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GEOTHERMAL EXPLORATION ASSESSMENT AND INTERPRETATION UPPER KLAMATH LAKE AREA, KLAMATH BASIN, OREGON

Mitchel Stark, Norman E. Goldstein
and Harold A. Wollenberg

September 1980

Prepared for the U.S. Department of Energy
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ABSTRACT

Data from public and private sources on the Klamath Basin geothermal resource are reviewed, synthesized, and reinterpreted. In this, the second and final phase of the work, geological, remote sensing, geochemical, temperature gradient, gravity, aeromagnetic, and electrical resistivity data sets are examined. These data were derived from surveys concentrated on the east and west shores of Upper Klamath Lake.

The geological, remote sensing, and potential field data suggest a few northeast-trending discontinuities, which cross the regional northwesterly strike. The near-surface distribution of warm water appears to be related to the intersections of these lineaments and northwest-trending faults.

The groundwater geochemical data are reviewed and the various reservoir temperature estimates compared. Particular attention is given to specific electrical conductivities of waters as an interpretational aid to the subsurface resistivity results. A clear trend emerges in the Klamath Falls/Olene Gap area; hotter waters are associated with higher specific conductivities. In the Nuss Lake/Stukel Mountain area the opposite trend prevails, although the relationship is somewhat equivocal.

The electrical resistivity data include Schlumberger, dipole-dipole, electromagnetic, and roving dipole survey results. Two-dimensional computer modeling techniques are used to develop a subsurface picture of the west shore of the lake. Extensive conductive bodies of less than 25 ohm-m appear to underlie the entire west shore area at depths ranging from 1,200 to 10,000 ft. The top of the conductive zone is consistently shallower beneath the valley areas. The conductive bodies may represent conductive rock formations such as clay or altered tuffs, or may be the result of

saturation with hot geothermal brines.

The various geological, geochemical, and geophysical tools are evaluated on a site-specific basis. An integrated approach is recommended because joint interpretation of two or more spatially overlapping data sets provides more information than separate interpretation.

INTRODUCTION

The Klamath Basin, located in south-central Oregon and northern California (Fig. 1), has been a locus of geothermal exploration activities for many years. Interest in the basin has been stimulated by the presence of numerous hot springs and over 400 wells, ranging in depth from 90 to 1900 ft, and containing waters of 60 to 145°C. The resource is currently used for domestic, institutional, and business heating, as well as for a few agribusiness projects near the City of Klamath Falls. Three known geothermal resource areas (KGRAs) have been identified in the region (Fig. 2): (1) Klamath Falls KGRA north and northeast of the City of Klamath Falls; (2) Olene Gap KGRA southeast of the city; and (3) Klamath Hills KGRA south of the town. Direct use of the hot water has occurred primarily within the Klamath Falls KGRA, and currently the city government of Klamath Falls, with support from the U.S. Department of Energy and the State of Oregon, has embarked on a project to develop a district heating system for the city.

Outside the Klamath Falls KGRA, geothermal developers have performed rather extensive exploration, relying mainly on electrical and electromagnetic methods coupled with studies of the regional geology and water geochemistry. 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 declined in recent years.

Working with the State of Oregon's Department of Geology and Mineral Industries (DOGAMI) and the U.S. Geological Survey (USGS), the Geothermal Group at Lawrence Berkeley Laboratory's Earth Science Division has attempted to collect all available exploration data pertaining to the area. The

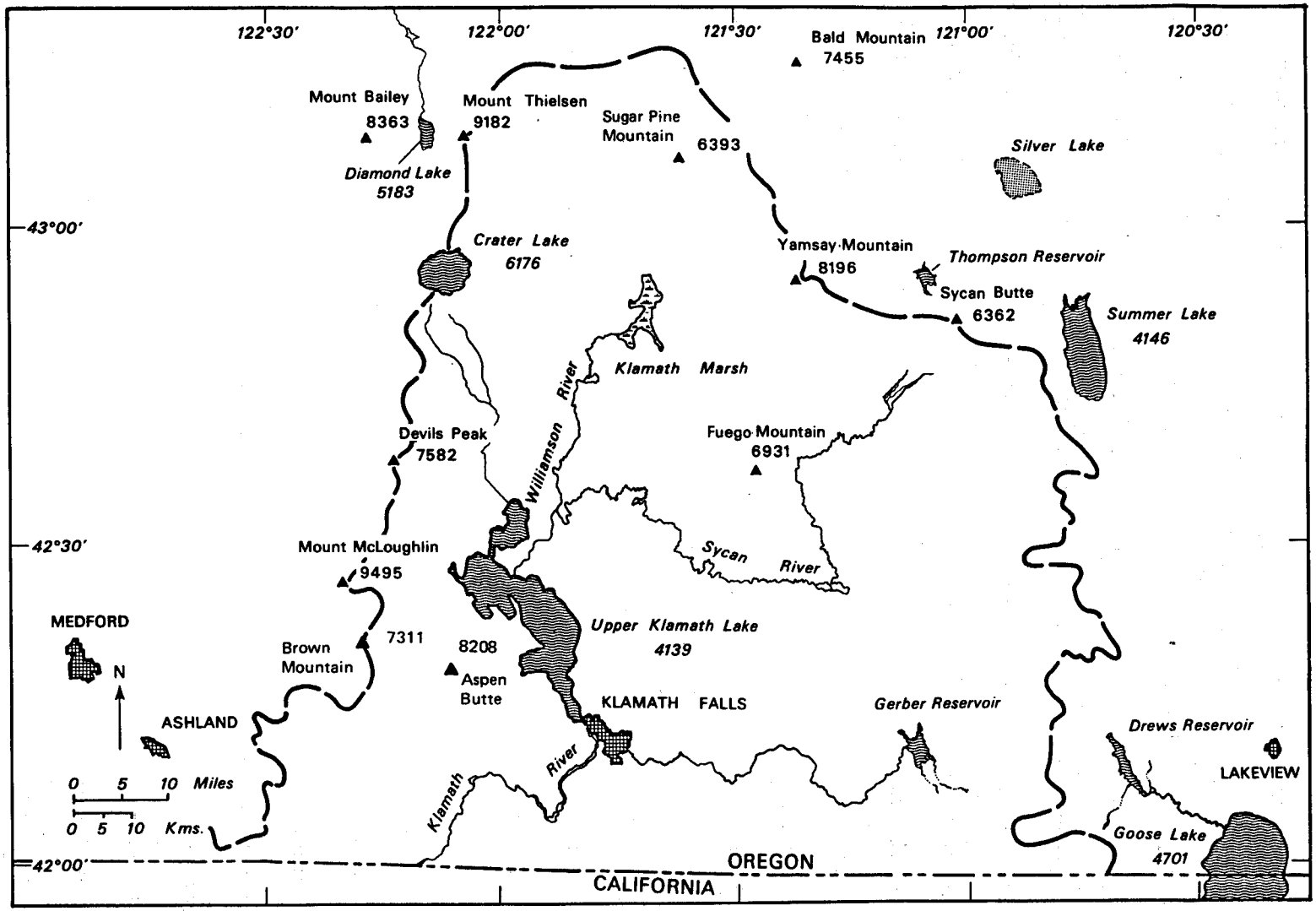

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Figure 1. Location map of the Klamath Basin, Oregon.

group has also compiled, assessed, and interpreted these data to develop conceptual models for geothermal reservoirs that might help guide future exploration in this area.

This report is the second and final in the series; the first (Stark, et al., 1979) was concerned with the Swan Lake Valley and the general area south of the City of Klamath Falls, including the Olene Gap and Klamath Hills KGRAs. This report concentrates on the remaining data, those from areas bordering Upper Klamath Lake (Fig. 2). For completeness we repeat some of the background information from the first report.

Data for this study have come from the open literature and from private companies who made their proprietary data available to LBL. The data base consists of over 100 documents, listed in Appendix 1.

GEOLOGIC SETTING

The geologic setting of the Klamath Basin 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.

Lithology

The stratigraphic section in Figure 3 shows the rock units recognized by Peterson and McIntyre. The basement rock consists of Pliocene basalts of undetermined thickness. These are unconformably overlain by the Pliocene Yonna Formation, a sequence of tuffaceous siltstones and sandstones, lacustrine sediments (largely diatomite), and basalt flows (Newcomb, 1958). The Yonna rocks are subaqueous deposits formed during

Known geothermal resources area boundary

Dipole-dipole and Schlumberger survey area (Harding-Lawson, 1974)

Schlumberger sounding and roving dipole survey area (Geoterrex, 1975)

Schlumberger, time domain electromagnetic, and roving dipole survey area (Argonaut, 1975)

Gravity and magnetics (VanDeusen, 1978) covers whole area

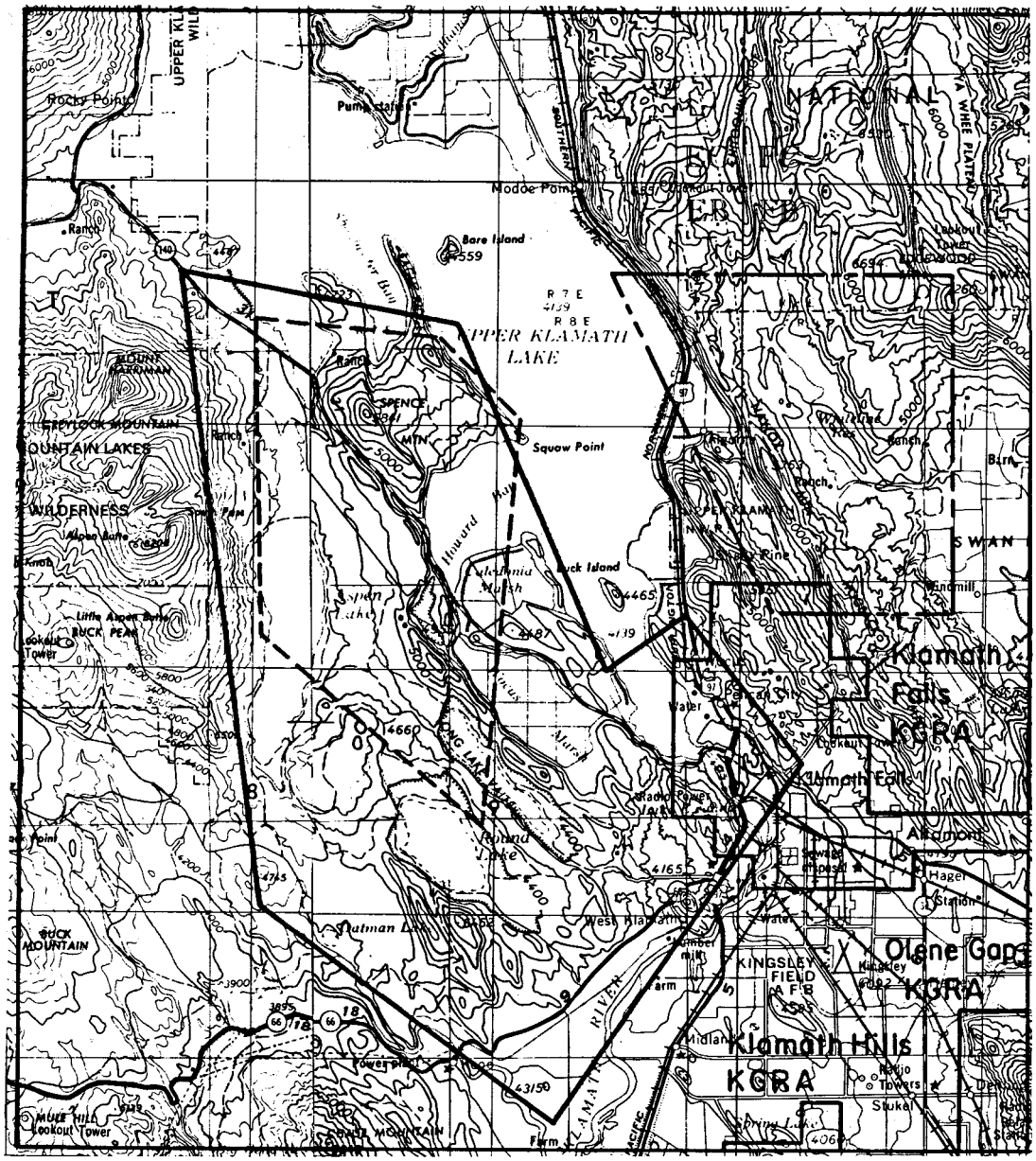

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Figure 2. Index map of geophysical survey areas.

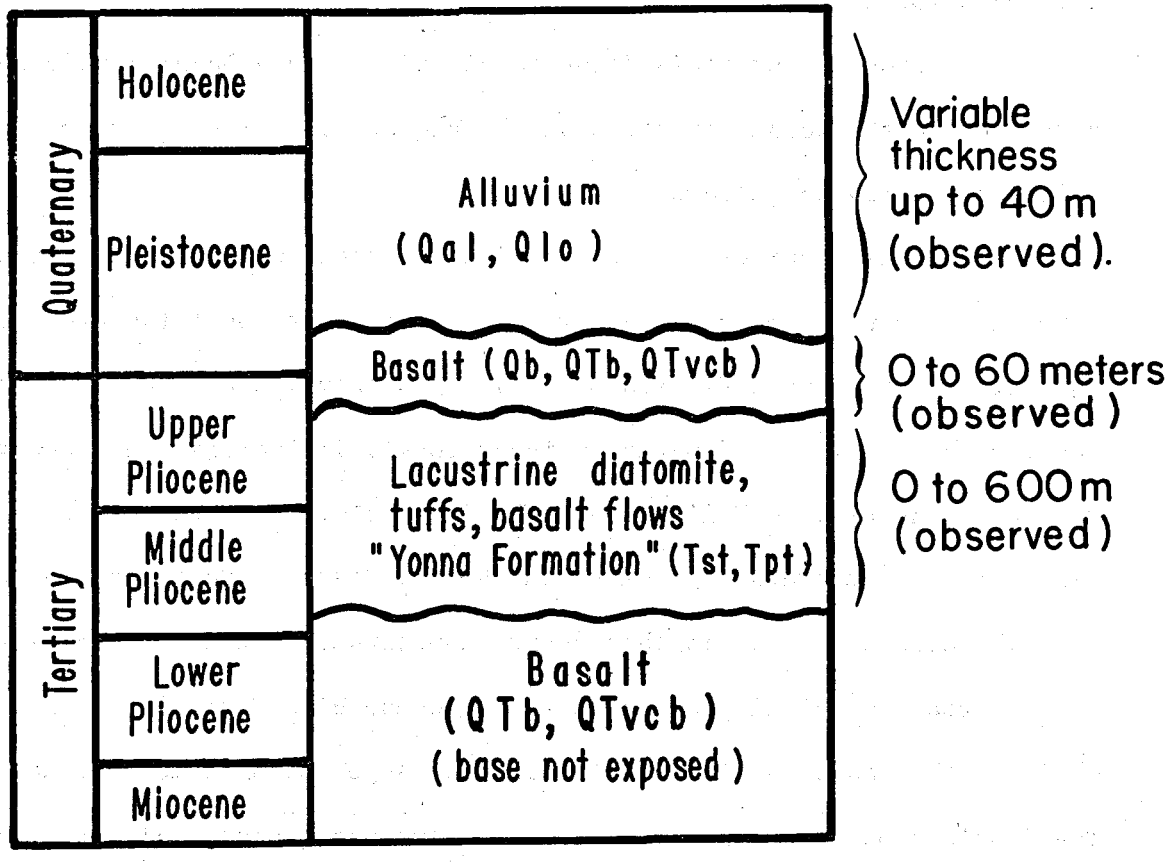

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Figure 3. Stratigraphic column for the Klamath Falls area (after Peterson and McIntyre, 1970).

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 m for the Yonna Formation.

Late Pliocene and Pleistocene basalt flows and volcaniclastic interbeds overlie the Yonna Formation at the higher elevations. Quaternary alluvium covers the valleys.

Groundwater aquifers exist in all these rock units, but the Yonna Formation includes impermeable strata, which act as confining beds for aquifers below. Upper Klamath Lake averages only 2.4 m in depth, but contains 7.2×10^8 m^3 of water, which strongly influences the groundwater regime in the Klamath Falls area. The lake water tends to obscure the near-surface temperature gradient in the immediate vicinity of the lake.

The area discussed in this report constitutes a transitional zone between two geological provinces, the Holocene High Cascade volcanic chain to the west, and the arid Basin and Range geomorphology to the east. The distinction is well expressed in the surface geology (Fig. 4). Thick andesite and basalt flows predominate in the Cascades, extruded from Quaternary volcanic centers such as Brown Mountain, Aspen Butte, and Mt. McLoughlin (Fig. 1). Some of the basaltic flows may have reached the Klamath Basin, appearing as the younger basalt unit in the stratigraphic column (Fig. 3).

The flows are mostly dense and hard, with fractured flows or scoriaceous tops serving as aquifers. No active volcanism has been reported, the most recent known eruption being the cataclysmic Mt. Mazama event about 6,700 years ago. The youngest volcano in the immediate area

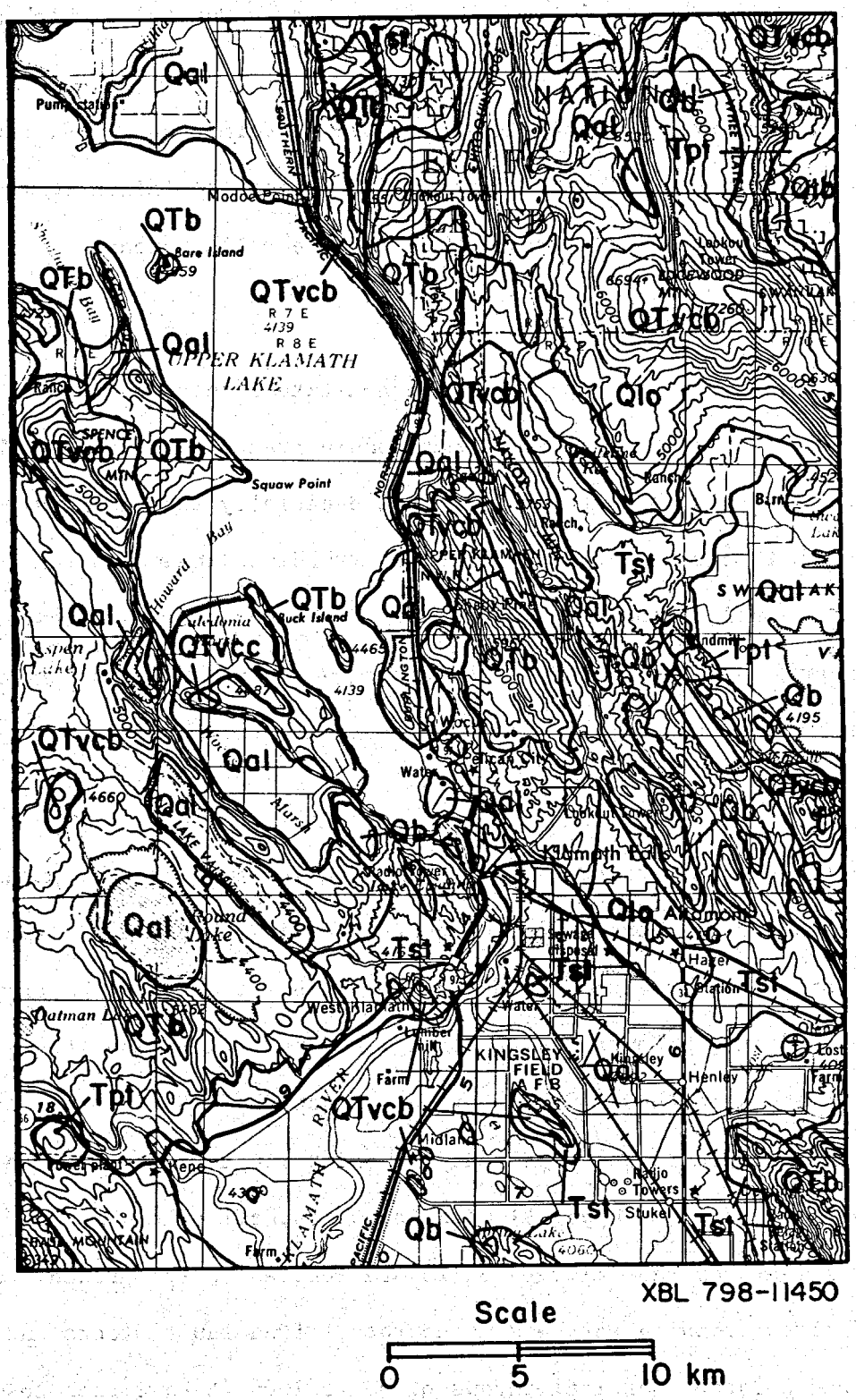

Figure 4. Surface lithologic map (after Peterson and McIntyre, 1970). See Figure 3 for description of rock units.

west of the Upper Klamath Lake appears to be Brown Mountain, which may have erupted in Holocene time.

The eastern area is characterized by Yonna Formation rocks, unconformably underlain (and possibly overlain) by basalts similar to those of the Cascades. Alluvial fill covers most of the valley areas.

Remote Sensing

We obtained four stereo-matched high-altitude infrared photographs, scale 1:125,000, of the central Klamath Basin area (EROS, 1979). They dramatically display structural features, especially the numerous northwest-trending fault scarps. Several northeast-trending lineaments can be discerned as well, although they are not as obvious as the northwest trending set; they are marked by tone changes and/or anomalous topography. The locations and meaning of these linaments are discussed below.

Structure

The structural setting of the Klamath Basin is somewhat typical of the Basin and Range geomorphic province. The Klamath graben is the predominant structural feature, trending N40°W and extending 80 km from the southern portions of Lower Klamath Lake to Crater Lake. The trend can also be followed another 100 km southeast, through Tule Lake and Alturas, California. Figures 5 and 6 present the major faults identified on the west and east shores of Upper Klamath Lake, respectively. Many of the smaller structural features near Klamath Falls are related to the graben. Numerous normal faults, trending northwest, separate tilted fault blocks and parasitic grabens and horsts. Vertical throws of up to 1600 ft have been observed on steeply dipping exposed fault scarps (e.g., Rattlesnake Point and Stukel Mountain). The historical record of earthquakes indicates that the area is still seismically active.

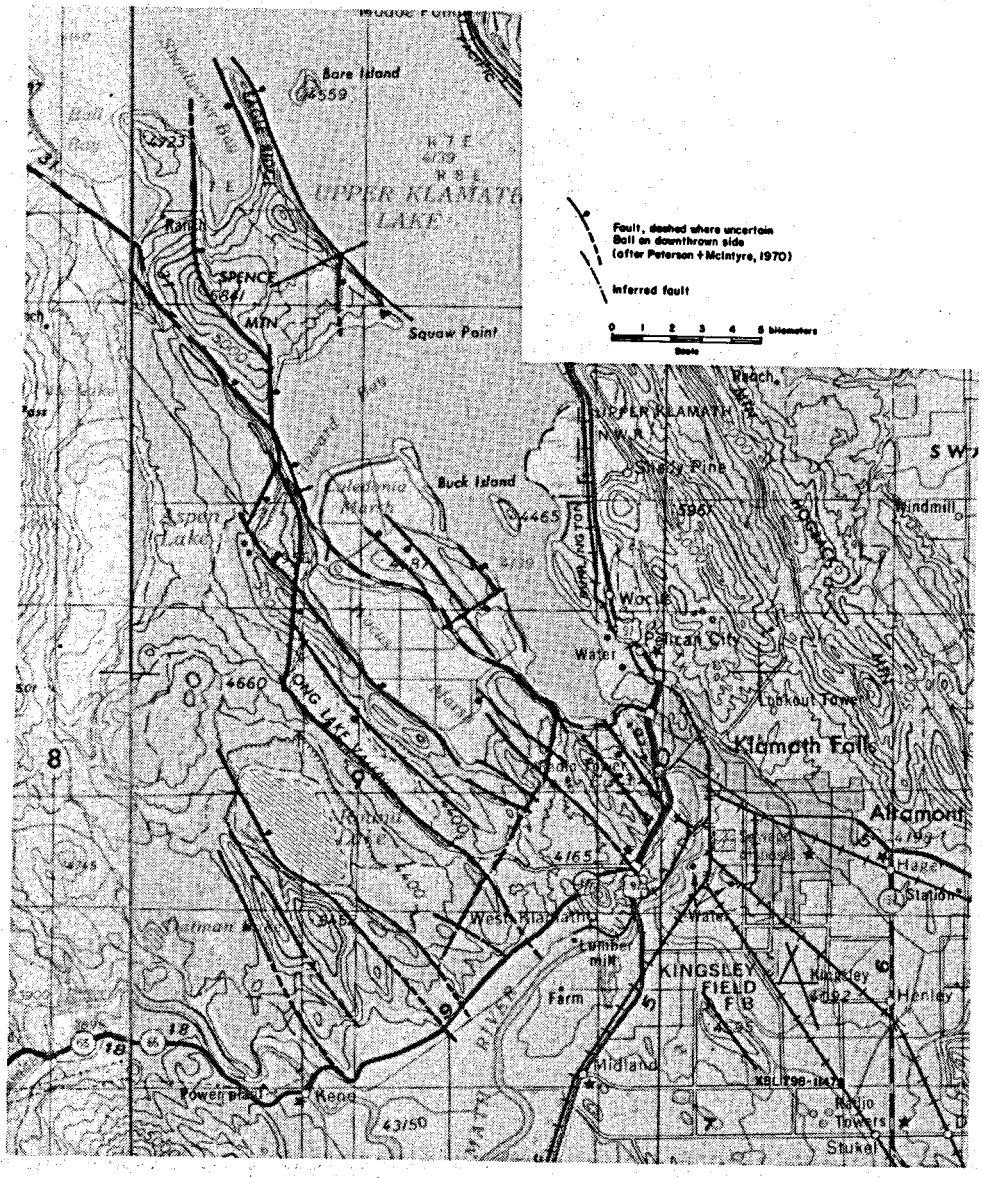

Figure 5. Locations of faults, west shore of Upper Klamath Lake.

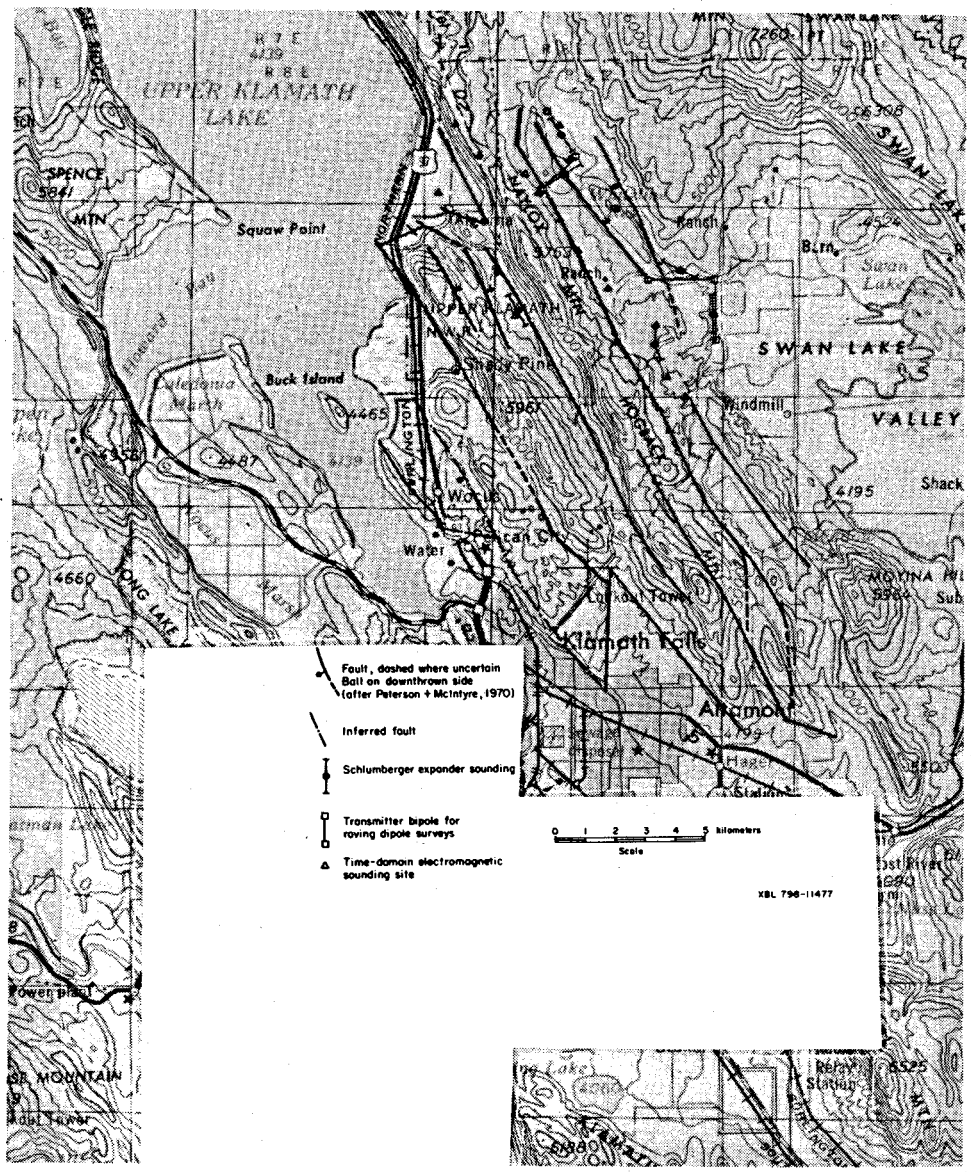

Figure 6. Locations of faults and electrical resistivity surveys, east shore of Upper Klamath Lake.

Most faults on the east shore of Upper Klamath Lake dip southwesterly, while those on the west shore dip northeasterly, suggesting that the axis of the graben passes through the lake. The fault pattern is made more complex by the presence of short north and northeast-trending cross-faults. Geophysical and remote sensing evidence has led us to infer longer northeast-trending cross-faults: one passing through Olene Gap and Spring Lake Valley (Stark et al., 1979), another northwest of the Klamath River and Lake Ewauma, and a third east of Klamath Falls. The latter two faults are discussed in this report and are shown in Figures 5 and 6.

There is a sharp bend in the graben trend from N40°W to almost due north, in the northern portion of Upper Klamath Lake. The bend is reflected in changes in the strike of faults and topographic "grain" at Spence Mountain, Eagle Ridge, Modoc Point, Chiloquin Ridge, and the Ya Whee Plateau Rim (Fig. 7). Spence Mountain is a particularly good example; the mountain peak is located at the intersection of the two trends.

The graben is also strongly distorted in the Klamath Falls area, but the distortion there is more complex. The flanks seem to neck together near the city; further south the graben opens up into a broader basin containing scattered horst blocks. Two of the above-mentioned northeast-trending faults are located south of the city. One runs south of Round Lake and Long Lake, ending near the southern tip of Upper Klamath Lake. The other crosses Spring Lake Valley, from the Klamath Hills past the northern tip of Stukel Mountain and on through Olene Gap. The graben appears to be offset along these faults in the right-lateral sense, its axis shifting from Upper Klamath Lake southwest to the Lower Klamath Lake Basin as depicted in Figure 7. This offset may be an expression of a

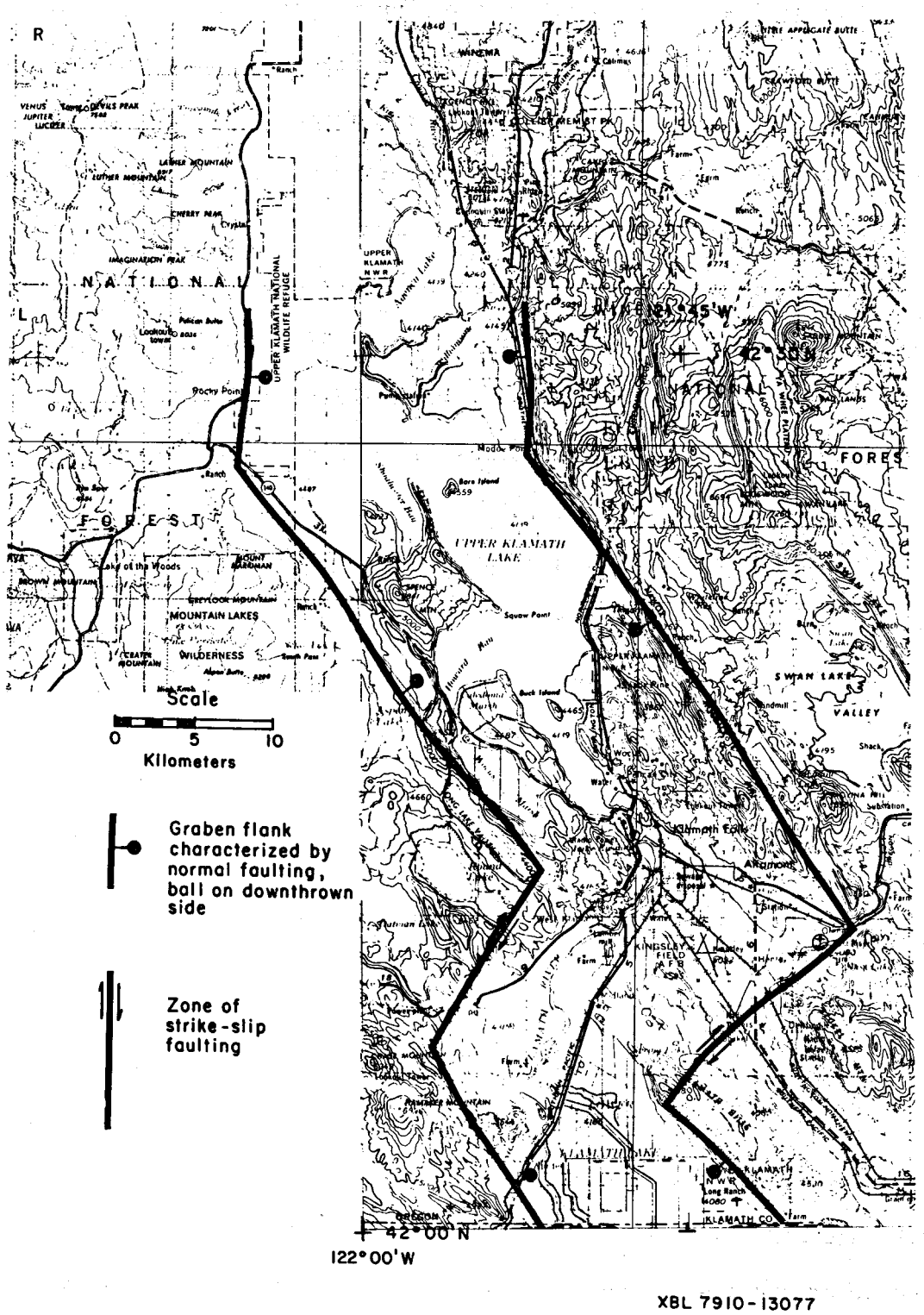

Figure 7. Schematic tectonic map of Klamath graben.

major northeast-trending discontinuity, which extends through southern Swan Lake Valley (Stark et al., 1979) and beyond. Within the Klamath graben, smaller components of left-lateral and dip-slip motion might be expected along these cross-faults, accomodating the strain caused by the graben offset.

This is at best a grossly oversimplified model of the graben. A glance at the topography in Figure 7 shows that the eastern boundary of the graben is difficult to identify. It is not clear whether Swan Lake Valley and the valley between the Klamath Hills and Stukel Mountain can be properly considered as part of the Klamath graben. On the western margin (Fig. 5), the northwest-trending normal faults seem to continue some distance into the Round Lake and Long Lake areas. These complications may be related to the "wrench-faulting" concepts used to explain features of continental rift zones.

No major faults are mapped in the High Cascades region west of Klamath Falls, although some of the normal faults in the graben extend a few kilometers into the mountains.

Geothermal Resources

The three KGRAs are shown in Figure 2. Klamath Falls KGRA encompasses the principal hot well area in the town and extends east-northeastward. A detailed description of the Klamath Falls geothermal setting is given by Lund et al. (1978). Hot water has been used by the residents, mainly for space heating, since the turn of the century. Presently, approximately 400 shallow wells, mostly 200 to 300 ft deep, are used to heat 500 structures. Water temperatures range up to 145°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.

Neither geophysics nor drilling have probed the deep geothermal system at Klamath Falls. For this reason, we have not investigated the area at length in our work. However, based on the extensive shallow geothermal manifestations, we feel that the urban area merits further exploration.

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 contains two hot wells (>90°C) and a few warm wells along the southwestern margin of the hills.

GROUNDWATER GEOCHEMISTRY

Extensive geochemical work was carried out by Geothermex for Weyerhaeuser (Appendix 2, File 72-11-27), and by the U.S. Geologic Survey (Sammel, 1976). Geothermex sampled 78 springs and 16 wells in an area of 26,000 km^2. Their work covered the entire Klamath Basin, as well as outlying areas in the Cascades, the Crater Lake area, and the Goose and Summer Lake valleys. The samples were analyzed for temperature, pH, and flow rate. Measurements for carbonate and bicarbonate ions were made in the field; calcium, magnesium, sodium, potasium, silica, chloride, bicarbonate, sulfate, boron, fluoride, bromide, and nitrate ion contents were determined in the laboratory.

Two principal water types were recognized by Geothermex: a cool bicarbonate water with low total dissolved solids (TDS) found mainly in the mountainous areas, and a warmer bicarbonate-chloride-sulfate water with higher TDS, more common in the structural basins. A few waters of

intermediate composition and temperature were sampled; presumably these are mixtures of the two types.

Geothermex estimated the equilibration temperature of the hot aquifer using SiO_2 and Na-K-Ca geothermometers, obtaining values of 120°C and 80 to 100°C, respectively. They also reasoned that the anomalously high values of SO_4 observed in the warmer waters could represent oxidized H_2S from a deeper steam reservoir. Such a steam reservoir would not affect the hot-water equilibria for the SiO_2 and Na-K-Ca geothermometers.

Sammel (1976) analyzed over 300 wells and springs, primarily in the Klamath and Lost River valleys and near Lower Klamath Lake. Temperature and specific electrical conductivity were measured at most wells and springs; also measured in wells were depth, water level, and discharge rate. Thirty-five waters were chemically analyzed for silica, calcium, magnesium, sodium, bicarbonate, carbonate, sulfate, chloride, fluoride, arsenic, boron, iron, lithium, and manganese. In addition, preexisting chemical data from another 22 wells were inventoried, making a total of 57 waters available for geochemical interpretation. Sammel made reservoir temperature estimates based on silica and Na:K equilibria. He also investigated the applicability of mixing models that account for dilution of geothermal fluids with groundwater, and examined the possibility of reservoir equilibration with more soluble forms of silica, such as chalcedony. He estimated a minimum reservoir temperature of 124 to 130°C, which is similar to the Geothermex estimates. He also felt that there is little mixing of groundwater with deeper hot water and that the maximum temperature in the hot-water aquifer is probably not substantially higher than 130°C. Sammel also considered the possibility of a deeper steam reservoir, using the same reasoning as the Geothermex workers.

Since the publication of these studies, a 1200-ft well has been

drilled in the Klamath Falls "steamer zone," with a reported bottom-hole temperature of 145°C (C. Goranson, oral commun.), which is 25°C hotter than measured in other wells in the basin. Temperatures as high as 120°C have been recorded previously in non-producing zones above the hot water aquifer, but water hotter than 113°C has not been produced. It is not yet known whether this new well can sustain production.

Specific Electrical Conductivity

Sammel (1976) measured the electrical conductivity of most of the well and spring waters, correcting the measurements in the field to 25°C to obtain specific conductivity data. This quantity, then, is not the the true conductivity of the water in situ, but is the estimated conductivity of the water if it were measured at 25°C.

These measurements were especially interesting to us as an aid to interpreting the resistivity survey data. Most rock materials are poor electrical conductors compared with the pore fluids they contain, so that, ignoring surface conduction effects, the minimum possible formation resistivity is close to the resistivity of its pore fluid.

We converted Sammel's specific conductivities (in μ ohm/cm) to specific resistivities (in ohm-m), and extrapolated to true fluid resistivity using empirical graphs by Keller and Frischknecht (1966, p. 19). That is, using these graphs we estimated the resistivities of the waters at their reported temperatures. The data from Klamath Falls, Altamont, and Olene Gap are plotted on log-log scale in Figure 8. There is an approximate straight-line trend here, although the data are severely clustered into two groups: hot conductive waters and cool resistive

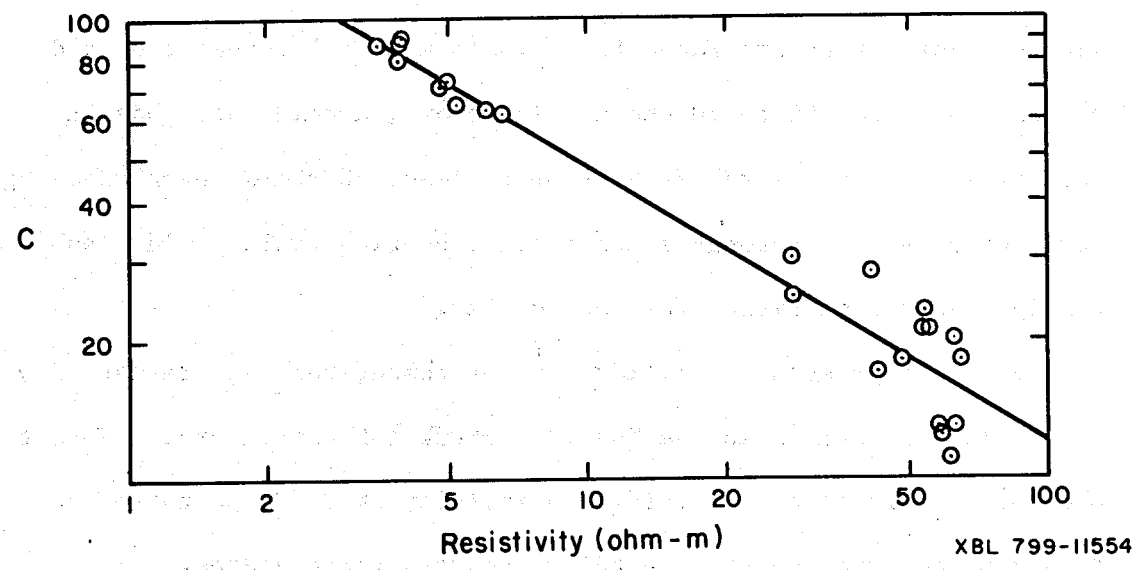

Figure 8. Resistivity vs temperature for Klamath Falls/Olene Gap waters.

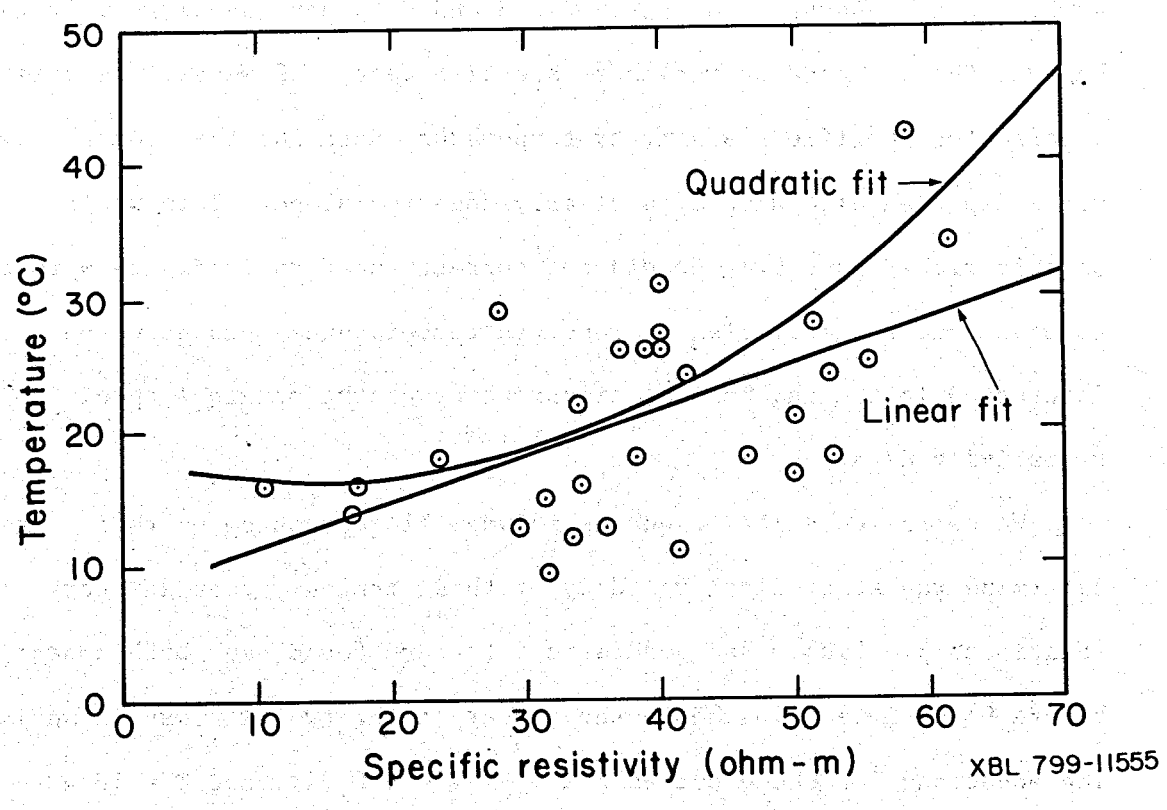

Figure 9. Specific resistivity vs temperature for Nuss Lake/Stukel Mountain waters.

waters. The hot waters range from 3.5 to almost 7 ohm-m; the cold waters range from 60 to 70 ohm-m. Therefore, a cold-water basalt aquifer should have a resistivity of at least 60 ohm-m, even assuming 100% porosity. A reasonable porosity assumption would yield a substantially higher resistivity for the aquifer.

Figure 9 presents a similar plot of temperature vs. resistivity for wells and springs in the Nuss Lake/Stukel Mountain area. Note that the abscissa is labeled specific resistivity at 25°C, so these values have not been recalculated to their reported temperatures.

The temperature-resistivity relationship here is less clear, but it appears to have a positive slope. This is just the opposite of what we found for the Klamath Falls/Olene Gap waters, and is contrary to what one would expect. Comparison of Figures 8 and 9 is not quantitatively valid because the independent variables are different. (However, the original uncorrected specific resistivity-temperature data for the Klamath Falls-Olene Gap area also display a clearly negative slope. This would be comparable with Figure 9.) We did not correct the data in Figure 9 to calculated true resistivities at reported temperatures because we became interested in the geochemical significance of the original specific resistivity data.

We performed a least squares polynomial regression on these data to determine the statistical validity of this seemingly contradictory relationship. Linear and quadratic fits were found, and both appear in Figure 9; an F test to choose the better of the two fits was inconclusive. The equations for these curves are $T = 7.71 + 0.34\rho$, and $T = 18.48 - 0.30\rho + 0.01\rho^2$. The parameter R^2, which represents the proportion of the variance about the mean explained by the regression, was calculated for

each fit; $R^2 = 0.78$ for the linear fit and $R^2 = 0.94$ for the quadratic. For the linear fit a Pearson correlation coefficient of 0.54 was obtained. These numbers indicate that the anomalous trend in the data is valid, but only marginally so. We are thus left to explain why the warmer waters in the Nuss Lake/Stukel Mountain area are more resistive than the cooler waters. In fact, the warmest waters plot at about 60 ohm-m, similar to the values observed for the coldest waters in Figure 8a, while the colder waters in Figure 9 are in the 10 to 20 ohm-m range.

Sammel (1976) noted the high conductivity of the cold groundwater in the Nuss Lake area, attributing this to long residence and cooling times in a warm, marshy environment. This would certainly explain the cold conductive waters. The warm resistive waters are more difficult to understand. We recommend making repeat measurements of some of the warmer waters, and new measurements on any unsampled waters before advancing an explanation for this phenonenon. Perhaps more detailed geochemical work could shed some light on the history of these waters.

In the light of these data, we must revise our earlier interpretations of an audio-magnetotelluric resistivity low discussed in our previous report (Stark et al., 1979). At that time we viewed the low as a possible indication of hydrothermal circulation related to a fault. Now we would allow that it is equally probable that the shallow low resistivity anomaly is caused by cooler but conductive groundwaters. Future prospectors in this area should heed these data. Electrical surveys, if used at all, should be designed to probe deeper than the conductive groundwater. It should also be borne in mind that the target may be relatively resistive.

GEOPHYSICAL STUDIES

Temperature Gradient Surveys

We examined two shallow-hole temperature gradient surveys in the basin. One was performed for Weyerhaueser (Appendix 2, File 74-3-9) in the Nuss Lake area, and contains no analysis or interpretation. The second was done for Thermal Power (1978) in the Klamath Hills. We did not attempt a reanalysis of these surveys.

Gravity

Van Deusen (1978) made a regional gravity survey, obtaining data at 465 stations over a 3000 km^2 area around Klamath Falls. Standard corrections were applied to produce free air and complete Bouguer gravity maps. Finally, a variable density reduction scheme was used to minimize correlation with topography. In this scheme, different Bouguer correction densities were assumed for volcanic and sedimentary areas. These were allowed to vary so that a computer program could find two densities that minimized correlation between topography and geology. A portion of the variable density map, covering the area of interest in this report, is reproduced in Figure 10.

A small high of about 3 mgal is associated with Spence Mountain, whereas the volcanic centers to the west in the Mountain Lakes Wilderness Area are characterized by a broad subregional low, with scattered local highs and lows over individual peaks.

Further south, in the pulp mill area, the gravity contours trend northeast, crossing the regional geologic strike. This local distortion may be related to a northeast-trending fault near the margin of the valley, as shown in Figures 6 and 7.

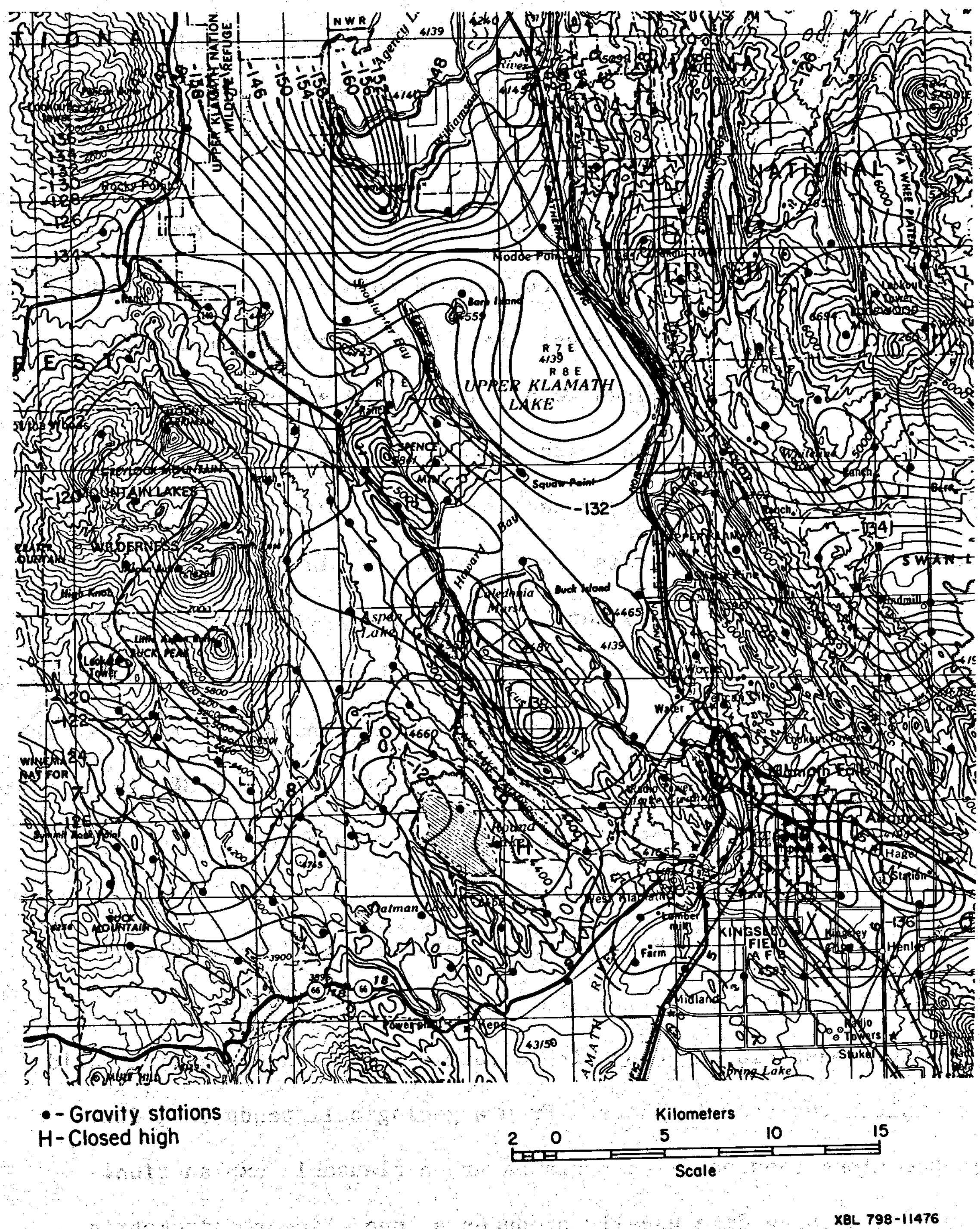

Figure 10. Alternate density Bouguer gravity anomaly, contour interval = 2 mgal (after Van Deusen, 1978).

The gravity contours follow the bend in structural and topographic trends noted in the preceding section on geology. This bend can be seen in the contours near Spence Mountain and Modoc Point.

Aeromagnetics

Van Deusen (1978) interpreted USGS aeromagnetic data (USGS, 1972 and 1973) for the Klamath Falls and Medford topographic sheets. These surveys were flown along east-west lines with an average line spacing of 3.2 km. North-south tie lines were spaced 50 km apart. Applying a variable continuation scheme to the data, Van Deusen constructed an aeromagnetic map to approximate data taken at a constant elevation above topography. A portion of this map is reproduced in Figure 11.

A large dipolar anomaly can be seen in the Spence Mountain area. The symmetric anomaly, 700 gammas peak-to-peak, is not easily explained by topographic or geologic effects. It is the signature of a thick dike or prismatic body with a net magnetization vector inclined 30° in an east-west direction (Vacquier et al., 1963) and buried about 1 km deep. How such a source could exist in this setting is not clear; some combination of remanent magnetism with subsequent tectonic rotation could be responsible.

A thin east-dipping body with strong remanent magnetization could also explain the anomaly shape. From a geological standpoint, dikes injected along tensional fault planes are a plausable explanation. However, a dipping dike usually produces a long, linear, asymmetric dipolar anomaly, quite different from the anomaly observed on Spence Mountain. A positive density contrast associated with either the dipping dike or the horizontally magnetized body could explain the small gravity high discussed above.

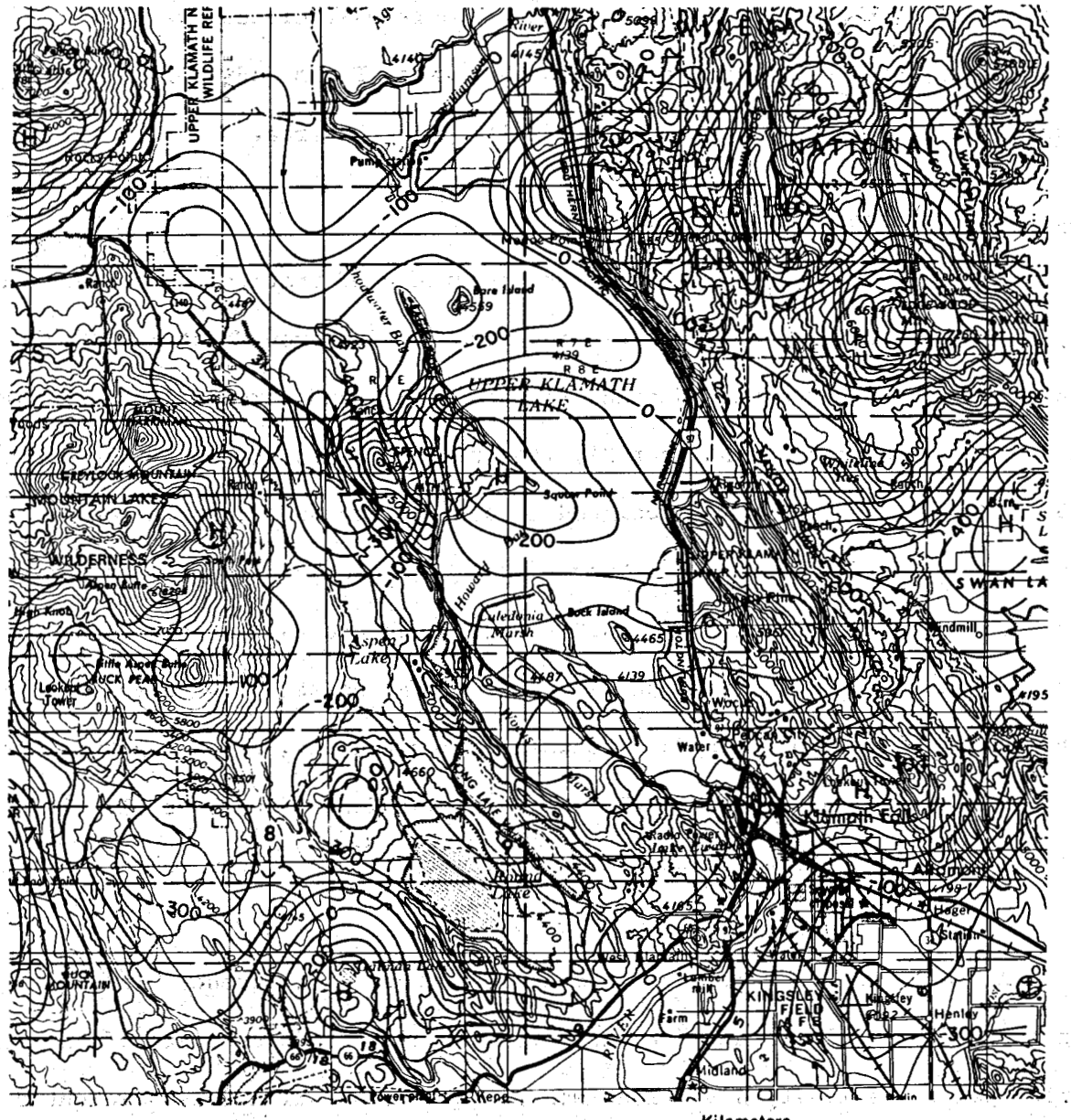

Figure 11. Total-intensity aero magnetic survey, variable--continued to constant elevation above topography, contour interval = 100 gammas (after Van Duesen, 1978).

Further south in the lumber mill area the magnetic contours are aligned, like the gravity contours, in the northeast direction. In fact, this trend can be followed through Klamath Falls and on into Swan Lake Valley, again suggesting cross-faulting in the area.

Regional Magnetotelluric Results

During September 1979, ten remote-reference MT stations were occupied by LBL researchers in a line extending from the Siskiyou Mountains (Cave Junction), across the Cascades and Klamath Basin, and terminating near the eastern edge of the basin, near Bly (Figure 12). With stations spaced 8 to 15 km apart, the survey was designed to provide regional information in support of the U.S. Geological Survey's High Cascade Program. Although good data were not obtained at the Provolt, Ruch and Ashland stations due to instrumental malfunctions and severe cultural noise, we were able to obtain reasonably reliable data between Parker and Bly, which together with the Swan Lake MT data between Klamath Falls and Yonna (Stark et al., 1979), permitted us to make a regional MT resistivity interpretation along a line 100 km in length.

At each station data were obtained for about 15 frequency windows in the .001 - .1 Hz band. For each station an averaged estimate of principal resisitivity directions was found. Each estimate is a weighted average of the principal directions of the impedance tensor in all of the frequency windows analyzed (Table 1). The impedance tensor for each station data set was then rotated into the appropriate direction and the resulting off-diagonal matrix elements, $Z_{xy}(\omega)$ and $Z_{yx}(\omega)$, were used to determine apparent resistivities $\rho_{xy}(\omega)$ and $\rho_{yx}(\omega)$ in the principal directions. However, this procedure leaves a 90° ambiguity as to the regional strike direction. Tipper strikes, based on the relationship

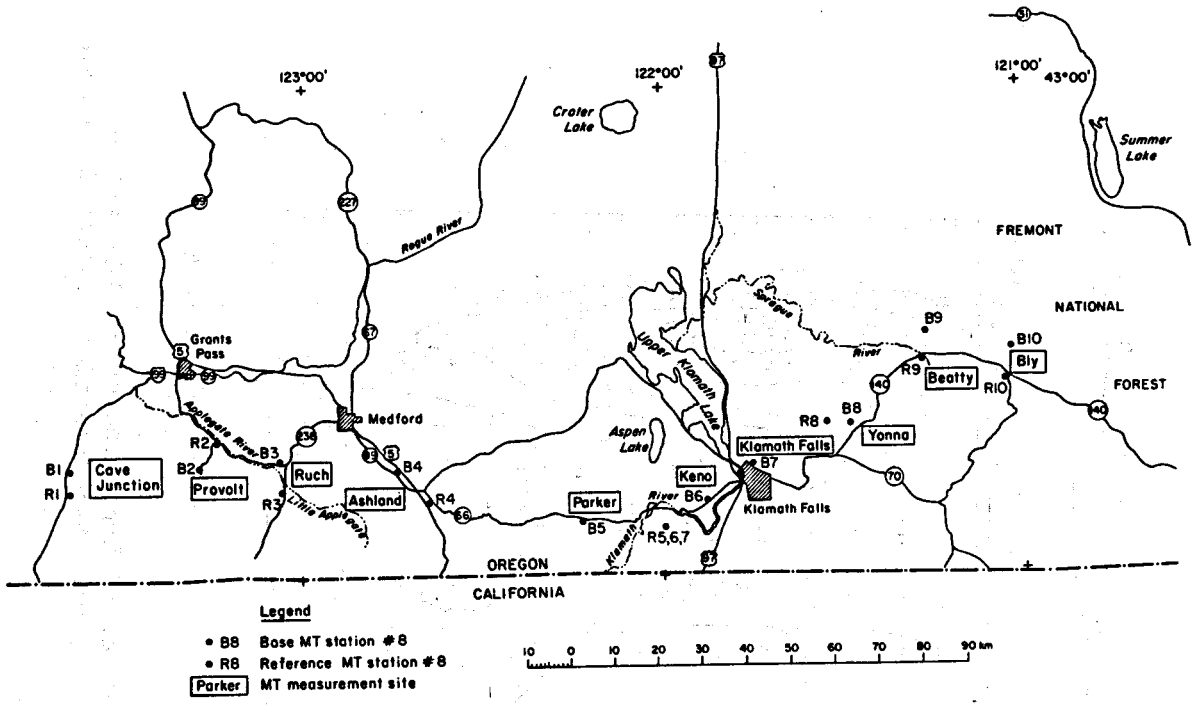

Figure 12. Magnetotelluric station location map.

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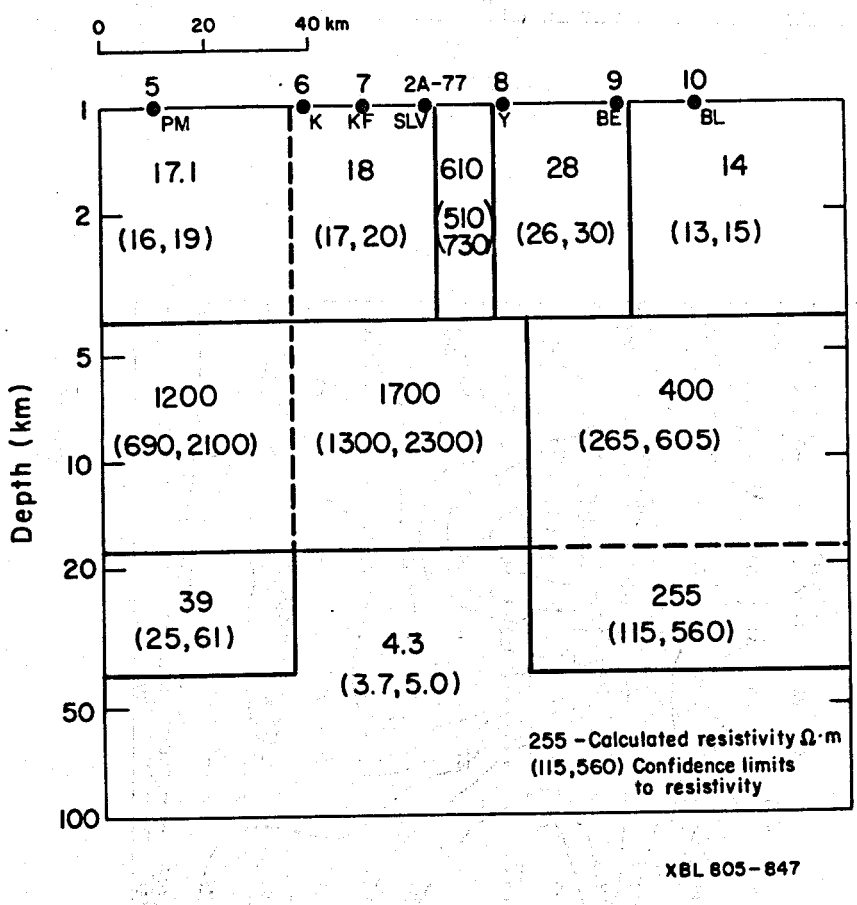

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Figure 13. Two-dimensional magnetotelluric resistivity model.

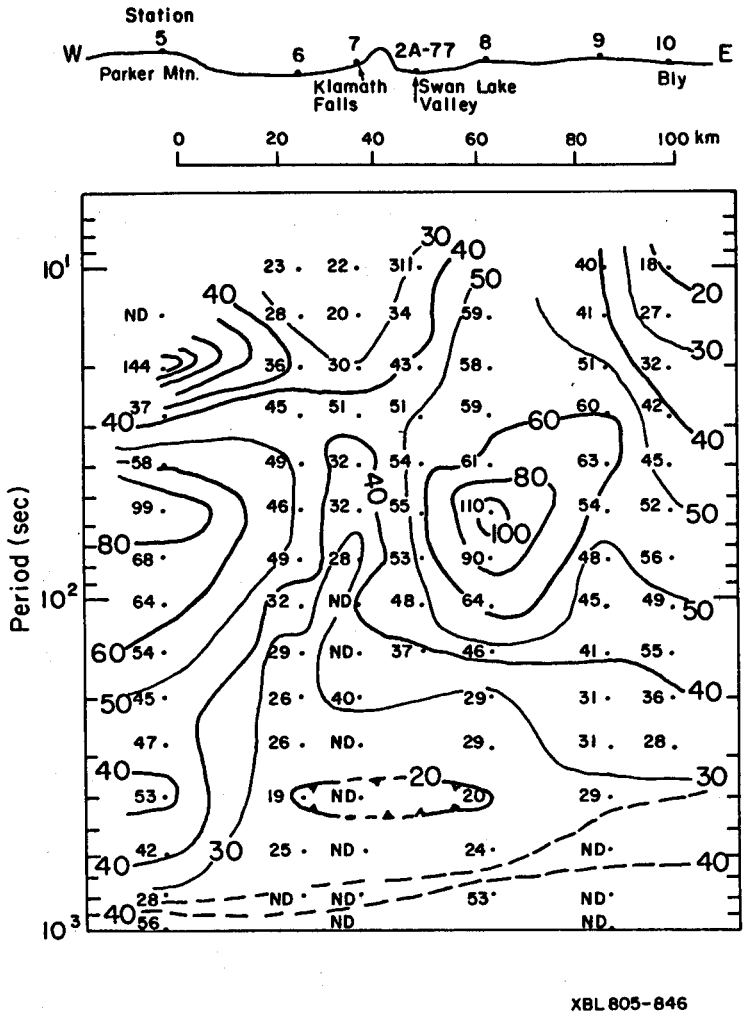

Figure 14a. Observed E-parallel apparent resistivity pseudosection, values in ohm-m.

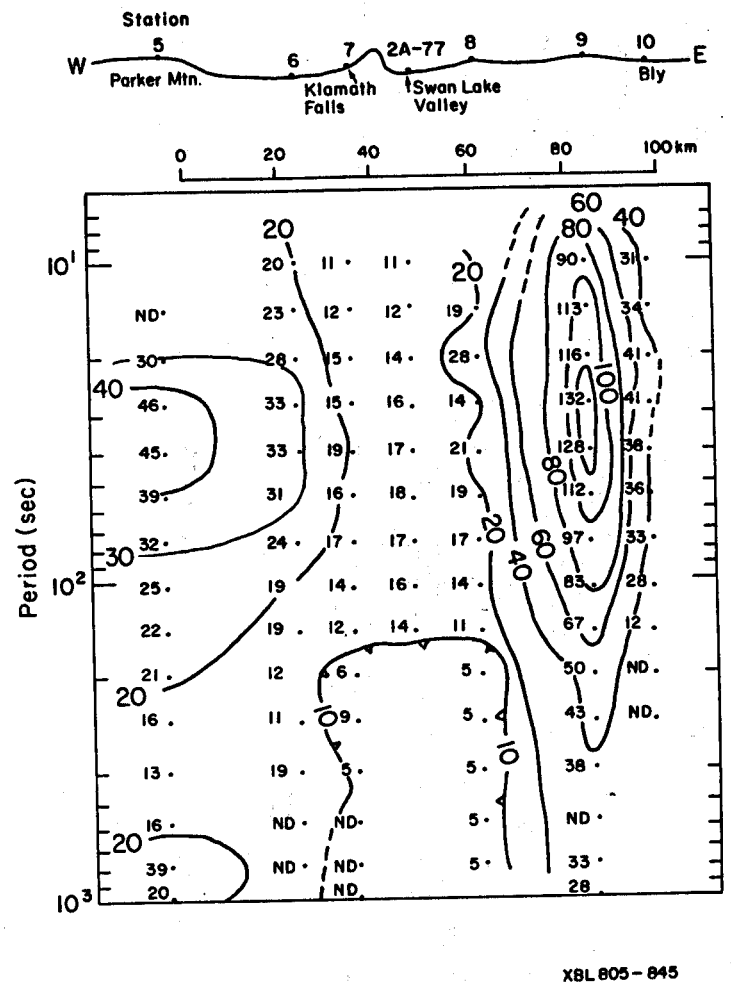

Figure 14b. Observed E-perpendicular apparent resistivity pseudosection, values in ohm-m.

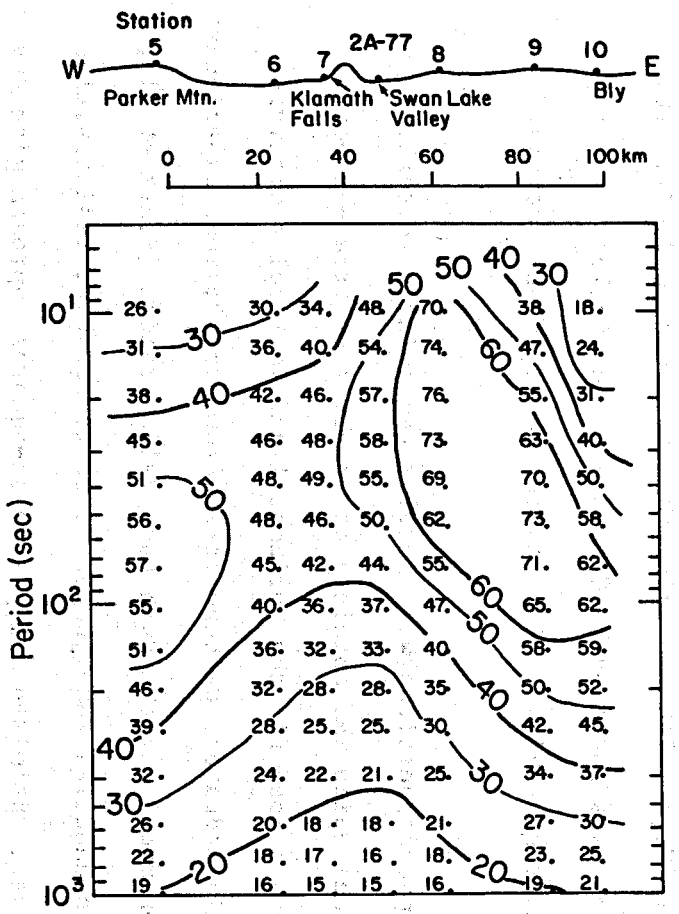

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Figure 15a. E-parallel apparent resistivity pseudosection calculated for two-dimensional model. Values in ohm-m.

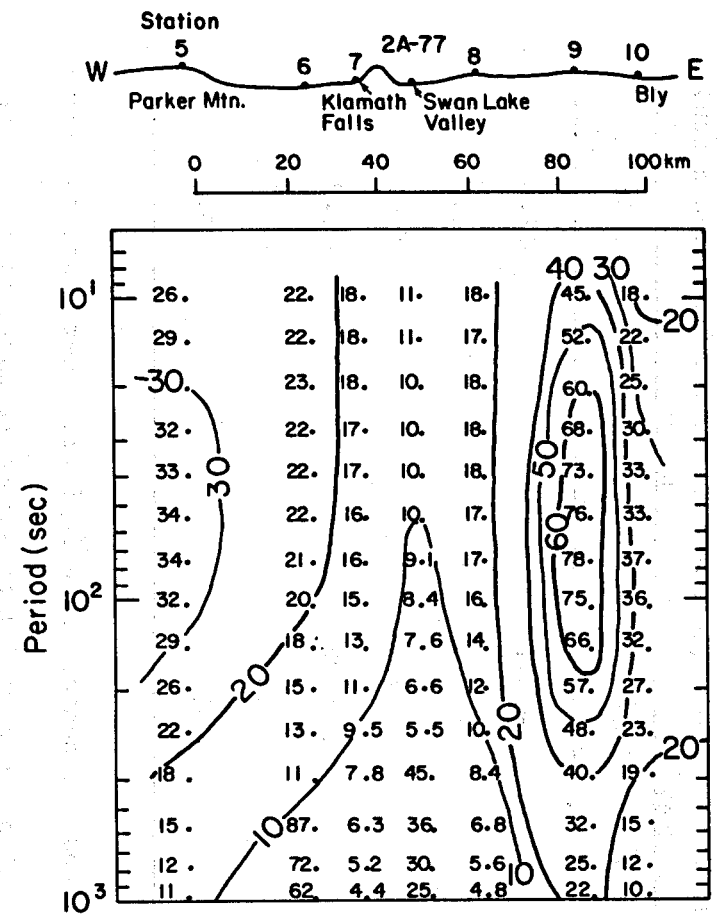

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Figure 15b. E-perpendicular apparent resistivity pseudosection calculated for two-dimensional model. Values in ohm-m.

Table 1. Average strike directions determined at the Klamath Falls magnetotelluric stations (measured clockwise from true north)

Station	Tensor Impedance Strike	Tipper Strike
Parker	-13.1	-28.6
Keno	- 2.9	-52.6
Klamath Falls	17.2	57.1
Yonna	18.6	- 2.2
Beatty	-18.0	-81.0
Bly	-18.2	- 5.5

between the vertical and horizontal magnetic fields, were used to choose which principal direction was parallel to strike (E-parallel or TE mode) and perpendicular to strike (E-perpendicular or TM mode). Figure 14 shows the pseudo-sections for both the observed E-parallel (Figure 14a) and E-perpendicular (Figure 14b) sounding curves. Station 2A-77, within the Swan Lake Valley, was obtained by Geonomics, Inc. in 1977. It gives consistent apparent resistivities with respect to adjacent stations 7 and 8.

The observed pseudo-sections were interpreted jointly in terms of a two-dimensional model which was obtained after numerous trial-and-error forward calculations helped fix the horizontal and vertical resistivity boundaries. In this endeavor, we benefitted from our previous experience in developing a 2-D model for the Swan Lake Valley region (Stark et al., 1979). After the boundaries were judged to be reasonable, resistivities within each block were optimized using a least-squares approach given by Jupp and Vozoff (1976). The resulting model is shown in Figure 13 and the calculated pseudosections for this model are shown in Figures 15a and b.

Comparing Figures 14a vs. 15a, and 14b vs. 15b, we see that the calculated psuedosections roughly match the observed data in general appearance, but the smaller details do not match. The problem here is that the area is not two-dimensional, as evidenced by the variability in geology and magnetotelluric strike directions. We also suspect that the area has been undersampled relative to the dimensions of lateral inhomogeneities. It is therefore problematical whether the additional effort needed to find better fits to the data would provide a commensurate improvement in subsurface information.

The gross resistivity structure indicated in Figure 13 agrees with contemporary ideas about crustal electrical properties. The near-surface conductive formations, the thick mid-crustal resistive unit and the deep conductor have been commonly interpreted from deep MT surveys (e.g. Stanley et al., 1977) and predicted from laboratory studies (e.g. Brace, 1971). A similar picture emerges from the long-spacing dc resistivity measurements reported for the Klamath Basin area by Cantwell and Orange (1965). Our MT model for the Swan Lake Valley area (Stark et al., 1979) shows the same features. The geologic meaning of our regional MT model (Figure 14) is discussed below in the Geologic Interpretation section.

ELECTRICAL RESISTIVITY SURVEYS

Figures 6 and 16 show the locations of the electrical resistivity surveys carried out on the east and west sides of Upper Klamath Lake, respectively. The data consist of the following surveys.

1. Twelve dipole-dipole lines and ten Schlumberger vertical electrical soundings were completed by Harding-Lawson Associates on the west side of the lake (Fig. 16) (Appendix 2, File 76-X-X-3). The dipole-dipole lines were laid out with unit spacings of 2000 ft and measurements

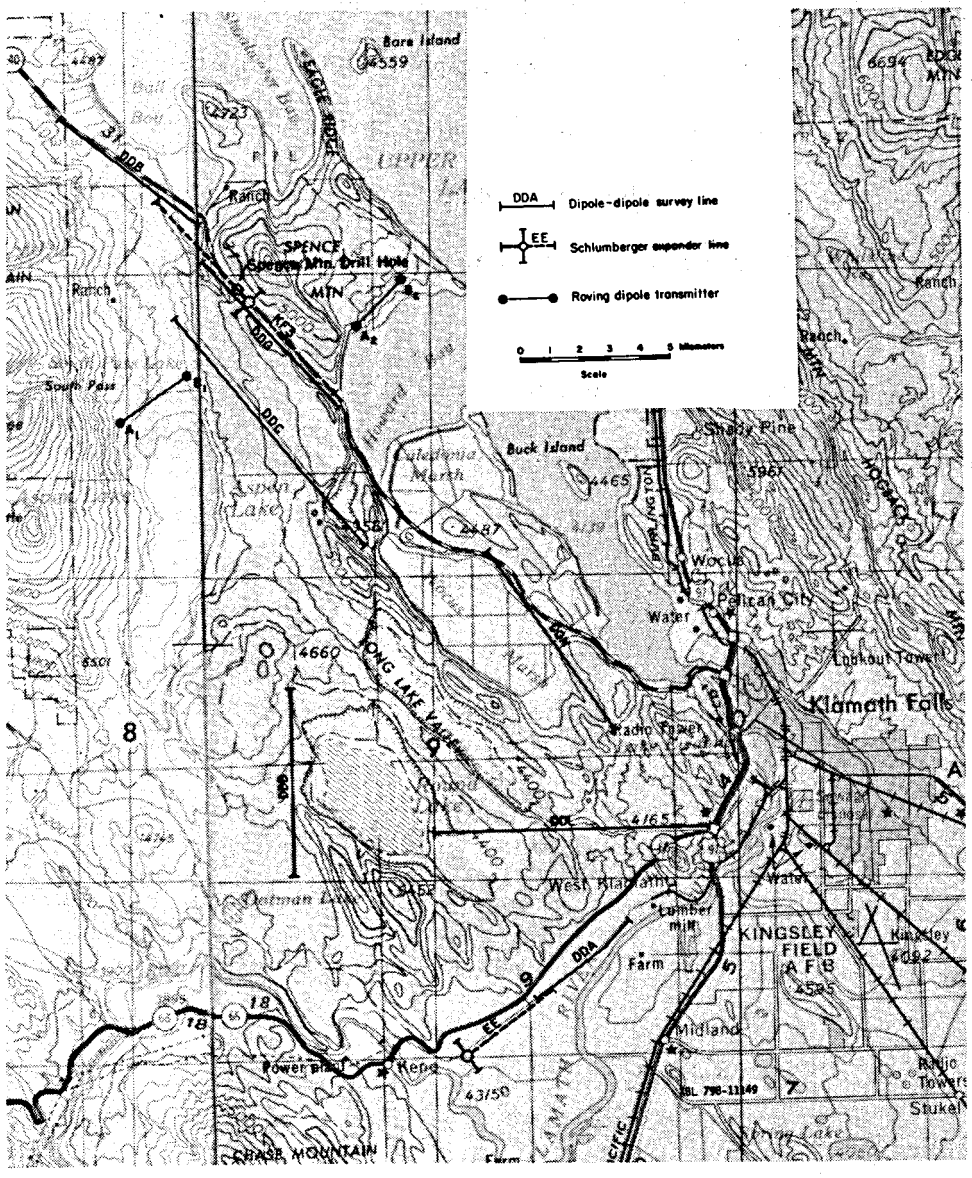

Figure 16. Location map of electrical resistivity surveys, west of Upper Klamath Lake.

were made with N spacings of up to 5 or 6. Total lengths of the lines ranged from 16,000 to 30,000 ft. The Schlumberger soundings were made by expanding the current electrodes in-line from AB/2 = 200 ft out to AB/2 = 2000 ft, with potential electrode spacings MN/2 of 40 to 100 ft. For deeper penetration, the soundings were further expanded in the equatorial array with AB/2 = 1600 ft, MN/2 ranging from 100 to 1000 ft, and the equatorial distance R ranging from 1000 ft up to a maximum separation of 8000 to 12,000 ft. Although the equatorial soundings were not expanded bilaterally, some of the unilateral soundings coincided with dipole-dipole lines. This provides some insight into the effects of lateral resistivity changes.

2. A two-source roving dipole survey and three Schlumberger soundings were carried out by Geoterrex, Ltd., on the west side of the lake (Appendix 2, File 76-X-X-3). Geoterrex placed their 2.5-km transmitter bipoles near the northern end of Aspen Lake and along Squaw Point (Fig. 16). Data were taken at 110 potential dipole sites in directions both parallel and perpendicular to the transmitters. The locations of the Schlumberger soundings also appear in Figure 16. All of these were done in the equatorial configuration with R spacings from 10 to 8000 m. At the larger spacings the soundings were made bilaterally as a check for lateral resistivity variations. The equatorial soundings were interpreted by using Dar Zarrouk curves (Zohdy, 1974) and an automatic inversion scheme to yield layered resistivity models.

3. A two-source roving dipole survey, 7 Schlumberger soundings, and 19 time-domain electromagnetic soundings were completed by Robert Furgerson (Appendix 2, File 76-X-X-3) on the east side of the lake (Fig. 6). Furgerson's roving dipole survey was conducted with two orthogonal transmitter bipoles at each source location. The two sources were

located near the northwestern corner of Swan Lake Valley, and in the Antelope Valley area, and each leg of the L-shaped configuration was over 1 mile long. This "rotating source" array allows some depth discrimation, because the depth of exploration is larger for a receiver located in an equatorial positon relative to the source than for a receiver positioned in-line, source-receiver distance being equal. Data were taken at about 100 L-shaped receiver sites, and a qualitative interpretation was made by the contractor.

Schlumberger soundings SEA 1, 2, 3, and 4 were expanded out from the centers of the transmitter dipoles (Fig. 6). Roving dipole data from equatorial receivers could then be converted into bilateral Schlumberger equatorial data for these soundings, out to a maximum value of R = 27,000 ft. SEA 5 was expanded in the standard Schlumberger array from AB/2 = 100 to 2000 ft. The same procedure was used in SEA 6 and 7, but the soundings were further expanded equatorially out to R values over 10,000 ft. SEA 7 was expanded bilaterally.

The standard Schlumberger portions of the soundings (out to AB/2 = 2000 ft) were converted into layered-earth resistivity models by means of an inversion scheme. The bilateral portions of the soundings were not similar enough to allow one-dimensional interpretation. SEA 5 was interpreted by means of a graphical method which assumes a nearby dipping resistivity boundary. This was deemed necessary because of the proximity of the sounding to a mapped fault at the base of Naylox Mountain (Fig. 6).

Furgerson also completed 19 time-domain EM soundings in the area and interpreted them by means of a complicated curve-matching scheme. The interpretation was based on a two-layered earth assumption, and resulted in an estimate of the resistivity of the half-space beneath the first layer at each site.

Spence Mountain Area

We attempted a fairly extensive reinterpretation of the data from the west side of Klamath Lake, particularly those from the vicinity of Weyerhaeuser's 2000-ft test well near Spence Mountain (Figure 16).

The volcanic centers of the Mountain Lakes Wilderness lie west of the site; to the northeast warm springs occur at Eagle Point. One speculation was that heated water might be flowing down from the Mountain Lakes area and emerging at Eagle Point, and a drill hole near Spence Mountain was planned to test this hypothesis and to gain stratigraphic information.

Before drilling, both Harding-Lawson (Appendix 2, File 74-2-12) and Geoterrex (Appendix 2, File 75-2-14) were contracted to carry out electrical surveys in this area. Harding-Lawson's dipole-dipole pseudosection DDG and Geoterrex's Schlumberger sounding KF3 are shown in Figures 17a and 18. In Figure 18 we have plotted only the data corresponding to R spacings over 800 m, even though data were taken at electrode spacings as small as 100 m. This was because we were primarily interested in modeling the deeper structure.

These data obviously suggest the presence of a conductive body at depth. Geoterrex interpreted sounding KF3 by means of a one-dimensional automatic inversion scheme. The most important feature of their final model is a sharp drop in resistivity from 1900 to 3.2 ohm-m at a depth of about 1500 ft. The calculated sounding curve for this model is incorporated in Figure 18.

Harding-Lawson's dipole-dipole line DDG overlaps Schlumberger sounding KF3, but they made no attempt at a quantitative interpretation of the dipole-dipole data. However, Furgerson (Appendix 2, File 76-X-X-3)

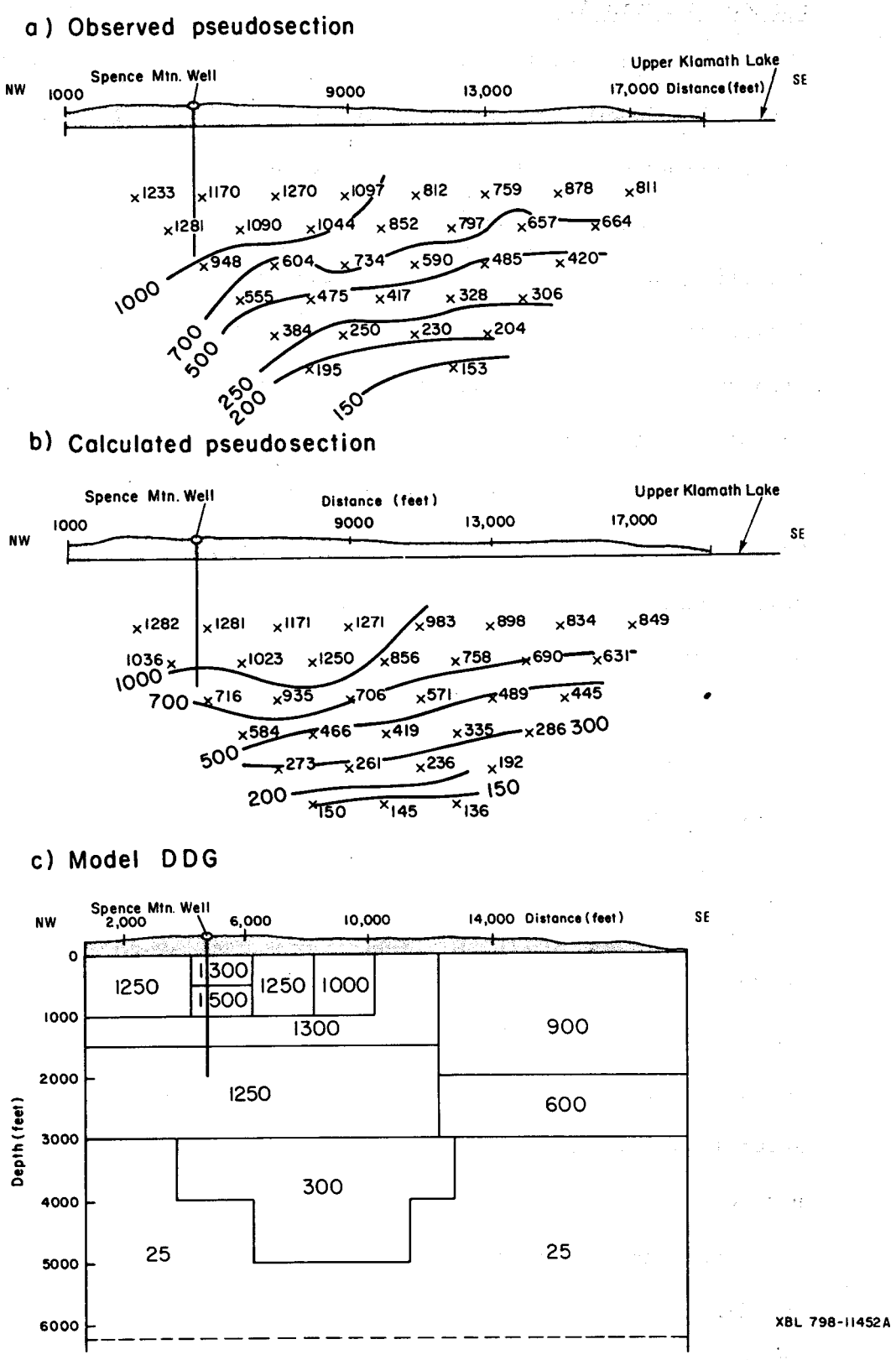

Figure 17. Dipole-dipole line DDG, values on ohm-m.

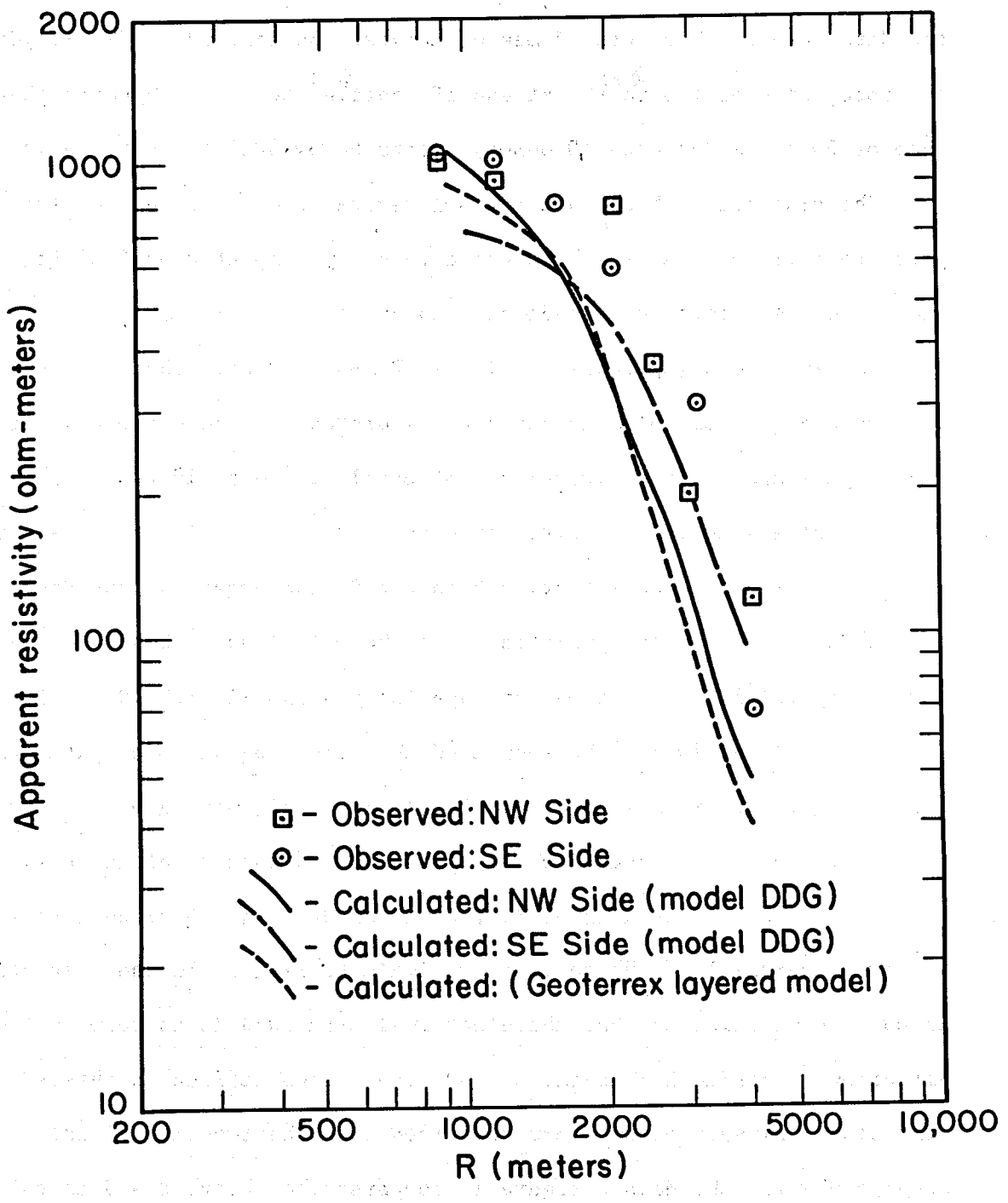

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Figure 18. Bilateral Schlumberger equatorial sounding KF3, with synthetic soundings for model DDG and Geoterrex model.

later made a rough two-layer interpretation of DDG, by comparing parts of the data to published sets of master curves. He concluded, "Two-layer interpretation of the southeast end of profile DDG . . . suggests that a zone of 80 ohm-m (or even 10 ohm-m) exists below 3000 to 4000 feet."

The discrepancy between the two interpretations was not resolved prior to drilling, but the hole was eventually completed at 2000 ft, deep enough to test Geoterrex's shallower conductor.

The well logs (Appendix 2, File 76-X-X-3) indicate that the entire section consists of volcanic material saturated with cold fresh water. The temperature log was virtually isothermal at about 11°C.

We reanalyzed the resisitivity data, arriving at a two-dimensional model (Fig. 17c), which satisfies both the Schlumberger and the dipole-dipole data sets and is consistent with the well logs. This model was derived by trial and error use of modeling program RESIS2D (Dey, 1976; Dey and Morrison, 1977). We then used the same program to compute Schlumberger soundings for the dipole-dipole model, making only minor modifications in that model to satisfy both data sets simultaneously.

It should be noted, however, that lines DDG and KF3 trend northwesterly, parallel to the regional geologic strike, while the assumption in our 2-D modeling is that the electrical structure is uniform in the direction perpendicular to the survey line. Thus we faced a three-dimensional situation, and were surprised that the two-dimensional model could fit the data. Figure 17 compares the observed and calculated dipole-dipole pseudosections; the observed and calculated Schlumberger curves are presented in Figure 18.

A very important feature of the model is that the depth to the conductive horizon is 3000 to 5000 ft; 4000ft beneath the Spence Mountain drill

site. This result is similar to Ferguson's two-layer interpretation. The 25 ohm-m resistivity value is not very well constrained by the data, and the true value could easily fall within the range of 5 to 25 ohm-m. This unit may or may not be conductive enough to indicate geothermal activity.

The Schlumberger data alone do not allow a unique interpretation. In Figure 18 we see that two radically different models produce equally good fits to the observed data. By simultaneously satisfying the dipole-dipole data we were able to determine the depth to the conductive horizon much more accurately. We found that a dipole-dipole pseudosection calculated for Geoterrex's layered model was a poor fit to Harding-Lawson's data.

For this area we believe that two-dimensional modeling was not necessary to establish a target depth. Furgerson's two-layer dipole-dipole interpretation could have been used in conjunction with the Schlumberger data to estimate a depth of 3000 to 5000 ft to the conductor.

The resistivity log of the Spence Mountain hole is of poor quality and is at best a qualitative tool for gross lithologic distinctions. Furgerson's (Appendix 2, File 75-7-2-3) analysis of the log indicated that the wellbore penetrates thick resistive (hundreds and thousands of ohm-meters) formations alternating with thinner strata of more conductive material. The resistive zones appear to correspond to massive basalt flows in the lithologic log, while the conductive zones probably correspond to fractured basalt, scoria, and/or tuff. Unfortunately, it is impossible to tell from the resistivity log whether the most conductive zones have resistivities on the order of ones, tens, or hundreds of ohm-meters. However, based on our specific-conductivity arguments we expect the lowest resistivities to be at least 70 ohm-m, since all the

water encountered in the well was cold.

Our model (Fig. 17a) shows the hole penetrating only resistive material (1000 to 1500 ohm-m). This is roughly compatible with the resistivity log; the thin "conductive" zones of over 70 ohm-m in the log would probably not be discerned in the surface resistivity data.

The exploration planners in charge of the Spence Mountain effort gathered a considerable amount of geological, geophysical, and geochemical information about the west shore area before choosing their site. Unfortunately, as is often the case, legal and financial considerations placed heavy constraints upon the location and depth of the hole. Shallow temperature surveys were not attempted because it was felt that the enormous regional groundwater flow would effectively mask the near-surface thermal gradient. For similar reasons, the planners chose not to run a full suite of well logs, and did not take core samples.

Geologic Interpretation of the Model DDG. The upper 300 ft of the model (Fig. 17a) consists of blocks ranging in resistivity from 600 to 1500 ohm-m. We see evidence for a lateral discontinuity between the 900 ohm-m block to the southeast and the 300 ohm-m material to the northwest. The discontinuity extends downward 3000 ft to the conductive block below. The meaning of this break is uncertain; it may be merely a topographic effect from Spence Mountain. The fact that DDG trends parallel to strike makes intepretation of lateral discontinuities difficult.

The variation among resistivities on either side of the break can probably be attributed to surface inhomogeneities, topographic effects, and actual resistivity contrasts among basalt flows.

The 300 ohm-m block may represent a thickening of the volcanic pile beneath Spence Mountain. Alternatively, we may be seeing the effects of

current channeling through the lake as the dipoles approach the lakeshore to the northwest and southeast. If this were the case, the actual depth to the conductive block might be closer to 5000 ft everywhere along the line.

The cause of the low resistivity (25 ohm-m) unit is still open to question, as the well was not deep enough to test the anomaly. The high specific resistivity of the regional groundwater (see geochemistry section above) rules out cold water in fractured or porous rock as an explanation for the low. Therefore, we would expect to see conductive formations, such as tuffs and clays, possibly saturated with hot water, at this depth. Presumably, the large regional cold groundwater flow would mask any thermal gradient due to a hot-water body at a depth of 3000 ft or more.

Other Data in the Spence Mountain Area. Dipole-dipole line DDC runs parallel to and 2 km southwest of DDG. Figure 19 presents our model for line DDC, and the observed vs. calculated pseudosections. This is a fairly rough fit, as we were mainly interested in understanding the gross features here. The model is similar to our model for DDG, but the resistivities in the upper 2000 ft are somewhat lower, and the depth to the conductive zone slightly shallower (2000 to 5000 ft). This model also features a strong lateral resistivity break, at 20,000 ft along the profile. This break corresponds to a short mapped fault (Fig. 5) which trends northeast, southeast side downthrown.

Northwest of line DDG lies dipole-dipole line DDB. For this we also attempted a rough fit to the observed data; the model and the observed and calculated data are shown in Figure 19. Presumably, the model represents dense basalt flows flanked by alluvium and unconsolidated sediments. The sedimentary formations appear to thicken to the northwest and the

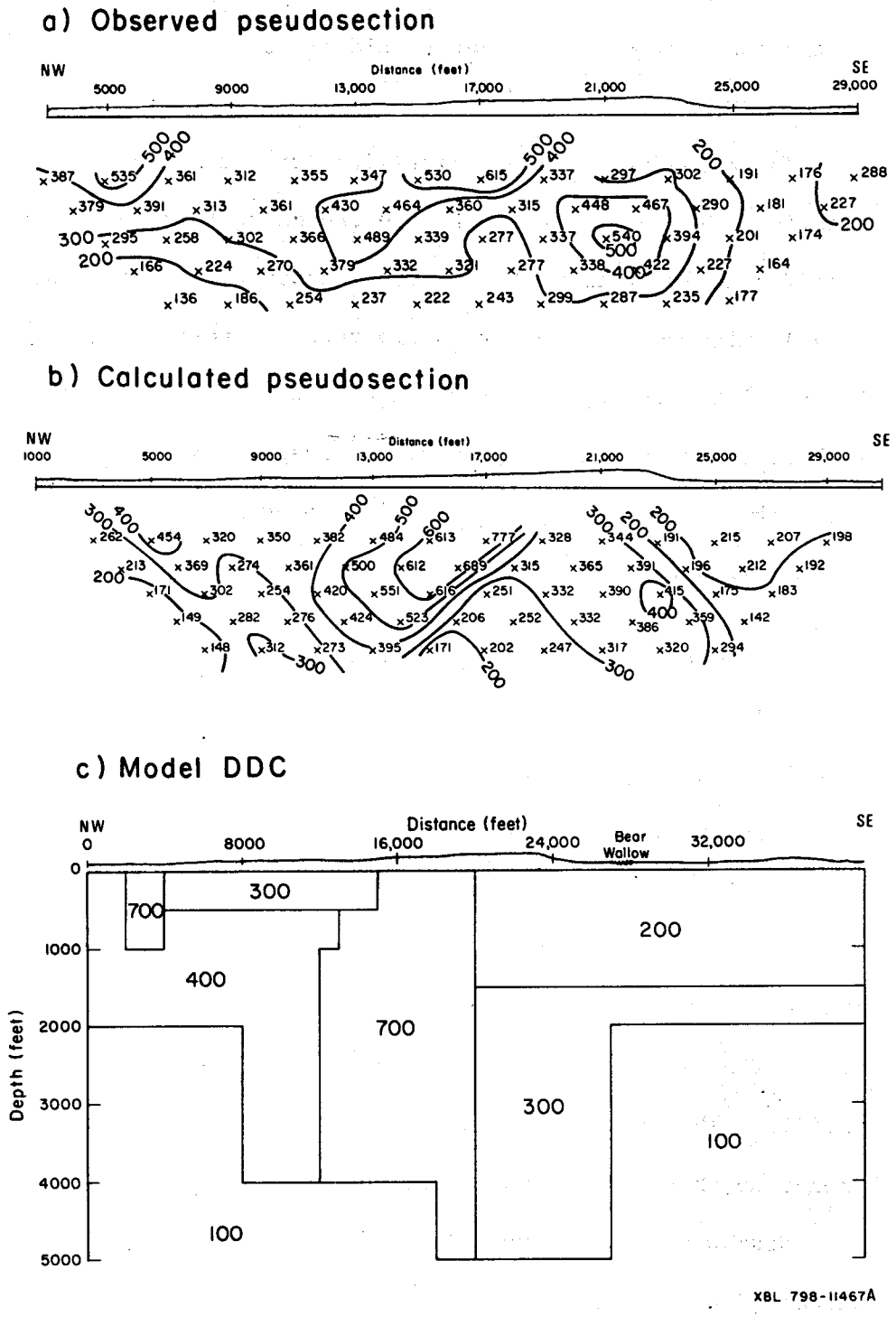


Figure 19. Dipole-dipole line DDG, values in ohm-m.

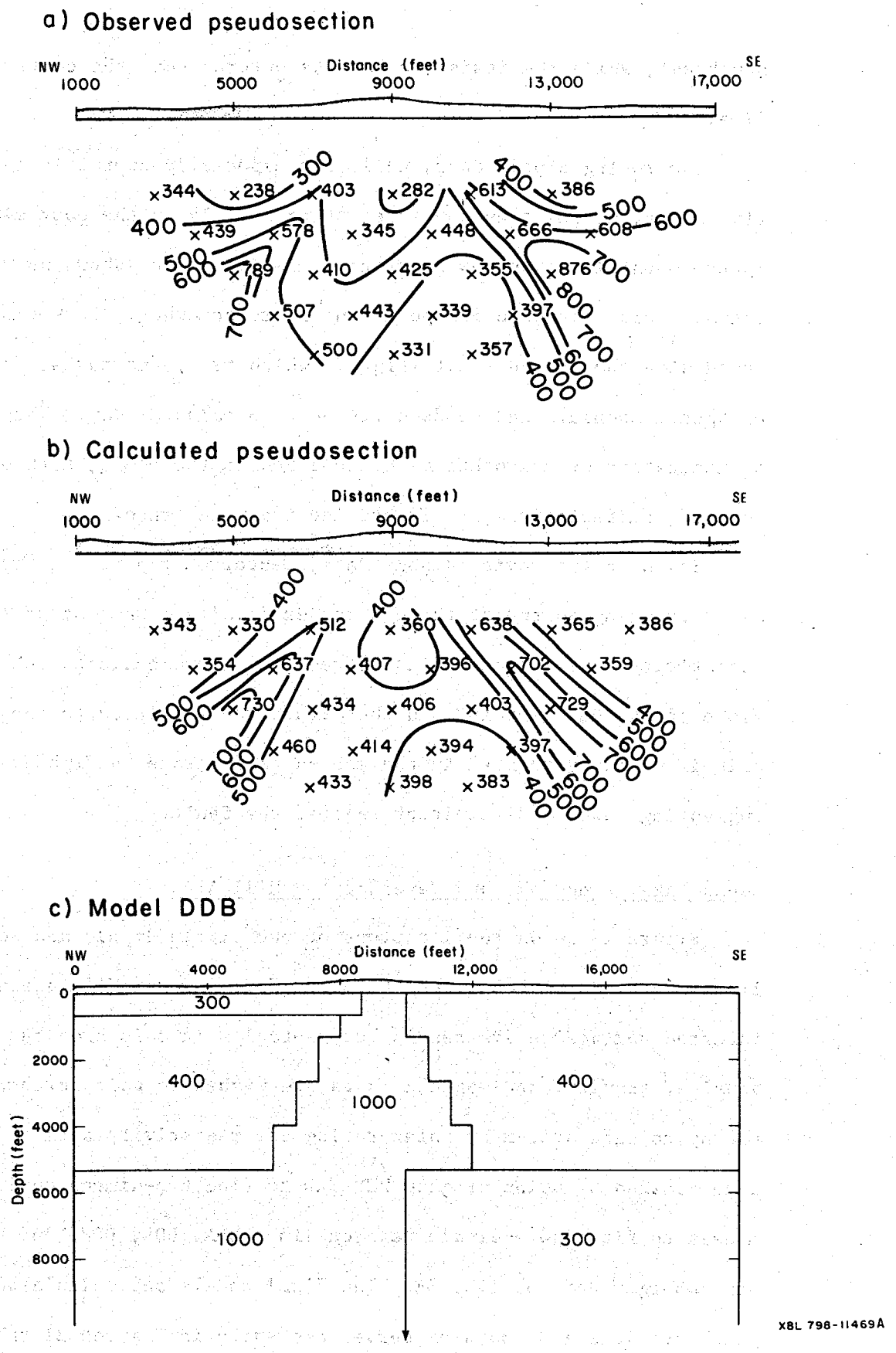


Figure 20. Dipole-dipole line DDB, values in ohm-m.

southeast, while the resistive basalts outcrop near the center of the line.

The roving dipole data, while not especially useful in a quantitative sense, do point up one interesting anomaly on the east slope of Spence Mountain. The low apparent resistivity zone shows up with both transmitters, although its position shifts somewhat. It seems to be associated with the mapped fault (Fig. 5) which trends northwest to the peak of Spence Mountain and bends north up to Shoalwater Bay. The anomaly may be indicative of hydrothermal circulation in the fault, although no surface manifestations are identified near the trace.

Based on the roving dipole data, Geoterrex reported a "conductive axis" trending northwest through the drill site. On most of the apparent resistivity maps the axis lies between the aforementioned low on the east slope of Spence Mountain, and the higher resistivities to the west. The axis is probably related to the mapped fault trace on Highway 140, suggesting lower resistivities east of the fault.

Round Lake, Long Lake and Weyerhaeuser Mill Areas

Figure 16 shows the locations of the dipole-dipole and Schlumberger lines in the Round Lake, Long Lake and Weyerhaeuser Mill areas. Having inferred northeasterly trending cross-faults in this area based on remote sensing, gravity, and magnetic data, we wished to gain further insight into the hydrologic system by interpreting the resistivity data. This was accomplished by using program RESIS2D to find two-dimensional resistivity models to fit dipole-dipole data on lines DDA, DDL, DDH, and DDD, and Schlumberger data on line EE. The final models and calculated and observed pseudosections and sounding curves are shown in Figures 21 through 25.

Interpretation is complicated by three-dimensional structure along most of these lines. Lines DDD and DDH trend more or less parallel to the northwest geologic strike, while DDA and EE run perpendicular to strike but lie right next to a major northeast-trending discontinuity. In fact, only data from line DDL can be reasonably approximated by a two-dimensional model. Resistivity models for the other lines may be useful for general subsurface information.

It is immediately apparent from inspection of the data and the models that most of the rocks in this area have lower resistivities than those the Spence Mountain area. Especially interesting are the conductive zones (on the order of 10 ohm-m) at depths of 1500 to 5000 ft in these models. None of these data show any evidence of resistive basement.

Model DDA, shown in Figure 21c, was designed to fit both dipole-dipole data along line DDA and Schlumberger equatorial data on line EE. Figures 21a and 21b show the observed and calculated data sets. The model contains several blocks of intermediate resistivity material (25 to 90 ohm-m) extending from the surface to a 7 ohm-m unit at a depth of 3500 to 5000 ft. The 7 ohm-m unit is displaced along two discontinuities, resulting in a shallower depth to its top on the northeast end of the line. Also interesting is the 5 ohm-m block which comes up to a depth of 1500 ft. This may represent fluid leakage from the deeper 7 ohm-m unit.

The fit of this model to the Schlumberger equatorial data is shown in Figure 22. As previously noted, the line parallels nearby mountains, which undoubtedly introduces sufficient three-dimensional effects to place our two-dimensional interpretation in question. Presumably, the mountains are more resistive than the valley sediments, and current

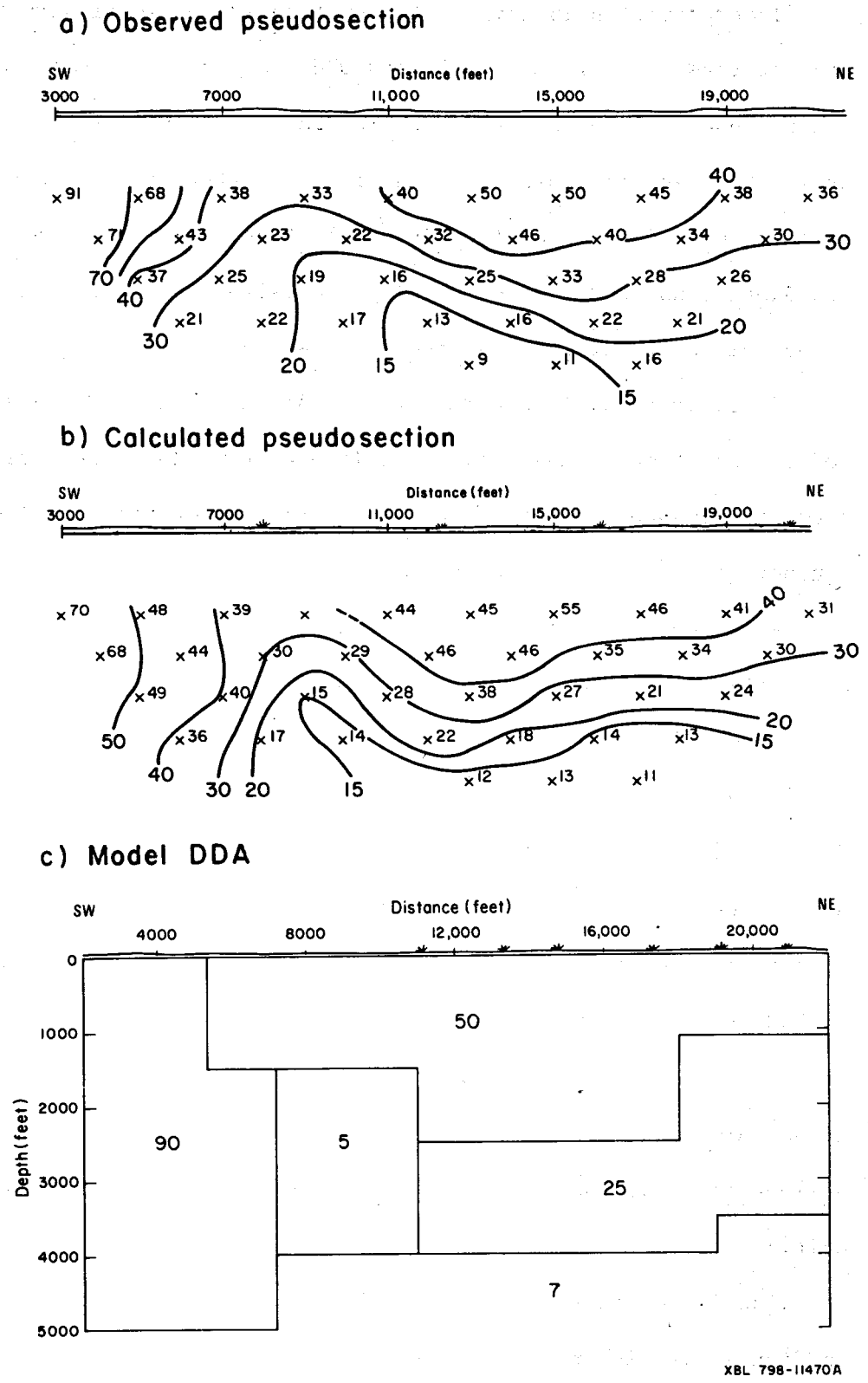


Figure 21. Dipole-dipole line DDA, values in ohm-m.

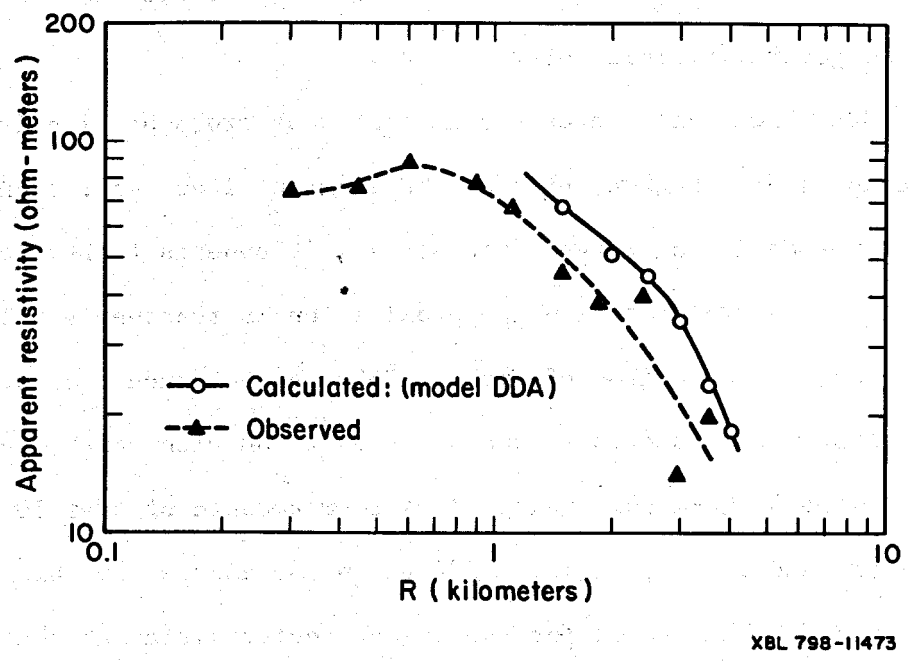


Figure 22. Schlumberger equatorial sounding EG, and calculated sounding for model DDA.

would tend to concentrate in the valley at larger electrode spacings. This means that the measured apparent resistivities are higher than would be found for a true two-dimensional earth. Consequently, we suspect that the true resistivities of the deeper blocks are even lower than shown in Figure 21c. At any rate, the simultaneous fitting of both data sets supports the general validity of the model.

Model DDL (Fig. 23a) represents an east-west cross-section from the edge of Round Lake to Highway 66 near the Klamath River. Although the line is not perpendicular to geologic strike, it appears to be close enough so that the two-dimensional approximation is reasonable. The fit is fairly good, as comparison of Figures 23b and 23c demonstrates. The apparent resistivities decrease toward the east and with depth; this is expressed in the 5 ohm-m unit which rises from a depth of over 10,000 ft at the western end of the model to 1300 ft in the east. In this respect it resembles Model DDA except for the higher resistivities at the western end.

Dipole-dipole lines DDD (Fig. 24) and DDH (Fig. 25) show similar features to DDA and DDL. Again, the models require deep conductive rocks that extend below the depth of resolution. The top of this conductor is found at shallower depths beneath valley areas, similar to models DDA and DDL. On DDH and DDD, however, we have no way of assessing the validity of the two-dimensional model; the lines are almost parallel to geologic strike, and there are no other resistivity data available to complement the dipole-dipole data. Therefore, we place less faith in these models and can use only the gross features for geologic interpretations discussed in the following section.

All of the electrical data in these areas indicate that the resis-

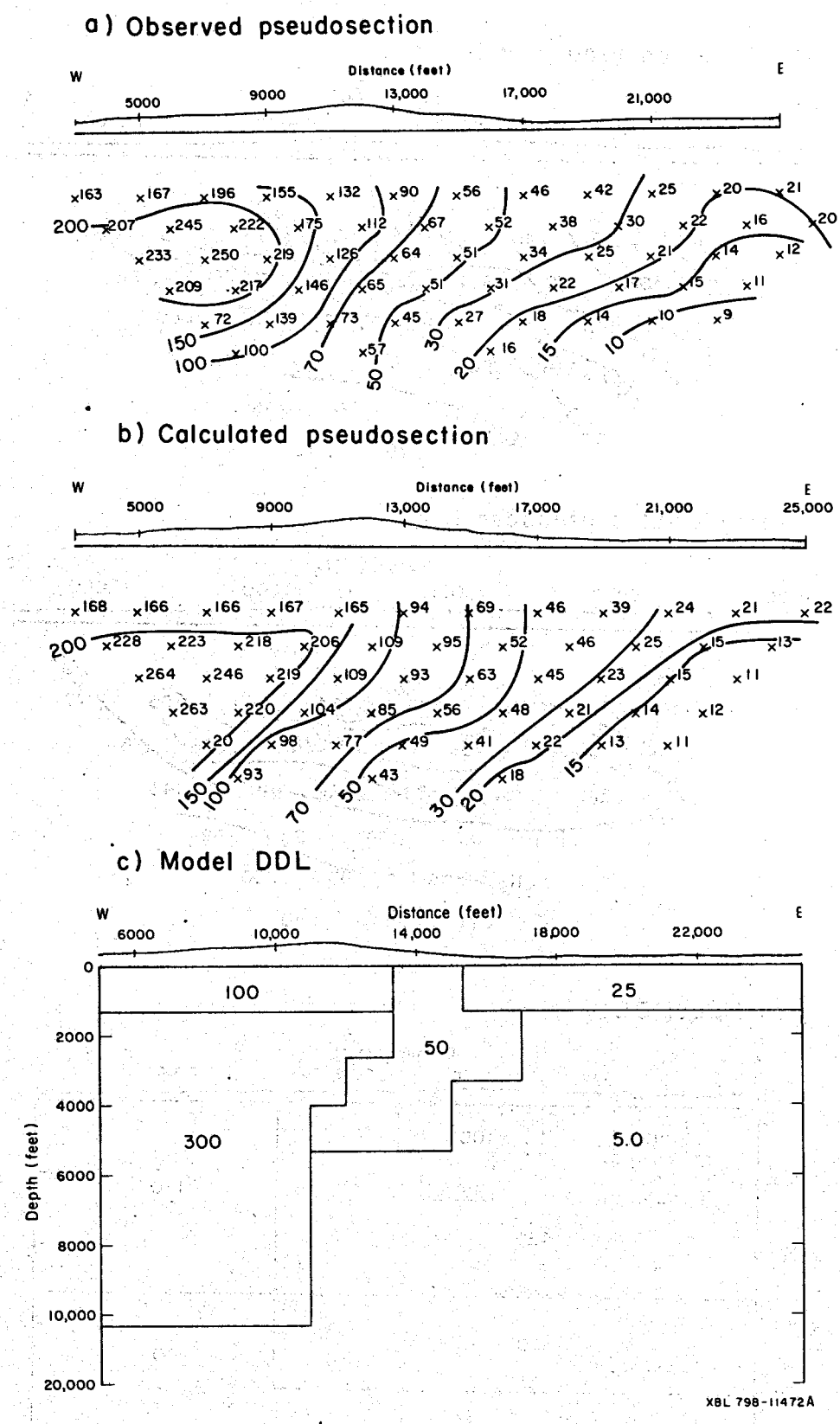


Figure 23. Dipole-dipole line DDL, values on ohm-m.

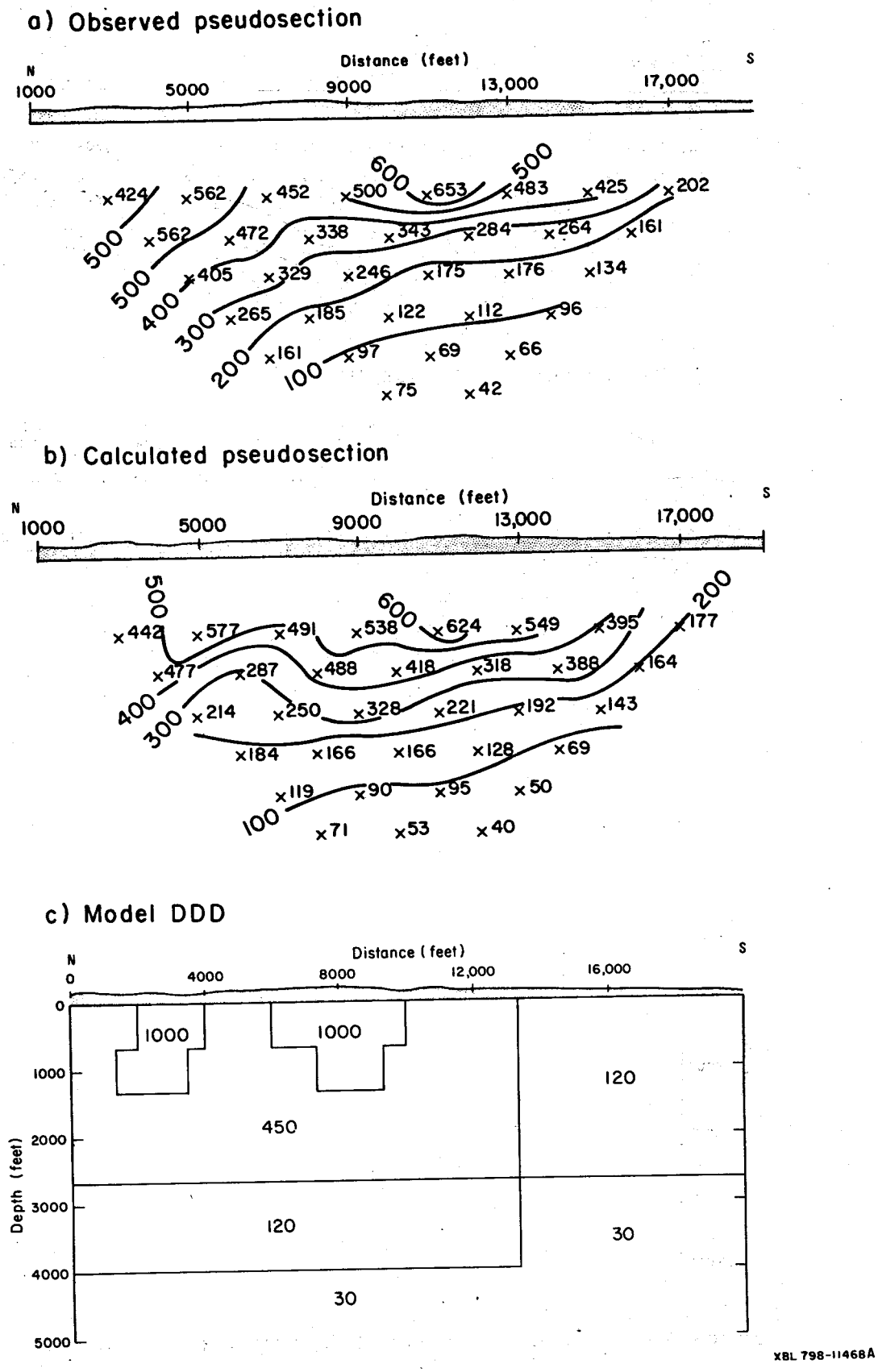
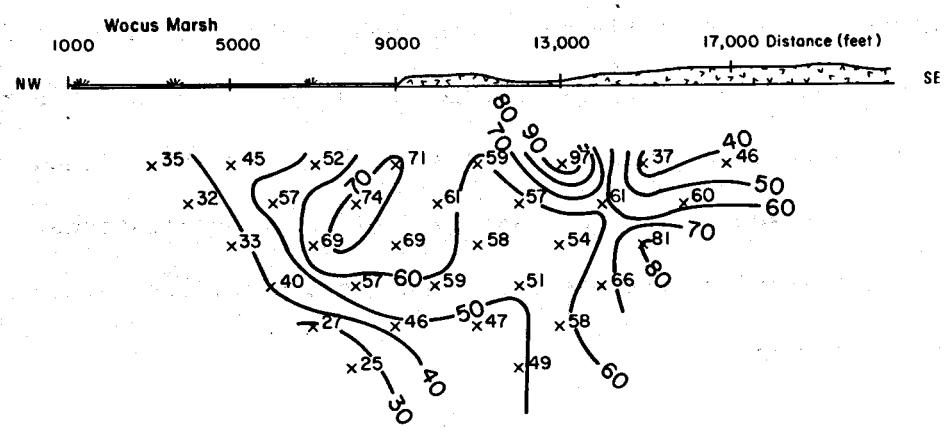
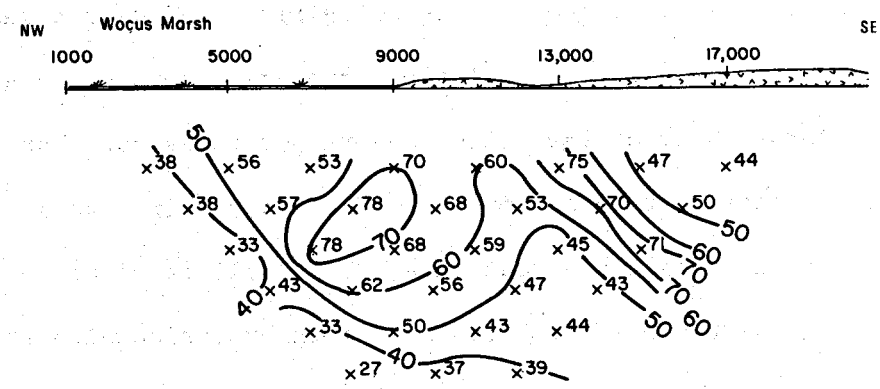


Figure 24. Dipole-dipole line DDD, values on ohm-m.

a) Observed pseudosection



b) Calculated pseudosection



c) Model DDH

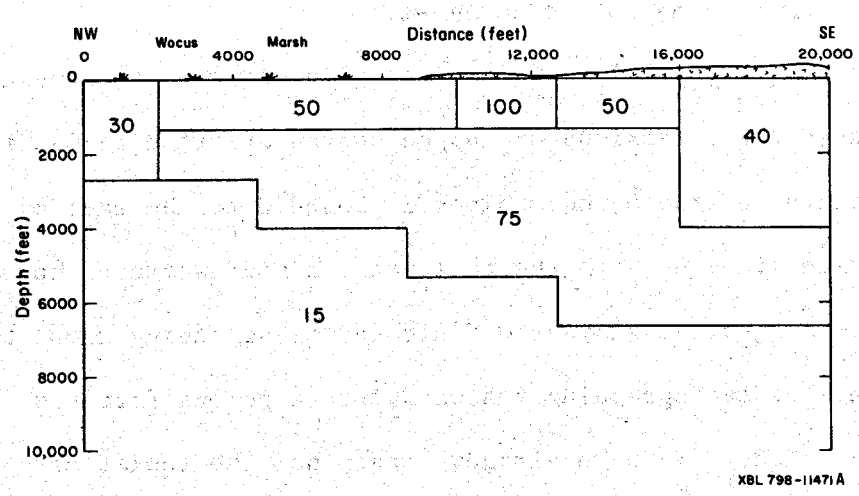


Figure 25. Dipole-dipole line DDH, values on ohm-m.

tivity decreases with depth, but we have no basis for establishing a lower limit for the resistivity of the deep conductive unit. Therefore, most of the models were formulated "conservatively" in that the resistivity of the deep conductor was set as high as possible without violating constraints imposed by the data and by geologic considerations. The modeled resistivities of these deep conductors should therefore be considered upper limits.

Geologic Interpretation of Models DDA, DDL, DDD, and DDH. Table 2 presents the temperatures, specific resistivities, and depths measured in wells in this area. There is little correlation between these three parameters. Most of the wells have temperatures somewhat above ambient groundwater, with a maximum of 27°C measured in a well near the quarry about 4 miles east of Round Lake. This well is close to the northeast-trending fault (Fig. 5), near its intersection with the fault along the northeast shore of Long Lake. All of the wells listed in Table 1 have specific resistivities above 20 ohm-m, with most of the values falling between 30 and 50 ohm-m.

Model DDA (Fig. 21a) contains lateral discontinuities which may correspond to the extensions of mapped northwest-trending faults (Fig. 5). For instance, the 5 ohm-m block is bounded to the east by a discontinuity which lines up with the fault on the southwestern shore of Round Lake. This suggests that heated fluid may be ascending along this fault zone, perhaps spreading westward into a porous formation to form the 5 ohm-m block. We have already noted that the resistivity of the local groundwater as measured in wells is substantially higher than 5 ohm-m, so this block could not be saturated with cold groundwater. The block's shape seems to rule out conductive clays or tuffs as an explanation; these materials are usually found stratified rather than in blocks.

Table 2. Temperatures, specific resistivities and depths of wells in the Lumber Mill area.

Temperature (°C)	ρ_{spec} (at 25°C in ohm-m)	Depth (m)
13	27.0	103
16	40.0	?
15	40.8	240
18	45.5	286
Cold	37.0	227
14	42.6	395
20	45.5	Spring
16	30.2	168
27	33.3	765
21	50.0	545
22	35.7	286
19	38.5	250
12	32.8	120

Note: After Sammel, 1976

The near-surface lateral changes in resistivity probably reflect variations in groundwater resistivity. One might expect relatively conductive marsh water in the 50 ohm-m block and cleaner, less conductive mountain water in the 90 ohm-m block.

The deep 7 ohm-m conductor is more difficult to understand. Furgerson (Appendix 2, File 76-X-X-3) speculated that it may reflect a regional trend of decreasing resistivity due to saline groundwater in the marshes to the southeast. Although we find no evidence for such conductive groundwater in the local wells (see Table 2), none of these wells is deeper than 800 ft, so we have no information on the groundwater characteristics in the deep conductive material. Deeper electrical methods, such as magnetotellurics, could better define the shape and depth extent of this material.

Model DDL (Figure 23a) also terminates at depth in a conductive (5 ohm-m) half space. In this case the resistive overburden thins dramatically from the mountains in the west to the valley in the east. The lateral discontinuities seem clearly related to the mapped northwest-trending faults bounding Long Lake Valley. The 25 ohm-m unit may represent leakage of conductive fluid along these faults; the warm well (27°C) at the quarry is located at about 18,000 ft along the survey line. The trace of the inferred northeast-trending fault (discussed in the geology section and shown in Fig. 5) crosses Line DDL and intersects one of the Long Lake faults near this well. Although it is one of the deeper wells in the immediate area (765 ft), it is not deep enough to penetrate the 5 ohm-m unit in model DDL, which lies at a depth of 1300 ft. This might be a good location for an intermediate-depth hole to investigate the conductive material.

Models DDD (Fig. 24a) and DDH (Fig. 25a) show the same gross char-

Models DDD (Fig. 24a) and DDH (Fig. 25a) show the same gross characteristics; each is underlain by a conductive half-space, similar to that found for DDA and DDL. These conductors are fairly deep, at least 2500 ft, and may not be as conductive as those beneath lines DDA and DDL. Moreover, the two-dimensional assumption is especially weak for line DDH and DDD as we discussed above.

The nature of the deep conductive zones seen in all of the electrical data is an important unresolved question. As we noted above, the resistivities assigned to these zones in the models are essentially upper limits; true resistivities may be 5 ohm-m or less, and the zones may all represent the same formation. However, it is difficult to imagine a common geologic formation underlying all these areas, particularly because the conductive horizons consistently appear at shallower depths in view of the fact that the conductive horizons consistently appear at shallower depths beneath the valleys than beneath the mountains. Another possible explanation for the conductive zones is that hot water rising along fault conduits, has spread laterally into deep fractured basalt flows or porous tuffs beneath mountainous areas and leaked laterally at the base of the sedimentary section under the valleys. If this is the case, we could have an enormous volume of hot water stored in the west shore area, from Spence Mountain southward to the Klamath River.

To our knowledge, there are no wells in the west shore area deep enough to test these hypotheses. Two target areas could be drilled in the future. One is southwest of the pulp mill, where the 5 ohm-m block in model DDA could be explored at a depth of 1500 to 2000 ft. Another good location is near the quarry along line DDL. The conductive zone here should be found below 1300 ft. This site seems promising because of its proximity to the northeast-trending fault and to the 27°C well. Both

sites are within a few miles of the mill; if the water is warm but not hot enough for power generation, then perhaps it can be used directly in the mill.

Whiteline Reservoir Area

Figure 6 presents the locations of roving dipole, Schlumberger, and EM surveys in the Whiteline Reservoir area. On the basis of these surveys, Furgerson (Appendix 2, File 76-X-X-3) concluded that there were no strong resistivity anomalies indicative of geothermal activity in the survey area. He did find that the fault along the southwestern slope of Naylox and Hogback Mountains has a strong effect on the resistivity structure, with much lower apparent resistivities measured by the roving dipole method southwest of the fault. A typical roving dipole apparent resistivity contour map is reproduced in Figure 26; the Plum Valley low shows up clearly. However, his EM interpretation indicated that the subsurface resistivity was at least 35 ohm-m, not conductive enough to warrant further exploration.

Furgerson also completed a Schlumberger expander sounding, SEA 5, out to AB/2 = 2000 ft southwest of the Naylox Mountain fault in Plum Valley (Fig. 6). The apparent resistivity curve he obtained (reproduced in Fig. 27 and labeled "Observed Curve") appears to contradict the EM interpretation; his two-layer interpretation indicates 15 ohm-m material down to 325 ft, with a resistive basement of at least 225 ohm-m extending to at least 2000 ft. Furgerson went one step further in his interpretation of this sounding; he applied a graphical method to compensate for the effect of the nearby fault, and the higher resistivity material beyond it. He assumed that the fault dips 60° and trends parallel to the sounding line, and that the earth northeast of the fault is a quarter-space of infinite resistivity. This allowed him to construct a sounding

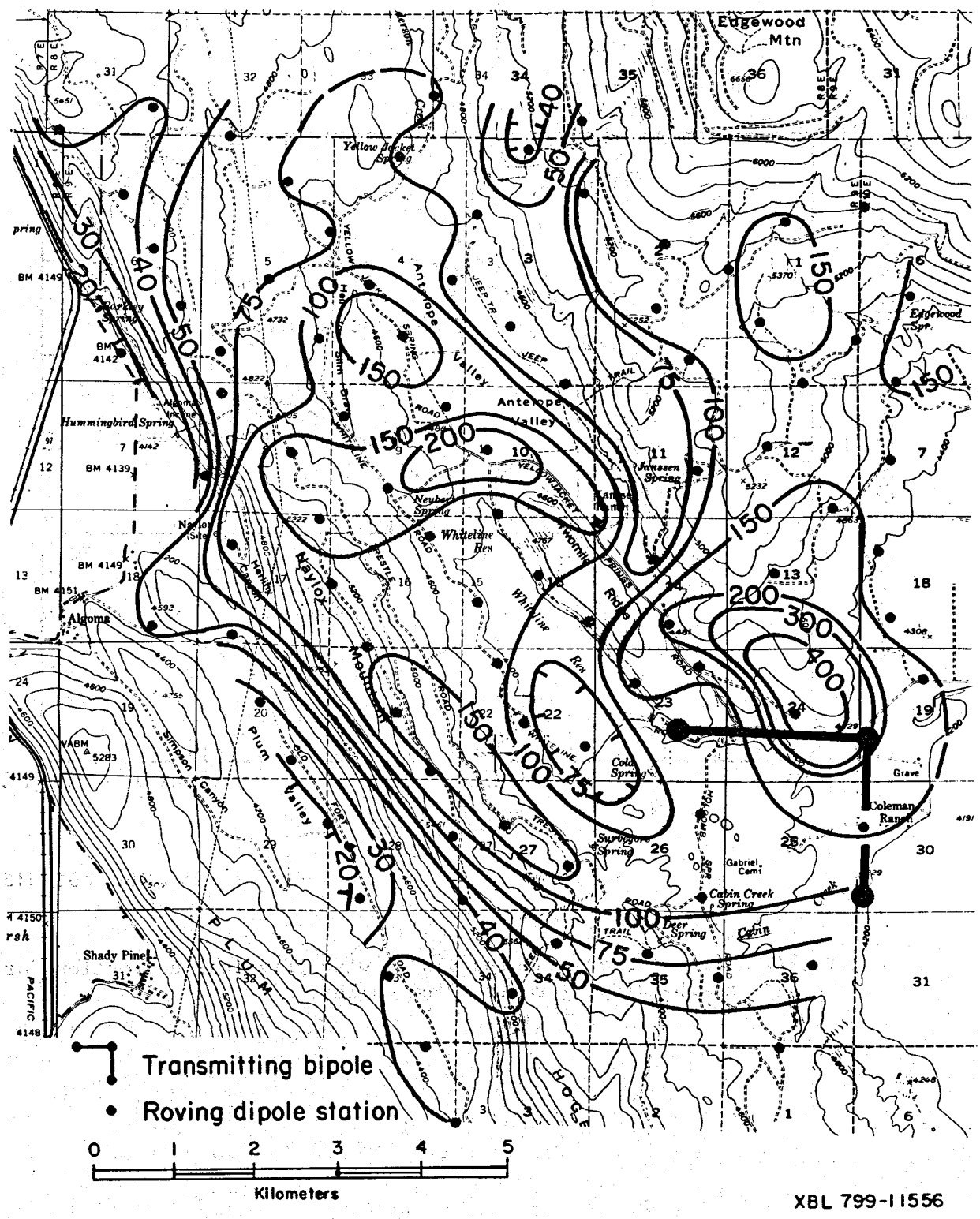


Figure 26. Average rotated apparent resistivity in ohm-m from Source 1, Whiteline Reservoir roving dipole survey.

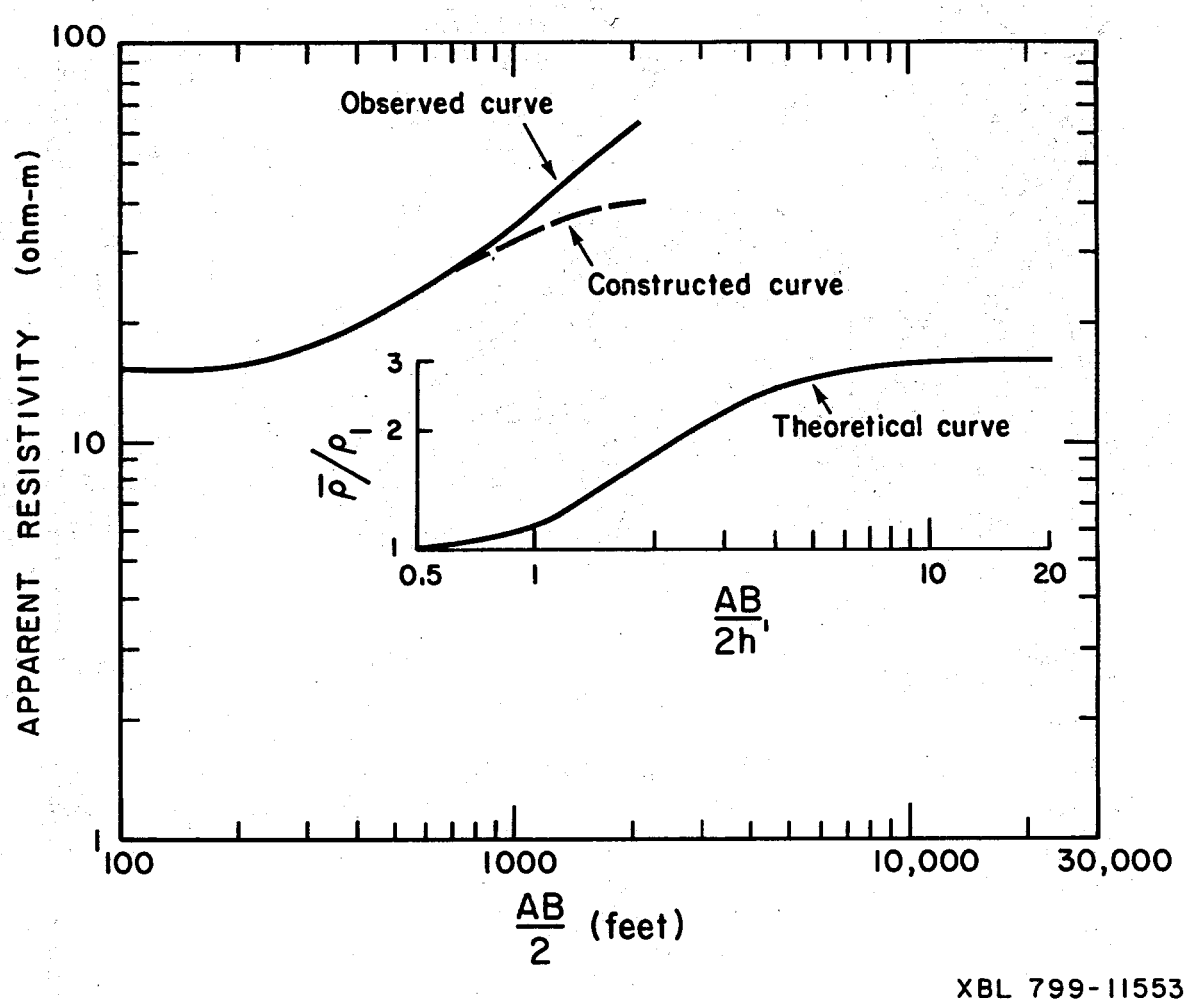


Figure 27. Schlumberger sounding SEA 5, with graphical correction for nearby dipping fault, Plum Valley.

curve with the effect of the fault "subtracted out." In Figure 27 we have reproduced the theoretical curve for a sounding next to the dipping fault and the curve constructed by subtracting out the theoretical curve. Furgerson interpreted the constructed curve to yield a three-layer model quite different from his original two-layer model. The three layers have resistivities of 15, 72, and 36 ohm-m (from top to bottom). The top layer is 300 ft thick and the middle layer is 600 ft thick.

This procedure interprets the sounding without resorting to two-dimensional computer modeling, but it is difficult to understand why the constructed curve was interpreted as a three-layer curve. We find that the constructed curve is a classic two-layer curve with a top-layer resistivity of 15 ohm-m underlain by a 40 ohm-m half-space.

Any interpretation of this curve must include a 15 ohm-m layer in the upper few hundred feet; this would seem to invalidate Furgerson's two-layer EM interpretation, which assumes a relatively resistive top layer.

This leaves only the roving dipole low to rely on for deeper subsurface information. We did not attempt to model the roving dipole data. We do feel, however, that the Plum Valley anomaly should be investigated further.

Another interesting roving dipole trend is found near the southeastern edge of the survey area, approaching the northwestern end of Meadow Lake Valley. Figure 26 shows a trend of decreasing apparent resistivity here. This area is of particular interest because it is adjacent to Holcomb Springs, where we found evidence (Stark et. al. 1979) for a resistivity low based on magnetotelluric and other roving dipole data.

Although we have not reinterpreted data in the Whiteline Reservoir area, we feel that the prospect was rejected prematurely. Ideally, roving dipole should be used as a reconnaissance technique, and more detailed methods should be employed to investigate specific anomalies. For instance, the Plum Valley Schlumberger line could be expanded for deeper penetration. Another possibility would be to reinterpret the Plum Valley EM data. The multilayer time-domain problem can be solved with a computer program; perhaps a three-layer model would be useful.

Synthesis and Geologic Interpretation of Resistivity Models

In this section, we shall first attempt to tie together our regional MT resistivity model with the dc resistivity models from the west and east shores of Upper Klamath Lake and with models for the Swan Lake Valley and Klamath Hills areas (Stark et al., 1979). The regional MT model (Figure 13) requires fairly conductive material (mostly about 18 ohm-m) material down to about 4 km. Our dc resistivity models for the west shore area all terminate in conductive zones (<25 ohm-m) at depth, but are quite resistive (>500 ohm-m in the mountainous areas) for the upper 0.5 - 3.0 km. The Whiteline Reservoir data (see previous section) and the Swan Lake Valley models (Stark et al., 1979) both indicate moderately resistive material (40-300 ohm-m) in the upper few hundred meters, with more conductive rocks below. The Klamath Hills models indicate moderately conductive (10-50 ohm-m) to very conductive (<10 ohm-m) formations for the upper kilometer. These can all be reconciled with Figure 13 by noting that the highest frequency points obtained for the regional MT survey were .1 Hz, corresponding to a depth of exploration on the order of 5 km. Therefore, any resistive formations shallower than 3 km would have little effect on these measurements; the conductive

units found at depth would be much more important. We therefore conclude that the upper 4 km is characterized by decreasing resisitivity with depth. The only exceptional area occurs between stations 2A-77 and 8 (Figure 13) where our model indicates a 610 ohm-m block extending from the surface to 4 km depth. This may be caused by the mountainous volcanic terrain between these stations, or may be an artifact of oversimplified two-dimensional interpretation. We suspect the former, because our Swan Lake Valley MT model (Stark et al., 1979) also requires a resistive near-surface block east of the valley.

The decreasing resistivity structure interpreted for the upper 4 km is probably caused by massive Quaternary basalts and andesites (in the Cascades) or tight welded diatomaceous Yonna tuffs (elsewhere) near the surface, underlain by fine-grained siltstones and tuffs of the lower Yonna Formation at depths of 1 km or more. Scoriaceous zones, rubble zones and tuffs, intercalated in the Tertiary basalt unit, may also contribute to the low resistivities at depths of 4 km and less. In some areas, hot brine saturation also depresses resistivities.

We have already noted that the thick mid-crustal resistive blocks seen in Figure 13 are not unusual. Moreover, our Swan Lake Valley MT model required blocks very similar in resistivity and position. However, the geologic meaning of these resistive blocks is not clear. Very little is known about the pre-Tertiary stratigraphy in this area; some workers have suggested that the Tertiary basalts are underlain by a Mesozic Franciscan-type assemblage consisting of diorites, metasediments, blueschists and ultramafics. Although not all of these rocks are typically resistive, extensive hydrothermal mineralization may have acted to reduce porosity, thereby increasing resistivity.

Figure 14 shows very conductive material below 18 km (in the Klamath graben) and below 40 km (elsewhere). Stanley et al. (1977) have discussed similar deep crustal conductive zones, suggesting that these zones are unusually shallow (<20 km) beneath some geothermal areas. They appear to be caused by partial melting in the deep crust and upper mantle; the shallowing phenomenon probably results from upwarping of isotherms associated with intra-crustal rifting. Thus, Figure 13 implies that the deep heat source associated with the Klamath graben encompasses Swan Lake Valley and areas further east as well.

EVALUATION OF EXPLORATION METHODS

In our previous report (Stark et al., 1979) we evaluated the gravity, magnetic, roving dipole resistivity, electromagnetic, dc resistivity, AMT, and MT prospecting methods as they were applied to the Klamath Basin. In this report we have examined the results of remote sensing, geochemical, gravity, magnetic, roving dipole, dipole-dipole, Schlumberger, EM, and temperature gradient surveys. Our comments regarding the usefulness and applicability of some of these techniques follow.

1. Remote Sensing: We used aerial infrared photographs to detect lineaments and faults. In this case the imagery proved most useful in substantiating the presence of cross-faulting inferred from other methods.

2. Geochemistry: Available wells and springs should always be inventoried at an early stage of exploration. The reservoir temperature estimates by Sammel (1976) and Geothermex (Appendix 2, File 72-11-27) have been placed in some doubt by the new well in Klamath Falls, which is

hotter than these estimates indicate. This means either that the reservoir is so compartmentalized that the temperature estimates are valid only for individual wells, or that the assumptions involved in the estimates were not valid. We found the specific conductivity measurements useful in geologic interpretation of resistivity anomalies.

3. Gravity and Magnetics: These methods are hampered by the fundamental non-uniqueness problem in inverting potential field data, particularly in the volcanic terrane of the Klamath Basin where magnetizations and densities can be so variable. In conjunction with other information, however, the data can be extremely useful for tracing faults and for estimating depth to basement. In this area, direct associations of gravity and/or magnetic anomalies with geothermal resources are not valid, because structural and lithologic changes can account for more variation than geothermal processes such as mass transport and elevated Curie point isotherms.

4. Roving Dipole Resistivity: This is a useful reconnaissance tool, but the data are difficult to interpret quantitatively unless supplemented by data from other resistivity methods. The Whiteline Reservoir survey did include Schlumberger and EM soundings for control, but in retrospect these soundings might have been more effective if made at a later time to define targets outlined by the roving dipole survey. Similarly, the west shore roving dipole survey should have been completed and analyzed before the dipole-dipole and Schlumberger work began there. Computer modeling can help pinpoint the sources of the often-deceptive roving dipole anomalies.

5. Schlumberger and Dipole-Dipole Resistivity: Schulumberger and dipole-dipole soundings can offer detailed, quantitative earth resistivity information if the surveys are properly implemented. If possible, lines

should be laid out perpendicular to geologic strike, so that three-dimensional effects are minimized and two-dimensional effects can be separated from changes with depth. We found that collinear, overlapping Schlumberger and dipole-dipole soundings were necessary to allow a well-constrained interpretation. Finally, joint computer modeling of the data sets should be undertaken. When these conditions are satisfied, a quantitative subsurface resistivity picture emerges which can be valuable in selecting a drill target.

6. Time Domain EM: This technique suffers from difficulty in interpretation. We certainly applaud efforts to develop and deploy field equipment to make these measurements, but at this time most interpreters are limited to very simple models. If more powerful methods of analysis can be developed, the technique could become quite useful.

7. Temperature Gradient Surveys. These seemed to be only marginally useful for exploration, because shallow, cold groundwater flow distorts the thermal gradient.

General Observations

When overlapping information is available, it is imperative to make interpretations based on several sets of data. For example, in the Spence Mountain area, simultaneous modeling of dipole-dipole and Schlumberger data sets led to a clearer understanding of the subsurface than was possible with either technique alone. The same scheme was used successfully in the pulp mill area. Another example was our use of well-water electrical conductivity measurements to aid in interpreting resistivity models.

CONCLUSIONS

In this project, we have examined the results of most types of geothermal exploration surveys in common use, with the notable exceptions of the self potential and active seismic methods. We have reinterpreted synthesized these data, focusing on various target areas and attempting to develop a clearer understanding of the system. Our conclusions are enumerated below:

1. The Klamath graben has been offset along northeast-trending cross faults which are inferred from geologic, remote sensing, gravity, aeromagnetic, and resistivity survey data. The shallow hydrothermal circulation is related to these faults and their intersections with north-west-trending normal faults.

2. Geochemical data indicate a reservoir temperature of about 120°C, but certain inconsistencies in the chemical geothermometry results might be explained by a hypothetical deep steam reservoir (Sammel, 1976). The 120°C estimates have been placed in some doubt by the recent drilling of a 145°C hole in Klamath Falls.

3. Analysis of specific conductivities of well and spring water shows that hotter waters are more conductive in the Klamath Falls and Olene Gap areas. In the Nuss Lake/Stukel Mountain areas, the hotter waters appear to be less conductive than the cooler waters, although the trend is poorly defined. This might be partially explained by the high TDS content of the local groundwater, due to long residence time in a marshy environment.

4. The resistivity data suggest that the entire area west of Upper Klamath Lake (including the Spence Mountain, Aspen Lake, Round Lake, Long Lake, and Weyerhaeuser mill areas) is underlain by extensive conductive (25 ohm-m or less) formations at depths ranging from 1200 to 10,000 ft

(Fig. 12). Our two-dimensional computer models indicate that the conductive units are found at shallower depths beneath the valleys. We assume that these anomalous conductors represent clays or altered tuffs, possibly saturated with geothermal waters.

5. In the Spence Mountain drill site area, our two-dimensional computer model, based on dc resistivity data (Fig. 17), suggests conductive formations below 3000 ft. This agrees with the information from the 2000-ft drillhole; the hole penetrates volcanic material saturated with cold fresh water.

6. In the Round Lake, Long Lake, and lumber mill areas north of the Klamath River (Fig. 16), the conductive bodies are indicated at depths as shallow as 1200 ft in our models (Figs. 21a and 23a). Again, the conductive units appear to exist at shallower depths beneath the valleys.

7. East of Upper Klamath Lake (Fig. 6), dc resistivity and time-domain electromagnetic data suggest conductive formations at depth. The data are not very definitive, but interesting roving dipole anomalies are found in Plum Valley and near Meadow Lake Valley (Fig. 26).

General Observations

We have attempted to extract all the information possible from the data we received. It has been a time-consuming process, but we feel that we have gained a clearer understanding of the geothermal system.

The deeper plumbing system is still poorly understood. It is not known whether the three hottest areas in Klamath Falls, Olene Gap, and the Klamath Hills are supplied by the same source, or whether they result from separate circulation patterns along the faults. Similarly, the

nature of the heat source remains unknown. Although there is no direct evidence for an igneous heat source, the basin is ringed on three sides by Quaternary volcanics - Crater Lake, the High Cascades, and Medicine Lake Highlands. It is possible to imagine discrete apophyses of cooling igneous bodies concealed beneath the basin. Equally plausible would be a Basin-and-Range type system, with deep circulation along fault zones penetrating a hotter-than-average crust.

A seismic velocity and attenuation study might detect evidence for a buried igneous body. Interference testing for communication between hot wells in the three KGRAs could help determine whether all the hot water emanates from a common source.

Only deep drilling can answer the fundamental questions about the nature of the resource. One purpose of this project has been to guide exploration planners. To this end we have pointed out several areas where additonal geophysical work and drilling might be warranted. These include Meadow Lake Valley, Nuss Lake, and the sawmill and quarry area. Drilling should be planned to intercept fault zones in these areas at depth. Many geophysical anomalies have not been tested, and several enticing sites remain to be drilled.

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APPENDIX 1

KLAMATH BASIN GEOTHERMAL RESOURCE BIBLIOGRPAHY

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APPENDIX 2

MATERIAL RECEIVED FROM GEOTHERMEX ON GEOTHERMAL EXPLORATION WORK FOR WEYERHAEUSER COMPANY AND PACIFIC POWER AND LIGHT COMPANY

Report, "Reconnaissance Evaluation of Geothermal Resources, Weyerhaeuser Company Lands, South-Central Oregon," James B. Koenig, December 1, 1971.

File 72-11-27, containing:

Report, "Geology and Conditions Relating to Geothermal Prospecting in the Quartz Mountain area, South-Central Oregon (Area 2)," J. R. McIntyre.

Report, "Geochemical Interpretation of Spring and Well Waters, Southcentral Oregon and Adjacent California," James B. Koenig and Murray C. Gardner.

File 74-3-9, containing:

Final Report on Geothermal Exploration of the Klamath Basin Area, Oregon, 1973-1974, March 9, 1974.

Bouguer Gravity Map of the Klamath Falls Area, Klamath and Jackson Counties, Oregon; Siskyou County, J. VanDeusen and H. R. Blank, 9 February 1974.

Bouguer Gravity Map of Oregon and California Klamath Falls and Vicinity.

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Aeromagnetic Map of the Klamath Falls and Part of the Crescent 1° by 2° Quadrangles, Oregon, 1972.

Geology of the Browns Mountain, Mt. McLaughlin Area, Southern Oregon Cascades, with Map Attachment.

Report, Supplementary Report Number One, Bouguer Gravity and Total Magnetic Intensity Maps of the Klamath Falls Area, Klamath and Jackson Counties, Oregon; Siskyou County, California, 7 November 1974, J. VanDeusen and H. Richard Blank.

File 75-2-14, containing:

Final Report on Geothermal Exploration of the Klamath Basin Area, Oregon, 1974-1975, by GeothermEx, Inc., February 14, 1975.

File 75-4X, containing:

Summary and Interpretation of Gravity, Aeromagnetic, and Electrical Resistivity Data in the Klamath Basin, Oregon, by GeothermEx, Inc., April 1975.

Geology and Site Selection for an Exploratory Drill Hole in the Spence Mountain Target Area, by GeothermEx, Inc., July 1975.

Review of Geoelectrical Survey Whiteline Reservoir Area.

Geology and Geothermal Resource Evaluation of the Copco Lake Area, Cascade Range, Oregon and California, by GeothermEx, Inc., October 1975.

Geologic Map, Copco Lake Area.

Plate 2, Geologic Cross-Sections of Copco Lake-Cascade Range Area, Oregon-California.

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Addendum to Final Report, Geothermal Exploration of the Klamath Basin Area, Oregon, 1975-1976, by GeothermEx, Inc., July 2, 1976.

File 76-X-X-4, containing:

Justice Core Drilling Company, Driller's Reports dated as follows:

December 19, 1975,	February 7, 1976	March 20, 1976	April 30, 1976
December 22, 1975	February 15, 1976	March 27, 1976	May 8, 1976
December 31, 1975	February 21, 1976	March 31, 1976	May 8, 1976
January 10, 1976	February 29, 1976	April 7, 1976	
January 17, 1976	March 6, 1976	April 17, 1976	
January 31, 1976	March 13, 1976	April 24, 1976	

File 76-X-X-3, containing:

Large Graph, Doak Mountain - Resistance and S.P. - compiled by FTI.

Weyerhaeuser/Pacific Power and Light No. 1 Daily Drilling Log, Master Copy.

Weyerhaeuser/Pacific Power and Light No. 1 Lithologic and Core History Logs, Master Copy.

Analysis and Evaluation of Electrical Resistivity Investigations in the Vicinity of Klamath Falls, Oregon by Harding-Lawson Associates, by R. B. Furgerson, August 4, 1974.

Electrical Geophysical Investigations of the Whiteline Reservoir Area, Oregon, by R. B. Furgerson, September 1975.

Report published by GeothermEx, including Conclusions, Recommmendations, Budget, Summary of Program Activities.

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Burgundy colored box, containing:

Resistivity Survey near Klamath Falls (Oregon) by Geoterrex LTD, October-November 1974.

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