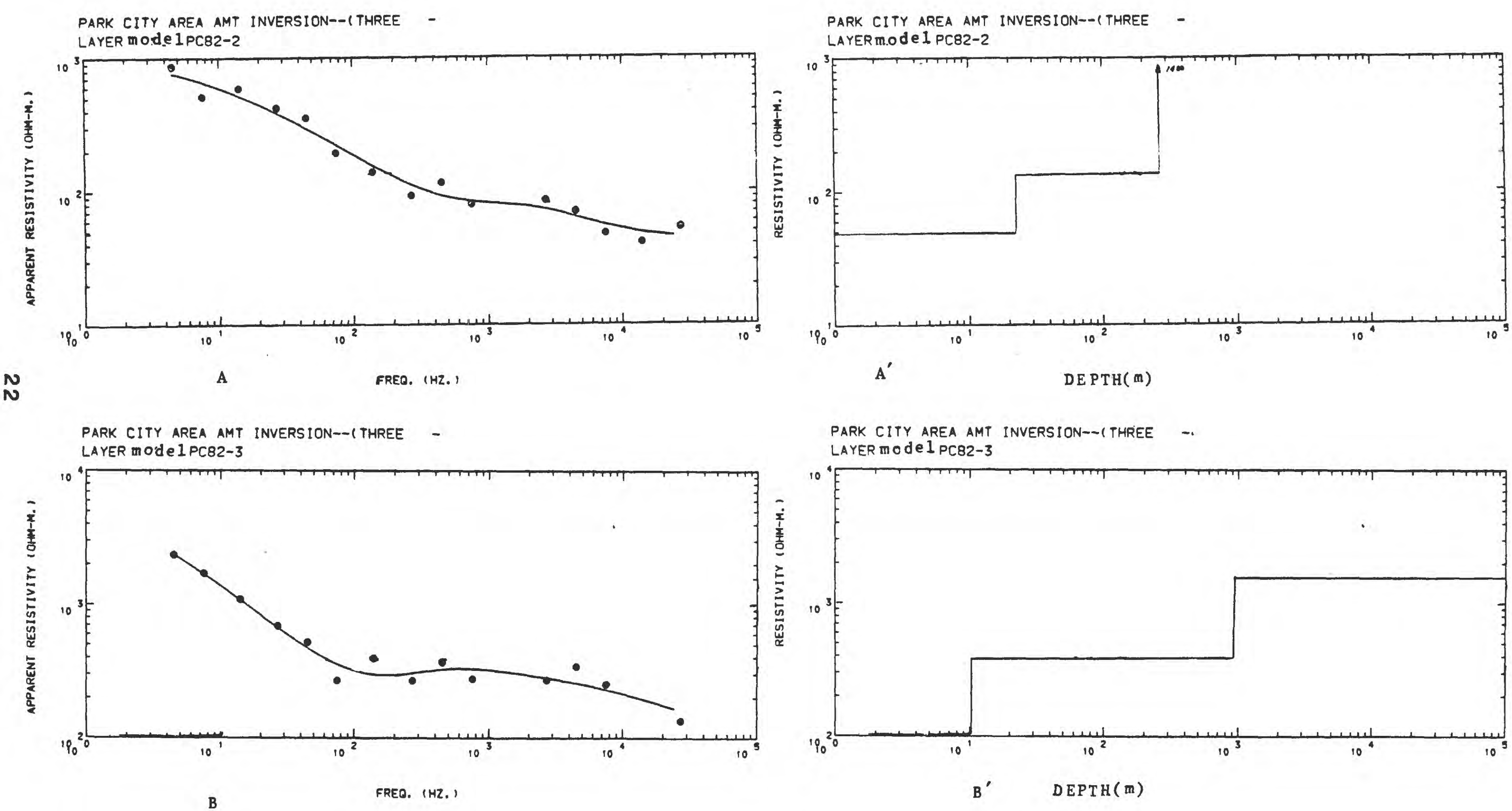


Figure 15. Plots of AMT soundings PC-82-2 (A) and PC-82-3 (B). The open circles (o) are the observed data, the solid curved lines are theoretical values computed for the three-layer model as shown.

Five Lakes area

The Five Lakes area is located about 5 miles southeast of the Tribal headquarters in the Nespelem quadrangle. The geology of the area (fig. 16) consists largely of surficial deposits of glacial till, soil, sand, and gravel. Small remnent of flows of the Columbia River Basalt Group are present mostly along the western side of the area. Granite and granodiorite, cut by northeast-trending rhyodacite dikes, comprise the major part of the bedrock units exposed in the area. In the north-central part of the area Carlson (1982, unpublished geologic map) mapped a hydrothermally altered zone in a garnetiferous leucocratic-granite (fig. 16), a possible location for a porphyry deposit.

Four AMT soundings and one large-loop (500 m) TDEM sounding were made in the area (fig. 16). The TDEM sounding was located at the site of AMT sounding 5LK 82-1 in the hydrothermally altered area. The TDEM sounding (fig. 17A) suggested that the granitic body became more conductive at 200-300 m depth than at the surface (fig. 17B). The data suggest that rock of about 1050 Ω-mextends from the surface to about 200 m depth, where the rocks become more conductive. The TDEM method did not resolve resistive rocks below the conductive zone.

Data from an AMT sounding (5LK 82-1) located at the center of the TDEM sounding was modelled to determine the parameters of a four-layer earth that would best fit, in a least-squares sense, the observed data. The resulting model (fig. 18), suggested a conductive zone at about 600 m depth. The two methods did not agree on the depth to the conductive zone and because the results of theoretical modelling are equivalent solutions, rather than unique, forward computations were made to see how well both methods would respond to the same four-layer earth model. The model selected (fig. 19) represented, a 250 Ω-m surface layer, a second layer of altered granitic rocks of 3000 Ω-m, a third layer of highly altered granitic rocks of 330 Ω-m and the fourth layer of fresh unaltered granite of 25,000 Ω-m. The thickness of the second layer was varied in 200 m increments from 400 m to 1000 m. The results of these computations suggest that the observed time-domain response would fit quite well in the model where the thickness of the second layer is about 610 m (fig. 19). The same model was then subjected to computations using plane-wave theory to determine the AMT frequency response. These calculations also suggest that the model would best fit the observed AMT data where the thickness of the second layer is about 610 m (fig. 20). TDEM measurements were not made in other areas because the data response over rocks of 2000 to 3000 Ω-m resistivity is marginal.

A diamond drill hole was made at the site of 5LK 82-1 AMT sounding to test at depth the center of the altered granitic rocks exposed at the surface. The hole bottomed at a depth of 221 m and thus did not test the conductive zone at around 610 m. The general consensus of the Tribal economicgeologists was that although the hole intersected minor amounts of mineralization, it did not intersect the center of a hydrothermally altered zone (Erickson, 1982, personal commun.)

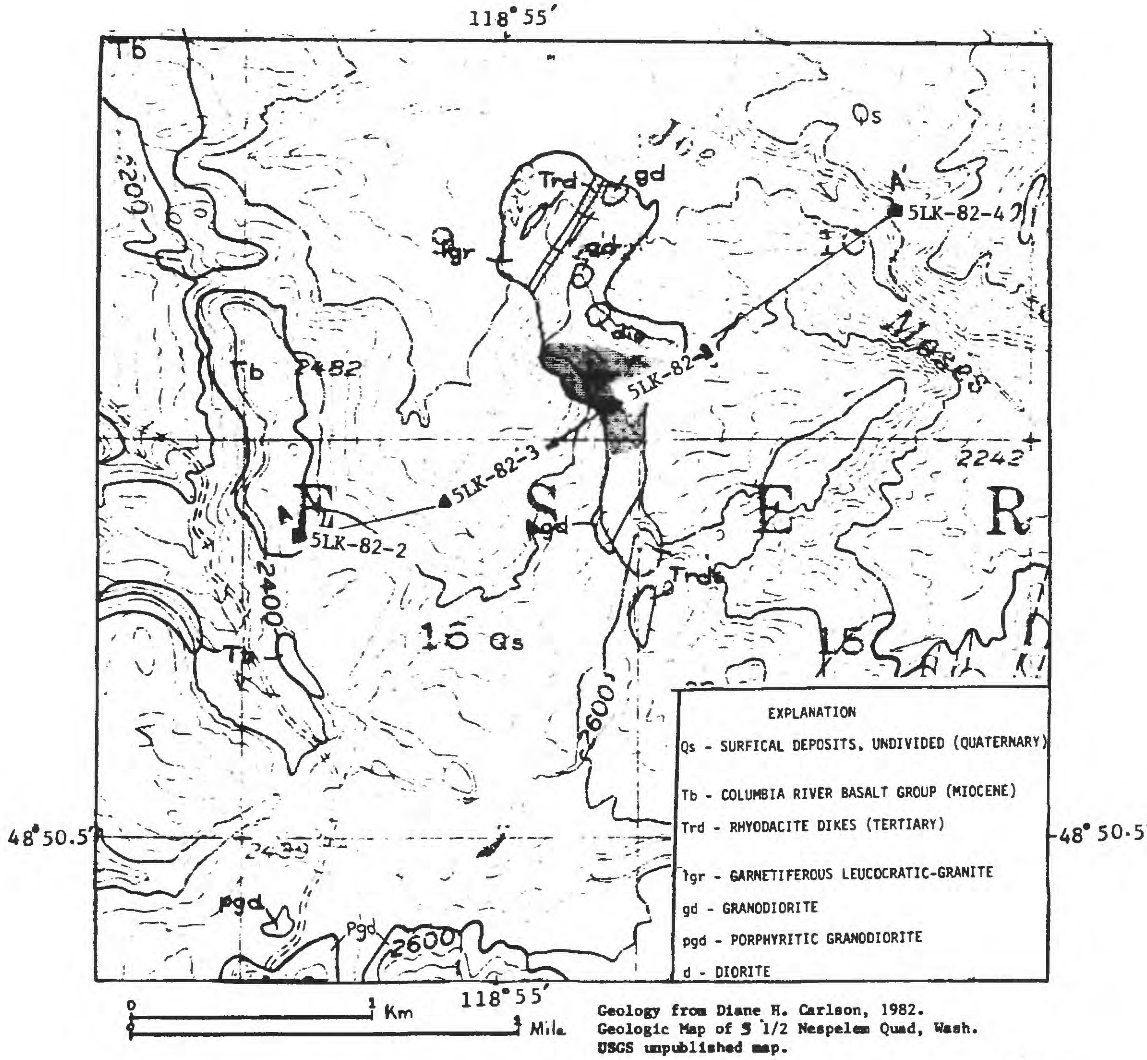


Figure 16. Geologic map of the Five Lakes area showing location of AMT stations; the shaded area shows the outcrop extent of the hydrothermally altered garnetiferious leucocratic-granite unit.

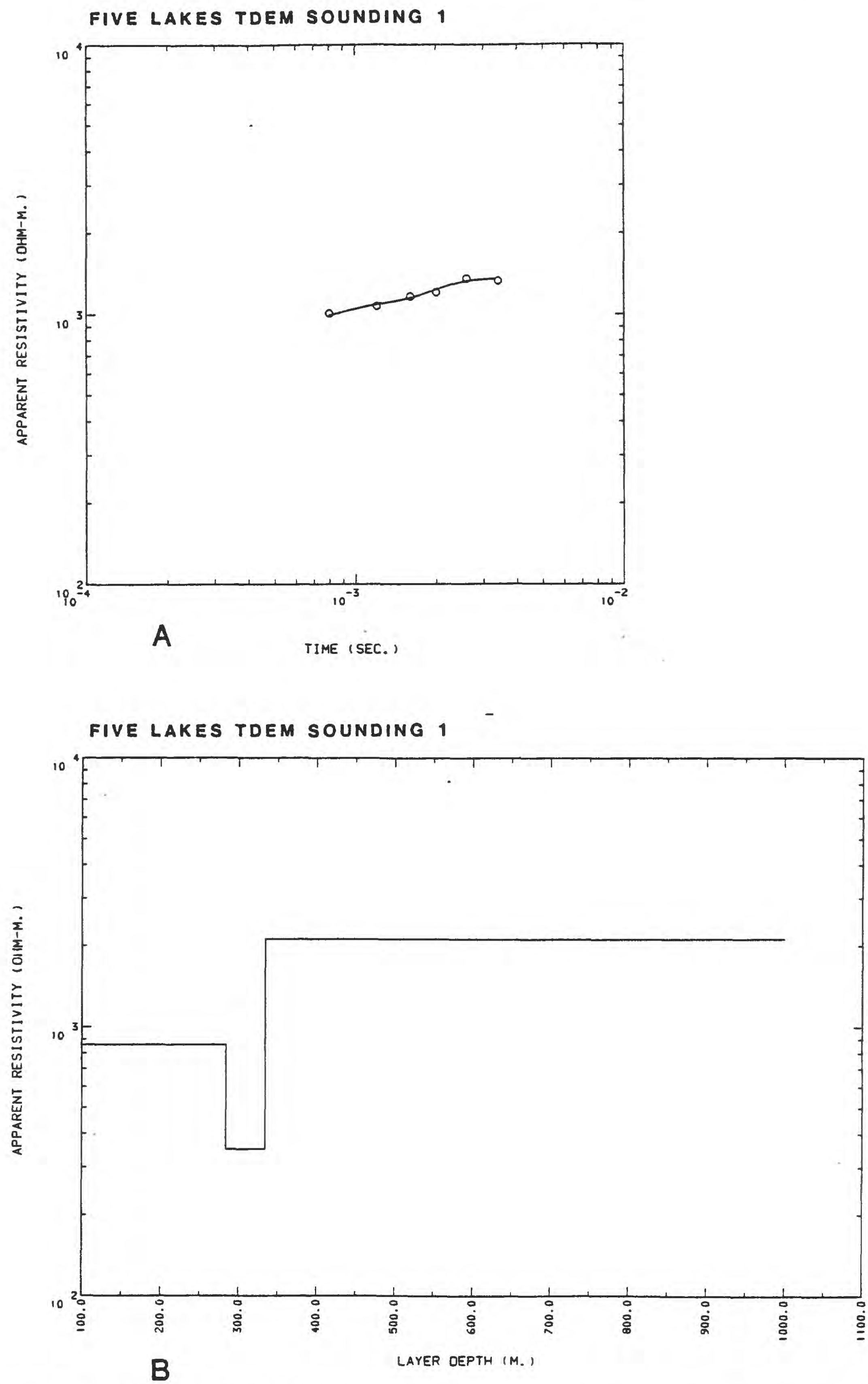
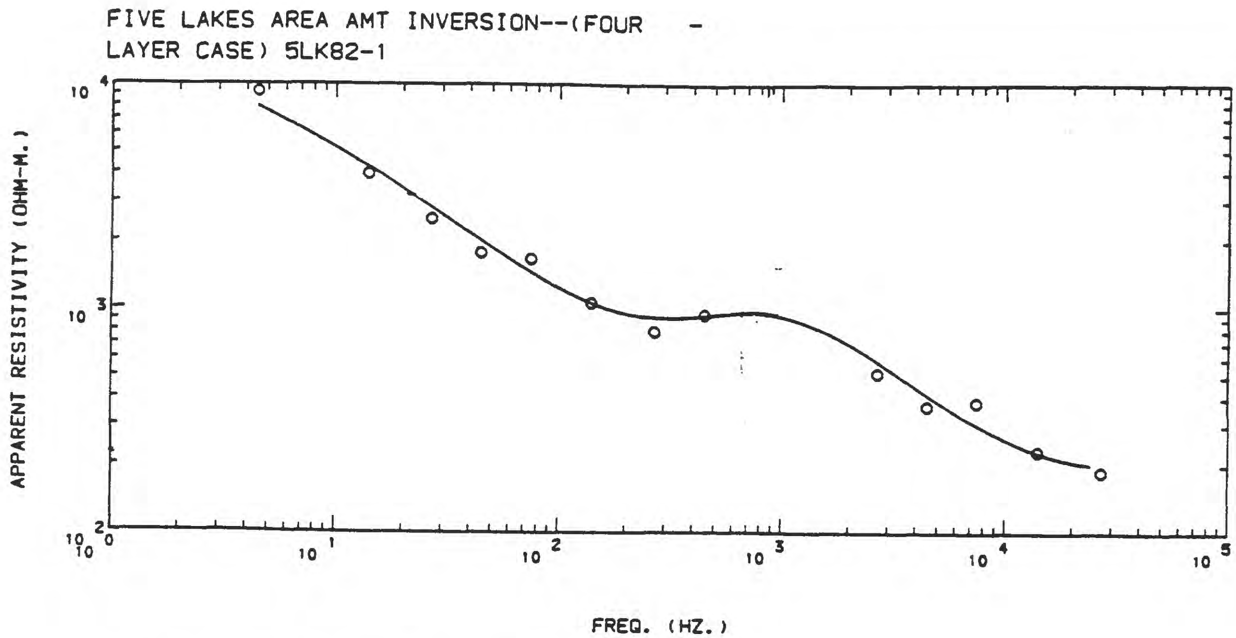


Figure 17. Plot showing (A); observed (o) apparent resistivity time decay curve for a time domain sounding, the solid lines are theoretical values computed for a four-layer model as shown in figure 17B.



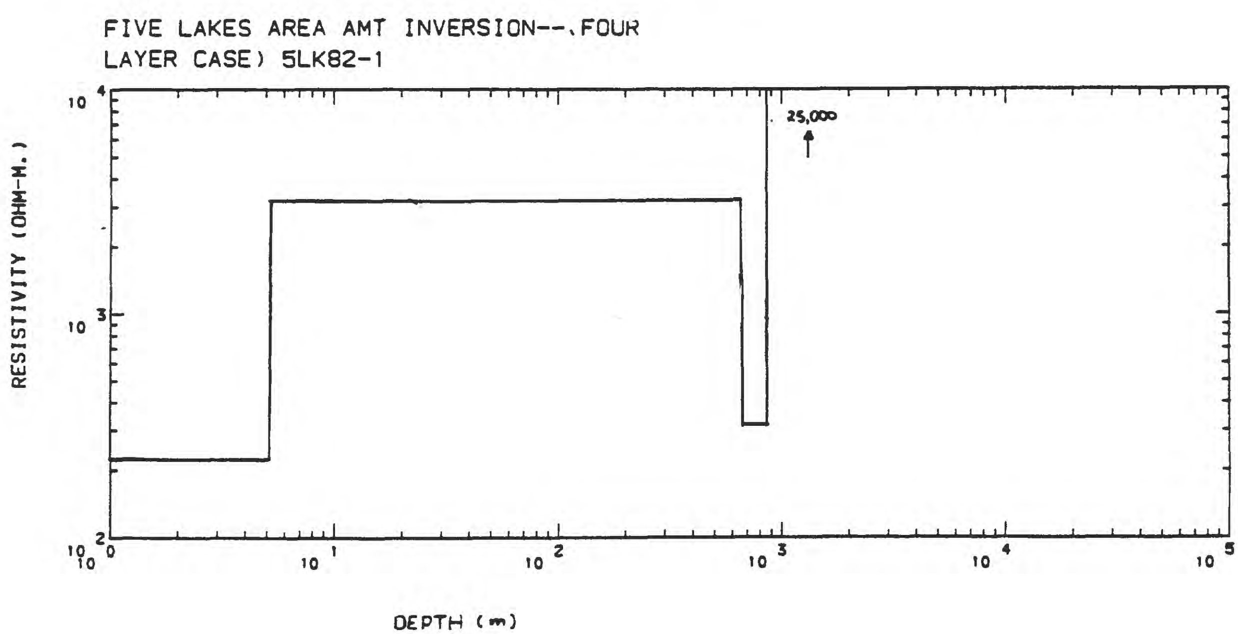


Figure 18. Plot showing a four-layer earth model determined by inverting the AMT sounding 5LK 82-1, in the Five Lakes area; the open circles (0) are the observed data, the solid curve line represents the computed values over a layered earth having resistivity-thickness values as shown by the solid step line.

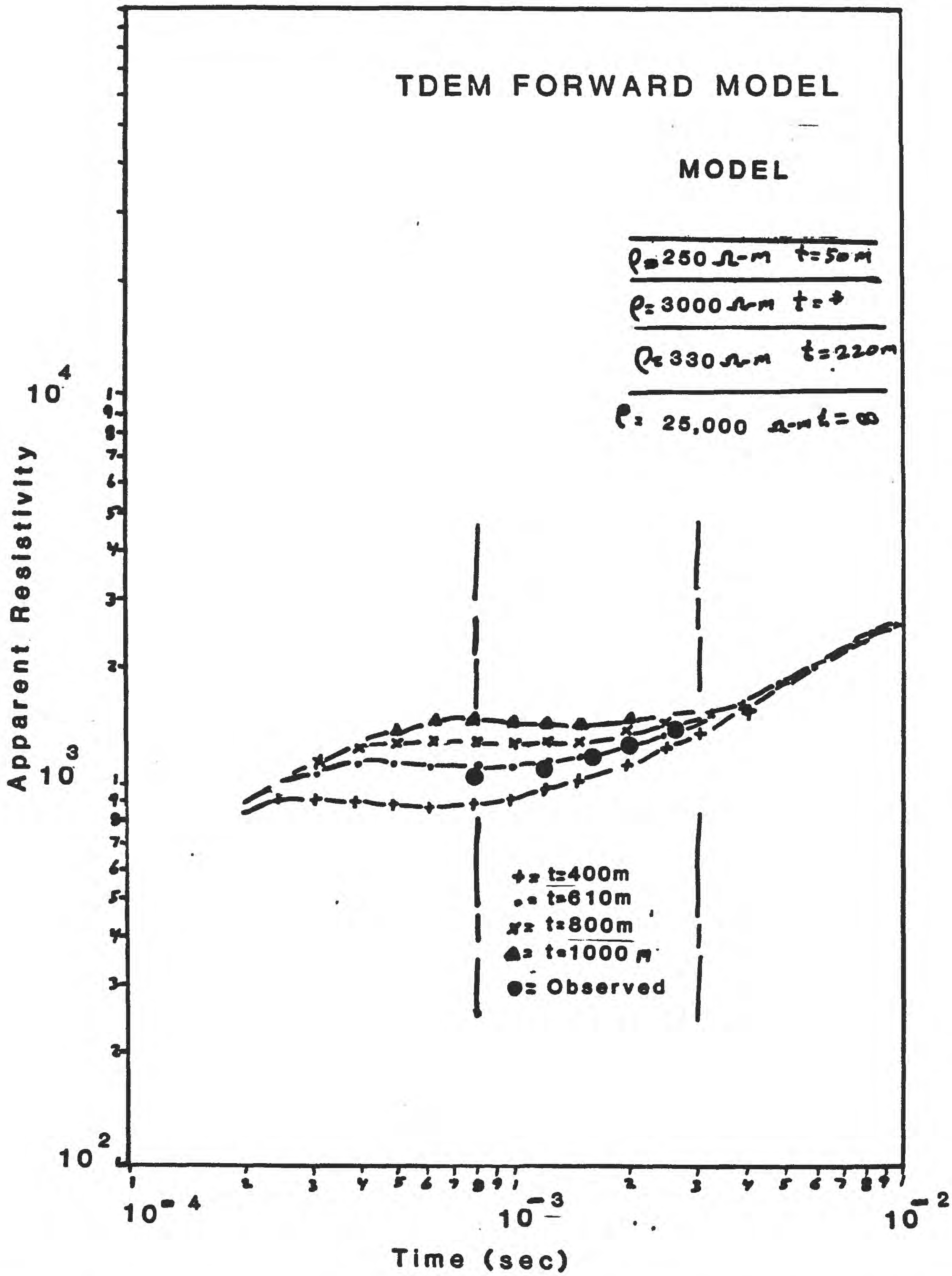


Figure 19. Plot showing the theoretical time-domain response decay curve over a four-layer earth model when the thickness (t) of the second layer is varied; the solid dots are the observed data for a TDEM sounding located at the site of AMT sounding 5LK 82-1, the vertical bars on the plot show the range of times that the observed response is considered repeatable.

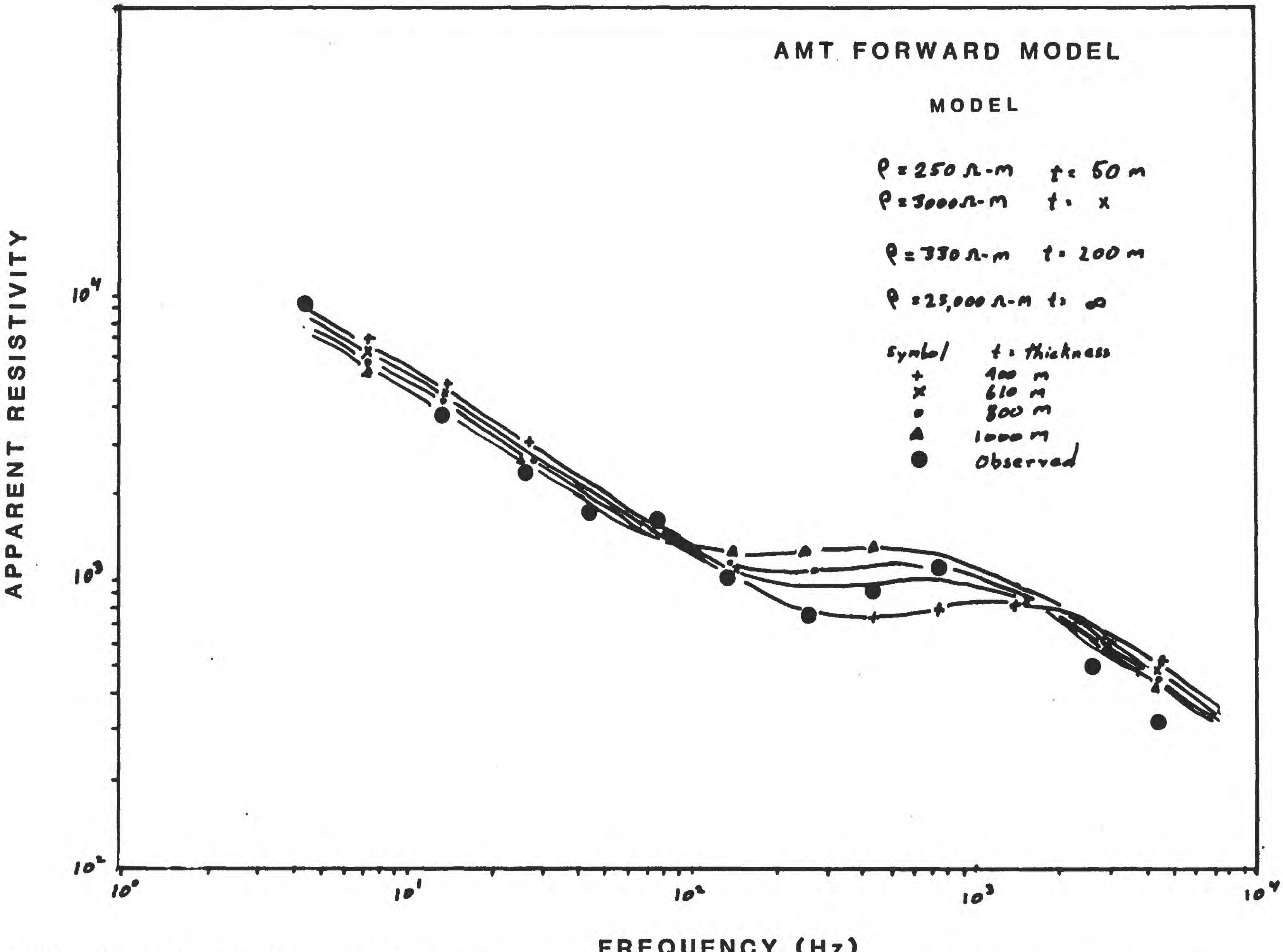


Figure 20. Plot showing theoretical values of apparent resistivity versus frequency for a four-layer earth model when the thickness (t) of the second layer is varied, the solid dots (•) are the observed data at AMT sounding 5LK 82-1 in the Five Lakes area.

AMT soundings (5LK 82-2, 5LK 82-3) to the southwest (fig. 16) were also modelled to determine the variation of layered resistivity with depth. AMT sounding 5LK 82-2 suggests a conductive surface layer 45 m thick overlying granitic rocks of about 3000 Ω-m (fig. 21). AMT sounding 5LK 82-3 located in the valley bottom between sounding 5LK 82-1 and 5LK 82-3 is similar to AMT sounding 5LK 82-1, except that the conductive zone is much nearer the surface (fig. 22A). AMT sounding 5LK 82-4, located northeast of 5LK 82-1, suggests that about 100 m of alluvium, and altered rock overlies fresh, very resistive (22,500 Ω-m) granitic rocks (fig. 22B).

In order to better visualize the results of the interpreted AMT soundings in the Five Lakes area, geoelectric section A-A′ (fig. 16) was prepared (fig. 23). Assuming similar granitic rocks underlie the area covered by section A-A′, variations of resistivity at depth might be related to degree of alteration that has reduced the resistivity of the granite. It seems likely, however, that some lithologic contacts are present along the section, so that the resistivities reflect lithologic changes both laterally and vertically.

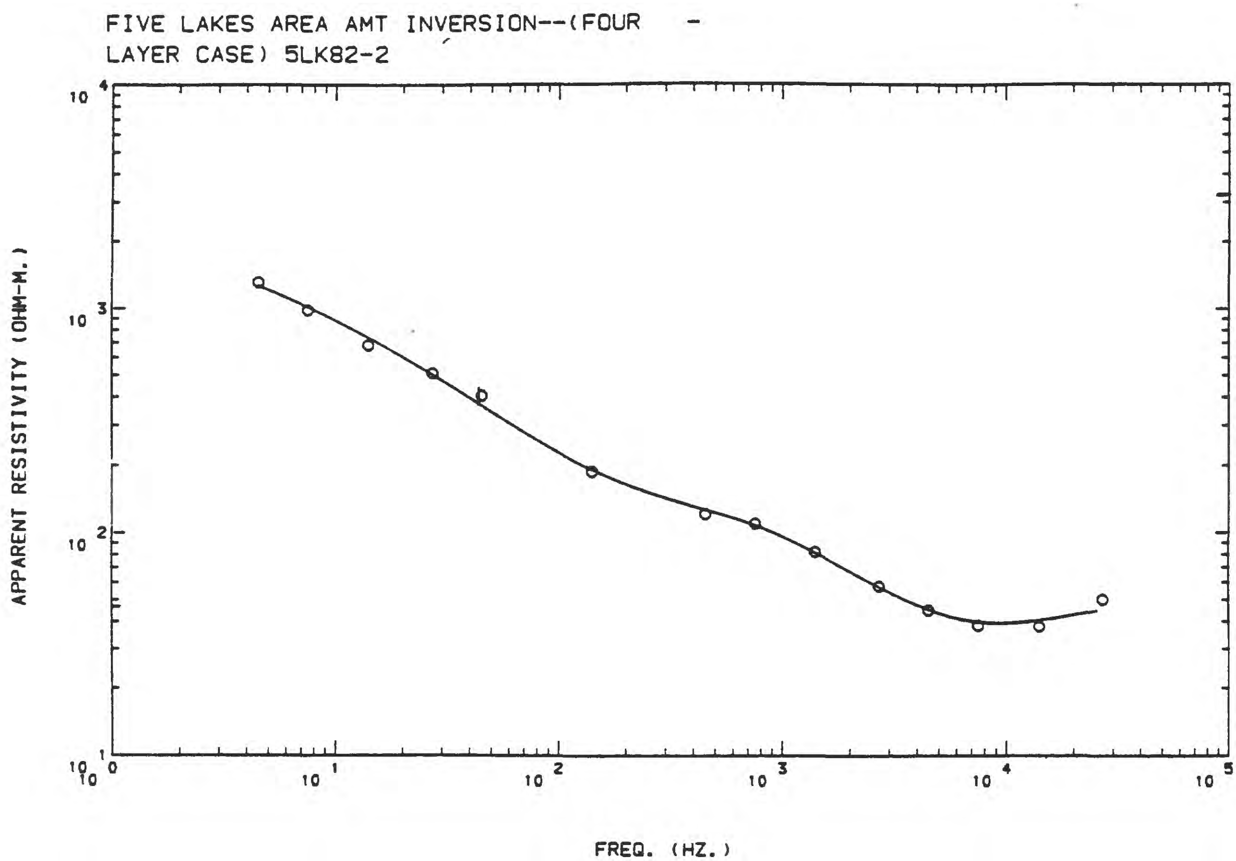
Stranger Mountain area

The Stranger Mountain area is located in the northeast part of the reservation in the Covada mining district (fig. 1).

The outcropping rocks of the Covada district are predominantly composed of metasedimentary rocks of the Ordovician Covada Group (fig. 24). The Covada Group consists primarily of argillite and quartzite with subordinate amounts of limestone, shale, greenstone, and graywacke. The metamorphic rocks have been severely deformed, and in the southwest part of the Stranger Mountain area intruded by the Meteor Plutonic body (unit Kg of fig. 24; called the Meteor Granodiorite by Weaver, 1913). The Plutonic rocks of the Meteor plutonic body was described by Dansart (1982, unpublished report) as consisting of at least five mappable phases that range from porphyritic granite to diorite in composition.

Exploration and mining in the Covada district dates back to the early part of this century, but the mines and prospects in the district have not been active for the past 30-40 years. Mining records indicate that silver, lead, zinc, copper, and gold were the principle minerals recovered from the district. Most of the mineralization occurs as quartz vein-type deposits that fill open fissures.

Geological and geochemical exploration in the Stranger Mountain area has revealed pervasive hydrothermal alteration along a N20W trending zone about 8.2 km (4.5 mi) long and 1 km wide (Dansart 1982, unpublished report). The most intense alteration in the Stranger Mountain area occurs on the eastern slope of the mountain (Dansart, 1982, unpublished report). The geophysical investigations reported here were primarily directed at supporting the drilling program that was planned to test for mineralization in the alteration zone. The principal objective of the geophysical program was to estimate the depth to intrusive rocks underlying the Covada Group on the east side of Stranger Mountain.



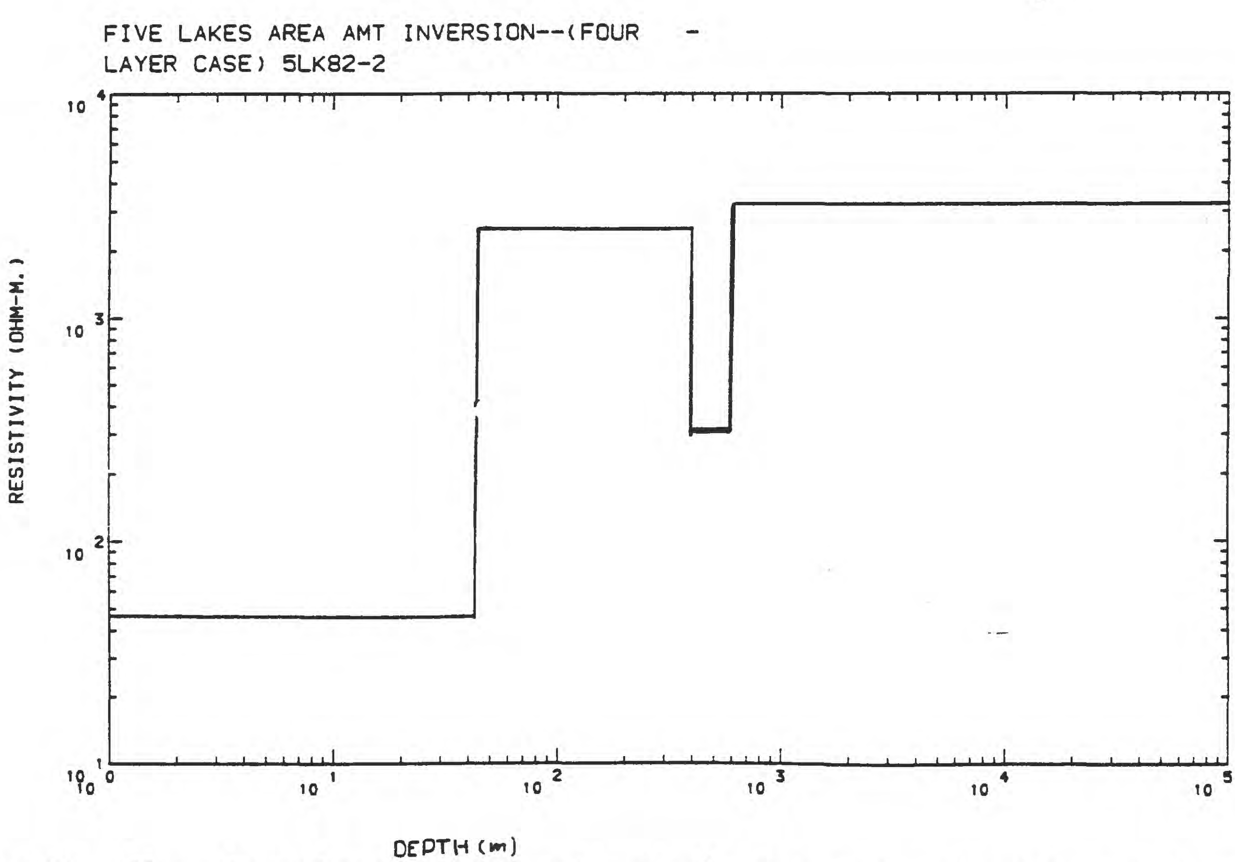


Figure 21. Plot of earth-model (step solid line) determined by least-square fit to observed data (0) for AMT 5LK 82-2 in the Five Lakes area; the solid curve line represents the computed resistivity values.

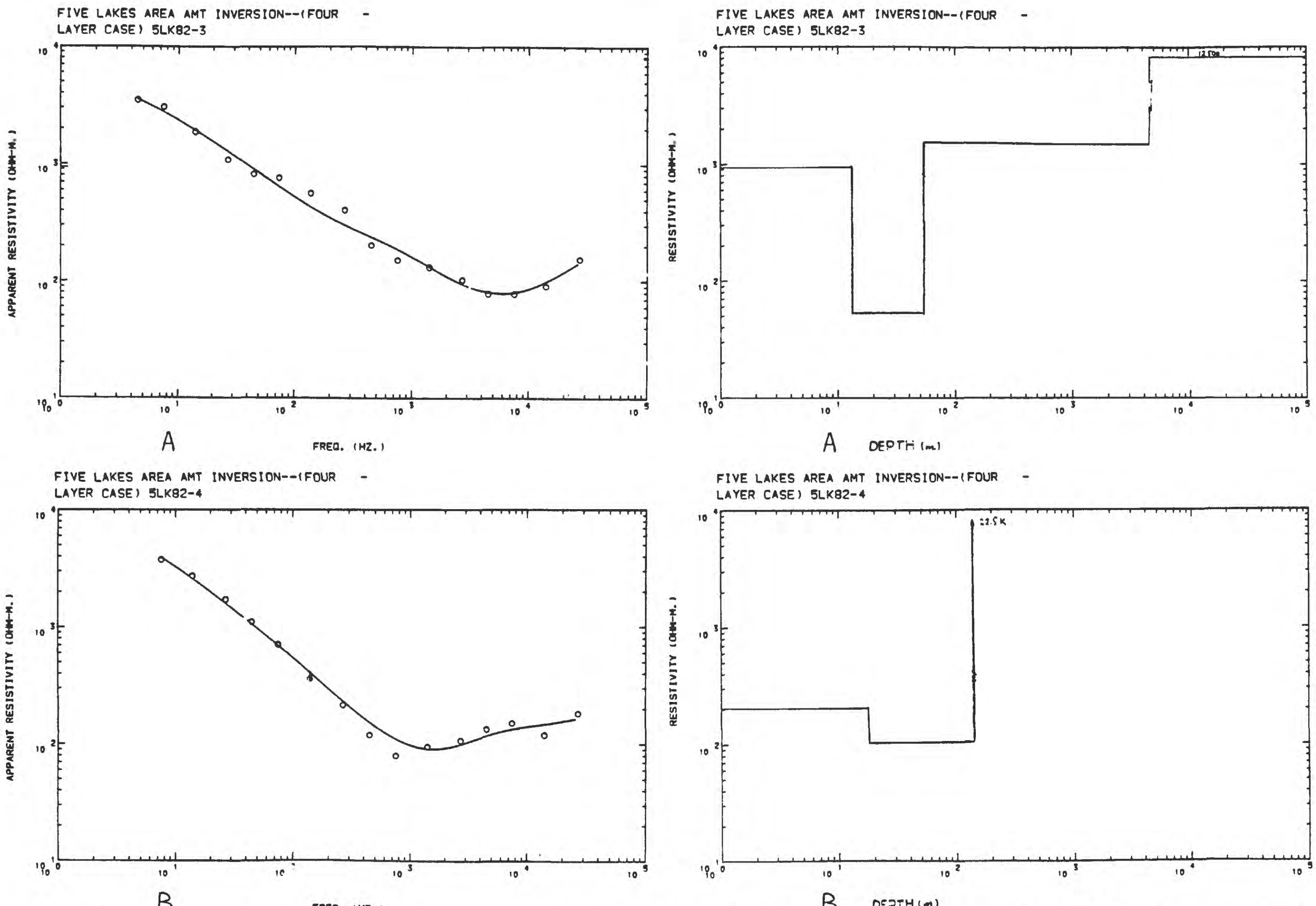


Figure 22. Plots showing four-layer earth models determined by inverting observed data (O), the curved lines are the computer resistivity values for soundings 5LK 82-3 (A), and 5LK 82-4 (B).

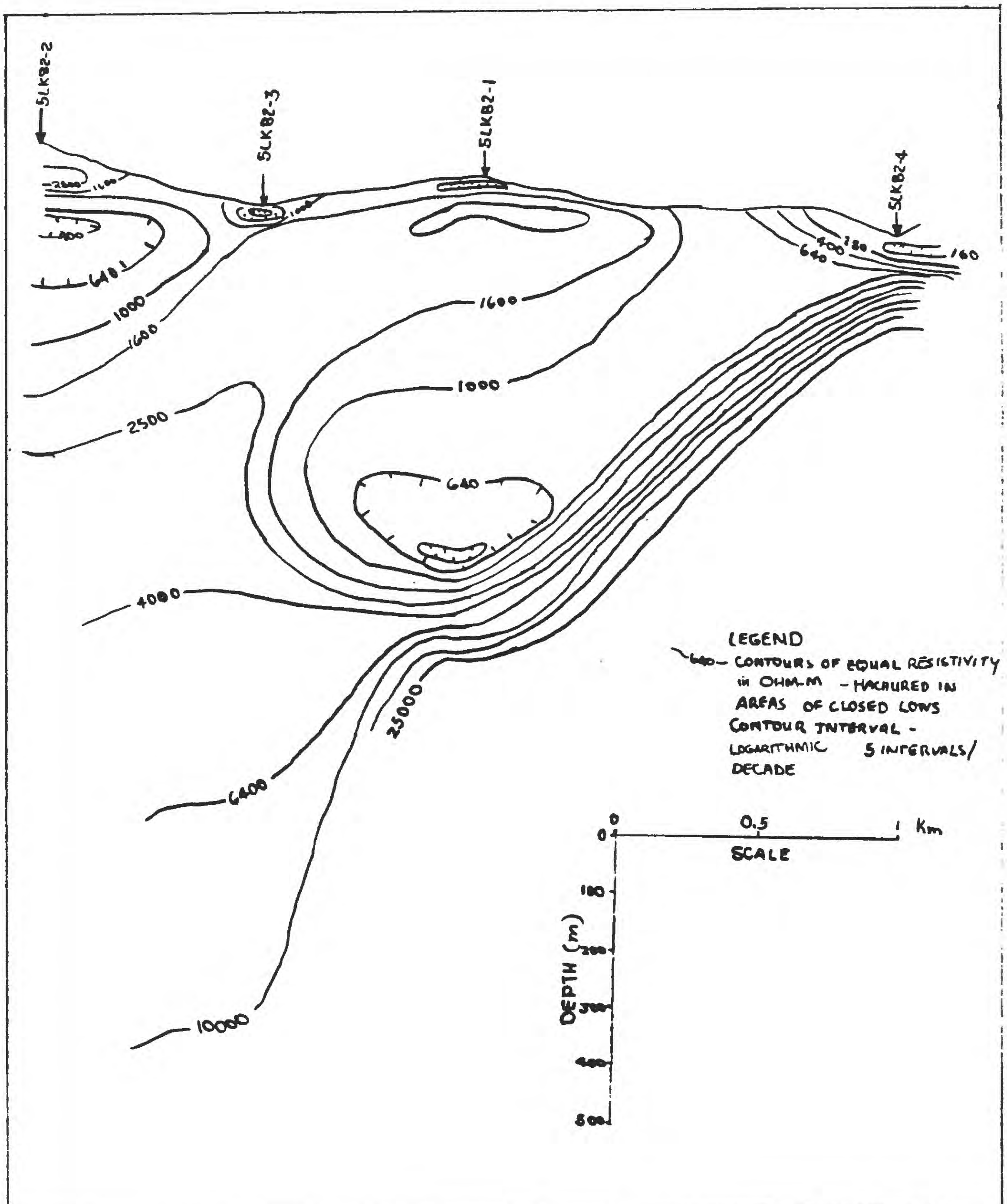
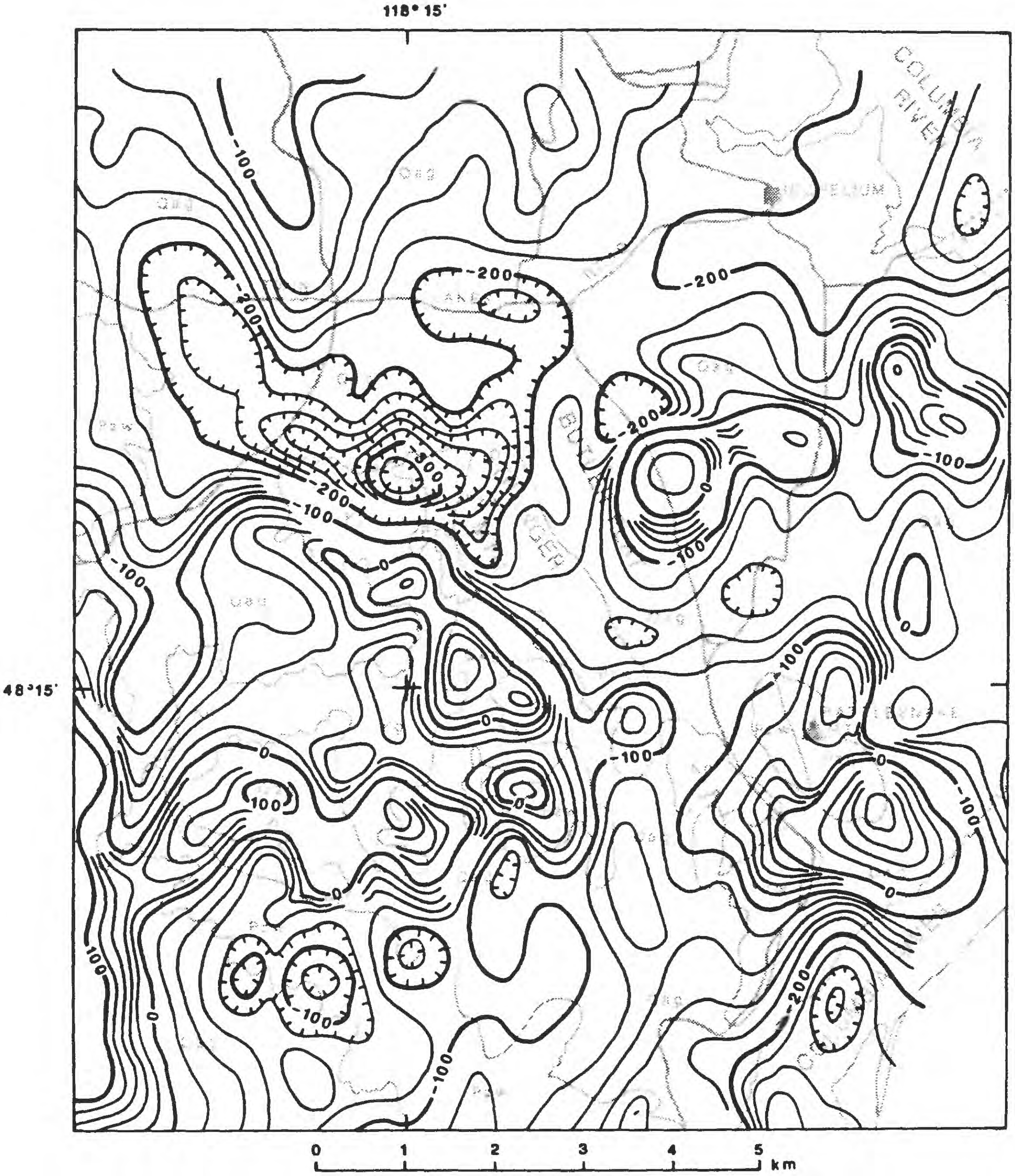


Figure 23. Contour plot along section A-A' in the Five Lakes area (fig. 16) showing the variation of resistivity with depth determined by modelling the observed data from the AMT soundings.



EXPLANATION

Qag	ALLUVIUM - GLACIAL DEPOSITS
Kg	GRANODIORITE, QUARTZ MONZONITE
Pzw	GRAYWACKE, IMPURE QUARTZITE
Pzg	GREENSTONE, INTERBEDDED QUARTZITE, SLATE AND GRAYWACKE

DATA SOURCE: BECRAFT (1966), CAMPBELL (1984), FOX AND BECRAFT, 1982 UNPUBLISHED MAP, SNOOK (1983) UNPUBLISHED MAP

Figure 24. Aeromagnetic map of the Stranger Mountain area in the Covada Mining District, Colville Indian Reserveration. Data is from a 1978 unpublished helicopter-borne gamma-radiation-magnetic survey.

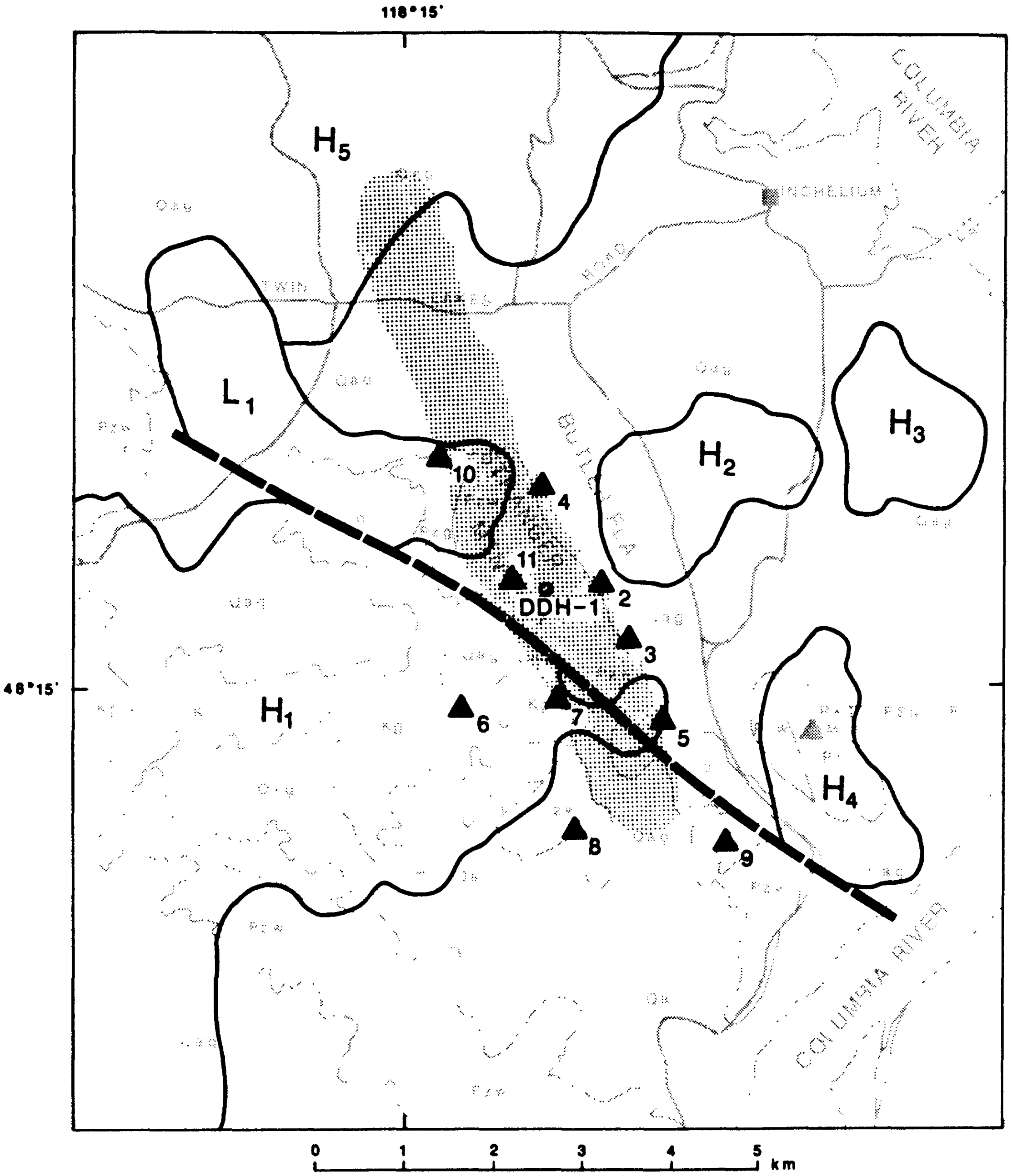
A review of the available geophysical data covering the area suggested that aeromagnetic data from a 1978 helicopter-borne gamma-radiation and magnetic survey of the eastern part of the reservation would be particularly useful in delineating lithologic units. The residual total-field magnetic data (with the regional magnetic gradient removed) are shown in figure 24. Two features of the magnetic map are noteworthy: (1) plutonic rocks are characterized by higher amplitude, up to 300 gamma, anomalies. (2) magnetic highs of lower amplitude are seen in areas covered by alluvium and glacial drift (these are thought to be associated with plutonic rocks in the near surface).

In order to address the areal distribution of plutonic rocks in the Stranger Mountain area, an interpretative map has been prepared (fig. 25). Areas of relatively high magnetic activity are indicated by H_1 (the subscript is for identification with the text discussion). An area of low magnetic anomaly is indicated by L_1. At the latitude of the study area, a line drawn through the point of steepest magnetic gradient generally defines the approximate boundary of the source of the anomaly for normally polarized magnetic bodies. Magnetic anomaly H_1 (fig. 25) correlates with the outcrop extent of the Meteor plutonic body, particularly along the southeast contact of the pluton with metasedimentary rocks. Plutonic rocks farther to the north, also presumably part of the Meteor plutonic body have a distinctively different magnetic character (L_1, Fig. 25). Rocks in this area may represent a less magnetic phase of the intrusive body. Analagous granitoid rocks hosting the Mount Tolman mineral deposit and biotite (muscovite) granitic rocks in the Twin Lakes quadrangle to the west have a similar low magnetic character (Flanigan and Sherrard, 1986).

Magnetic anomalies H_2, H_3, H_4, and H_5 (fig. 26) are relative magnetic highs that cannot be directly related to outcropping plutonic rocks and are thought to be related to near surface intrusive rocks.

Steep magnetic gradients that align linearily along the northeast side of magnetic anomaly H_1 suggest the presence of a northwest trending fault zone. The zone passes through the Stranger Mountain area a few hundred meters southwest of the summit of the mountain and generally forms the contactboundary between the magnetic phase of the Meteor pluton on the south and the less magnetic phase on the north.

Eleven AMT soundings were made in the Stranger Mountain area during the 1982 and 1983 field seasons. The data, particularly from the 1983 field work, were noisy. It was found that drilling operations going on at the time of the survey caused an interference problem that was most noticeable around 1400 Hz. AMT station locations are shown on figures 25 and 26 so that comparisons may be made between the data sets. The results of the AMT survey are summarized on figures 26A-D. The apparent resistivity maps at three frequencies (7500, 75, and 7.5 Hz) indicate the earth response of the method at increasing depths (fig. 26A-C). Notice that apparent resistivities at 7.5 Hz (fig. 26C) are considerably higher than those sensed at 7500 Hz (fig. 26A). At 7500 Hz the skin depth is 116 m at 400 Ω-m apparent resistivity, whereas at 7.5 Hz the skin depth is 3.7 km. Thus, at 7500 Hz the apparent resistivity map (fig. 26A) reflects only the changes in earth resistivity in the first hundred meters or so both in depth and laterally, whereas at 7.5 Hz (fig. 26C) the resistivity map reflects resistivities associated with lithologic, structural and moisture content from the surface to several kilometers depth.



EXPLANATION

Figure 25. Map of the Stranger Mountain area showing the interpreted areal distribution of rocks of moderate magnetic character (H), and rocks of low magnetic character (L). The subscript after the H_1 and L_1 are for identification with the text discussion. The heavy bar line indicates the location of an interpreted fault zone. AMT Sounding locations indicated by triangle. Shaded area indicates zone of hydrothermal alteration.

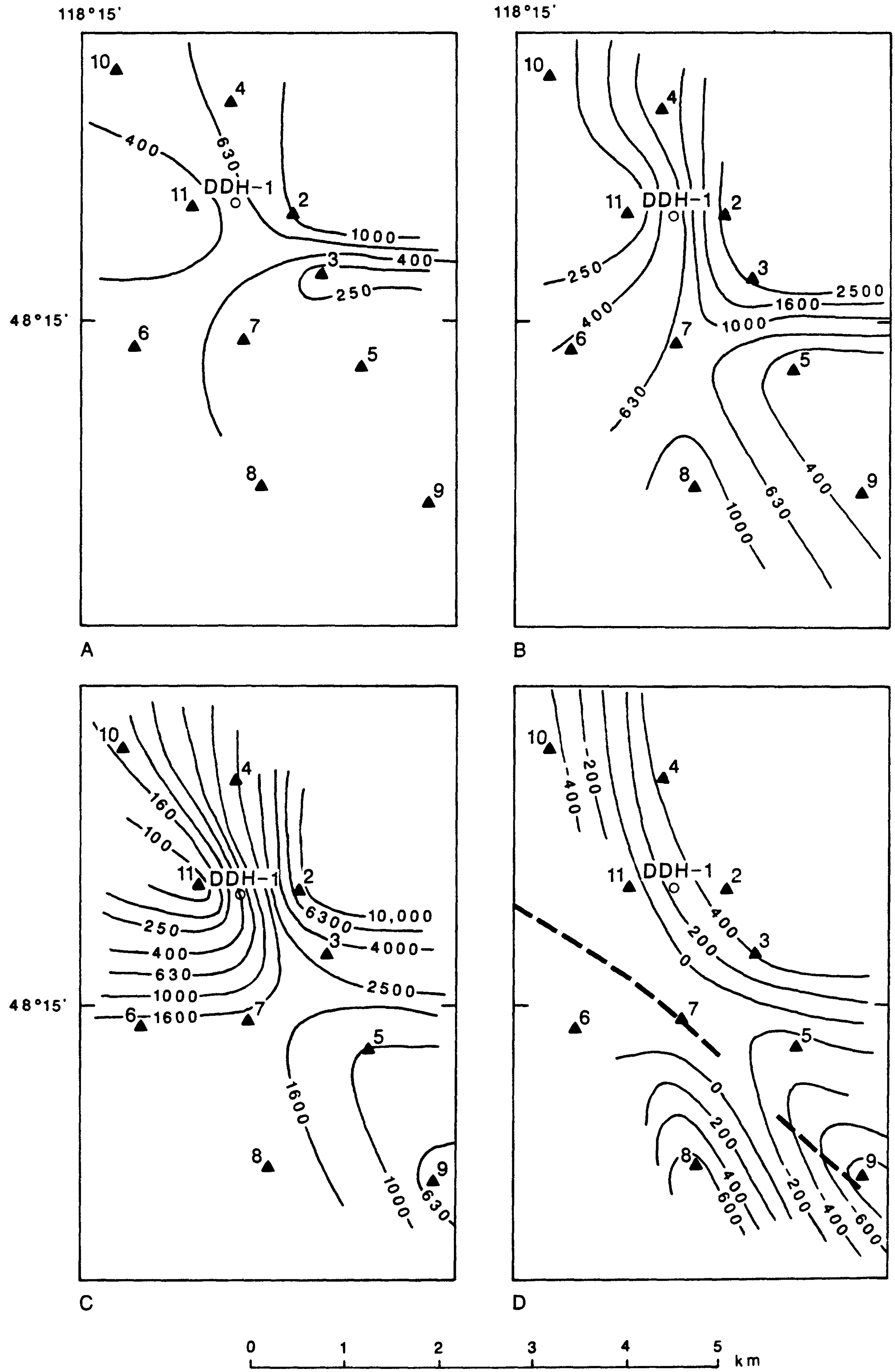


Figure 26. Maps showing AMT apparent resistivity at 7,500 Hz (A), 75 Hz (B) and 7.5 (C). Map D is a contour map of the unaltered plutonic bedrock surface elevation (meters).

An interpretation of the AMT soundings was accomplished by inverting the observed data so that the resultant non-unique layered-earth model fits, in a least squares sense, the observed data (Anderson, 1979, Bostick, 1977) There are several factors bearing on the accuracy of such interpretive techniques: first, the solutions are non-unique, or equivalent solutions. This problem can be minimized by combining results of several geophysical techniques which measure different physical properties or measure the same physical properties in different ways. Secondly, the USGS AMT equipment measures parameters of the magnetic and electric fields propagating from random sources so as to determine the scalar apparent resistivity in two orthogonal directions. In areas where there are no significant lateral discontinuities of resistivity, the orthogonal sounding curves are nearly identical. However, in the presence of major lateral discontinuities, the orthogonal sounding curves can be different. Interpretation of such a sounding site in terms of layered earth models is ambiguous. Such is the case in several soundings in the Stranger Mountain area. This problem is illustrated using the "worst case" sounding (fig. 22). Notice the wide discrepancy between the measured apparent resistivities for the two polarizations (fig. 27A). The interpreted layered-earth models for the two polarizations are shown in figures 27B and 27C. If one assumes that resistivities lower than 1000 Ω-m relate to metasedimentary rocks and resistivities higher than 1000 Ω-m are indicative of plutonic rocks, then two widely differing estimates of depth to the plutonic rocks are obtained. However, the presence of such discrepancies in the two sounding curves signals the presence of a distinct lateral boundary.

Another problem that often occurs in the interpretation of AMT soundings such as those in figure 27 is the lack of a clear break in resistivity between metasedimentary and plutonic rocks. Most probably there is a overlapping area of resistivities where it is impossible to distinguish between the two rock types.

Bearing these uncertainties in mind, the interpreted depths to the intrusive plutonic rocks in the Stranger Mountain area are summarized in the form of a contour map (fig. 26D). Soundings 2 and 4 were affected by proximity to lateral changes of conductivity, although to a lesser extent than sounding 3 (fig. 27). Soundings 10 and 11 did not sense unaltered, resistive bedrock within one kilometer depth, probably because of their location in relation to the interpreted northwest structure zone which would be expected to increase the conductivity of the rocks to great depth. Sounding number 5, although located on altered granodiorite indicated that rocks of about 300 Ω-m resistivity extend to at least 800 m depth. Sounding number 9 is very similar to sounding 5, except that it is located in an area of outcropping metasedimentary rocks of about 400 Ω-m resistivity that extend to at least one kilometer depth. Soundings 6 and 7, located very close to outcropping intrusive rocks, show that rocks of 400 to 600 Ω-m extend to some 700 m depth where the rocks become more resistive.

One drill hole in the Stranger Mountain area (DDH-1), located between AMT soundings 2 and 11 on the eastern slope of the mountain intersected plutonic rocks at 1810′ (552 m) below the surface. Collar elevation of the hole is about 2600′ (792 m) making the elevation of the plutonic rocks intersection at 790′ (241 m).

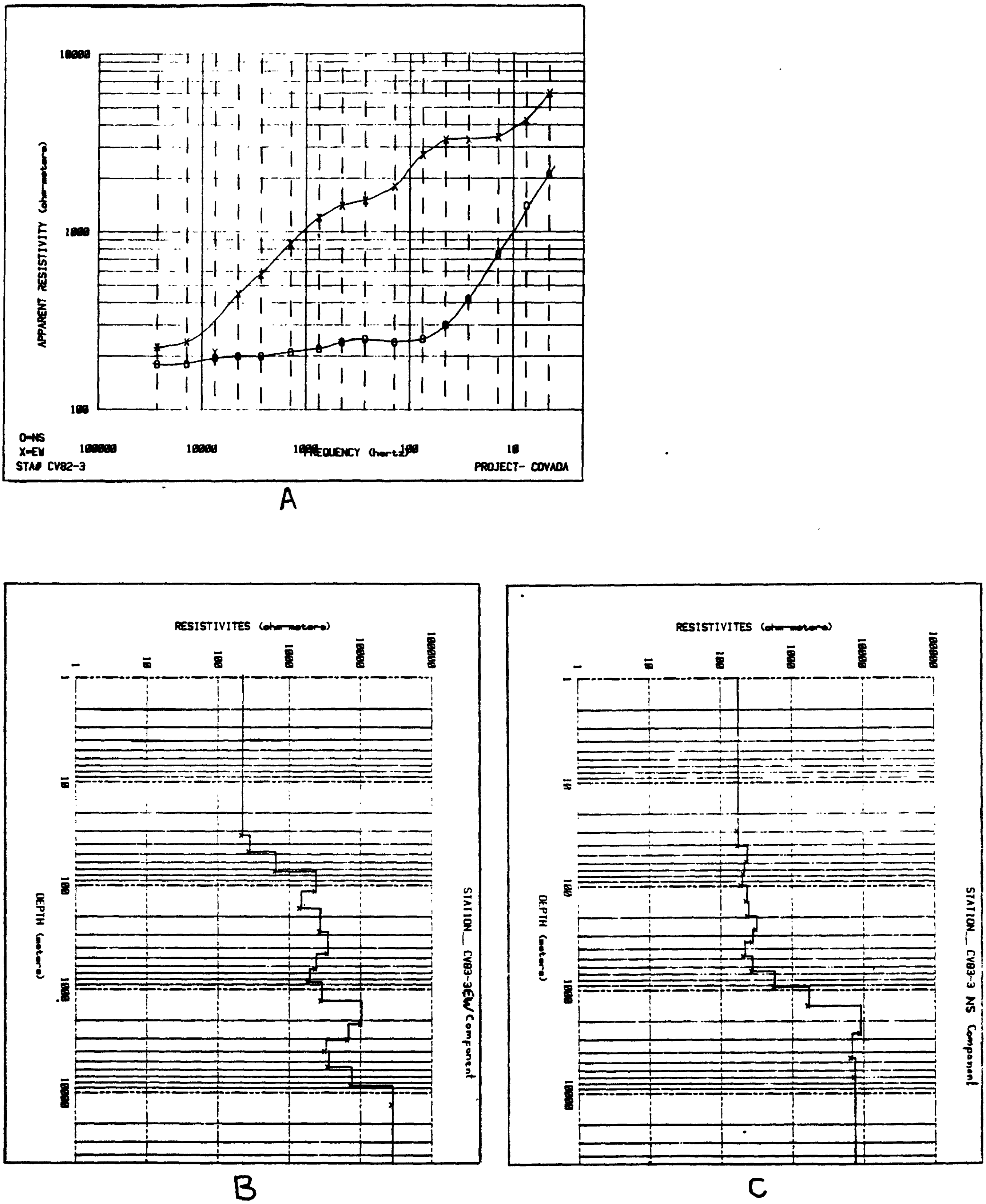


Figure 27. AMT plots showing: observed field sounding curves (A), interpreted layered earth models for the east-west E-field (B) and the north-south E field (L).

A second drill hole in the Stranger Mountain area was located at or very close to the site of AMT sounding number 4. The hole collared at about 1800′ (549 m) elevation, intrusive rocks were encountered at 725′ (221 m) depth, making the elevation of the intrusive intersection 1075′ (328 m).

The AMT data suggest that the surface of the unaltered intrusive rocks dips sharply (at least 400 m/kilometer) toward an interpreted northwest-trending structure zone.

Summary and Conclusions

Electromagnetic soundings were made in six areas on the Colville Indian Reservation. Three of the areas (Mineral Ridge, Keno Trail, and Five Lakes) approximate geologic environments similar to that which hosts the Mount Tolman copper-moly deposit, that is, altered intrusive granitic rocks at or very near the surface. Based on control soundings over the Mount Tolman deposit, areas of highest conductivity (low resistivity) were delineated on the southern flank of Squaw Mountain in Mineral Ridge area and immediately west of the Keno mine in the Keno Trail area. In the Five Lakes area, granitoid rocks become more conductive at depth than they are at the surface, where altered granite is present. In the valley about one half kilometer southwest of the first drill hole (site of AMT sounding 5LK-1) the conductive granitic zone appears to be nearer the surface.

In the Park City and Stranger Mountain areas the geologic environment suggests alteration and possible mineralization associated with intrusive rocks beneath a thick section of metasedimentary rocks. In the Park City area limited AMT data suggest that the intrusive rocks surface dips steeply to the west and to the south from the site of AMT sounding PC-1.

At the Stranger Mountain study area, airborne magnetic data outline the areal extent of moderately magnetic rocks associated with the Meteor plutonic body. Further, the magnetic data show that granitoid rocks to the east of the town of Meteor are different in their magnetite content than the main mass of the Meteor plutonic body. The data also suggest the possibility of a major northwest trending structure is present, near the summit of Stranger Mountain, separating two phases of the Meteor plutonic body.

The AMT data generally confirm the presence of the interpreted fault zone in the Stranger Mountain area. The surface of the interpreted intrusive pluton, both north and south of the fault, is inferred to dip steeply toward the fault. Pervasive alteration along a 8.4 km, N. 20 W. trending zone may be directly, or at least in part, related to a major fault.

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