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TELLURIC CURRENT EXPLORATION FOR GEOTHERMAL ANOMALIES IN OREGON

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This study was supported in part by the U.S. Bureau of Mines grant No. SO122129 to the Oregon Department of Geology and Mineral Industries. Because of its timely interest, the article is being published in The ORE BIN rather than in a more technical journal in order to make the information immediately available to those involved in geothermal exploration in Oregon and elsewhere.

Introduction

A reconnaissance telluric current* exploration program for geothermal anomalies in southern and eastern Oregon was initiated in 1971 by the Geophysics Group at Oregon State University. During 1971 and 1972, observational data were obtained from a total of 19 field stations. The program concentrated on the Klamath Falls area, where 10 stations were occupied, and on a profile including a total of 9 stations extending from Siletz at the Pacific Coast to the area around Vale in the extreme eastern part of the state. The locations of the stations are shown in Figures 5 and 6. The principal purpose of this program was to test instrumentation, field procedure, data processing methods, and the general applicability of the telluric current method in reconnaissance exploration for geothermal resources. The results obtained are to be applied to improve all aspects of our methodology and to prepare for a more substantial effort in this field.

The field procedure applied on the present program deviates from the standard telluric method in that the telluric data obtained at the field stations are compared with the magnetic field recorded at a fixed base station. Our method is therefore a variant of the standard magneto-telluric method,

* Natural electric currents that flow on or near the earth's surface in large sheets. Methods have been developed for using these currents to make resistivity surveys.

but since we are mainly interested in large-scale lateral variations of the earth's conductivity, we have preferred to refer to the method as a telluric rather than magneto-telluric method.

Rationale for the Telluric Current Method

Regional reconnaissance exploration for geothermal resources is concerned with the initial detection and recognition of geothermal anomalies of economic interest. An elementary investigation (Bodvarsson, 1966) of resource energetics shows that the heat capacity of rock is such that in terms of electrical energy it is realistic to expect that very roughly about 1 kwhr can be generated per cubic meter of resource volume. This estimate is based on the assumption of the conditions in known fluid-phase, high-temperature geothermal systems where base temperatures of the order of 250°C are encountered and by using a recovery factor of 10 percent. Hence, the generation of 250 Mw at base-load condition for 50 years would require a resource volume of not less than 100 cubic kilometers. This volume could, for example, have the shape of a disk with a diameter of 8 km and thickness of 2 km. Invariably such a reservoir would be surrounded by a thermal halo of considerable extent and the total associated thermal anomaly could extend over areas of several hundred square kilometers and downward into the deeper crust. The exploration targets are, therefore, quite extensive features.

Most of the important known geothermal resources are leaky in the sense that they generate thermal surface manifestations such as hot springs and conspicuous thermal rock alteration. The high temperature character can be recognized on the basis of the physical and chemical characteristics of the surface display. In general, the leaky resources are easily recognized, and there is little need for sophisticated reconnaissance type exploration work.

There is, however, considerable evidence that geothermal systems of great economic potential may be totally concealed and display no surface leakage at all (Bodvarsson, 1961, 1970). In fact, geothermal fluids have a tendency to chemically seal outlets and thereby contribute to the eradification of surface manifestations (Bodvarsson, 1961). Resources of this type can be detected only with the help of more elaborate techniques, such as thermal and electrical exploration methods.

The thermal methods involve regional temperature probing or heat-flow mapping with the help of temperature data from very shallow boreholes. Large geothermal resources within drillable depths are invariably associated with conspicuous surface heat-flow anomalies and can therefore be recognized in regional heat-flow maps of sufficiently detailed nature.

The application of the electrical methods is based on the fact that the formations within geothermal systems have a low electrical resistivity (Bodvarsson, 1970). Values in the range of 1 to 10 Ωm have been observed within many high-temperature geothermal reservoirs. This is the consequence of high temperatures and high mineral content of reservoir interstitial waters.

The resistivity contrast between the hot formations and the surrounding country rock quite often involves factors ranging from 10 to 100. Most major geothermal systems are associated with large-scale electrical resistivity anomalies, and this is especially true with the fluid phase systems. Electrical methods are therefore important tools in geothermal exploration work.

Electrical exploration methods fall into two categories, those based (1) on controlled artificial current source fields, and (2) on natural current fields provided by magnetic micropulsations and other ULF natural activity. The second class of methods, which includes the telluric and magneto-telluric methods, has a considerable advantage in reconnaissance type exploration work involving exploration targets of relatively large dimensions and depths of more than 1 or 2 kilometers. The artificial current sources in such circumstances would require a considerable amount of equipment and field effort. The advantage of the second class of methods is obtained at the cost of less resolving power and greater ambiquity in interpretation, but since target dimensions and resistivity contrasts are unusually large, this disadvantage is not considered to be too important.

For the present purpose, the natural field electrical methods have a certain economic advantage over the thermal methods. Heat-flow mapping is based on the measurement of the vertical flow of heat, which usually has to be derived from temperature and heat conductivity data obtained from shallow boreholes. The minimum depth of such boreholes is 10 to 20 meters, and the selection of drilling locations has to be carried out with considerable care. The field effort required at each station to obtain one or two hours of telluric records is considerably smaller. Moreover, since the telluric currents are horizontal, each telluric station can sample a larger formation volume than the corresponding heat-flow station. In a given area it should therefore be possible to obtain useful reconnaissance type data with the help of fewer telluric field stations than thermal stations. It is clear that carefully measured heat-flow data can be more accurate and have a greater resolution than telluric data, but in reconnaissance type geothermal exploration work the economic advantage of the telluric method appears to outweight this disadvantage. These are the main reasons for selecting the telluric method for our work in Oregon.

In this study it was considered of advantage to install a fixed magnetic base station, rather than to rely on a telluric electrical field base station. The magnetic data allow us to obtain absolute conductivity values. The magnetic base station was installed at Corvallis, Oregon, some 280 km north of the Klamath Falls area. Investigations of micropulsation activity in southern California (Benioff, 1960) have indicated that the micropulsation field at moderate latitudes does not vary appreciably over such distances. On the other hand, the field stations at Vale in eastern Oregon are located almost 500 km from the base station, and the general magnetic coherency cannot be expected to be as good, although individual magnetic events with a good coherency appear to exist.

Expected Resolution

It is important to raise the question as to the overall quality of the exploratory information which can be expected from a telluric current field program of the type described above. Unfortunately, the information content of the observational field data depends to a considerable extent on the local conditions at the individual field stations. Moreover, the theory of telluric currents in electrically non-homogeneous geological structures is a matter of great complexity and not much work of practical relevance has been devoted to the subject. We therefore limit ourselves to the following quite superficial remarks.

For the present purpose, the earth can be assumed to be a semi-infinite perfect reflector of the magnetic field generated by the oscillating ionospheric currents. The penetration of the induced telluric currents is limited by the skin effect which is measured by the skin depth, that is, the depth at which the current amplitude has been attenuated to $1/e = 0.37$ of its surface value (Keller and Frischknecht, 1966, p. 213). Relevant values of the skin depth for homogeneous isotropic half-spaces at various resistivities and at periods from 10 to 50 seconds are given in Figure 1.

Approximately 2/3 of the telluric current flows in the horizontal region above the skin depth. Hence, this depth gives a fairly good measure of the thickness of the formations sampled by the telluric currents and the associated electrical field. Assuming perfect source current conditions and a homogeneous half-space, the above described telluric method will give the true resistivity of the half-space regardless of the frequency. In a layered

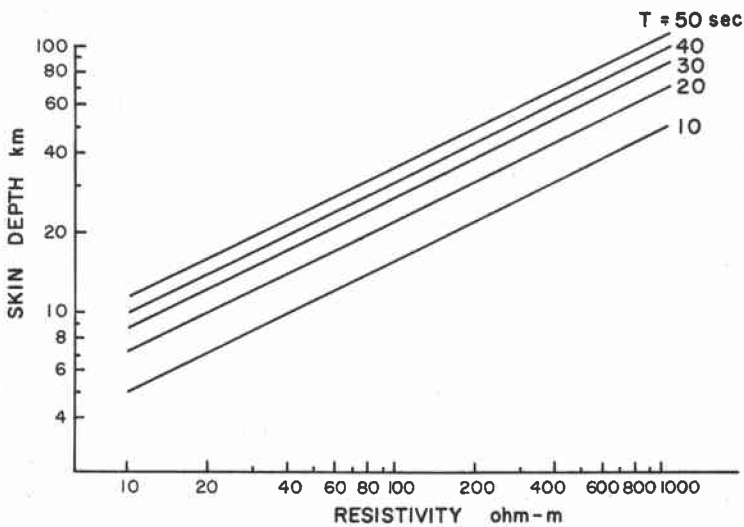


Figure 1. Data on the skin depth in a homogeneous half-space.

half-space, the method gives a certain weighted average of the vertical resistivity distribution in the region where the bulk of the telluric current flows. Obviously, the averaging is biased toward the shallower sections.

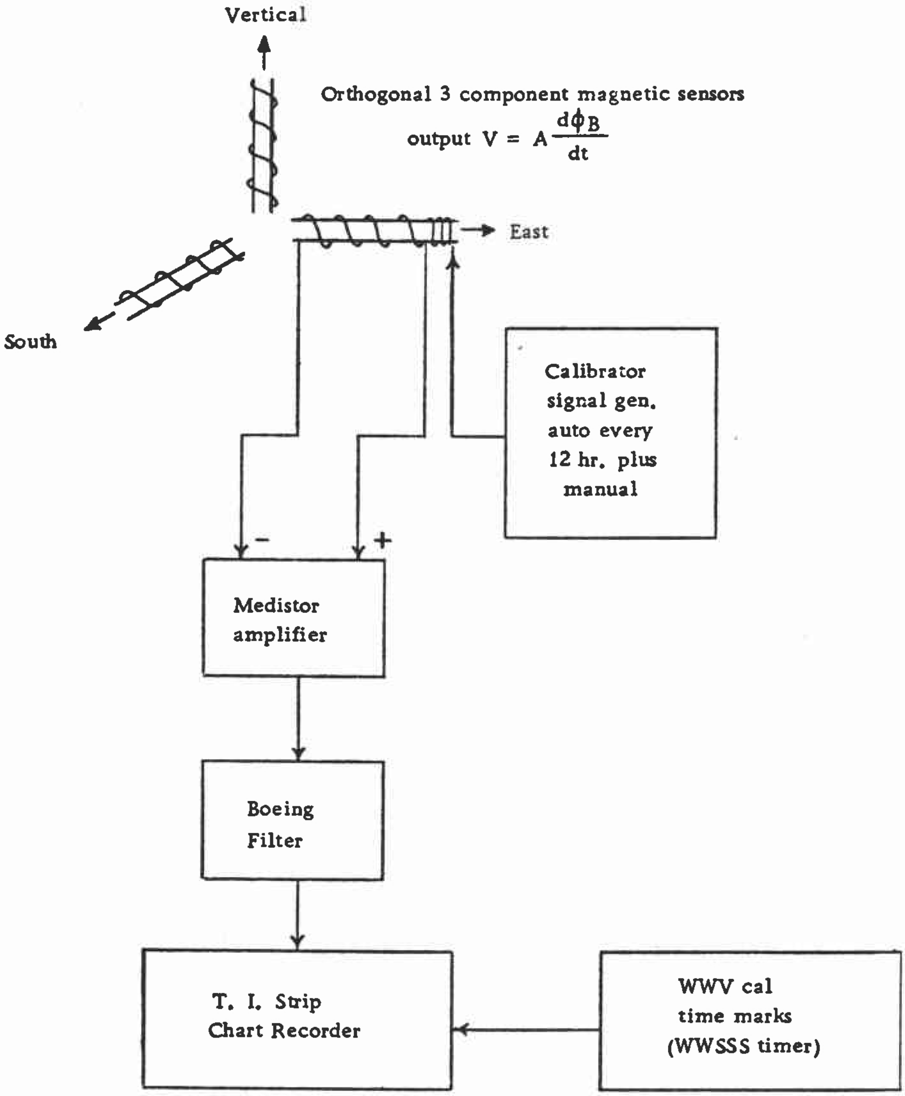
The telluric current pattern is distorted by lateral inhomogeneities and anisotropicities which commonly occur in the field. The conditions in the local region between and around the field electrodes are of primary importance, particularly where the electrodes have been placed within a local low resistivity anomaly. The electrical field readings are then abnormally low and the station yields an apparent resistivity value which can be grossly in error. Substantial apparent anisotropies may also be introduced by purely local conditions. Clearly, difficulties of this kind are common to all electrical methods using conductive contacts. The principal precautions against serious errors of this type are (1) to select the field stations with care to avoid local zones of low resistivity and anisotropicity, and (2) to scrutinize all conspicuously low and anisotropic apparent resistivity values by repeated measurements at several stations in the local area. This is of particular importance for the present project since the low resistivity anomalies are the primary exploration targets.

Directional and density inhomogeneities in the overhead ionospheric currents are further sources of errors. Usually, the interpretation of telluric and magneto-telluric data is based on the assumption of uniform and unidirectional source currents. Deviations from this idealized model lower the quality of the observational material and are perhaps the main cause of the often excessive scattering of observational magneto-telluric resistivity data. As indicated above, this matter is of particular concern with regard to the present project since such difficulties are likely to be enhanced by the distance between the magnetic base station and the electrical field stations. To minimize this effect, it is important to obtain field records for sufficiently long periods of time and to edit the data by rejecting sections with low magnetic-telluric coherency.

Instrumentation and Field Procedure

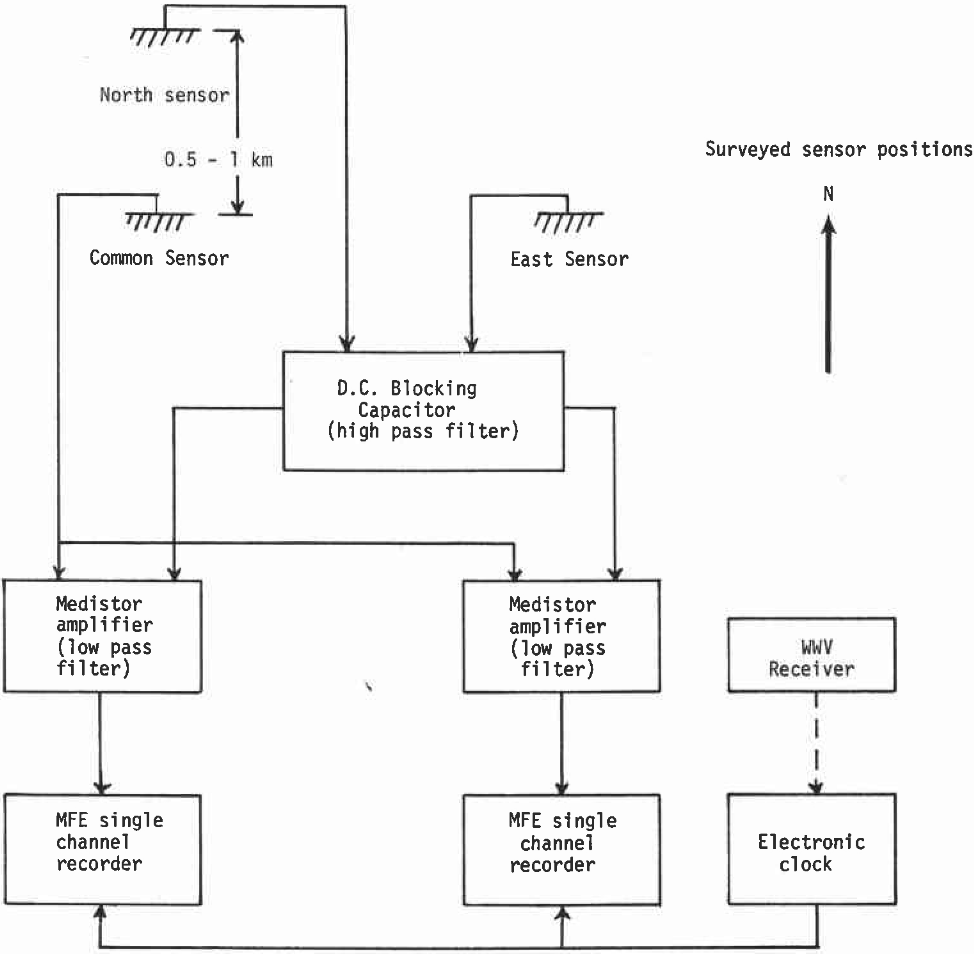
The instrumentation used on the present project consists of two separate parts, (1) the magnetic base station at Corvallis, and (2) the portable telluric field equipment. Block diagrams of the two systems are shown in Figures 2 and 3. The magnetic data aquisition system was provided by the Boeing Company, Seattle, Washington. A description of the magnetic sensors has been given by McNicol and Johnson (1964).

In brief, the magnetic sensors consist of three mumetal-cored induction coils each with 4.8×10^5 turns of wire. The diameter of the cores is 1 inch. The three coils were buried in the ground at the World Wide Standard Seismic Network Station at Corvallis, where the associated electronic equipment was housed, and were placed along three local orthogonal axes, geographic north, east and vertical. The station crystal clock provided an



Output: Voltage versus time proportional to magnitude of micropulsations

Figure 2. Magnetic data-acquisition system.



Output: Voltage versus time, each absolutely calibrated usually expressed mv/km

Figure 3. Telluric data-acquisition system.

absolute time reference. The amplified magnetic signals were recorded on Texas Instrument strip chart recorders. The magnetic system was calibrated by using an artificial oscillating magnetic field.

The telluric sensors, which consisted of three lead metal probes inserted into the ground at the individual field stations, formed an orthogonal L-shaped array where one arm pointed north and the other east. The length of the arms ranged from 200 to 500 meters, depending on local conditions. Each probe consisted of a piece of metallic lead plate 5 mm thick, 600 mm wide, and 1,000 mm long, rolled up into a tube 200 mm in diameter, and buried in the ground. Local D.C. fields were blocked out with a non-polar 20-micro farad capacitor. The output signals were amplified and recorded on a four-track strip-chart recorder. Each field station was occupied for a time sufficient to provide 1 to 2 hours of telluric field data.

Observational Data

A comparison of the individual telluric field records with simultaneous orthogonal magnetic base station records shows that the coherency generally varies considerably over the record length. In most pairs of simultaneous records, there were, however, individual wave packets or events in the 10- to 50-second period band which showed a good coherency and which could be considered likely to furnish representative values of the electromagnetic impedance ratio. It was, therefore, decided to base the data processing on such wave packets only and to apply the simple individual event method of Berdichevsky and Brunelli (1959) to obtain the impedance ratios at the various frequencies. The method has also been described by Keller and Frischknecht (1966, p. 246).

Usually, between 5 and 10 events could be processed for each pair of orthogonal field components. The impedance ratios obtained were then applied to derive an apparent resistivity with the help of the well-known basic equation for magneto-telluric investigations (see Keller and Frischknecht, 1966, p. 217),

$$\rho_a = (\mu_o T/2\pi)\ (E/B)^2 \qquad (1)$$

where ρ_a is the apparent resistivity, T is the period, $\mu_o = 4\pi \times 10^{-7}$ is the permeability of free space, E the amplitude of the horizontal electrical field, and B the amplitude of the orthogonal horizontal magnetic field, both amplitudes measured at the ground surface, all in MKSA units.

Many geological formations exhibit a substantial anisotropy, that is, the apparent resistivity depends on the direction in which the fields are measured. In the following, we therefore use the subscripts n and e for north-south and east-west, respectively, and refer to ρ_{an} as the apparent resistivity value based on E_n/B_e and to ρ_{ae} as the value based on E_e/B_n.

An illustration of the results is obtained by plotting the apparent resistivities derived from the individual component pairs against the event periods. Typical plots of this kind are given in Figure 4, which shows the processed apparent resistivity data from the Corvallis base station (12) and from South Klamath Hills (6) in the Klamath Falls region.

As indicated by the examples in Figure 4, the apparent resistivity data exhibit a considerable irregular scattering, which in most cases covers a relative range from 1 to 3; that is, the highest values are about three times as large as the lowest. At most stations, the maximums are observed in the 20- to 30-second period band.

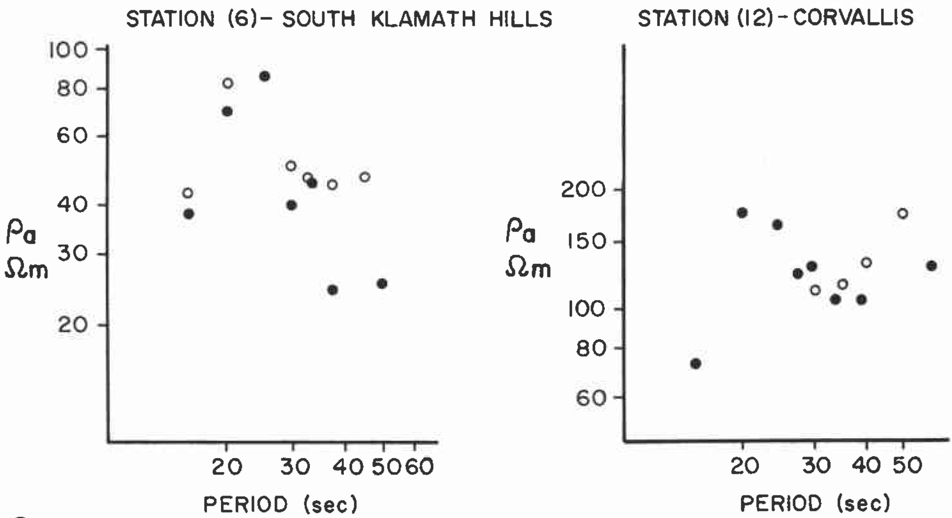


Figure 4. Apparent resistivities versus period for stations (6) and (12). Full circles represent ρ_{an}, the north-south resistivities, and the open circles ρ_{ae}, the east-west resistivities.

Scattering of this kind is frequently encountered in magneto-telluric work, and along the lines discussed above, we point out that the following causes may contribute to this situation: (I) Non-uniform source current fields; (II) enhanced non-coherency due to the distances between the magnetic base station and the individual field stations; (III) numerical errors introduced by the individual event analysis method; and (IV) instrumental errors. Obviously, all errors in the observed impedance ratios are enhanced by the squaring of the impedance ratio in equations (1).

At this juncture, it appears that the non-uniformities under (I) are a substantial cause of the scattering. Since the results obtained at the Corvallis base station exhibit a similar character as the other field stations, the distance factor mentioned under (II) does not appear to be a primary cause. We have still to evaluate the influence of the data-processing method listed under (III). The maximums observed in the 20- to 30-second band may partially be instrumental.

Preliminary Numerical Results

In view of the character of the observational material and since we are mainly interested in a fairly large-scale average resistivity at each station, there is at this time not much incentive to attempt a more elaborate interpretation of the present data. In our present analysis, we therefore rely on the simple procedure of taking averages over the apparent resistivity values observed in the 10- to 50-second period band for each direction at the individual stations. This procedure yields two values, $\bar{\rho}_{an}$ and $\bar{\rho}_{ae}$, for each station. The first is the averaged apparent resistivity in the north-south direction, and the second is the value for the east-west direction. These data are listed in columns (1) and (2) in Table 1. Moreover, the table also lists in column (3) the averages for the two directions. Since the penetration of telluric currents depends on the skin depth, the trend of the apparent resistivities with increasing periods gives a certain indication about the downward trend of the resistivity. This information is given in the last column of Table 1. The averaged resistivity from column (3) in Table 1 is plotted on the maps in Figures 5 and 6.

Data Evaluation and Discussion

A preliminary review of the data given in Table 1 and shown in Figures 5 and 6 can be summarized as follows. We will focus our attention on the averaged apparent resistivity data in column (3) of Table 1.

(1) Data from a total of 19 field stations are available. The average values given in column (3) of Table 1 vary from a low of 15 to a high of 360, that is, by a factor of 24. The variability is one order of magnitude greater than the scattering of the data at the individual stations.

(2) Six of the ten data obtained in the Klamath Falls area are well below 100 Ωm. With one exception, these are the lowest values observed on our project. This is of primary interest since Klamath Falls is an area of known geothermal activity (Peterson and McIntyre, 1970). Stations (6) and (7) which yield values of 60 and 40 Ωm, respectively, are close to geothermal surface manifestations. Moreover, stations (1), (3), and (9) to the northwest and north yield low values, particularly station (1). Since the Klamath Falls area is the only area with known geothermal display investigated by us, we conclude that our results exhibit an encouraging correlation with geothermal activity. Nevertheless, we have to emphasize that other non-thermal factors may also be involved, and in this respect we point out that there is an abrupt decrease in the observed resistivity from station (5) to station (6). Since the distance between these two stations is only 7 km, we surmise that local geological factors are of some importance.

Table 1. Average apparent resistivities for the 10- to 50-second period band

Station	Name	(1) North-south resistivities, $\bar{\varrho}_{an}$	(2) East-west resistivities, $\bar{\varrho}_{ae}$	(3) Average (1) and (2) (rounded off)	(4) Downward trend
Klamath Falls area					
(1)	Lake of the Woods	10 Ωm	20 Ωm	15 Ωm	D
(2)	Miess Lake	210	260	240	I
(3)	Indian Springs Flat	100	40	70	D
(4)	Lake Miller	40	420	230	U
(5)	Tulane	280	330	310	I
(6)	S. Klamath Hills	50	70	60	D
(7)	Noble	40	30	40	D
(8)	Nuss Lake	30	240	140	D
(9)	Swan Lake	10	130	70	D
(10)	Scranz	30	120	80	U
West-East profile					
(11)	Siletz	110	100	110	I
(12)	Corvallis	130	130	130	U
(13)	Sweet Home	120	200	160	I
(14)	Sisters	330	360	350	D
(15)	Hampton	140	130	140	U
(16)	Harney Basin	360		360	D
(17)	Vale-Negro Rock	40	10	25	D
(18)	Vale-E. Cow Hollow	70	330	200	D
(19)	Vale-Alkali Flats	220	170	200	U
Column average		120	170	150	

D - decreases; I - increases; U - uncertain

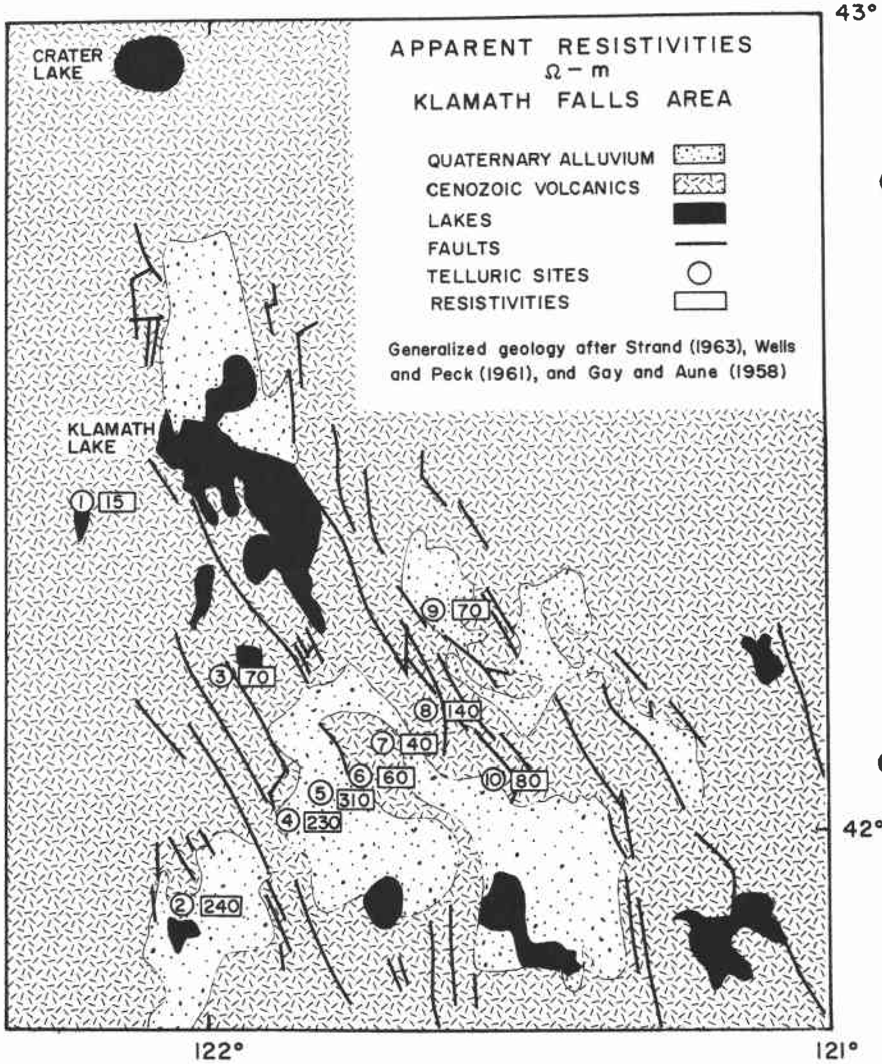


Figure 5. Average apparent resistivities in the Klamath Falls area listed in column (3) of Table 1.

(3) On the other hand, the resistivity values obtained so far in Klamath Falls are considerably above values observed by D.C. resistivity methods in known high-temperature geothermal areas (Banwell, 1970). The present data are, therefore, not indicative of typical high-temperature conditions there. The data are, however, too few to draw definite conclusions.

(4) The very low values observed at stations (1) and (17) are of particular interest although they cannot be correlated with any known

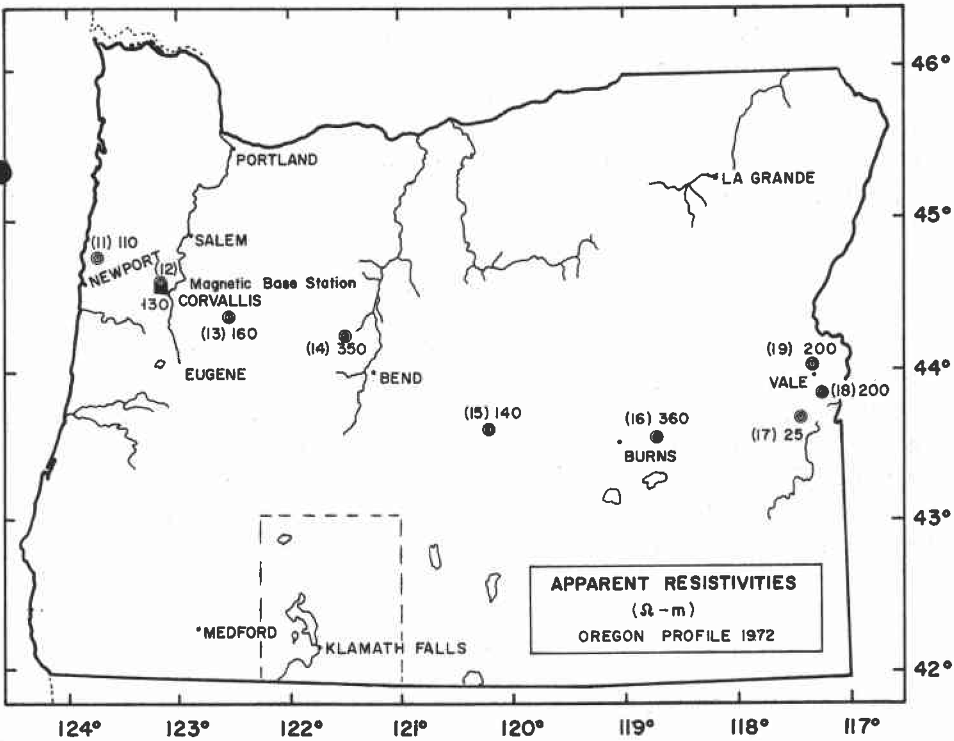


Figure 6. Average apparent resistivities on the profile from Siletz to Vale listed in column (3) of Table 1. The figure in brackets is the station number. The dashed line outlines the area of Figure 5.

local thermal surface display. A further investigation is definitely warranted.

(5) At ten of the stations the apparent resistivity decreases with increasing depth. In particular, this is true of the stations with low values and is very probably of significance with regard to geothermal anomalies.

(6) Six of the stations exhibit a very pronounced anisotropy involving ratios up to 10. There is little doubt that local effects at the station sites are important causes of some of the high ratios. On the other hand, it is noted that generally the east-west resistivities are higher than the north-south values. This appears to be a reasonable result since the general geological strike in the Klamath Falls and Vale areas is not far from being north-south.

(7) Because of the sparsity of stations along the Siletz-Vale profile, we are unable to comment on the distribution of apparent resistivities along the profile. It appears reasonable that relatively low values are observed in the coastal region and in the Willamette Valley. The values observed

east of the Cascades are typical of values observed in mafic Tertiary volcanics (Bodvarsson, 1950).

(8) We conclude that, in spite of obvious shortcomings, our preliminary results indicate that the telluric method applied has a potential of becoming a reconnaissance tool of significant interest in the exploration for geothermal resources.

Acknowledgments

This work was supported by the National Science Foundation under Grant GA-25896. We are also indebted to the Boeing Company, Seattle, WA; Weyerhauser Company, Tacoma, WA; Pacific Power and Light Company, Portland, OR; and the Oregon Department of Geology and Mineral Industries, Portland, OR, under Bureau of Mines grant SO 122129, for partial support of our work. N. V. Peterson, Oregon Department of Geology and Mineral Industries, provided valuable guidance in selecting field stations.

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WASTE RECYCLING FILM AVAILABLE FROM MINES BUREAU

The recycling of urban and industrial waste is the subject of "Wealth out of Waste," a 16mm film now available from the U.S. Bureau of Mines.

The film shows why waste disposal has become a national problem and details the technology, including Bureau-developed processes, which can separate the refuse into reusable components for manufacture into new products or for use in energy production.

Prints of the 27-minute sound and color film are available on free, short-term loan to schools, civic, professional, business, and scientific organizations interested in resource development and conservation. Write Motion Pictures, Bureau of Mines, 4800 Forbes Avenue, Pittsburgh, Pa., 15213. Borrowers should state they have a 16mm sound projector and an experienced operator; they will be responsible for return postage and for any damage to the print beyond normal wear.

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POTENTIAL-HAZARDS MAP OF MOUNT RAINIER PUBLISHED

"Potential hazards from future eruptions of Mount Rainier, Washington," by Dwight R. Crandell is a map with descriptive text that shows by color and pattern the distribution of mudflows and tephra (airborne volcanic debris) and the varying degrees of risk to human life in those areas in the event of a volcanic eruption. The map, at a scale of 1:125,000, and text are on a single sheet designated as Miscellaneous Geologic Investigations Map I-836. The publication is for sale by the U.S. Geological Survey Distribution Section, Federal Center, Denver, Colorado, 80225 for 75 cents.

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PROSPECTING WORKSHOP OFFERED

Clackamas Community College is sponsoring a Prospecting Workshop in Room B-104 on the evening of August 23 at 7:00 p.m. An all-day field trip will be held on August 24 in the Quartzville area. Both the lecture and field trip will be led by Jerry Gray of the Department staff. Tuition for the workshop is $12.00 and pre-registration is recommended. Additional information may be obtained by calling 656-2631, ext. 311.

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FIRST VOLUME OF OREGON LAKES INVENTORY PRINTED

"Lakes of Oregon, Volume 1, Clatsop, Columbia, and Tillamook Counties" by R. B. Sanderson, M. V. Shulters, and D. A. Curtiss, has been issued as an open-file report by the U.S. Geological Survey in cooperation with the Oregon State Engineer. The 95-page, bound booklet describes 33 lakes in the three counties. Each lake is briefly described as to location, size, use, water temperature, and other pertinent characteristics, and is illustrated with an aerial photograph and a map showing shape and depth. Volume 1 is the beginning of a much-needed inventory of Oregon Lakes that will be a very useful reference. The volume is printed in limited supply. Information concerning its availability can be obtained from the U.S. Geological Survey Water Resources Division in Portland or from the Oregon State Engineer's office in Salem.

* * * * *

JOHN ALLEN RETIRES FROM PORTLAND STATE UNIVERSITY

Dr. John Eliot Allen has retired from the faculty of Portland State University after 17 years as head of the Earth Sciences Department and a long career that had considerable influence on geological education and research.

Dr. Allen had stepped down as chairman and head of the Earth Sciences Department at PSU last year, continuing to teach during the recently ended school year. He has a long list of publications both in the scientific journals and in materials written for the layman. He received his bachelor and master's degrees from the U of O and his doctorate from the University of California, Berkeley. Between 1939 and 1944 he was a geologist with Oregon Department of Geology and Mineral Industries. He is succeeded as head of the Department by Dr. Richard E. Thoms, who joined the Earth Sciences Department staff in 1964.

* * * * *

AVAILABLE PUBLICATIONS

(Please include remittance with order; postage free. All sales are final - no returns. Upon request, a complete list of Department publications, including out-of-print, will be mailed)

BULLETINS

8. Feasibility of steel plant in lower Columbia River area, rev. 1940: Miller . . . $0.40
26. Soil: Its origin, destruction, preservation, 1944: Twenhofel 0.45
33. Bibliography (1st suppl.) geology and mineral resources of Oregon, 1947: Allen. . 1.00
35. Geology of Dallas and Valsetz quadrangles, Oregon, rev. 1963: Baldwin. . . . 3.00
36. Papers on Tertiary foraminifera: Cushman, Stewart & Stewart. vol. 1 $1.00; vol. 2 1.25
39. Geology and mineralization of Morning mine region, 1948: Allen and Thayer . . 1.00
46. Ferruginous bauxite deposits, Salem Hills, 1956: Corcoran and Libbey 1.25
49. Lode mines, Granite mining district, Grant County, Oregon, 1959: Koch . . . 1.00
52. Chromite in southwestern Oregon, 1961: Ramp 3.50
57. Lunar Geological Field Conf. guidebook, 1965: Peterson and Groh, editors . . . 3.50
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60. Engineering geology of Tualatin Valley region, 1967: Schlicker and Deacon . . . 5.00
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64. Geology, mineral, and water resources of Oregon, 1969 . . . . 1.50
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