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GEOHERMAL RESOURCE EXPLORATION  
ASSESSMENT AND DATA INTERPRETATION,  
KLAMATH BASIN, OREGON-  
SWAN LAKE AND KLAMATH HILLS AREA

M. Stark, N. Goldstein, H. Wollenberg,  
B. Strisower, and M. Hege

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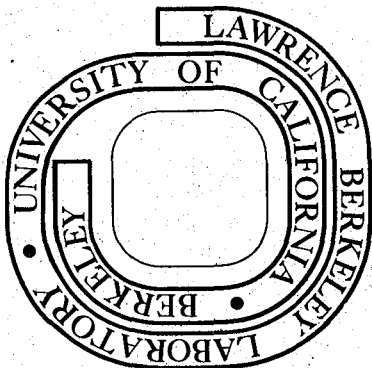
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M. Stark, N. Goldstein,\* H. Wollenberg,  
B. Strisower, and M. Hege

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This work was done under the auspices of the U.S. Department of Energy.

\*Principal Investigator



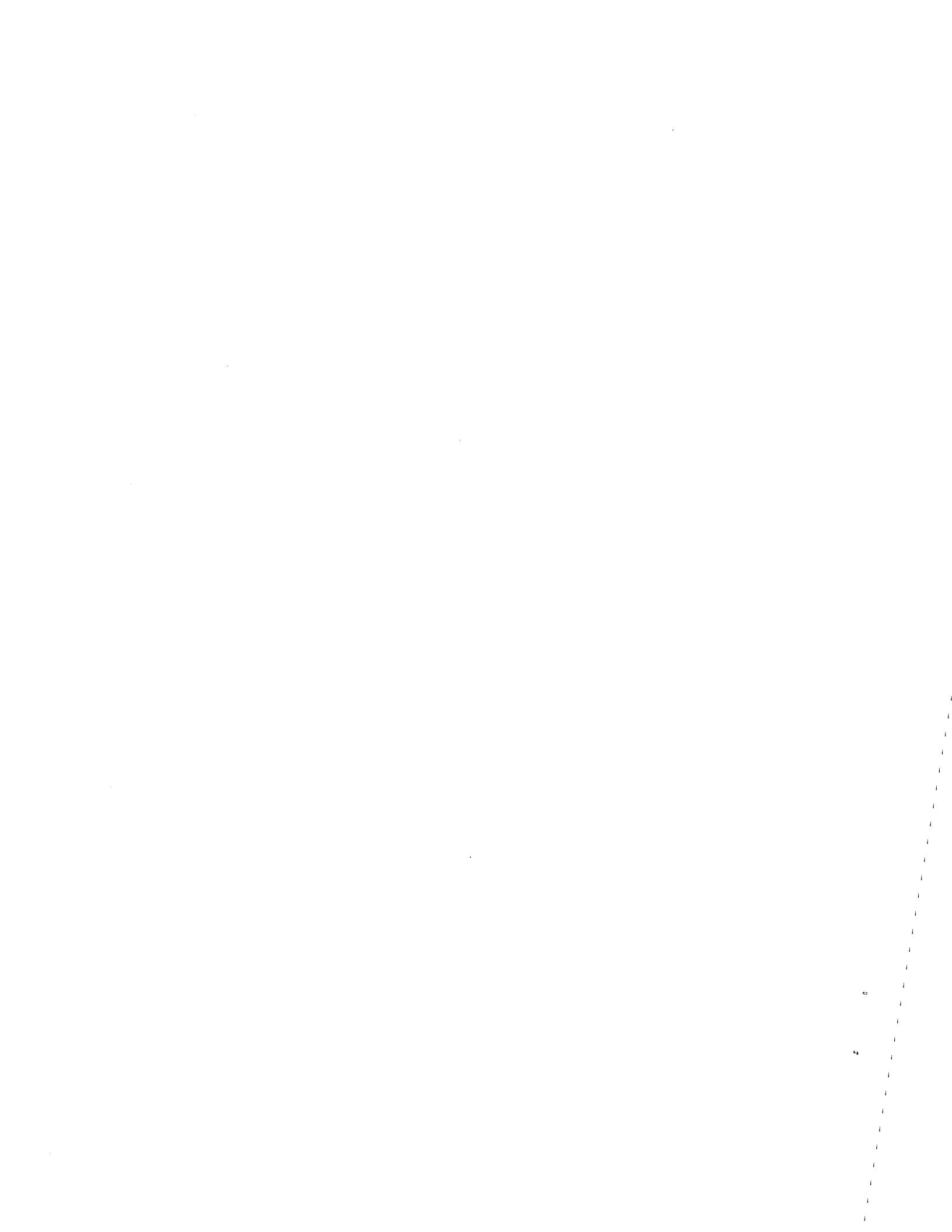
## ABSTRACT

A synthesis and preliminary interpretation of predominantly geophysical information relating to the Klamath Basin geothermal resource is presented. The Swan Lake Valley area, northeast of Klamath Falls, and the Klamath Hills area, south of Klamath Falls, are discussed in detail. Available geophysical data, including gravity, magnetic, electrical resistivity, microseismic, roving dipole resistivity, audio-magnetotelluric (AMT) and magnetotelluric (MT) data sets, are examined and reinterpreted for these areas. One- and two-dimensional modeling techniques are applied, and general agreement among overlapping data sets is achieved. The MT method appears well suited to this type of exploration, although interpretation is difficult in the complex geology. Roving dipole and AMT are useful in reconnaissance, while gravity and magnetics help in defining structure. For the Swan Lake Valley the data suggest buried electrically conductive zones beneath Meadow Lake Valley and Swan Lake, connected by a conductive layer at 1 kilometer depth. In the Klamath Hills area, the data suggest a conductive zone centered near the northwestern tip of Stukel Mountain, associated with a concealed northeast-trending cross-fault. Another conductive zone appears near some producing hot wells at the southwestern edge of the Klamath Hills. These conductive zones may represent geothermal reservoirs. Specific types of follow-up work are recommended for each target area.



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## INTRODUCTION

The Klamath Basin, located in south-central Oregon and northern California (Figure 1), has been the locus of geothermal exploration activities for several years. Exploration interest in this area was stimulated by the presence of numerous hot springs and over 400 wells containing waters of 60°C to 115°C which are currently used for domestic, institutional, and business heating, and for a few agri-business projects. Three Known Geothermal Resource Areas (KGRA's) have been identified in the area (Figure 2): (a) Klamath Falls KGRA north and northeast of the town of Klamath Falls, (b) Olene Gap KGRA east of the town, and (c) Klamath Hills KGRA south of the town. Exploration activities have been conducted by several companies within the KGRA's, as well as within lands adjacent to Klamath Falls. Two unsuccessful deep holes have been drilled thus far in the search for a higher temperature resource suitable for electric power generation, and the general level of interest in the area has consequently declined over the last two or three years.

In an attempt to re-stimulate exploration activity, the Earth Sciences Division Geothermal Group of LBL, working with the State of Oregon's Department of Geology and Mineral Industries (DOGAMI), and the U.S. Geological Survey (USGS), has attempted to collect all available exploration data pertaining to the area, to compile, assess, and interpret them in terms of subsurface geology, and to develop conceptual models for a geothermal reservoir. The end-product of the study is intended to be a document useful to geothermal exploration planners, containing not only an evaluation of the resource potential, but also an assessment

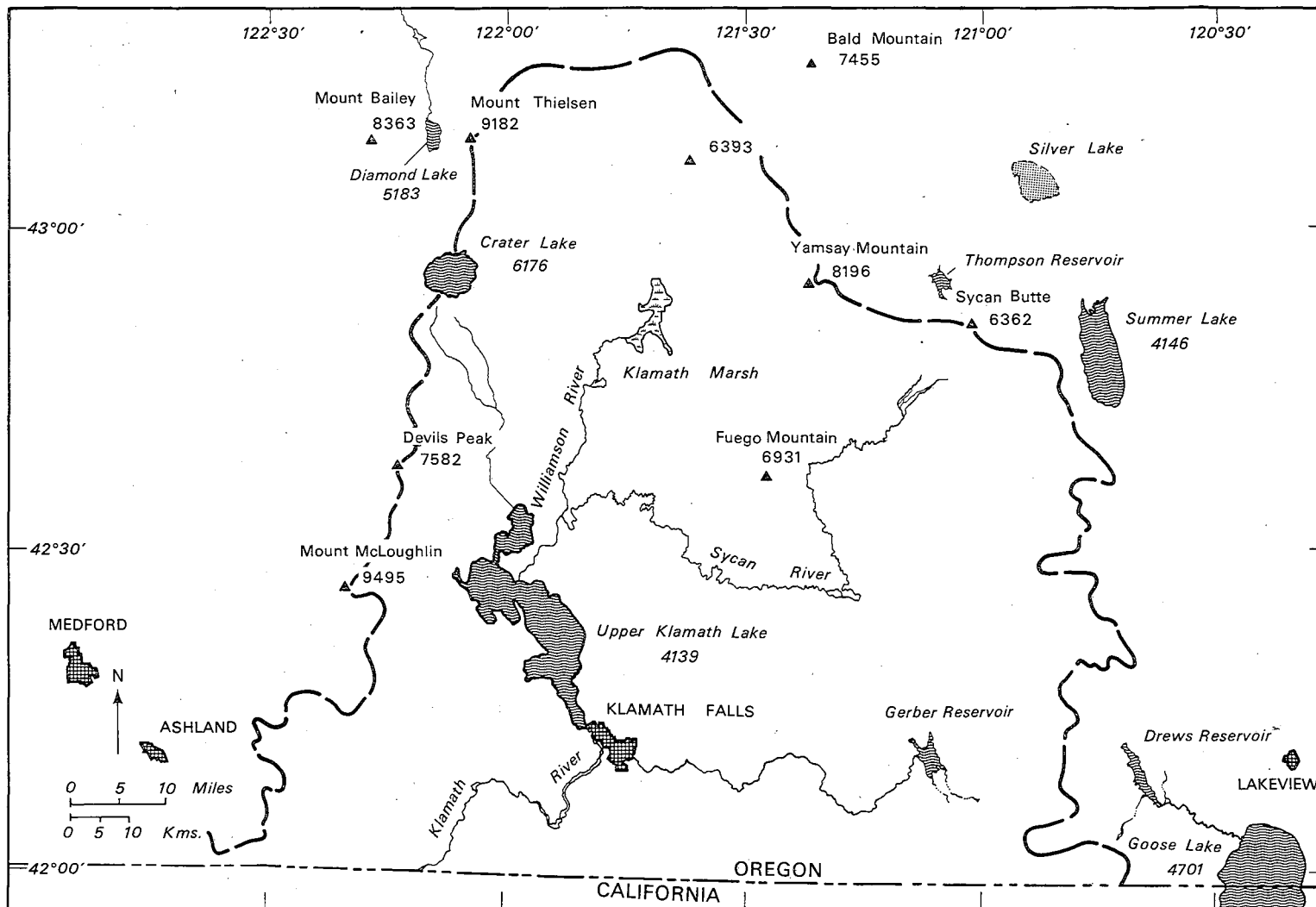
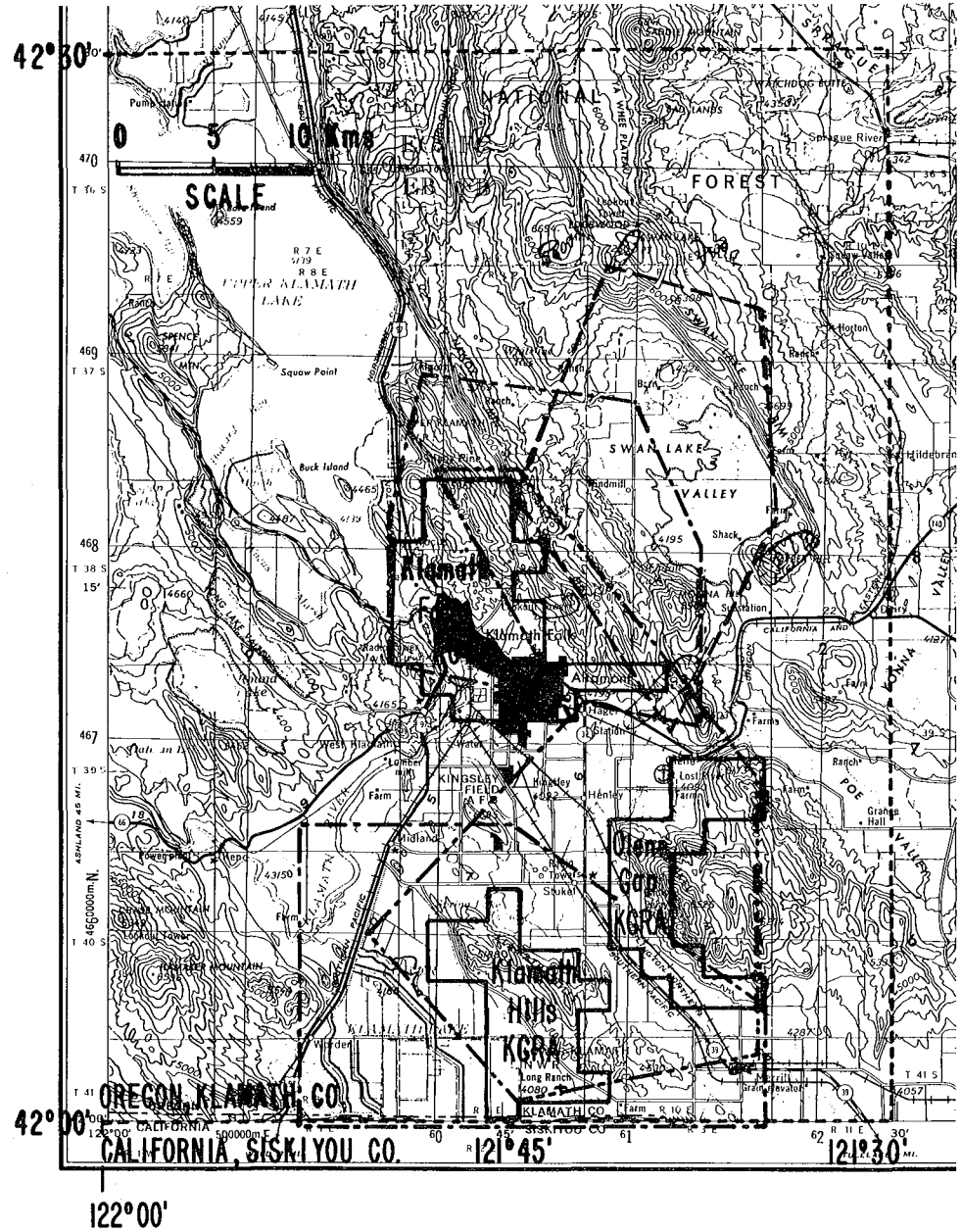


Fig. 1. Klamath Basin.

XBL 784-1822

- Known geothermal resources area boundary
- - - - Telluric-magnetotelluric survey area (Geonmics 1977)
- - - - Aeromagnetic and gravity survey area (Van Deusen 1978)
- - - - Roving dipole survey area (Group Seven, 1972)
- - - - Audio-magnetotelluric survey area (Senterfit & Bedinger, 1976)



XBL 789-6509

Fig. 2. Index map showing study areas.

of exploration techniques and a suggested exploration strategy. This report deals with work performed during the period, June-September 1978.

Data for this work have come from the open literature (e.g., journal articles, university dissertations, and reports by various government organizations) and from files of private companies who made their proprietary, confidential data available to LBL. Gulf Mineral Resources Company, Thermal Power Company, and Creslenn Oil Company have contributed data to this study. The data base consists of over 100 relevant documents, listed in the Appendix.

Although the general area of interest is the entire Oregon portion of the Klamath Basin (Figure 1), the actual area of study has been restricted to the region around Klamath Falls, the principal area where exploration efforts have been made. Survey data available to LBL cover the areas outlined in Figure 2. The availability of data, more than any other aspect, has directed our initial attention to the two specific areas discussed in this report: (a) the Swan Lake Valley area, and (b) the Klamath Hills area. Because so much of the data is geophysical, this report concentrates primarily on that aspect of exploration. Prior to this study, most of the data received only a cursory examination and preliminary interpretation. We have attempted to do a far more thorough and detailed analysis of the data in order to demonstrate the procedures involved in a proper interpretation, to determine how much information can be extracted, and to evaluate the applicability of the various techniques to the particular exploration problem.

#### GEOLOGY

The geologic setting has been described by Peterson and McIntyre (1970). The Klamath Basin is bounded by the High Cascades to the west, the Medicine Lake Highlands to the south in California, and the high desert country to the east. The basin is drained by the tributaries of the Klamath River which flows southward into California before

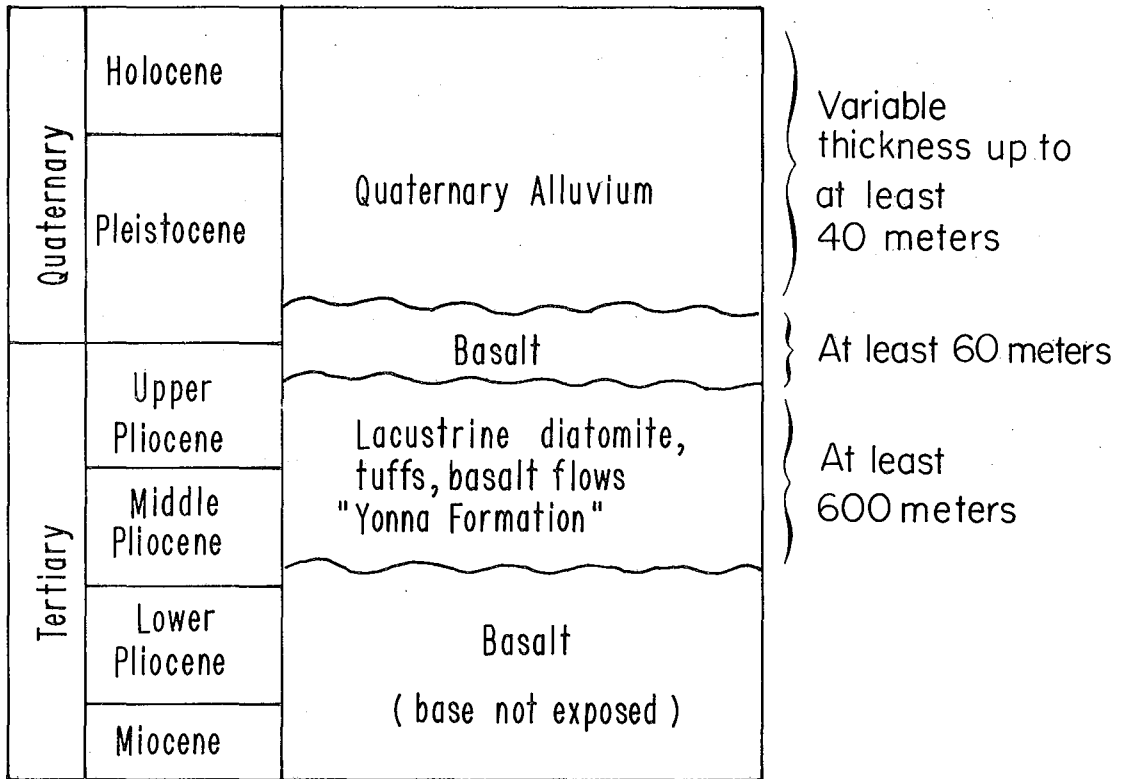
discharging into the Pacific Ocean. The area is part of the Basin and Range geomorphic province. Numerous normal faults, trending N40°W, break the area into grabens and horsts. The Klamath Lake graben may be traced for 50 miles from the Medicine Lake volcanic field to Crater Lake. It encompasses Upper Klamath Lake and attains a width of about 10 miles.

The steeply dipping Basin and Range faults have vertical offsets that are estimated to attain 1600 feet in places (e.g., Rattlesnake Point and Stukel Mountain). Although the predominant fault direction is northwesterly, there is geologic and topographic evidence for north- and northeast-trending cross faults which truncate or offset topographic features.

The stratigraphic section in Figure 3 shows Peterson and McIntyre's rock units. The basement rock consists of Pliocene basalts of undetermined thickness. These are unconformably overlain by the Pliocene Yonna formation, a designation given to a sequence of tuffaceous siltstones and sandstones, lacustrine sediments (mainly diatomites) and basalt flows (Newcomb, 1958). The rocks are sub-aqueous deposits formed during a period when the region was covered by lakes and swamps. Explosive and quiescent volcanism were nearly contemporaneous with deposition, as evidenced by maars, tuffs, and thin basalt flows in the Yonna Formation. Newcomb (1958) reports a maximum observed thickness of about 600 meters for the Yonna formation.

Late Pliocene and Pleistocene basalt flows and volcanoclastic interbeds are found overlying the Yonna Formation at the higher elevations. Quaternary alluvium covers the valleys. Groundwater aquifers exist in all these rock units, but the older Pliocene basalt unit provides the highest yields. Impermeable strata within the Yonna Formation act as confining beds for aquifers below.

The three KGRA's are shown in Figure 2. Klamath Falls KGRA encompasses the principal hot well area covering the town and extends



XBL 7810-6540

Fig. 3. Stratigraphic column for Klamath Falls area (after Peterson and McIntyre, 1970).

east-northeastward. Hot water has been used by the residents, mainly for space heating, since the turn of the century. Presently, approximately 400 shallow wells, most in the 200 to 300 foot depth range, are used to heat 500 structures. Water temperatures range up to 113°C. The main hot water well area is located adjacent to one of the fault scarps forming the eastern boundary of the Klamath Lake graben.

Olene Gap KGRA covers an area which includes much of the northern and western portion of Stukel Mountain. Geothermal manifestations include a few wells and springs with temperatures up to 87°C in Olene Gap, and a few warm wells with temperatures up to 42°C near the northwestern tip of Stukel Mountain.

Klamath Hills KGRA is discussed below in the Klamath Hills section.

#### SWAN LAKE VALLEY AREA

##### Topography and General Geology

Located 10 to 18 kilometers northeast of Klamath Falls, Swan Lake Valley is a flat, roughly rectangular valley bounded on all sides by mountains, except for an opening near its southern corner (Figure 4). Swan Lake itself lies near the northeastern edge of the valley, forming a natural sump for streams flowing from the north and west. The valley is a closed hydrologic basin under normal conditions. Swan Lake Rim, rising more than 300 meters over the valley floor, bounds the valley to the northeast. To the southwest lies the smaller Meadow Lake Valley which is considered a part of the Swan Lake Valley area in this report.

Both valleys are grabens, bounded by northwest-trending, steeply-dipping normal faults and filled with Quaternary alluvium and Yonna Formation rocks. Cross-faults may truncate the valleys on the northwest and southeast edges, but none have been identified in published geologic maps. The surrounding mountains are composed primarily of Yonna Formation rocks and Pliocene basalt flows.

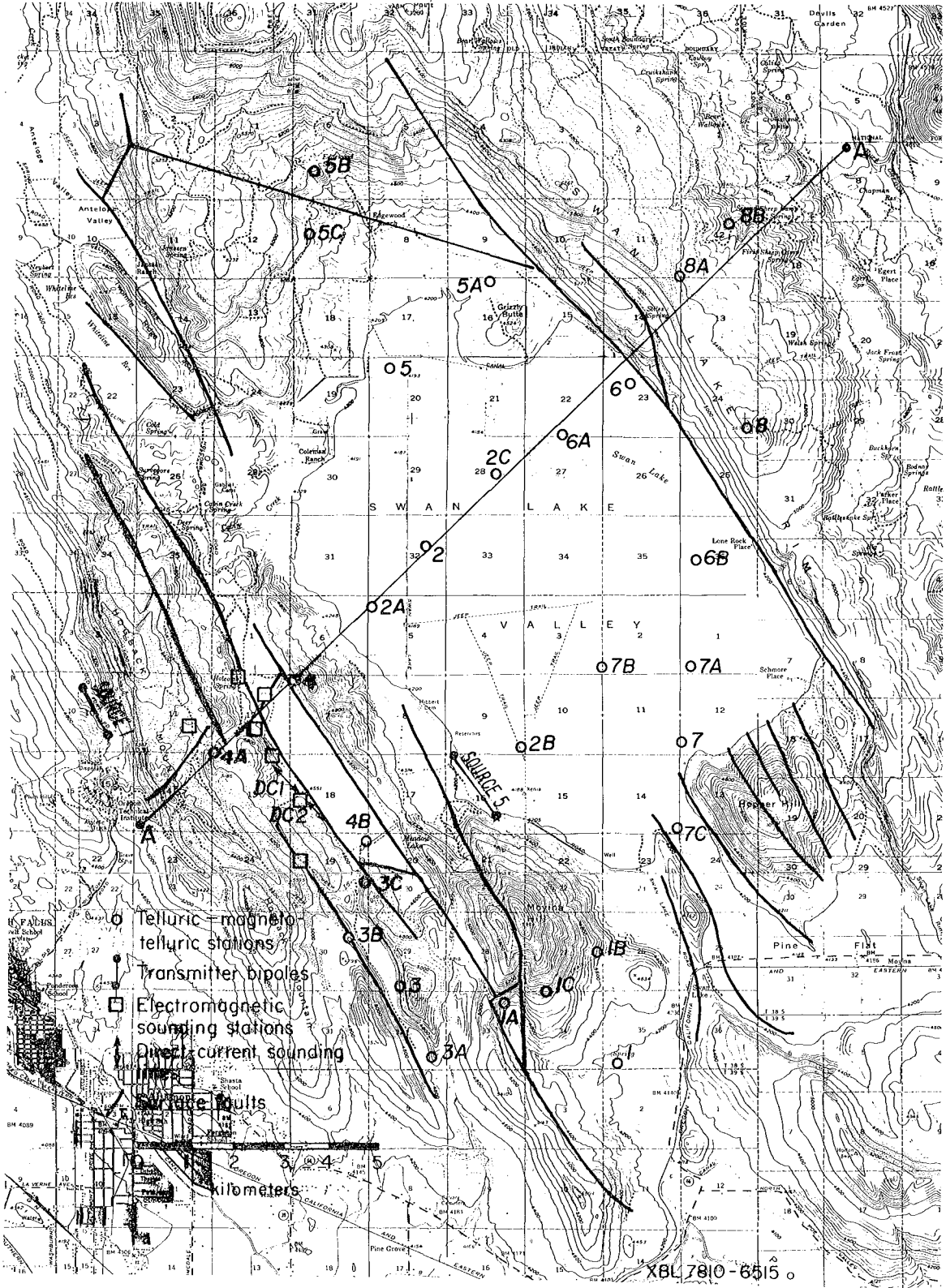


Fig. 4. Swan Lake Valley base map.

Holcomb Spring, near the northern end of Meadow Lake Valley, produces warm water (Geonomics, 1977).

### Gravity Survey

Van Deusen (1978) made gravity measurements at about 20 stations in the area as part of his regional study. In his thesis, he presented the gravity data in three forms: free air anomaly, complete Bouguer anomaly, and alternate density Bouguer anomaly. In our interpretations we have dealt only with the complete Bouguer anomaly (Figure 5).

A gravity low dominates the Swan Lake Valley, presumably caused by the density contrast between valley sediments and basalts. Van Deusen modeled valley structure beneath profile B-B' (Figure 6b). Using a density contrast of  $1.0 \text{ gram/cm}^3$  he found the sediment thickness to be about 300 meters. However, he stressed that this thickness is a minimum value because the assumed density contrast may be too large.

We constructed the profiles in Figures 6a and 6c along lines A-A' and C-C' from Van Deusen's contours. Applying a "glacial thickness" formula (Grant and West, 1965), we obtained sediment thicknesses ranging from 350 meters (using a density contrast of  $1.0 \text{ gram/cm}^3$ ) to 1500 meters (using a density contrast of  $0.3 \text{ gram/cm}^3$ ). The true sediment thickness probably lies between these values.

The gravity contours seem to mimic the topographic contours around the entire valley, suggesting that the valley is bounded by upthrown blocks on all sides. The profile A-A' shows a flattened gravity gradient near Meadow Lake Valley, probably due to a graben structure there.

We may attempt two-dimensional modeling along these and other profiles in the future.

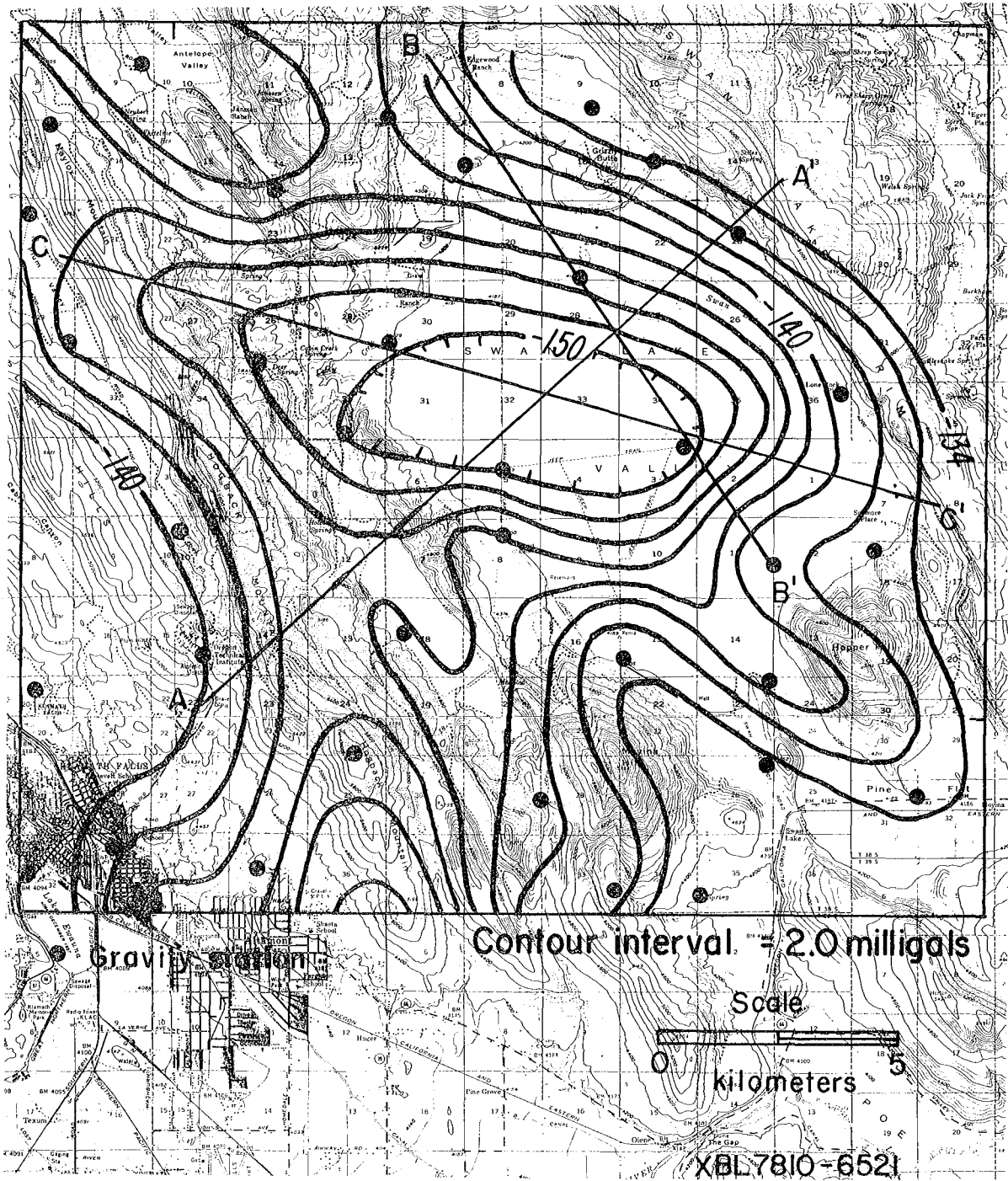
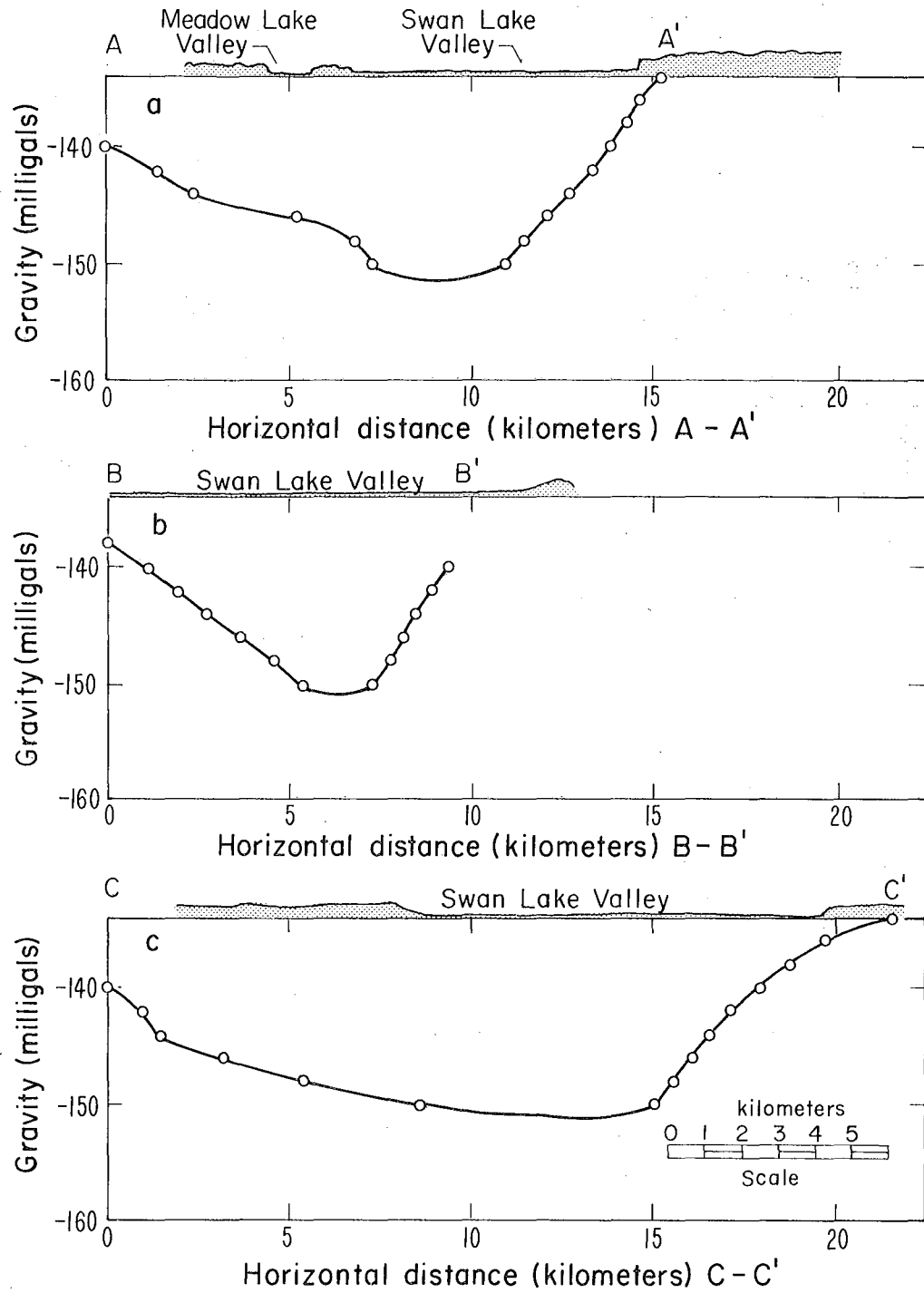


Fig. 5. Complete Bouguer gravity contours, Swan Lake Valley (after Van Deusen, 1978).



XBL 789-6510

Fig. 6. Three gravity profiles across Swan Lake Valley.

### Aeromagnetic Survey

Starting with the data from Scintrex's (1972) aeromagnetic survey, Van Deusen (1978) applied the technique of variable continuation to synthesize an aeromagnetic survey flown at constant elevation above topography. The original survey was flown at 9000 feet barometric elevation, and Van Deusen's treatment approximated a survey flown at 2000 feet above the land surface.

Both the original and variable-continued data sets indicate a magnetic high centered on the north sector of Swan Lake Valley. Figure 7 displays this rather surprising anomaly. Normally, one would expect a magnetic low over a sediment-filled valley surrounded by basalts. One possible explanation is that the valley is underlain by some highly magnetic basalt flows. Based on a measurement of the anomaly gradients, the magnetic source appears to be located at a depth of about 900 meters. This is consistent with the basement depth estimated from the gravity data.

### Roving Dipole, Electromagnetic and Direct Current Resistivity Sounding Surveys

Group Seven Incorporated (1972) performed roving dipole, direct current (dc) resistivity soundings, and electromagnetic (EM) sounding surveys in an area which included the western quarter of the Swan Lake Valley area. Figure 4 shows the locations of bipole sources, dc resistivity sounding lines and EM stations occupied. Approximately 50 pairs of dipole receivers were located in the Swan Lake Valley area. The receivers measured voltage drops relative to sources 1,5 (Figure 4) or 8 (outside the area and not shown in Figure 4) or, in some cases, from two or three sources. The calculated apparent resistivities were then plotted at the receiver locations and contoured. Where measurements were obtained relative to multiple sources the apparent resistivities were averaged.

We replotted the data from each bipole separately in order to apply one- and two-dimensional modeling techniques. Figures 8, 9,

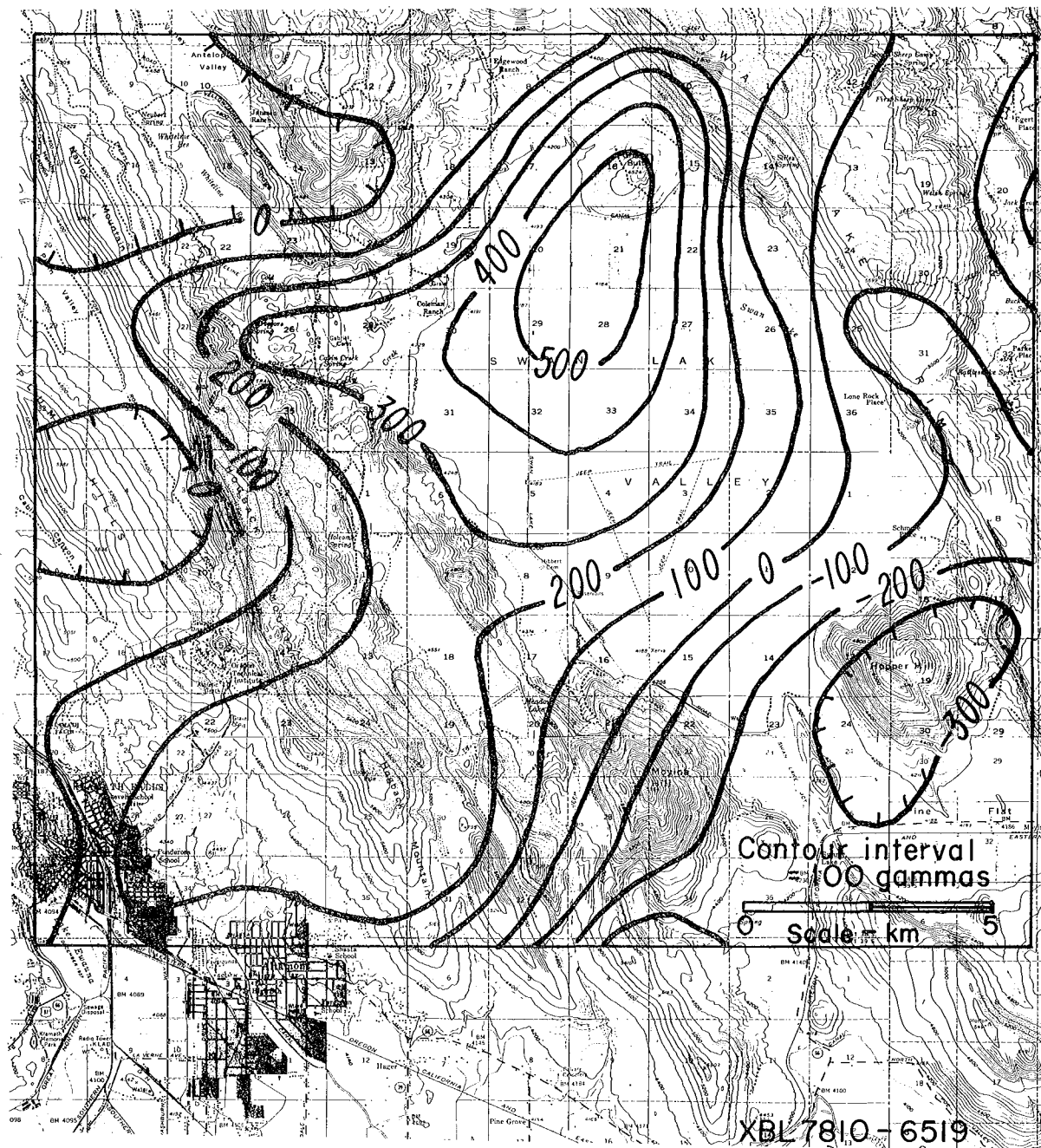


Fig. 7. Total intensity magnetic field variable—continued to 2000-foot elevation above land surface, Swan Lake Valley (after Van Deusen, 1978).

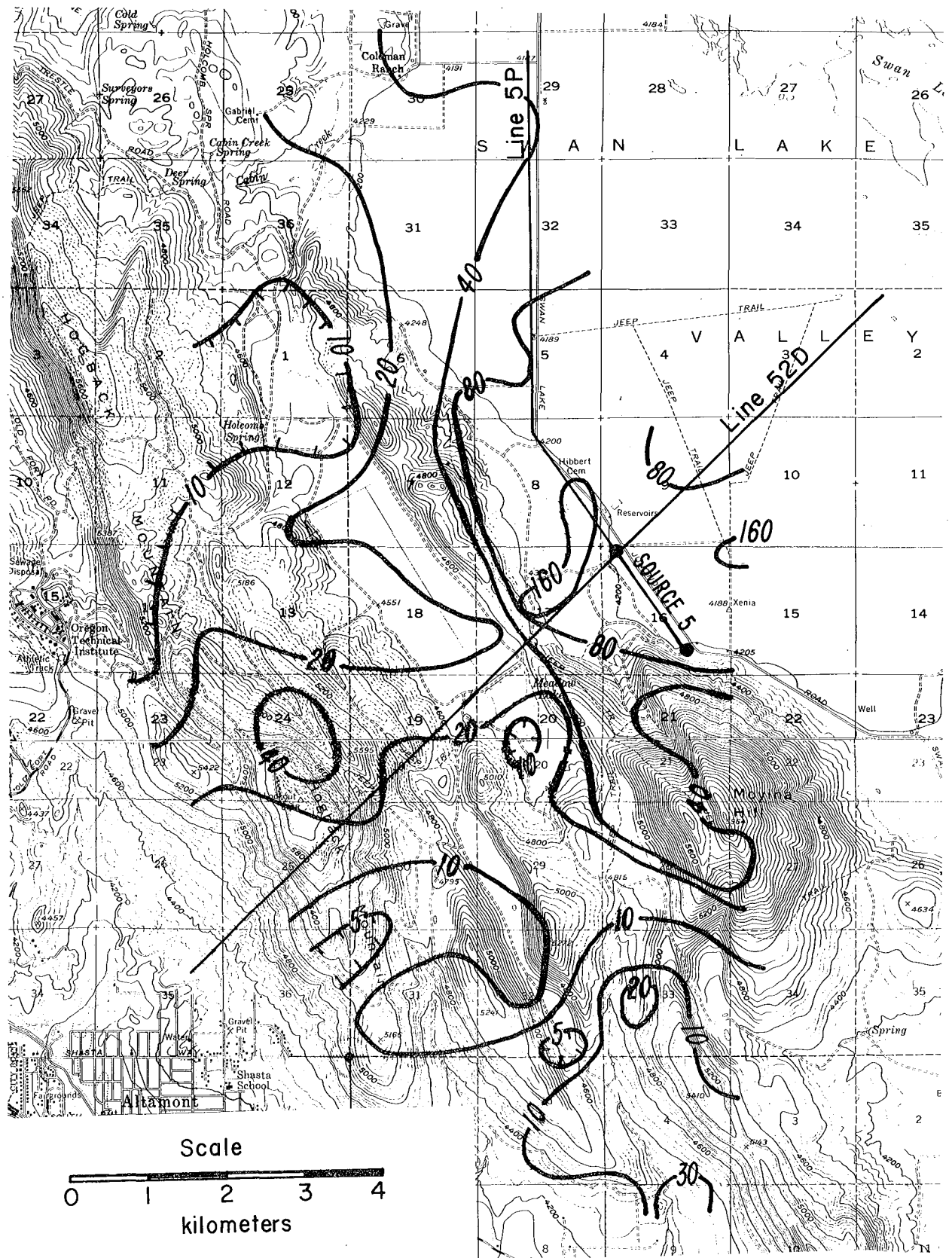
and 10 show the contoured apparent resistivities from Sources 5, 1, and 8, respectively. One by-product of the separation was the emergence of a low apparent resistivity zone in the Klamath Falls "steamer zone." This can be seen in Figures 9 and 10. This low does not appear on Group Seven's apparent resistivity map of the averaged readings.

We attempted one-dimensional curve-matching along line 5P (Figure 8), which runs along the western margin of Swan Lake Valley. This was seen as the only area which might be suited to one-dimensional interpretation. The observed curve was matched against theoretical two-layer curves, and the best model indicates a drop in resistivity from 185 ohm-meters to 30-ohm meters at a depth of 1 kilometer (Figure 11).

We then used program RESIS2D (Dey, 1976) to compute theoretical apparent resistivity maps for two-dimensional models striking perpendicular to line 52D (Figure 8). Guided by our magnetotelluric interpretation for the area (discussed in the next section), we performed several iterations of program RESIS2D, arriving finally at the two-dimensional Model 52D (Figure 12). Figure 13 compares the calculated apparent resistivity contours with the observed data. The agreement is good in a gross sense. Fine details in the observed data are probably due to the effects from small surface inhomogeneities which cannot be modeled in two dimensions.

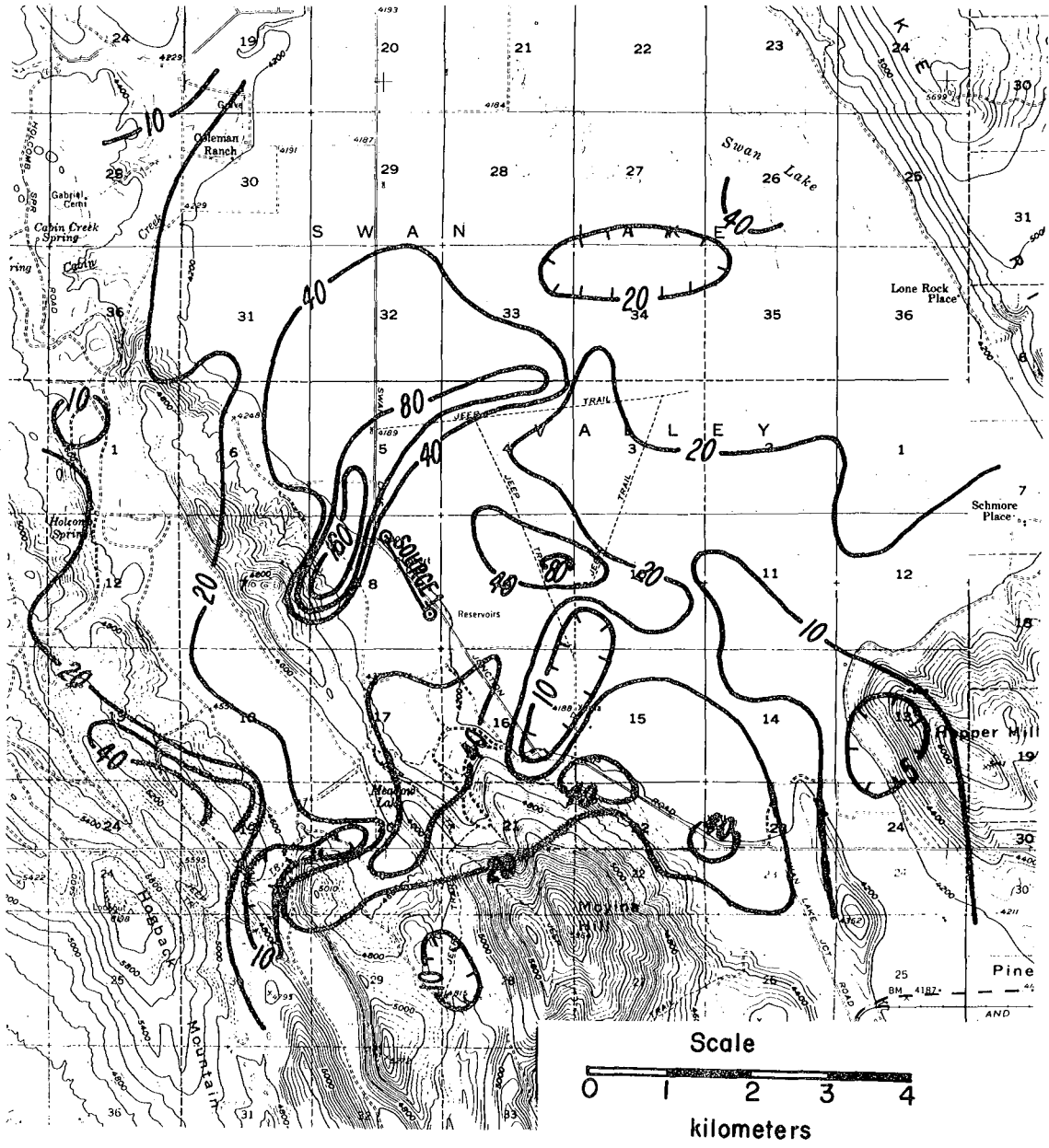
The model represents the Meadow Lake graben flanked by the western edge of Swan Lake Valley to the northeast, and by Hogback Mountain to the southwest. Meadow Lake graben is a conductive feature (5 ohm-meters) of large but undetermined depth extent. Flanking the graben resistant basement (2000 ohm-meters) is encountered at a depth of 1.4 kilometers. This two-dimensional model is consistent with the one-dimensional interpretation discussed above and shown in Figure 11.

The EM and DC soundings analyzed by Group Seven yielded layered-earth interpretations which are not consistent with this model; they indicate conductive material (5 to 40 ohm-meters) down to depths of



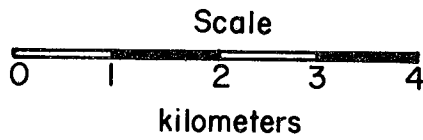
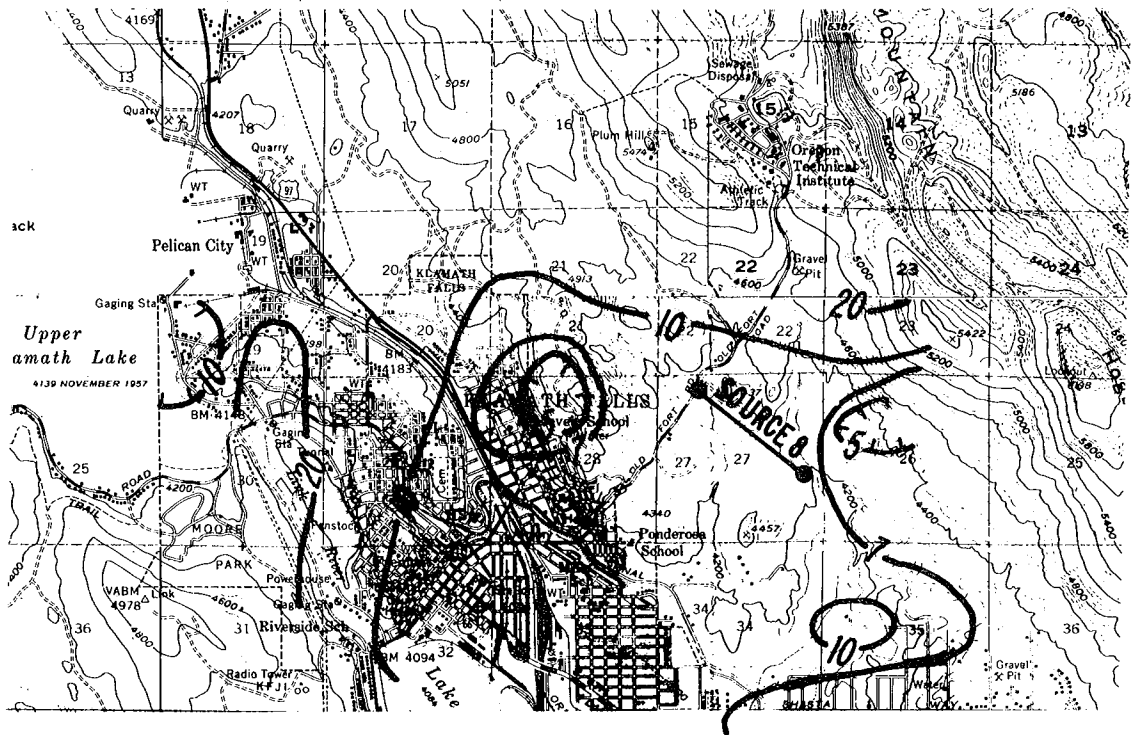
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Fig. 8. Roving dipole apparent resistivity from Source 5, Swan Lake Valley.



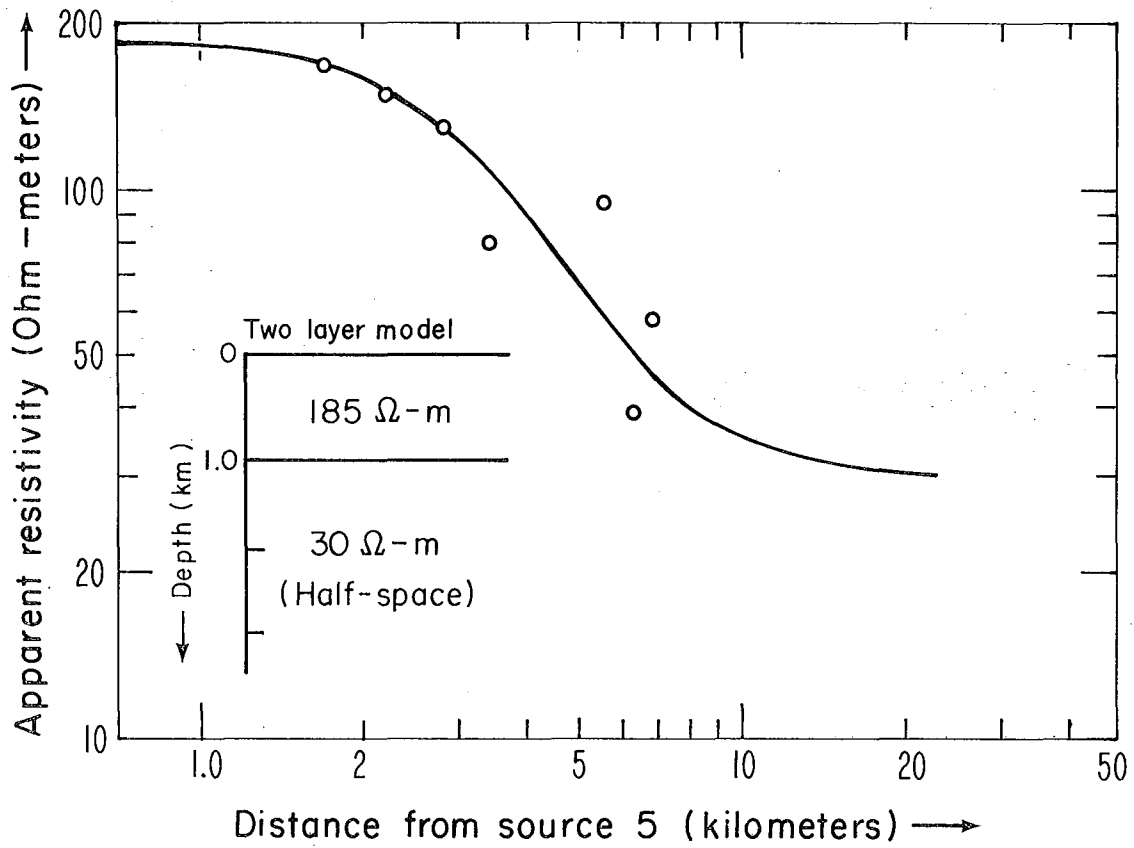
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Fig. 9. Roving dipole apparent resistivity from Source 1, Swan Lake Valley.



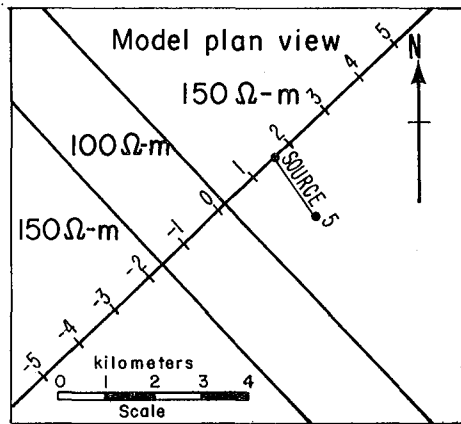
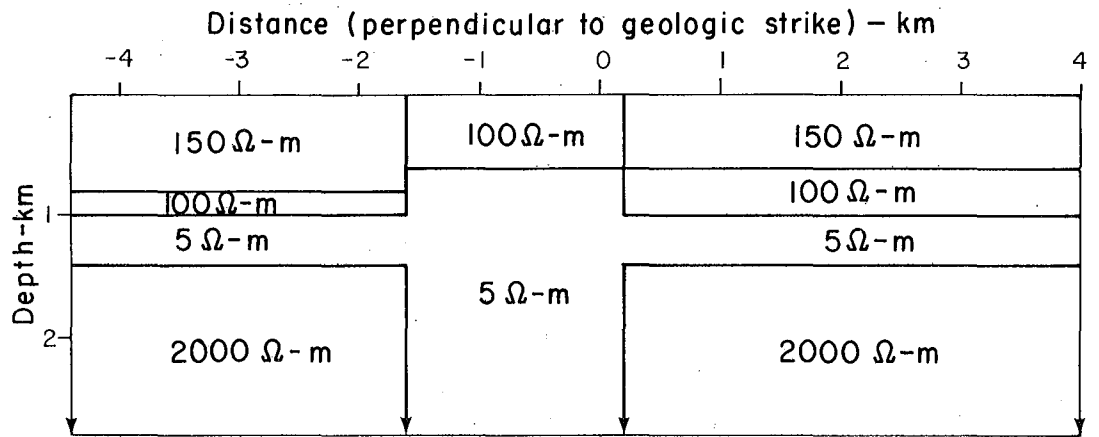
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Fig. 10. Roving dipole apparent resistivity from Source 8, Klamath Falls area.



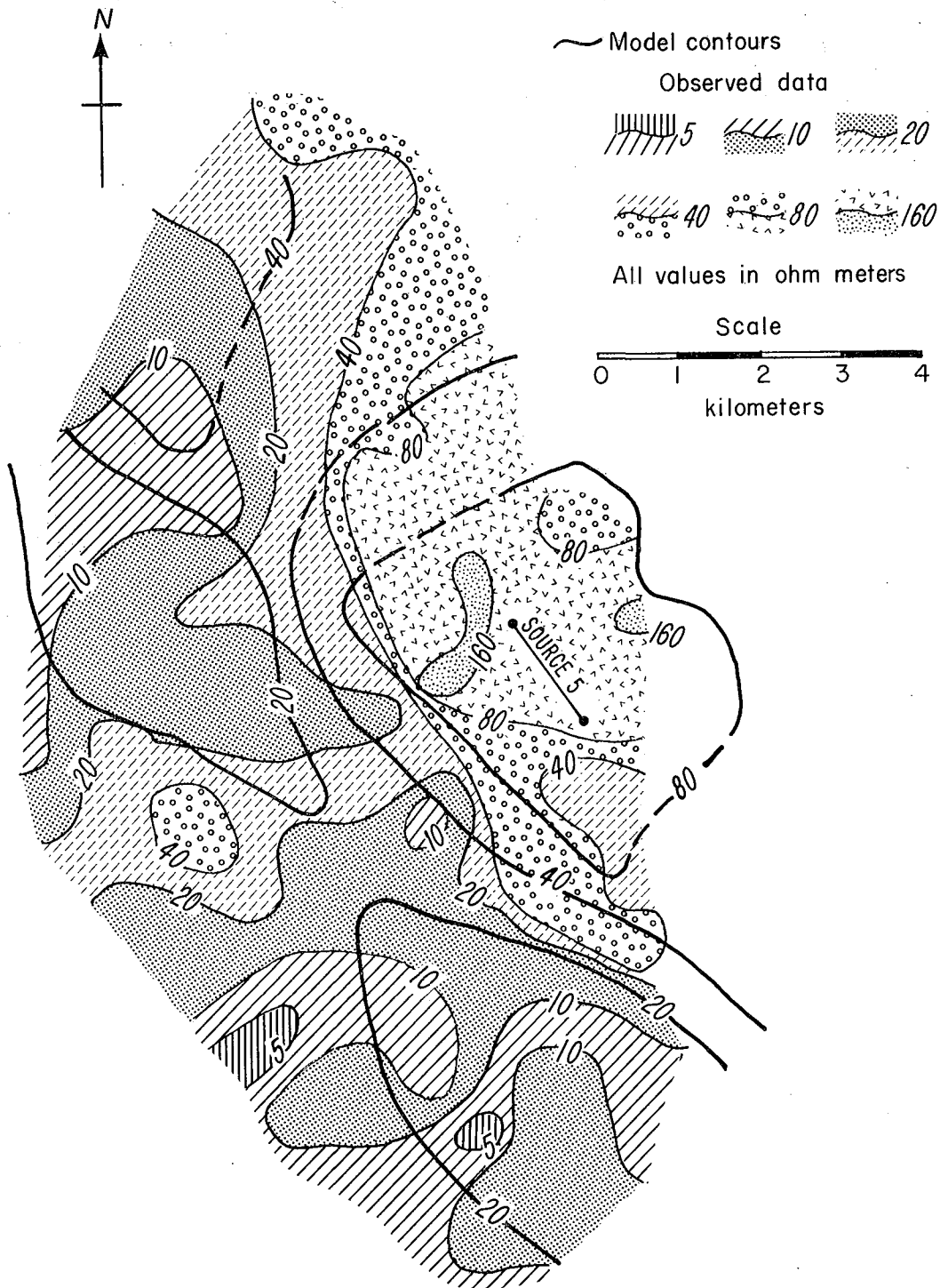
XBL 7810-6516

Fig. 11. Roving dipole profile along Line 5P, with two-layer model, Swan Lake Valley.



XBL 7810-6518

Fig. 12. Resistivity model 52D.



XBL 7810-6534

Fig. 13. Source 5 observed data vs. model 52D calculated data.

a few hundred meters, underlain by more resistive material (over 100 ohm-meters).

We attribute the disagreement to the fact that the earth structure between Source 5 and the EM receivers is not one-dimensional, and attempts to interpret it as such have led to error. Similarly, the dc soundings were made adjacent to or across a mapped fault (Figure 4), so these one-dimensional interpretations are also questionable.

#### Magnetotelluric Survey

Geonomics Incorporated (1977) conducted a telluric-magnetotelluric survey in the Swan Lake Valley area in September 1977. Tensor sounding curves were obtained for 29 stations, of which 8 were five-component magnetotelluric base stations and 21 were two-component remote telluric stations (Figure 4). Judging from the Geonomics report, data quality appears to be exceptionally good; smooth and complete sounding curves, rotated into the principal resistivity directions, were obtained for the frequency range 0.01 to 50.0 Hz.

Geonomics associated the transverse electric (TE) mode with the principal resistivity direction having the electric component oriented more nearly parallel to regional geologic strike (N40° W). Interpreted sections for both transverse electric (TE) and transverse magnetic (TM) data sets were constructed by linking together one-dimensional inversions of the sounding curves for each station along the line A-A' (Figure 4).

Because of the questionable assumption of a layered earth inherent in Geonomics' interpretation, we reinterpreted the data along line A-A' using the two-dimensional modeling program EMCDC (Madden, 1970). This program, based on the transmission-surface analogy, computes theoretical TE and TM soundings at selected points along a line perpendicular to a specified earth resistivity model. Model parameters are adjusted until the calculated TE and TM soundings at each station match the corresponding observed soundings. Best fits are determined visually

by comparing pseudo-sections of apparent resistivity plotted at each period for each station (e.g., Figures 14 and 17).

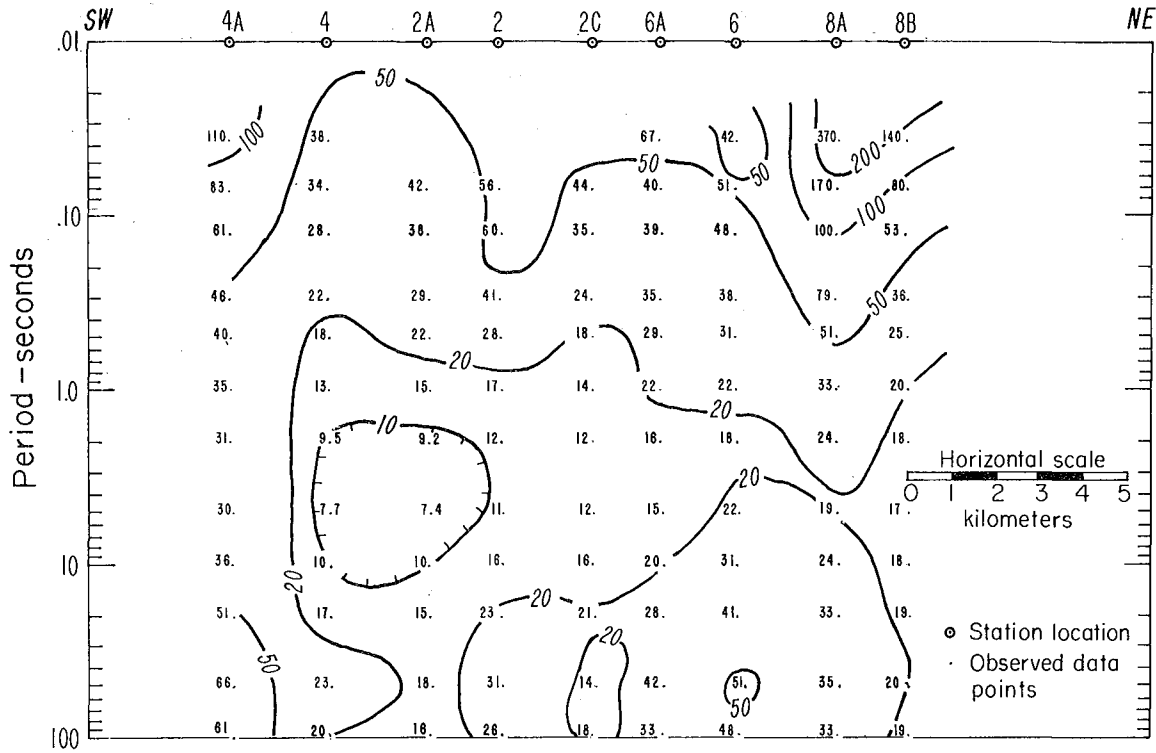
There was some uncertainty regarding mode identification. The scientist in charge of processing these data for Geonometrics indicated that the TE and TM modes might have been misidentified at stations 4, 8A, and 8B (I.K. Reddy, personal communication, 1978). In this light we revised the observed apparent resistivity pseudo-sections by interchanging the TE mode with the TM mode at the stations in question. Comparisons of Figures 14 and 15 with Figures 19 and 20, respectively, show the resulting differences. To account for the two possible data sets, two separate models were sought. The models derived are called OMI (original mode identification) and SMI (switched mode identification). The models are shown in Figures 16 and 21 and their calculated TE and TM pseudo-sections are shown in Figures 17, 18, 22, and 23. Two-dimensional models were fitted to the TE data sets as these are more amenable to interpretation than the TM data sets.

Lastly, we performed a two-dimensional inversion on the switched-mode data, using program SM2D (Jupp, 1976). This program iterates the forward modeling program EMCDC a specified number of times, changing the resistivities of each block at each iteration based on computed partials for inversion. That is, after an initial model is submitted, the program finds a better model with the same electrical boundaries but with different resistivity values. The TE and TM modes are inverted together, so the final model is a "best fit" for both modes.

After five iterations on Model SMI, the inversion program yielded Model ISMID (Inverted Switched-Mode Identified Data). The model is shown in Figure 24 and its calculated TE and TM pseudo-sections are shown in Figures 25 and 26. The TM pseudo-section for ISMID is a definite improvement over those for SMI and OMI, but the TE pseudo-section for ISMID does not fit as well as those for SMI and OMI.

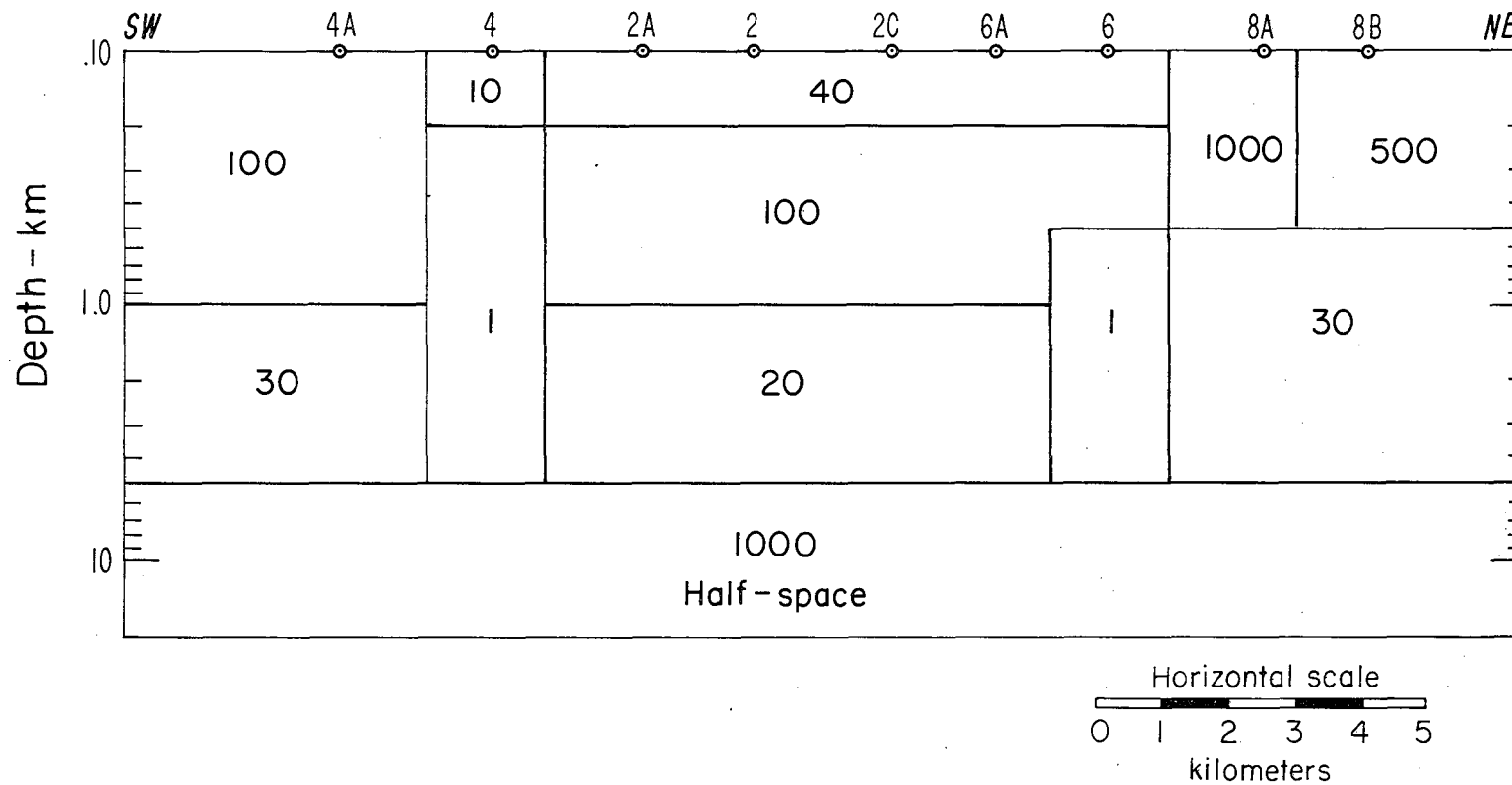
Although the two-dimensional modeling approach is a major improvement over one-dimensional inversion, the true subsurface structure is





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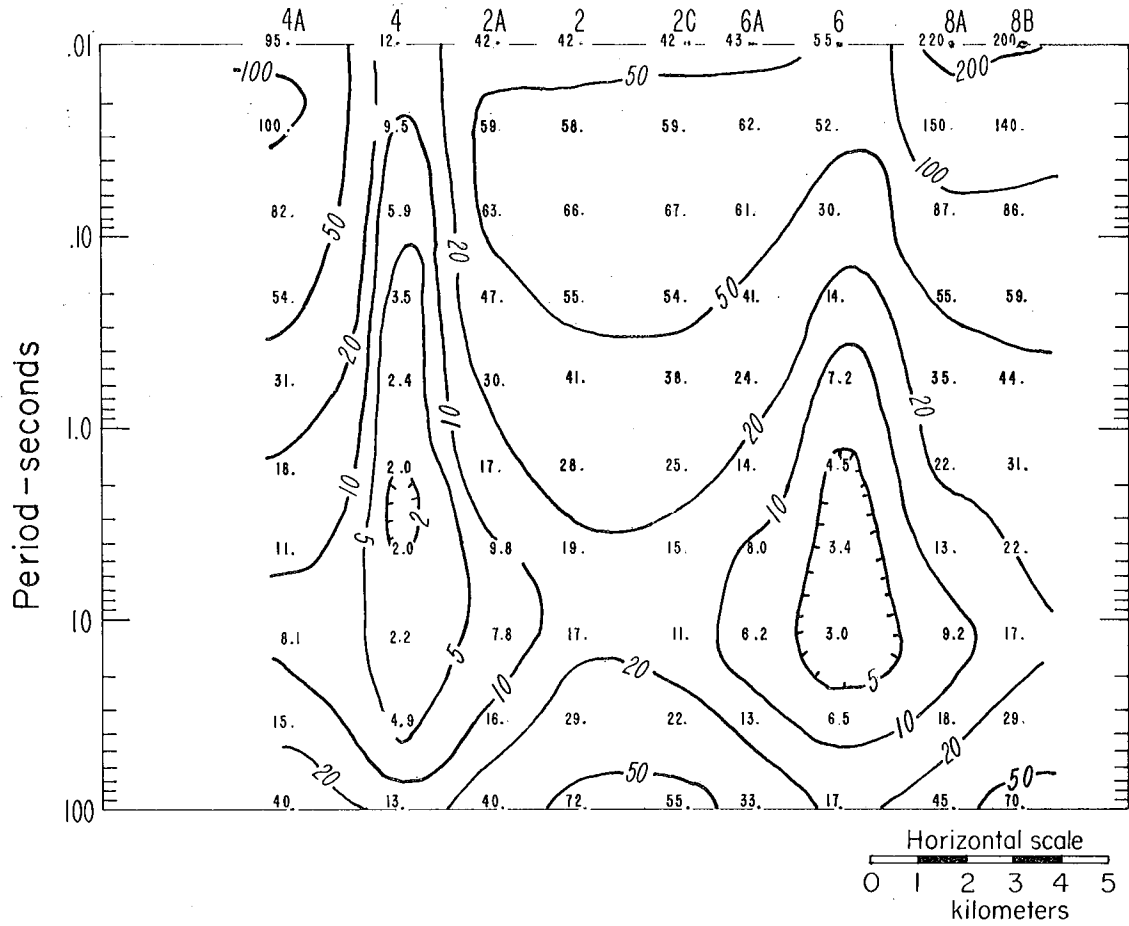
Fig. 15. TM mode magnetotelluric pseudo-section Line A'A', Swan Lake Valley.



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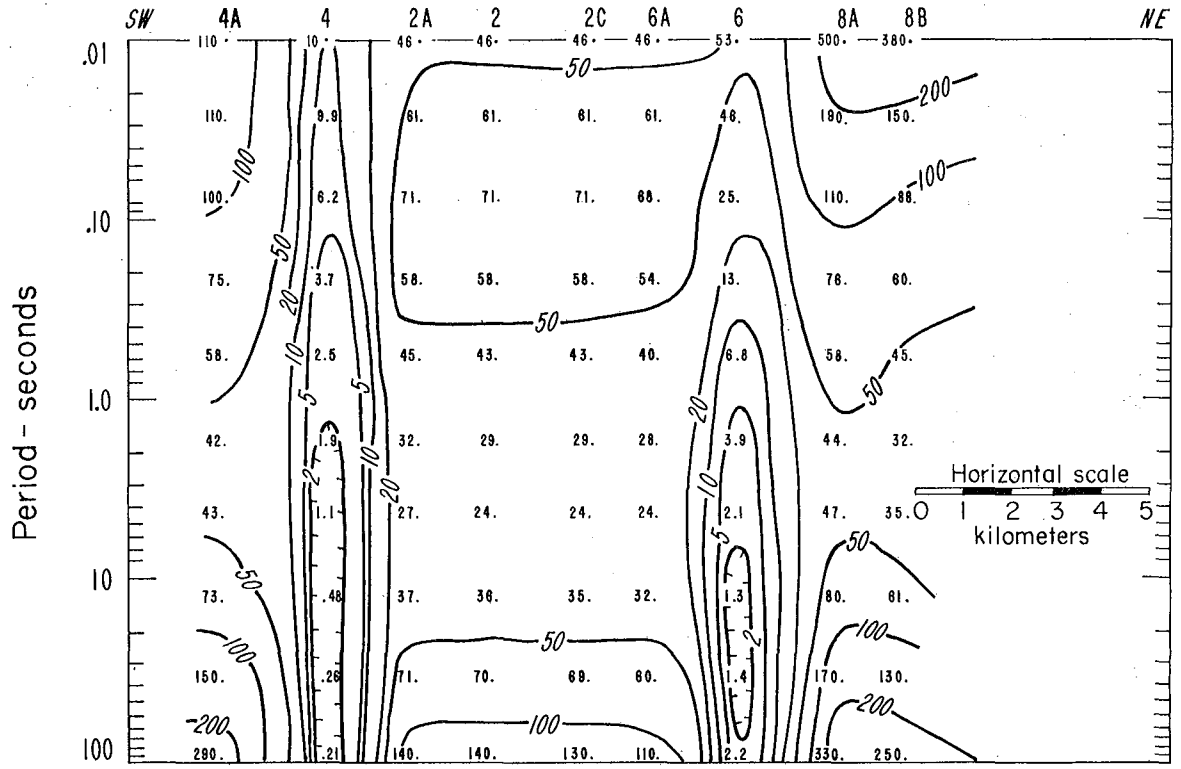
XBL 789-6513

Fig. 16. Resistivity model "OMI" (values in ohm-meters).



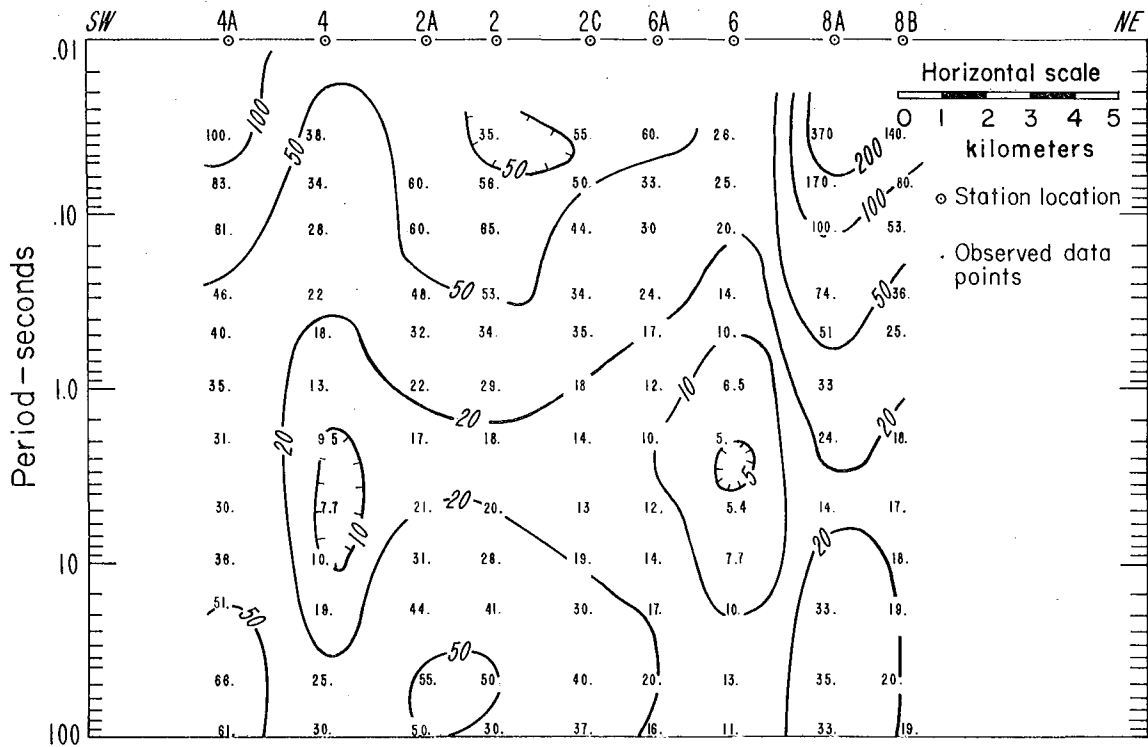
XBL 789-6514

Fig. 17. TE mode pseudo-section calculated for model OMI.



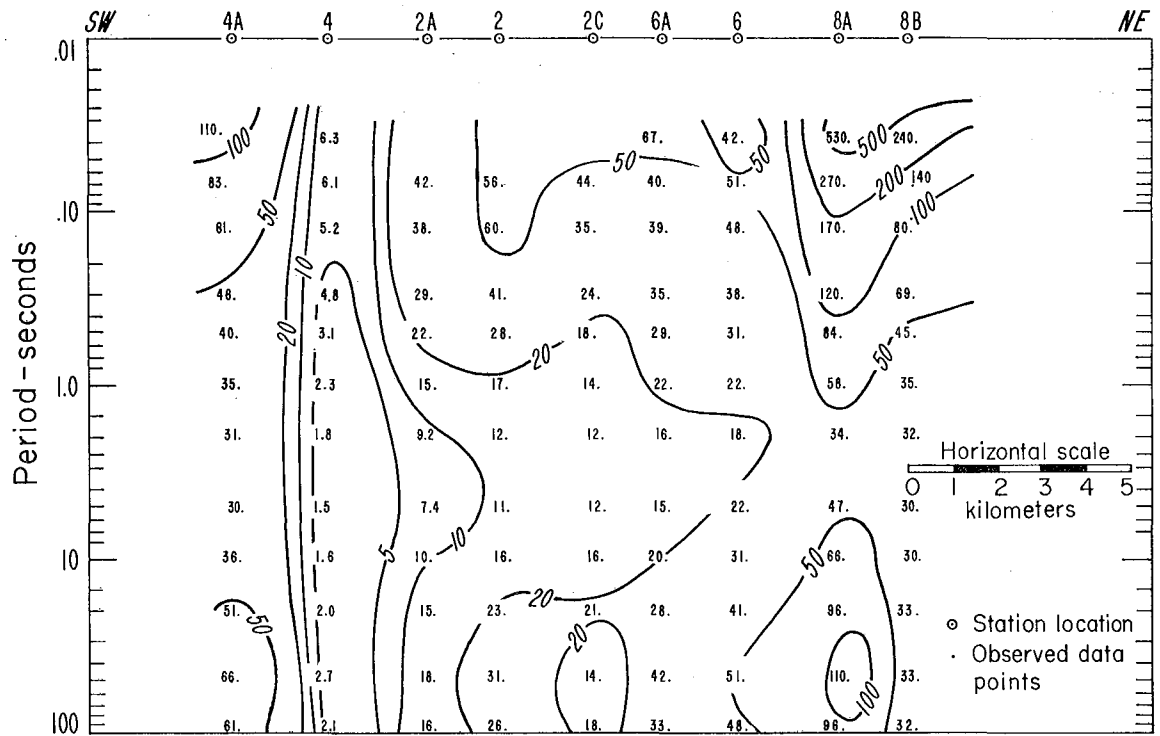
XBL 7810-2090

Fig. 18. TM mode pseudo-section calculated for model OMI.



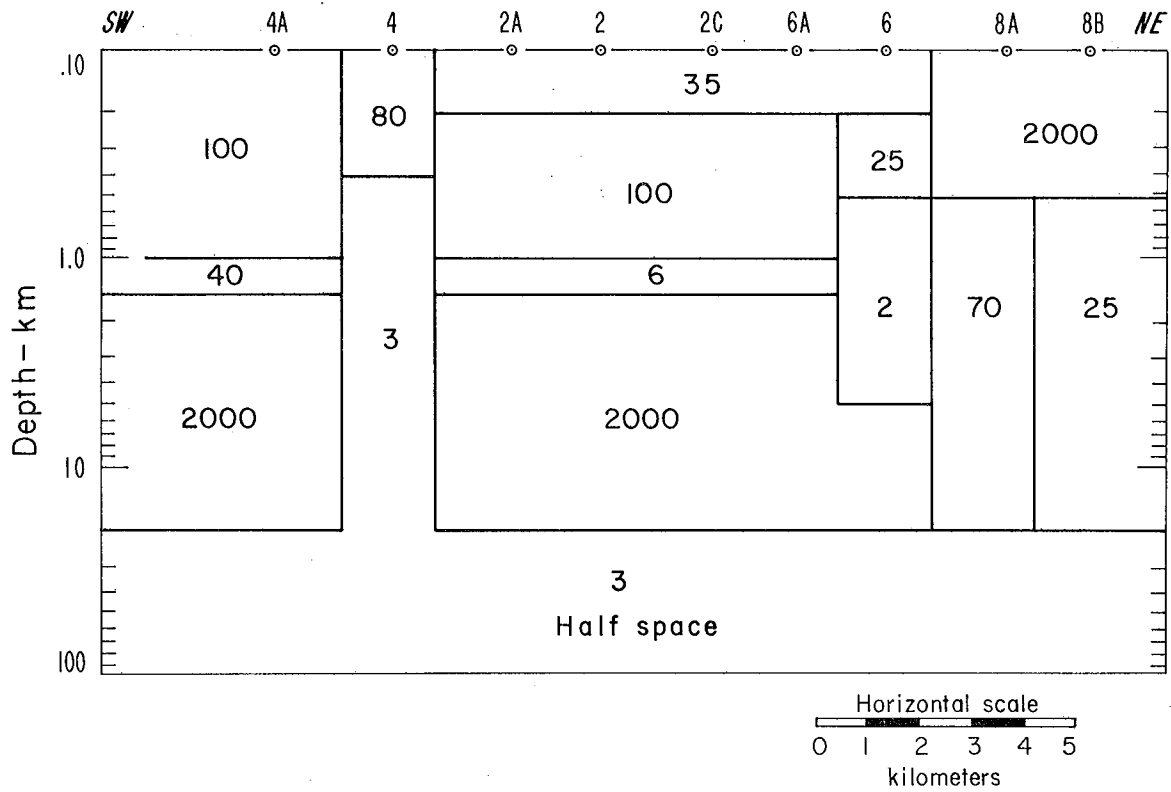
XBL 789 - 2085

Fig. 19. TE mode magnetotelluric pseudo-section, modes switched at stations 4, 8A, and 8B, Line A-A', Swan Lake Valley.



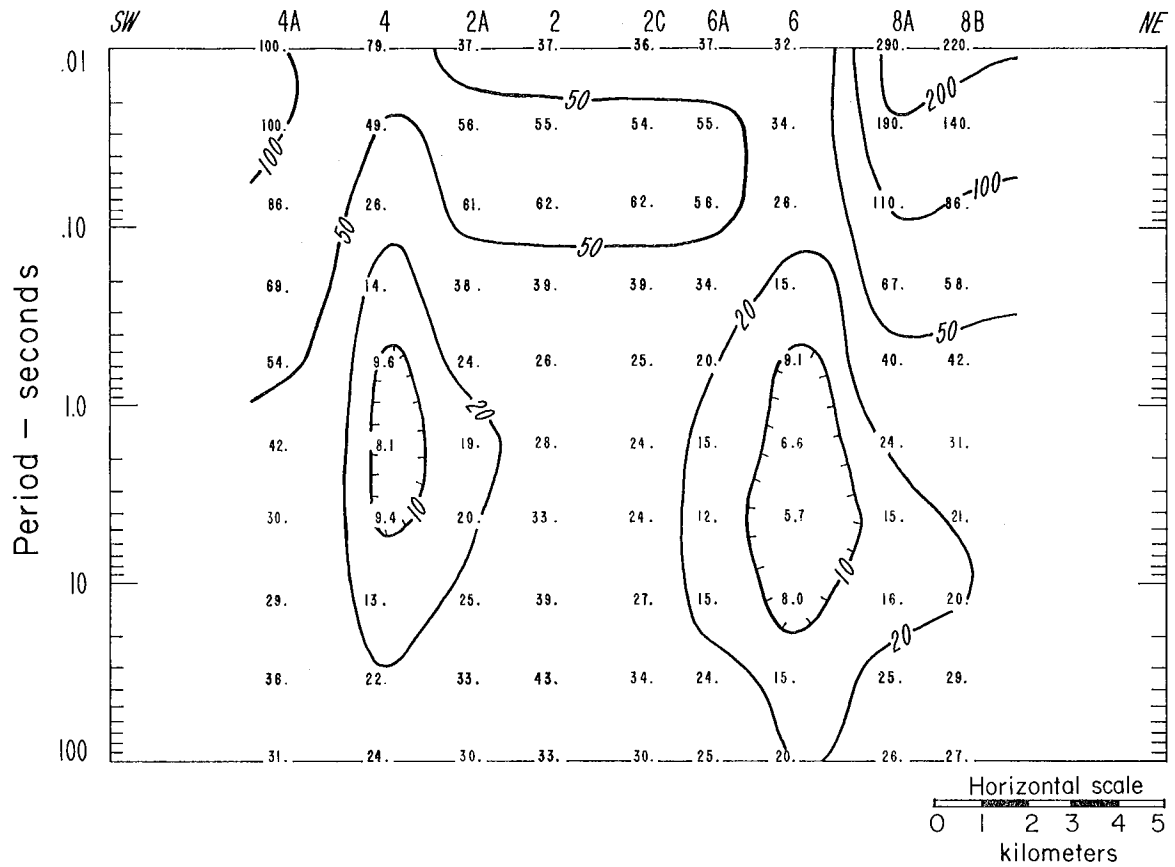
XBL 7810-2087

Fig. 20. TM mode magnetotelluric pseudo-section, modes switched at stations 4, 8A, and 8B, Line A-A', Swan Lake Valley.



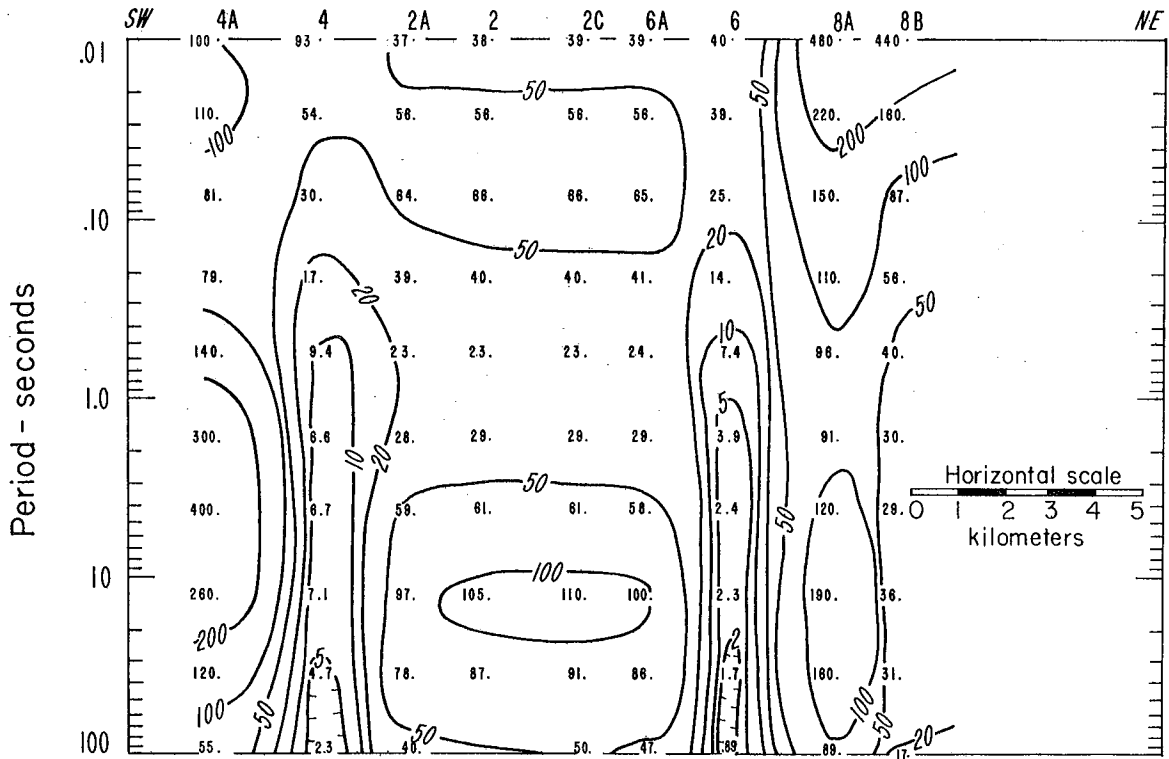
XBL 789-2096

Fig. 21. Resistivity model "SMI" (values in ohm-meters).



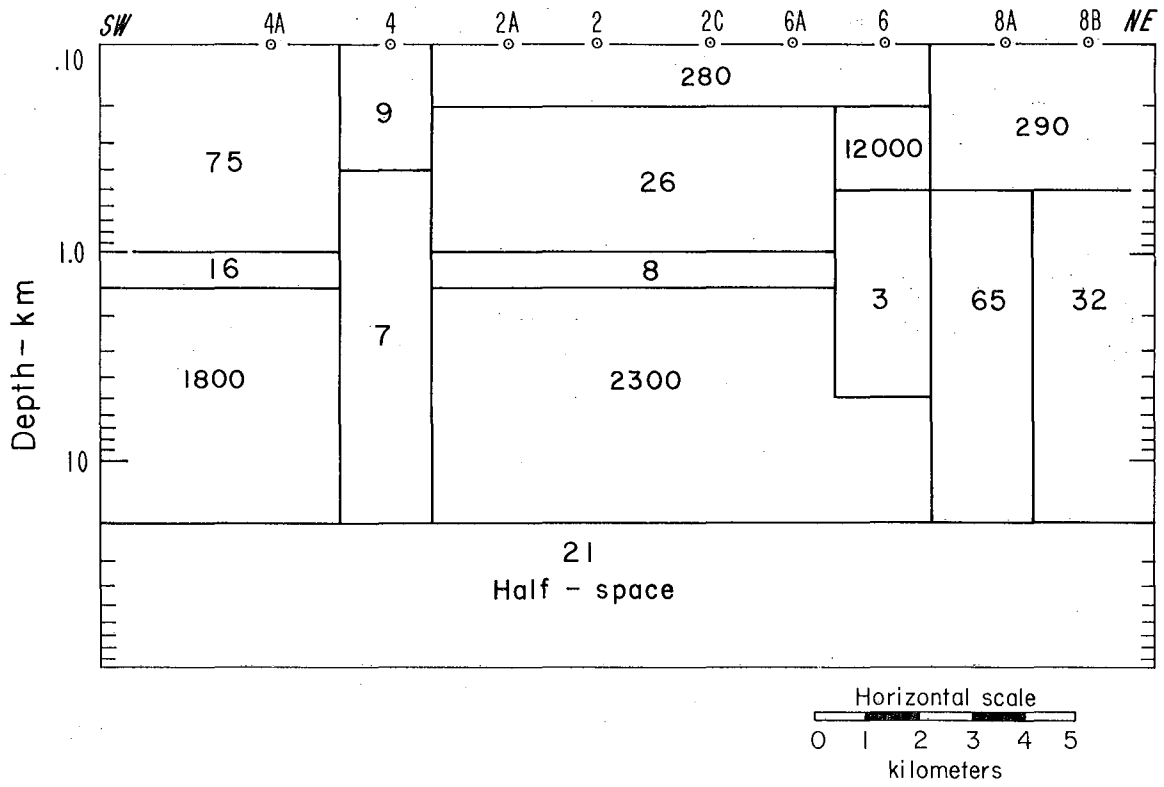
XBL 7810-2089

Fig. 22. TE mode pseudo-section calculated for model SMI.



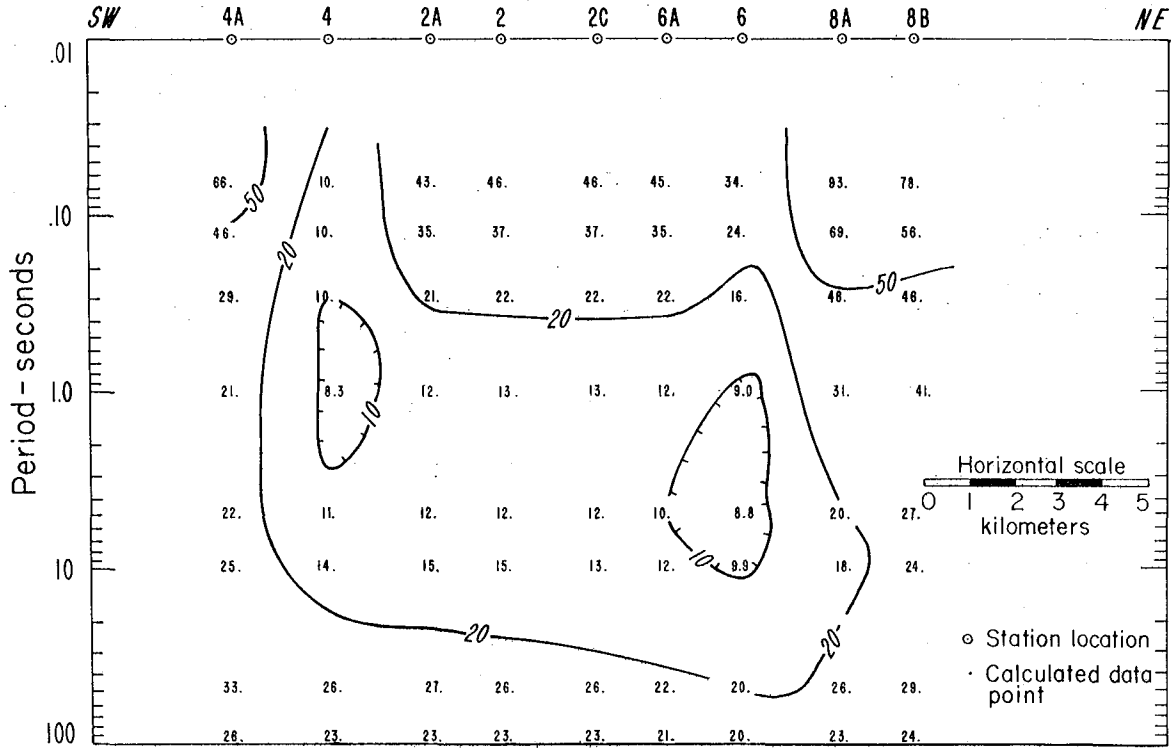
XBL 7810-2091

Fig. 23. TM mode pseudo-section calculated for model SMI.



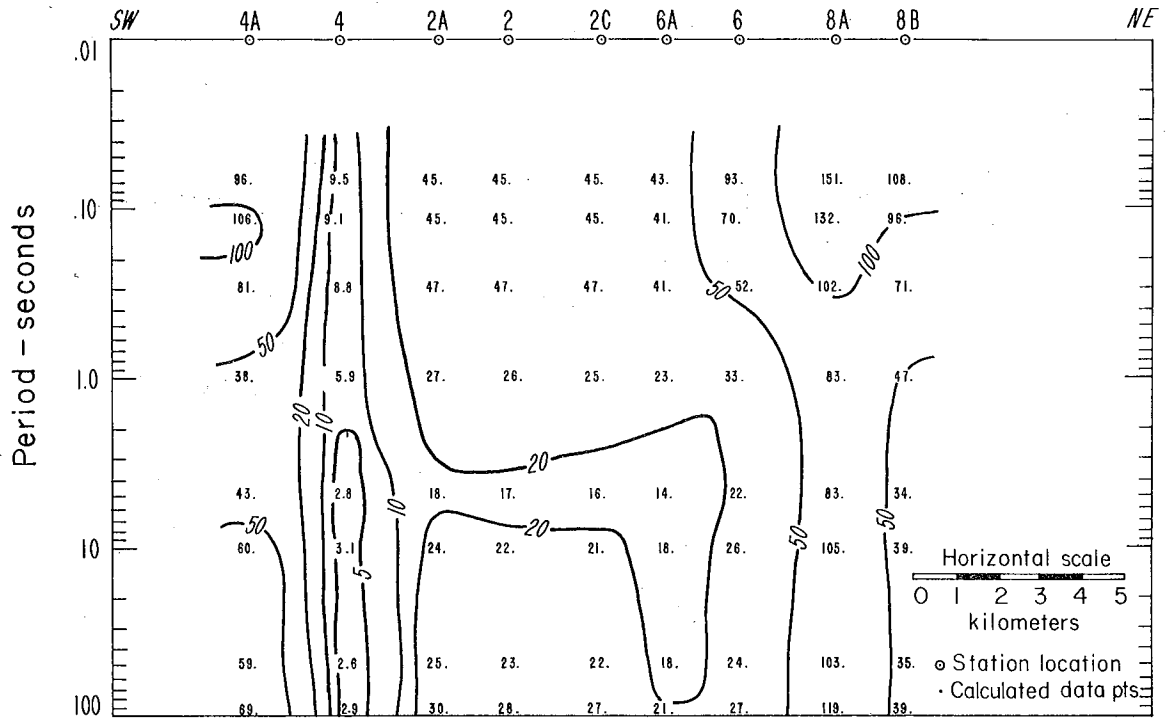
XBL 789-2095

Fig. 24. Resistivity model "ISMID" (values in ohm-meters).



XBL 7810-2088

Fig. 25. TE mode pseudo-section calculated for model ISMID.



XBL 789-2086

Fig. 26. TM mode pseudo-section calculated for model ISMID.

probably highly three-dimensional. This is evidenced by the difficulty in obtaining two-dimensional pseudo-sections that simultaneously match both the TE and TM observed data. Unfortunately, state-of-the-art three-dimensional modeling routines are still prohibitively expensive to use, so two-dimensional modeling remains the best practical interpretation scheme. However, the results from simple three-dimensional geometries modeled by other workers (e.g., Hohmann and Ting, 1978) can be applied in a qualitative fashion to help understand the situation in Swan Lake Valley.

In general, the third dimension tends to accentuate differences in the TE soundings between stations separated by vertical resistivity boundaries. It also seems to accentuate TE apparent resistivity changes with respect to period caused by layering (horizontal boundaries). This may be the case in Swan Lake Valley, where the observed TE pseudo-sections (Figures 14 and 19) show extreme variation of apparent resistivity with respect to both horizontal distance and period. One might also speculate that the observed electrical isotropy at station 4A is due to some symmetrical three-dimensional electrical structure, rather than a layered-earth situation.

#### Synthesis and Geologic Interpretation

The earth models presented in the previous sections are intended to provide rough, flexible guides to subsurface geology rather than accurate representations. The MT models are plagued by questions of mode identification and three-dimensionality, and the solutions are not unique. Therefore, we sought independent confirmation of our findings in the form of overlapping geophysical data. In addition, we endeavored to determine if the models were geologically reasonable.

The roving dipole and MT data sets overlap in the western portion of the Swan Lake Valley area. Therefore, we attempted to fit the roving dipole data with the western portion of our MT model SMI. A few minor adjustments to this model proved sufficient to satisfy the roving dipole data (compare Figures 12 and 21).

The gravity, aeromagnetic, roving dipole, and MT data sets all suggest a lithologic change at a depth of about 1 kilometer beneath Swan Lake Valley. This may mark the transition from the Yonna Formation to the underlying basalt flows. Overlapping geophysical evidence lends credence to our interpretations, but more detailed exploration work is needed to provide adequate constraint on the model parameters. For the time being, however, we will use model ISMID as a rough guide to subsurface geology. This model was chosen because it fits the observed TM data better than models SMI and OMI, and we feel that this is a favorable characteristic in this three-dimensional area.

The geologic interpretation is fairly straightforward. We will discuss possible lithologic counterparts for the resistivity units in model ISMID (Figure 24).

The central portion of Swan Lake Valley is underlain by resistive to moderately conductive material (280 to 26 ohm-meters) to a depth of 1 kilometer. This may represent relatively impermeable lacustrine alluvium overlying Yonna Formation rocks. This is underlain by 500 meters of 8 ohm-meter material--possibly an aquifer in the older basalt unit. Beneath this lies 19 kilometers of electrically resistive (2300 ohm-meters) basement rock, probably consisting of tight basalts or other igneous rock. Finally, at a depth of 20 kilometers we reach conductive, lower crust rocks (21 ohm-meters). A similar interpretation of the electric layers is applicable in the area southwest of Meadow Lake Valley.

Meadow Lake Valley itself appears as a conductive (7 to 9 ohm-meter) dike-like feature about 2 kilometers in width. In the model, this zone merges with the lower crustal rocks at a depth of 20 kilometers. However, the zone may not extend so deep in actuality; it is difficult to resolve the "bottom" of a conductor with the MT method. Regardless of its true depth extent, we interpret the conductive zone as a highly fractured fluid-filled fault zone.

Beneath the northeastern edge of the Swan Lake Valley lies another conductive block with a resistivity of 3 ohm-meters. In the model we show a lower boundary for the conductor, but again this feature is not well resolved. The conductor may represent a complex, sheared fault zone similar to the one on the southwestern side of the valley. Alternatively, we might be seeing the effect of alteration and hydrothermal circulation along the boundary fault. Directly above the conductor lies a highly resistive block with a resistivity of 12,000 ohm-meters. The true resistivity of the block may not be that high, but it is reasonable to infer an impermeable, possibly mineralized cap rock overlying the conductor.

At the extreme northeastern end of the model, Swan Lake Rim appears as a resistive (290 ohm-meter) basalt block, fault-displaced upward from similar rock underlying the valley.

#### The Geothermal Target

The data suggest that Swan Lake Valley is bordered by two conductive zones which are connected via a conductive layer. The conductive border zones occur beneath Meadow Lake Valley and beneath Swan Lake. The conductive layer lies 1 to 1.5 kilometers below the valley floor.

These zones may be permeable regions saturated with geothermal fluids which have ascended along fault zones. At this stage several follow-up exploration techniques could be suggested to help determine whether thermal anomalies exist and to help define the conductive "layer" at depth. Shallow temperature gradient drilling along northeast-trending lines from Meadow Lake Valley to the Swan Lake Rim, detailed resistivity (dipole-dipole or Schlumberger soundings) across the center of Swan Lake Valley, and more detailed gravity surveys would help to pinpoint a drill target in the area. In addition, the waters from Holcomb Spring should be chemically analyzed to estimate equilibration temperatures. The depth to conductive lower-crust indicated by the MT data is rather shallow (20 km). This phenomenon has been reported in several geothermal areas (e.g., Stanley et al., 1977).

Most of our work in the Swan Lake Valley area has focused on Line A-A'. There are, however, other areas of interest which we plan to study with the available data. These include:

1. An area south of Moyina Hill which has MT apparent resistivities measuring less than 1.0 ohm-meters (Geonomics, 1977).
2. A small roving dipole low apparent resistivity zone located west of Meadow Lake Valley (Group Seven, 1972).
3. The eastern and southeastern portion of Swan Lake Valley, which has low MT apparent resistivities and may be underlain by an elevated conductive lower crust (Geonomics, 1977).

#### KLAMATH HILLS AREA

##### Topography and General Geology

Located 13 to 26 kilometers south of Klamath Falls, the Klamath Hills rise about 300 meters from the surrounding flatlands (Figure 27). They stretch northwest-southeast for a total length of about 18 kilometers, attaining a maximum width of almost 5 kilometers. To the southwest lies Lower Klamath Lake, which has been completely drained and reclaimed for farmland. Spring Lake Valley and the valley of the Lost River are located northeast of the Hills. We will refer to this area as the Lost River-Spring Lake Valley. Further northeast, Stukel Mountain stands almost 800 meters above these valleys.

The structure here is typical of the Basin and Range geomorphic province and the Klamath Hills are essentially a horst. Peterson and McIntyre (1970) mapped Yonna Formation rocks and basalt flows in the Hills, with Quaternary alluvium and lacustrine sediments covering the valleys.

The area is classified as a KGRA based on the presence of several warm and hot wells, including two wells with temperatures exceeding

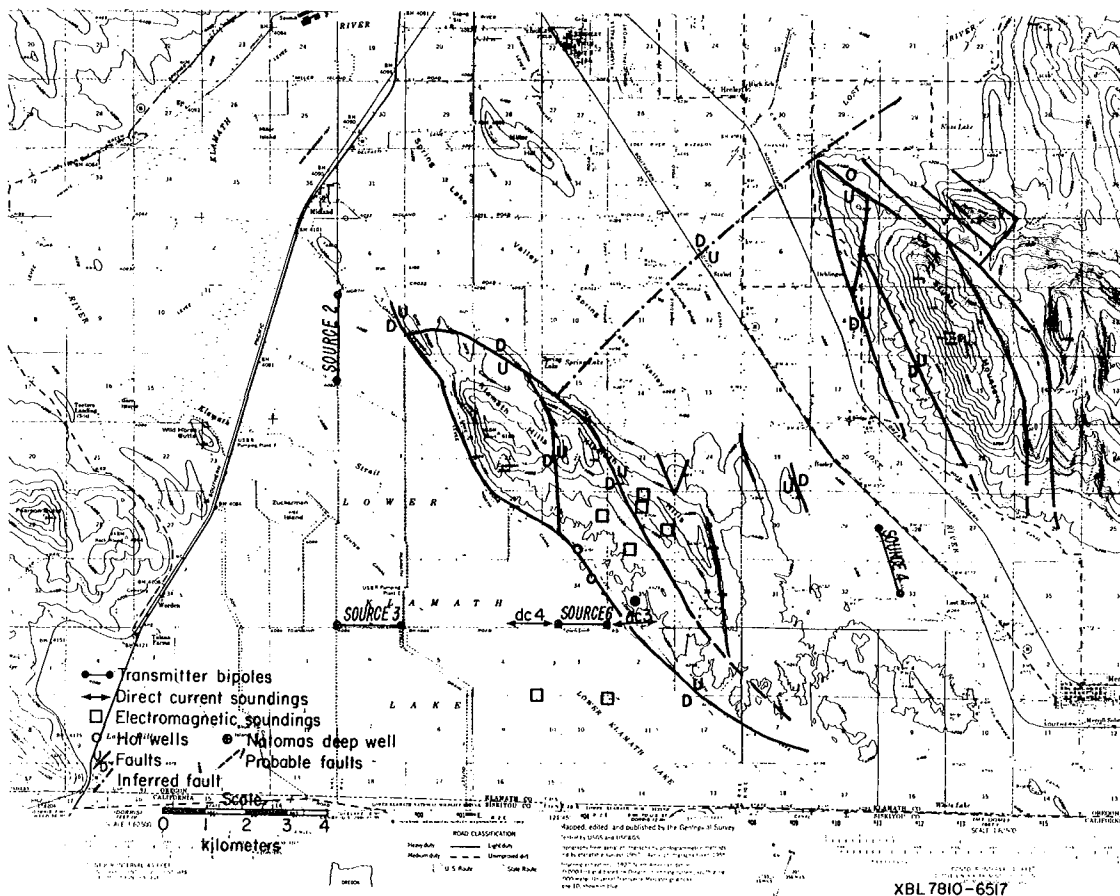


Fig. 27. Klamath Hills area base map.

90°C. These two are located in Sections 27 and 34, T40S, R9E. We will refer to these as the Hot Wells. In addition, several warm wells, with temperatures from 20°C to 50°C, exist along the southwest edge of the Hills (Sammel, 1976). Other warm wells are located near Miller Hill and near the northwestern tip of Stukel Mountain.

#### Gravity Survey

Van Deusen (1978) occupied about 25 gravity stations in this area as part of his regional study. As in Swan Lake Valley, we have dealt only with his complete Bouguer reduction and profile models (Figure 28). Van Deusen's model for profile A-A' indicates a 1 kilometer thickness of valley fill overlying basement. His model for profile D-D' predicts only 100 meters of valley fill. These estimates were made assuming a density contrast of 1.0 grams/cm<sup>3</sup> and thus both thickness estimates should be considered minimum values. True fill thicknesses may be 2 or 3 times greater.

The gravity contours form a saddle between Stukel Mountain and the Klamath Hills, centered near the town of Hosley. This may be caused by a raised northeast-trending basement ridge between the two mountains. The associated gradient to the northwest suggests a fault running roughly between Olene Gap and Spring Lake (Figure 27).

#### Microearthquake Study

Microgeophysics Corporation conducted a ten-day microseismic survey with an array centered on the Klamath Hills (Natomas Company, 1978). Eleven high-frequency (5-30 Hz) instruments were operated with amplifications ranging from  $5 \times 10^5$  to  $2 \times 10^6$ . The array was designed to record earthquakes down to magnitude -0.5, but no events were recorded during the ten-day span.

The lack of seismic activity is somewhat surprising in view of the historical seismicity (Couch and Lowell, 1971). The record of felt earthquakes does not indicate many events, but the area is definitely

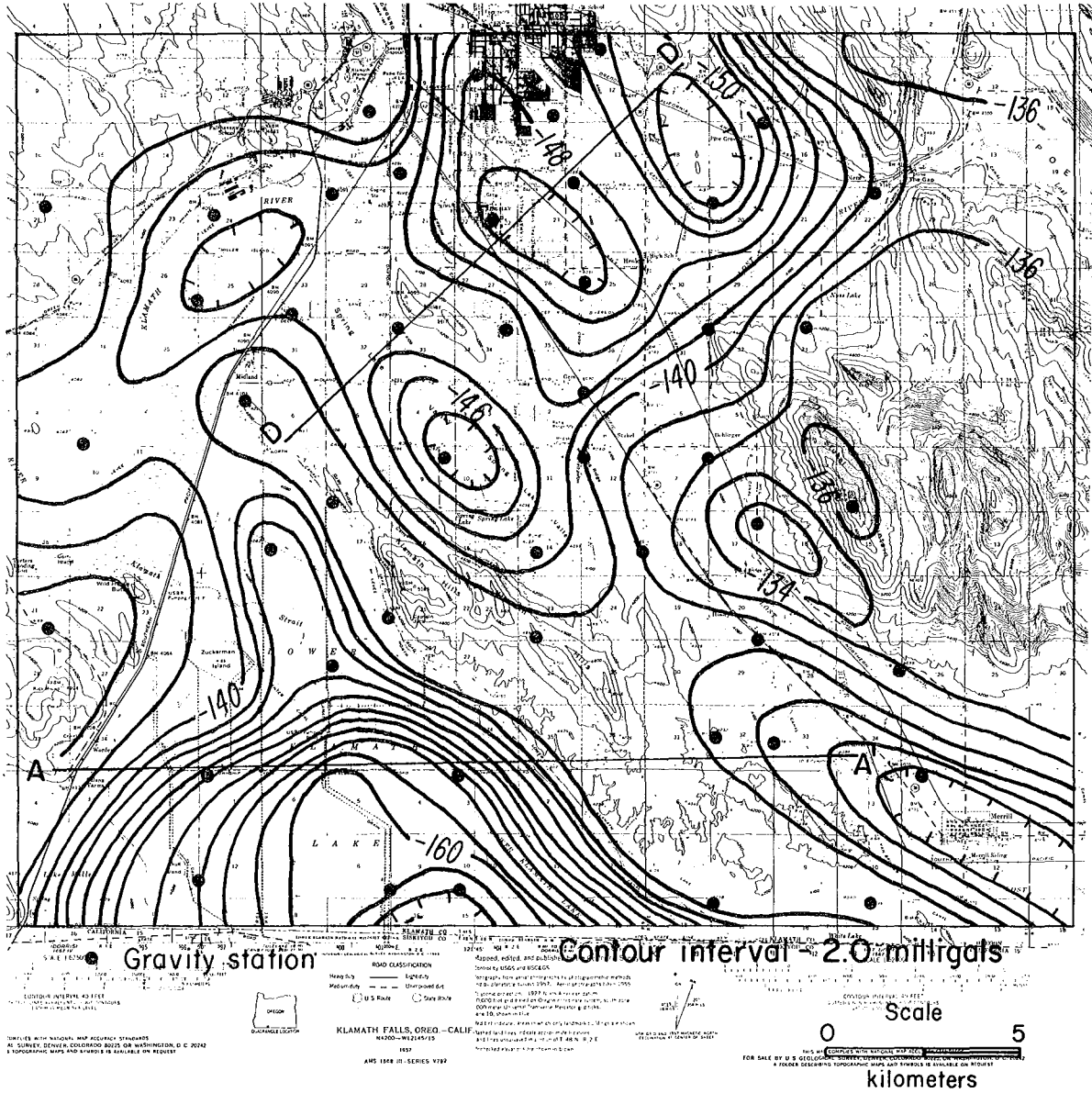


Fig. 28. Complete Bouguer gravity map, Klamath Hills area (after Van Deusen, 1978).

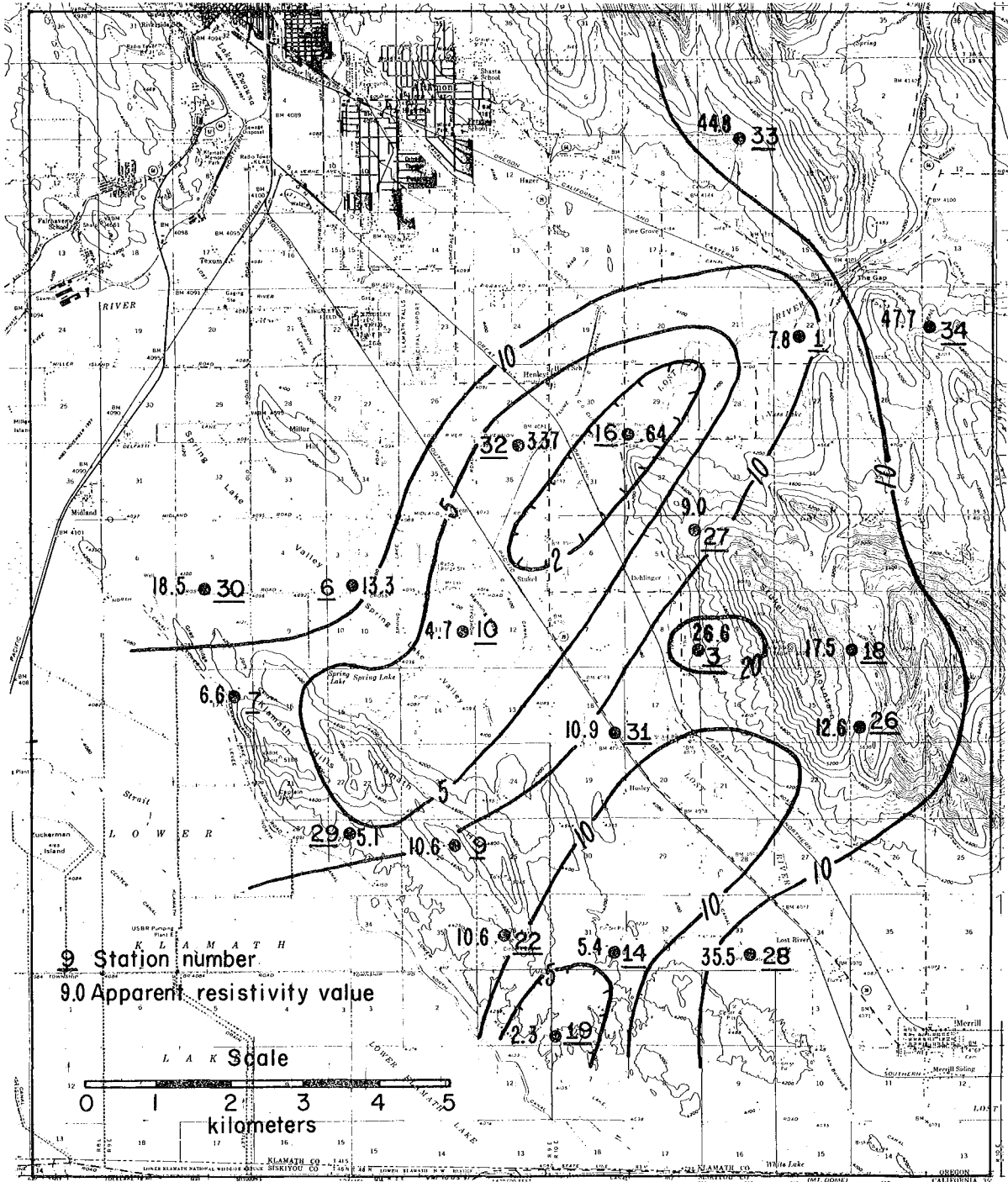
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seismically active. This is also borne out by abundant field evidence of geologically recent fault displacements. We therefore conclude that the study was conducted during an unusually quiet time. A successful study would have yielded information about the locations and earthquake mechanisms of active faults in the area, thus helping to delineate possible target areas.

#### Audio-Magnetotelluric Survey

Senterfit and Bedinger (1975) made scalar audio-magnetotelluric (AMT) measurements at 23 stations with both North-South and East-West telluric dipole orientations. Their U.S. Geological Survey system was tuned to 12 pre-selected narrow frequency bands between 7.5 Hz and 18.6 KHz. The brief open-file report contains no interpretation, only a tabulation of apparent resistivity values. At each station and frequency, 1 to 10 repeat measurements were made, and the average apparent resistivity was tabulated along with the standard deviation. Data precision varies, with most of the standard deviations falling in the range of 10% to 30% of the observed apparent resistivities. Significant discrepancies between the North-South and East-West apparent resistivities suggest that the geology is multidimensional and that a tensor survey is necessary for realistic interpretation. A further limitation of the AMT survey is the rather shallow depth of exploration associated with these frequencies and resistivities. Even at the lowest frequency, 7.5 hertz, skin depths are on the order of 500 meters.

Twenty of the 23 AMT stations were located in the Klamath Hills area, mostly in the Lost River---Spring Lake Valley and in the Klamath Hills. We plotted and contoured the North-South and East-West apparent resistivities at three frequencies: 7.5 Hz, 27 Hz, and 6.7 KHz. Figure 29 presents the contour map for the North-South telluric polarization at 7.5 Hz. Perhaps the most arresting feature on the map is the general northeasterly trend of the anomalies, particularly



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Fig. 29. Audio-magnetotelluric apparent resistivities, north-south telluric orientation at 7.5 Hz., Klamath Hills area (data from Senterfit and Bedinger, 1976).

the low centered on station 16. This trend is perpendicular to the regional northwest geological trend, and the low resistivity zone is suggestive of a fault. This zone appears at all three of the plotted frequencies, and for both telluric directions.

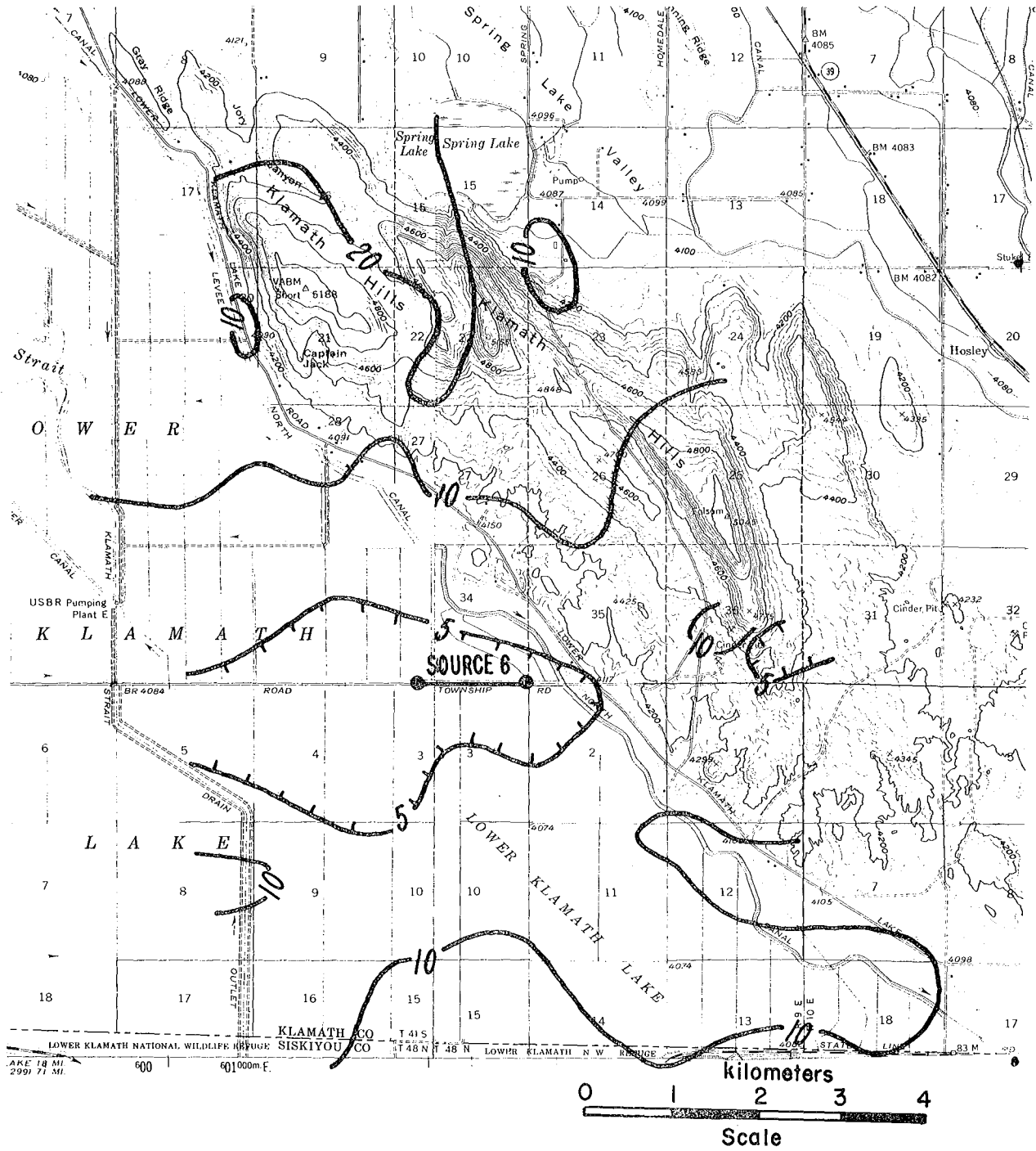
Southeast of this low is a high apparent resistivity zone followed by another conductive zone. These anomalies are also northeast trending, and show up, at least in a general way, to all three frequencies. The high resistivity zone is centered on the town of Hosley, and its contours resemble those of the gravity high located in the same area. This reinforces the notion of a buried basement ridge crossing the valley beneath Hosley.

#### Roving Dipole Resistivity Survey

Group Seven Incorporated (1972) conducted roving dipole resistivity surveys over a 250 square kilometer area including Lower Klamath Lake, the Klamath Hills, and the Lost River-Spring Lake Valley. Figure 27 shows the locations of the four bipole sources. Potential dipoles were placed at approximately 420 stations and apparent resistivities were calculated at each station. At stations with readings from more than one bipole source, the calculated apparent resistivities were averaged.

We replotted and contoured the apparent resistivities from each source separately, disclosing anomalies that were somewhat masked by the averaging process. The results were then compared with theoretical values calculated for two-dimensional models. Figures 30-33 show the separated apparent resistivity maps.

We used program RESIS2D (Dey, 1976) to generate apparent resistivity maps for our models. A trial-and-error process led to the two-dimensional models 62D and 32D shown in Figures 34 and 35 for Sources 6 and 3, respectively. The models are nearly identical. Both include a resistive dike-like body at the edge of the Klamath Hills, and a conductive



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Fig. 30. Roving dipole apparent resistivity from Source 6, Klamath Hills area.

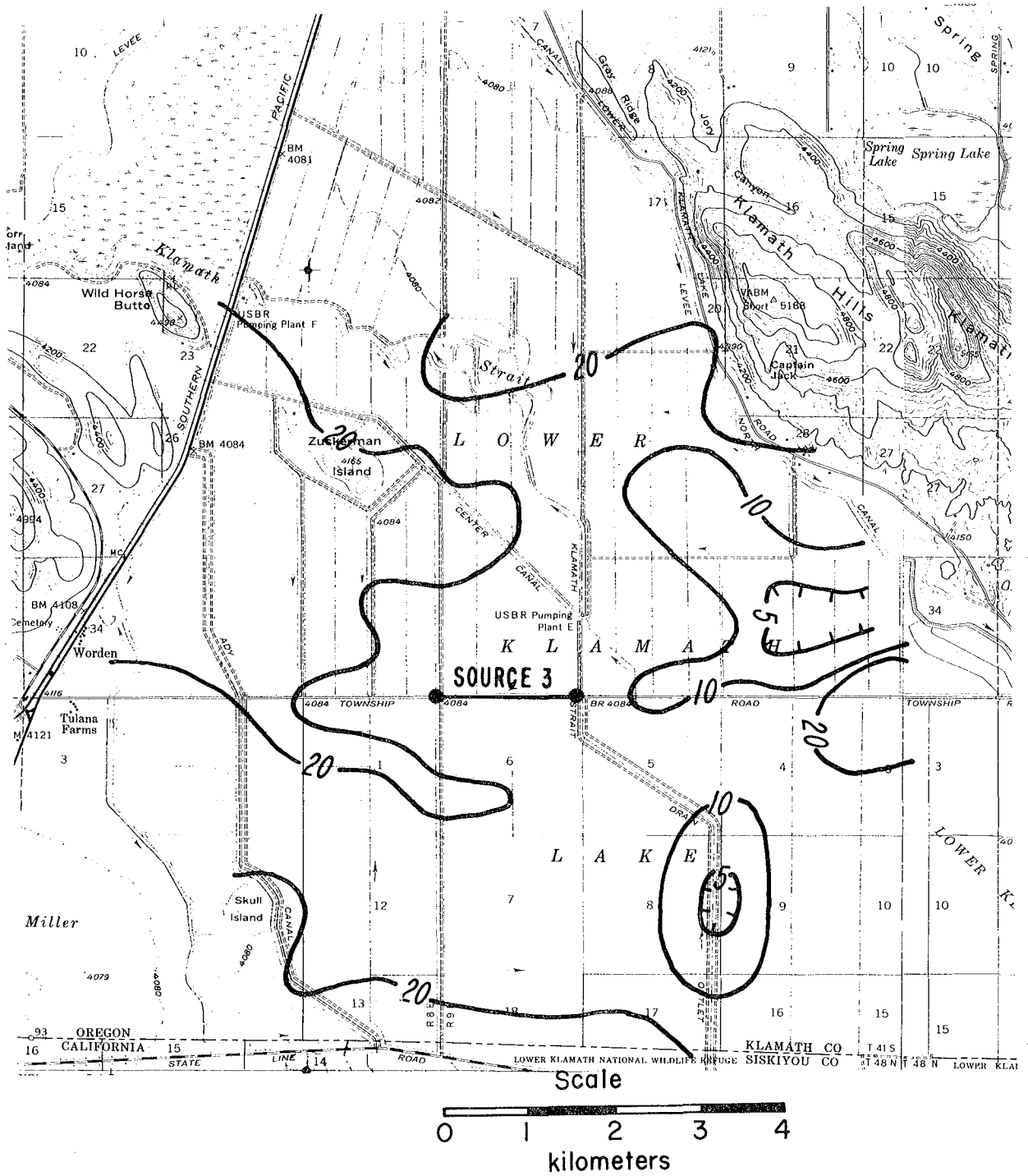
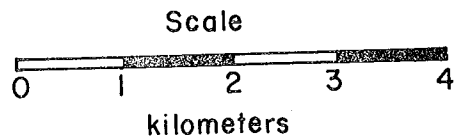
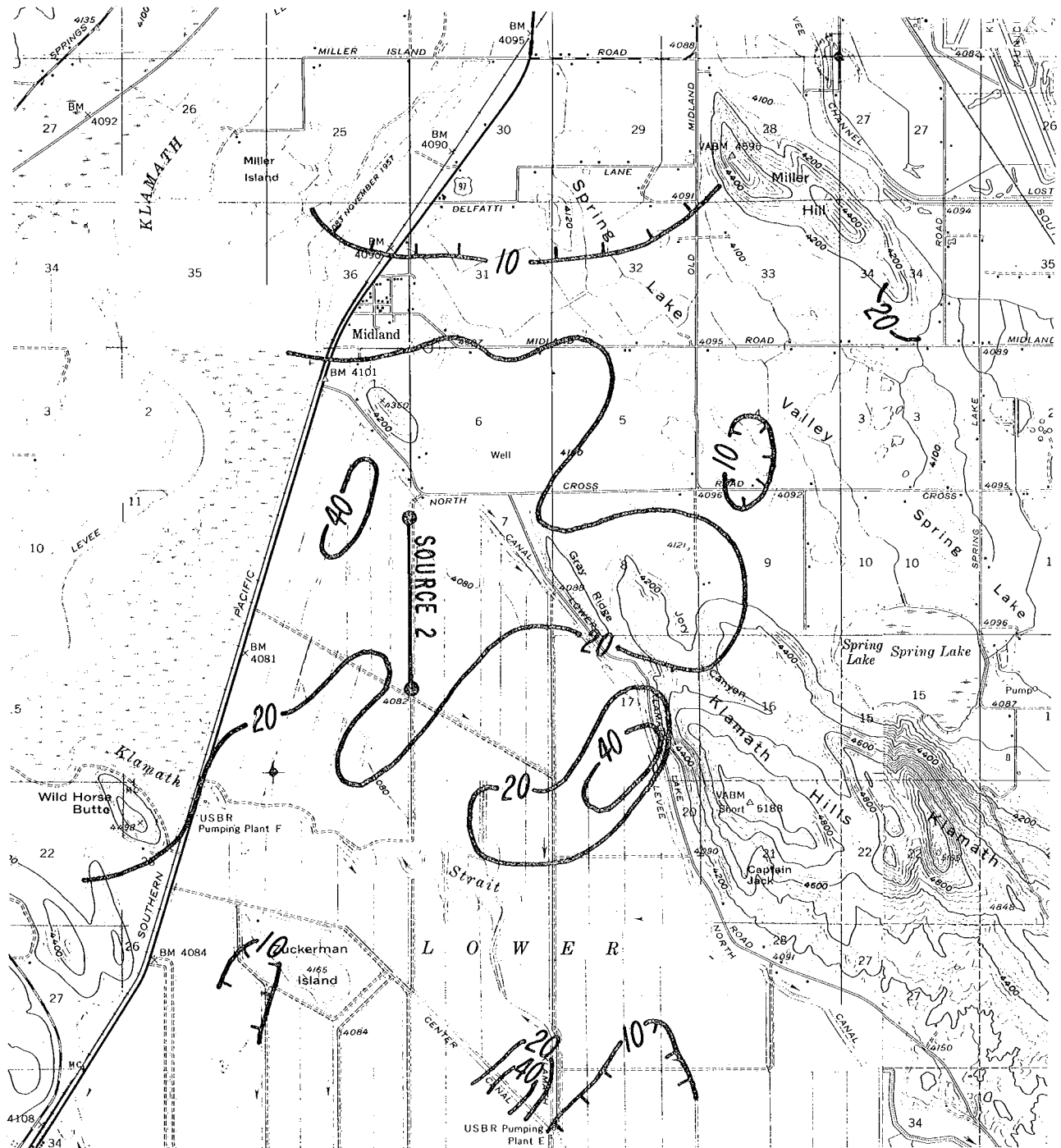


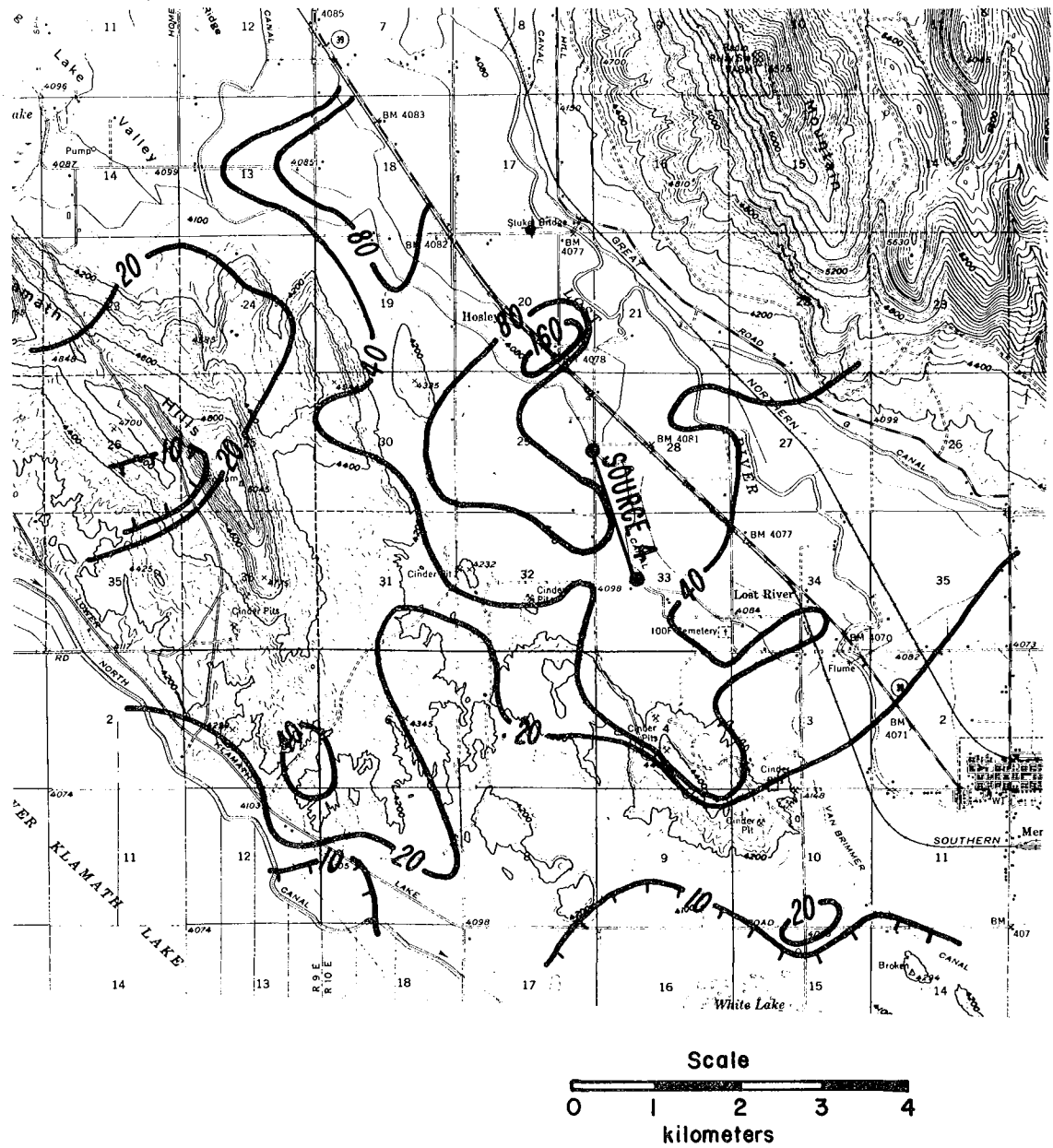
Fig. 31. Roving dipole apparent resistivity from Source 3, Klamath Hills area.

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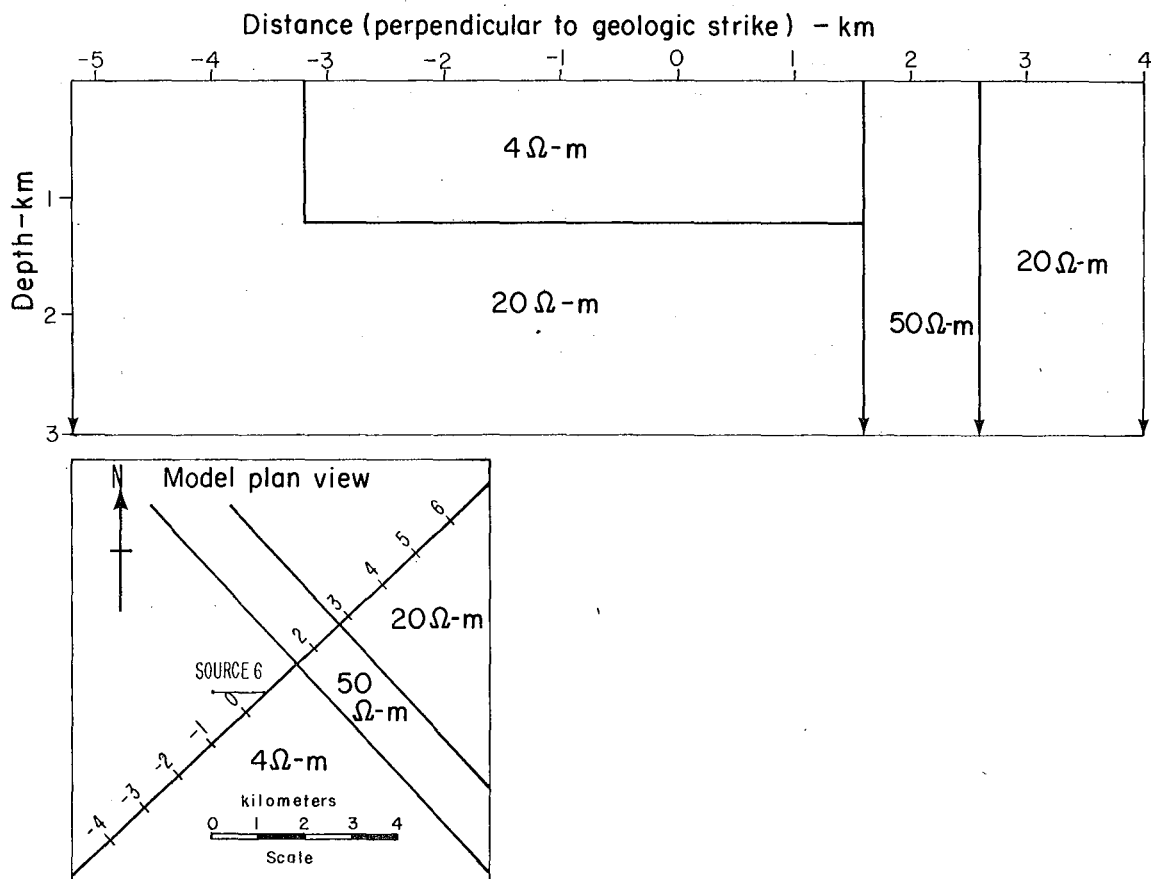
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Fig. 32. Roving dipole apparent resistivity from Source 2, Klamath Hills area.



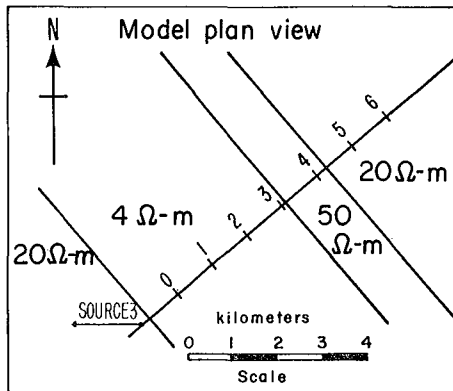
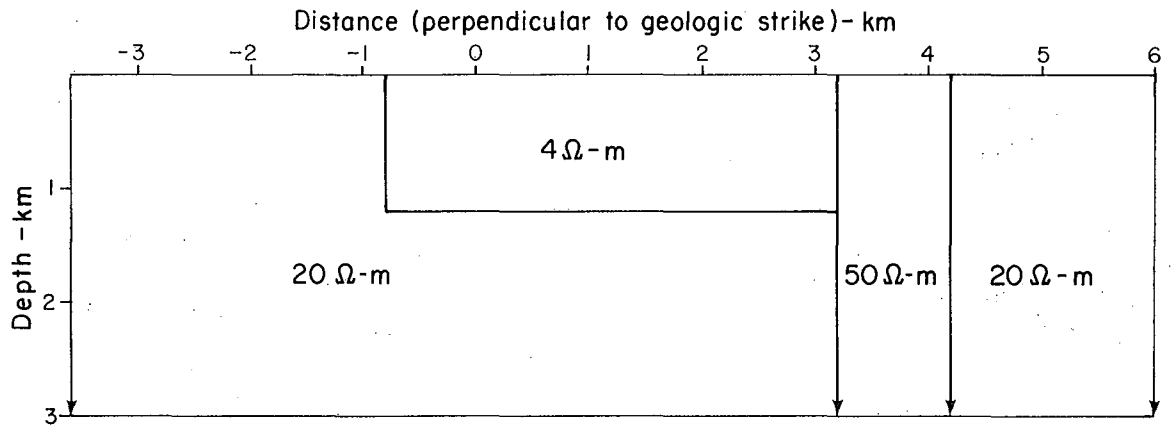
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Fig. 33. Roving dipole apparent resistivity from Source 4, Klamath Hills area.



XBL 7810-6522

Fig. 34. Resistivity model 62D.



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Fig. 35. Resistivity model 32D.

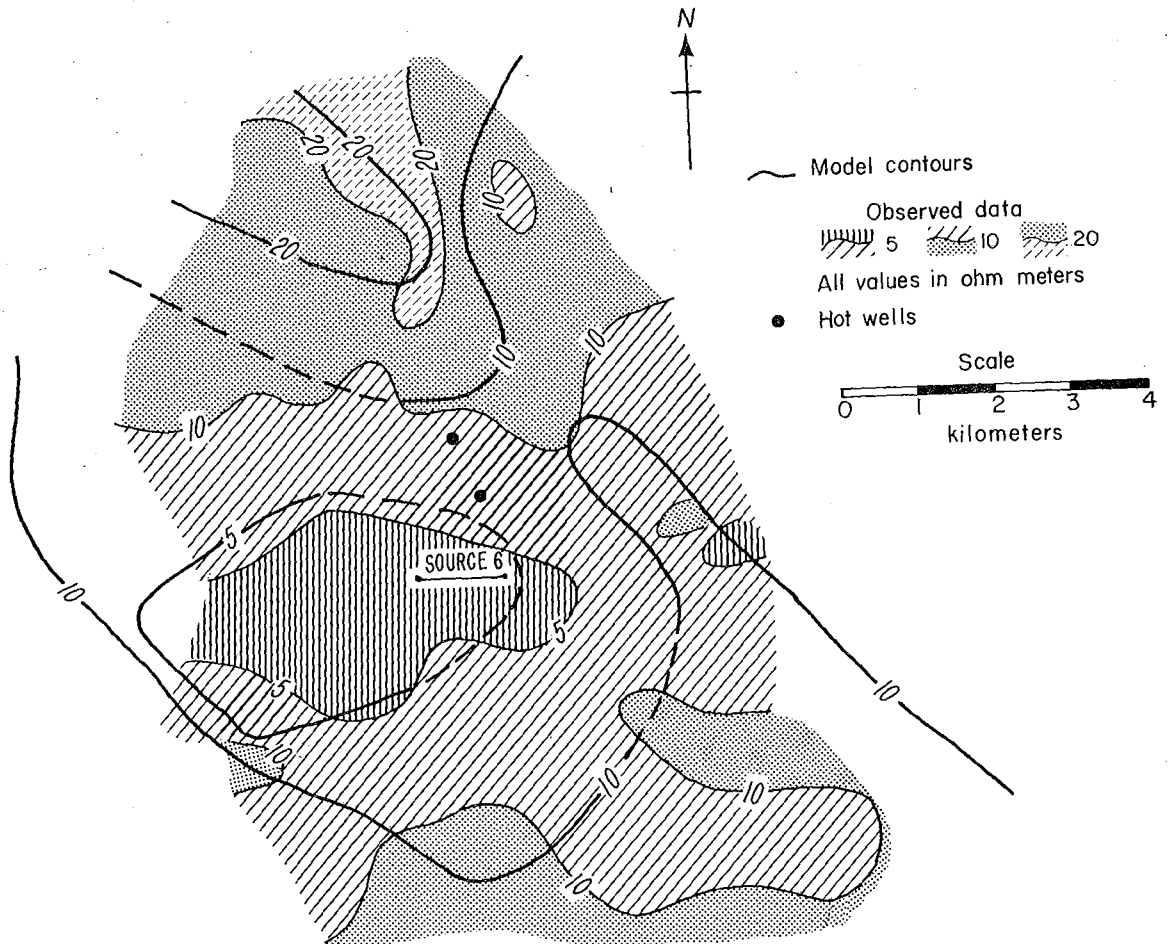
surface block stretching southwest from the Hills. Figures 36 and 37 show the fits of the calculated maps superimposed on the observed data. These are very general fits. The true electric structure is probably strongly three-dimensional, making a more accurate fit difficult to achieve. Nevertheless, the relationships among these models and their fits do provide insight into the electrical and geological structure.

The conductive zone in model 32D is 0.75 kilometer narrower than its counterpart in model 62D. This indicates that the zone is not infinitely long along strike, but is truncated somewhere to the northwest. The poorer fit of model 32D may be caused by the closer proximity of Source 3 to the truncation. The observed apparent resistivities northwest of the profile line are substantially higher than those to the southeast.

The data from Source 2 (Figure 32) appear to be consistent with these models, but the conductive zone is located near the southeastern edge of the area covered, rendering this correlation somewhat marginal.

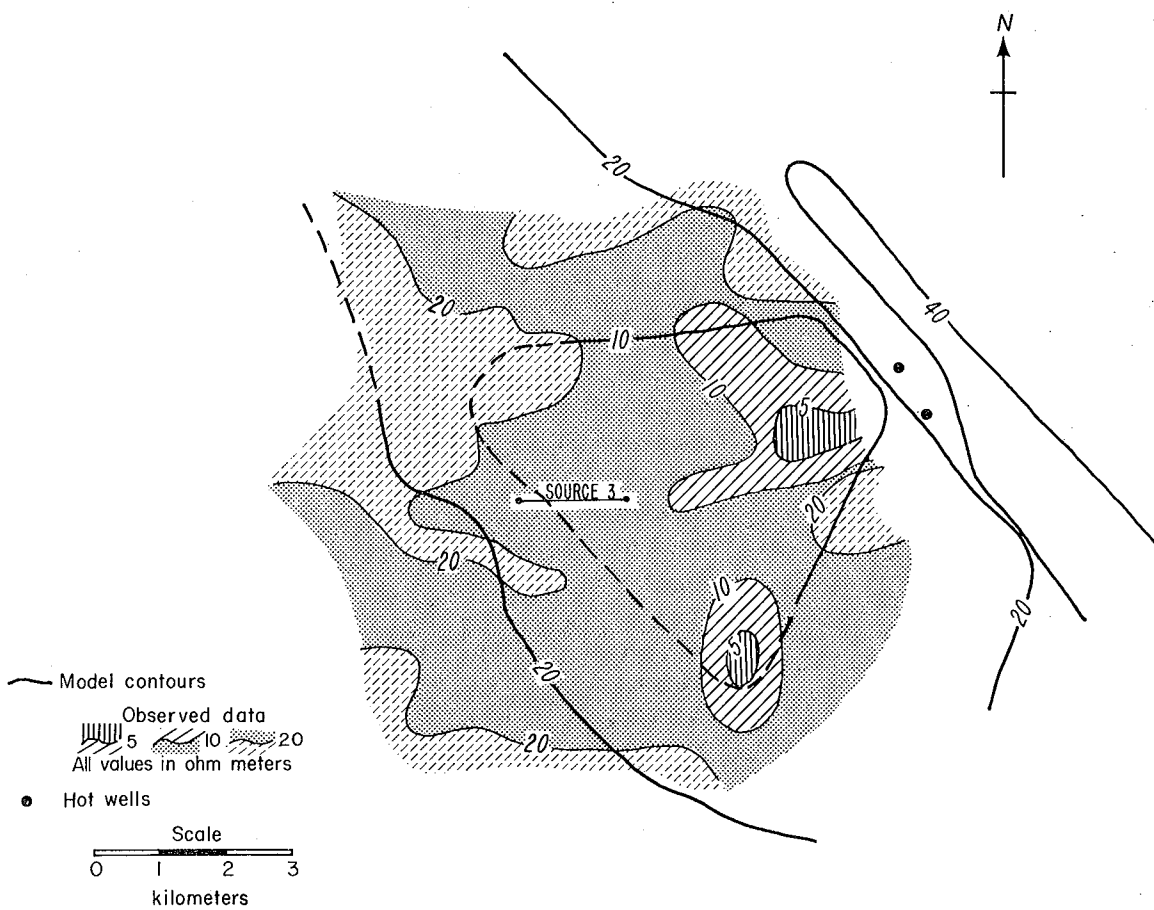
Source 4 (Figure 33) covers the Lost River-Spring Lake Valley and the Klamath Hills. The transmitting bipole was aligned in a northwesterly direction. The apparent resistivities in the immediate area around the bipole are quite high, while those in the Hills cover a broad range but are, in general, lower. The values in the valley far away from the source are also lower. Thus the valley seems to have higher resistivity near the source. This, again, may be related to a shallow northeast-trending basement ridge near Hosley.

The data from Source 4 near the southwestern edge of the Klamath Hills are also consistent with Models 62D and 32D. There are some high values near the edge of the Hills, corresponding to the resistive dike-like feature in the models. The few readings from Source 4 in Lower Klamath Lake are lower than those in the Hills. Again, this is marginal data and these correlations are rather weak.



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Fig. 36. Source 6 observed data vs. model 62D calculated data.



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Fig. 37. Source 3 observed data vs. model 32D calculated data.

### Direct Current and Electromagnetic Soundings

Figure 27 shows the locations of the five EM stations and the two dc electric sounding lines occupied by Group Seven (1972) in this area. Group Seven made layered-earth interpretations from these soundings and used them in conjunction with their roving dipole work.

The dc sounding lines extend east (DC3) and west (DC4) from bipole source 6. The interpretation of the data from DC4 indicates a conductive layer (5 ohm-meters) from the surface to a depth of at least 1500 meters. This agrees with our roving dipole model 62D (Figure 34).

DC3 yielded a more complicated interpretation, but the most important feature is a 3 ohm-meter layer between 40 meters and 430 meters depth, underlain by more resistant rock. Taken at face value, this suggests that the conductive layer in model 62D actually thins as it approaches the Hills. However, the layered-earth assumption is especially questionable here, because the DC3 line passes over a mapped fault (Figure 27), suggesting that some of the distortions and discontinuities of the sounding curve are due to lateral resistivity changes.

Similarly, the EM soundings require two-dimensional interpretation in the geologically complex environment of the Klamath Hills. Group Seven's one-dimensional inversions indicated very low surface resistivities extending to a few hundred meters depth, underlain by more resistive rock. These interpretations should be regarded with caution.

### Synthesis and Geological Interpretation

In the Lost River-Spring Lake Valley, we postulate one or more concealed northeast-trending faults crossing the valley northwest of Hosley. The southeast side of this structure is upthrown, resulting in a buried basement ridge trending between the Klamath Hills and Stukel Mountain beneath Hosley (Figure 27).

The roving dipole, gravity, and AMT data sets are all consistent with this interpretation. In particular, the AMT data suggest a fault running roughly from Olene Gap to Spring Lake. This may connect with the mapped north-trending fault between Spring Lake and the Hot Wells (Figure 27).

The gravity data indicate only 100 to 300 meters of alluvium overlying the inferred fault. Thus it is not surprising that the fault is detected at the lowest frequencies of the AMT survey. It is surprising, however, that the conductive zone appears at very high frequencies with skin depths of tens of meters. This may mean that the fault has displaced all but the most recent valley sediments.

The inferred fault trends perpendicular to the regional geologic strike, and should intersect several northwest-trending faults in its path. Obvious intersection points are at Olene Gap and off the northwestern tip of Stukel Mountain. Geothermal activity may be enhanced at fault intersections. For example, Figure 27 shows that two mapped faults intersect near the Hot Wells.

The tectonic role of this inferred fault is uncertain; it may act as a transform between sets of northwest-trending normal faults. If this is the case, left-lateral strike-slip may be an appreciable component of displacement along the fault. This is one place where a microearthquake study could be extremely useful.

On the southwest side of the Hills, the most important feature is the conductive zone near the Hot Wells. This may be the result of fluid ascending along the fault zone and spreading out into sediments underlying Lower Klamath Lake. The northwest-southeast extent of the zone is uncertain, but it seems to be truncated a few kilometers north of Source 6.

The 50 ohm-meter dike-like feature in the roving dipole models may represent an impermeable fault zone or a basaltic dike. Impermeable faults are not uncommon in the Klamath Basin; mylonitization and

silicification seem to cause this phenomenon. On the other hand, some fault zones are highly fractured and permeable (Leonard and Harris, 1974). Thus it is reasonable to interpret linear zones, whether conductive or resistive, as faults.

#### Geothermal Targets

We have presented evidence for two targets in the Klamath Hills area: the Hot Wells area and the inferred fault zone.

The Hot Wells area is an established geothermal resource, but the reservoir area is sharply truncated by faults to the east, and appears to be quite limited in areal extent. For example, the 5,800 foot hole drilled by Natomas (Figure 27) was essentially isothermal. We speculate that they drilled into the impermeable zone of model 6A, completely missing the zones of hydrothermal circulation. We recommend that future drilling be done on the southwest side of the fault. More detailed electrical resistivity work, such as dipole-dipole or EM soundings, is needed to determine reservoir extent.

Work is also needed in the Lost River-Spring Lake Valley, particularly around the inferred fault zone. At the northwestern tip of Stukel Mountain, there are several warm wells ranging in temperature up to 42°C (Sammel, 1976). However, the wells along the segment of the inferred fault zone between Stukel Mountain and Spring Lake do not, for the most part, exceed 20°C in temperature. This may mean that at the tip of Stukel Mountain, the extra permeability afforded by two intersecting faults has allowed increased geothermal circulation. This area also exhibits the lowest AMT apparent resistivities (Station 16, Figure 29). However, the specific electrical conductivity of the well waters here is only about one-tenth of the values measured in the Hot Wells (Sammel, 1976); both measurements were made at a water temperature of 25°C. Thus it comes as somewhat of a surprise that the true resistivities at a few hundred meters depth are probably in the range of 1 to 10 ohm-meters for both areas.

Archie's Law is useful to consider here:  $\rho_r = \rho_f \phi^{-n}$ , where  $\rho_r$  is the resistivity of the rock with its fluid,  $\rho_f$  is the resistivity of the fluid and  $\phi$  is the porosity;  $n$  is about 2 for most rocks. We know that  $\rho_r$  near station 16 is roughly 10 times  $\rho_f$  near the Hot Wells, even assuming that the fluid is the same temperature in both areas. This means that the rock at station 16 must be about 3 times more porous or that the fluid must be substantially hotter or more concentrated at depth for the apparent resistivity there to be nearly equal to that in the vicinity of the Hot Wells.

The generality of Archie's Law is somewhat questionable in these types of rock, but it is useful in providing a rough approximation of what can be expected below. In this case it indicates that at depth beneath the tip of Stukel Mountain the fluid is much warmer, contains a higher ionic concentration, or the rock is significantly more porous. A combination of these factors may be at work.

The first step in future exploration is to prove the existence of the fault and determine whether a temperature anomaly is evident. Gravity, passive seismic, dipole-dipole resistivity and shallow temperature gradient holes would be useful in this regard. Pumping tests should be performed in existing wells to estimate the permeabilities in these rock units, and to establish any relationship between warm wells in the conductive zone and those elsewhere along the inferred fault.

Another interesting structure is the north-trending fault between Spring Lake and the Hot Wells. There are a few warm wells in the Klamath Hills along this fault (Sammel, 1976). This fault may play an important role in the groundwater or hydrothermal circulation.

#### EVALUATION OF GEOPHYSICAL METHODS

In this study, we have examined and interpreted gravity, magnetic, moving dipole resistivity, electromagnetic, direct current resistivity,

AMT and MT data sets. A brief assessment of each method as a geothermal prospecting tool in the Klamath Basin follows:

1. Gravity and Magnetics: These methods seem suited for resolving structure, and are best used in conjunction with other techniques. They are useful for mapping faults and for helping to determine alluvium/sediment thickness in valleys.
2. Roving Dipole Resistivity: This can be a useful reconnaissance tool, but when used without other resistivity methods it is difficult to interpret in a meaningful, quantitative fashion. Computer modeling shows that the anomaly source may lie some distance from the anomaly, except for near-surface sources (Dey, 1976). Nonetheless, we see low apparent resistivity anomalies around the Klamath Falls "steamer zone" and the Klamath Hills Hot Wells. There is no theoretical or practical justification for averaging apparent resistivity values from multiple transmitters.
3. DC and EM Resistivity Soundings: From our limited examination of scanty data we can only conclude that one-dimensional interpretations are inadequate and misleading in this area. At least two-dimensional interpretations are needed, and this would require a greater station density than shown in the Klamath data.
4. AMT and MT: These methods offer perhaps more promise, but more headaches in interpretation, than the other techniques discussed. A major advantage of MT is that it often allows crustal modeling to depths of tens of kilometers. However, owing to local surface inhomogeneities and three-dimensional deep structure, it is rarely possible to satisfy both TE and TM data sets by means of a two-dimensional mode. Scalar AMT, as performed by the U.S. Geological Survey, or scalar MT surveys, normally have limited interpretational possibilities. However, in the Lost River-Spring Lake Valley, the scalar AMT data seem to reveal concealed structures.

## CONCLUSIONS

The Swan Lake Valley and Klamath Hills areas are small parts of the Klamath Basin geothermal system. They have contrasting hydrologic styles. Swan Lake Valley is a confined basin surrounded by highland recharge areas, while the Klamath Hills and Stukel Mountain are isolated mountain areas surrounded by large sediment-filled valleys.

Their geothermal circulation systems share similar characteristics. Both systems appear to be highly compartmentalized, with large changes in well-water temperatures over short distances. The faults play a controlling role, in some cases allowing upward transfer of heated water, in other cases posing as a barrier to horizontal circulation. Some junctions of two or more faults seem especially favored with geothermal activity. These observations lead to general guidelines for exploration. In each area, temperature variations in existing wells must be compared with fault locations and correlated with geophysical data where available.

The existence of a hotter, deeper reservoir is only a matter for speculation at this time. Sammel's (1976) geochemical evidence is not encouraging in this regard. His predicted reservoir temperature is about 130°C, based on several chemical geothermometers. There is little evidence to support or refute the existence of an anomalous heat source such as a magmatic or hot igneous body. We favor the concept of deep circulation along fault zones in a thinned continental crust as the heating mechanism, similar to systems described by Hose and Taylor (1974) in northern Nevada.

This is a progress report on an ongoing project. We have not finished studying the geophysical data in our hands, and more data should be forthcoming. We plan to continue our interpretations, expanding into other areas of the Klamath Basin where data are available.

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## APPENDIX

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