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# CONTROLLED-SOURCE EM EXPERIMENT AT MT. HOOD, OREGON

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## ABSTRACT

As part of a joint federal and state geothermal resource assessment of the Mt. Hood stratovolcano in Oregon, Lawrence Berkeley Laboratory performed a series of deep electromagnetic soundings over the frequency range 0.1 to 200 Hz. The soundings, performed with a large-moment horizontal loop system (EM-60), permit an analysis of earth resistivity in the region. Horizontal loop sources were placed at three locations around the volcano and magnetic fields were recorded at nine receiver sites located between 1 and 2 km from the individual sources. Square wave currents of up to 150 A (p-p) were impressed into the loops and at each receiver location amplitude and phase spectra or ellipticity of normal and radial magnetic fields were analyzed to obtain one-dimensional resistivity models. Layered earth inversions yield similar two-layer models of a resistive surface layer, 0.5 to 0.7 km thick, overlying a conductive layer of indeterminate thickness. A sounding at the north side of the mountain shows a 3 ohm•m layer at a depth of 0.7 km. This result agrees well with magnetotelluric results in the same area (Goldstein and Mozley, 1978). The cause of the high conductivity zone may be high-temperature, water-saturated conditions beneath the cold meteoric water zone.

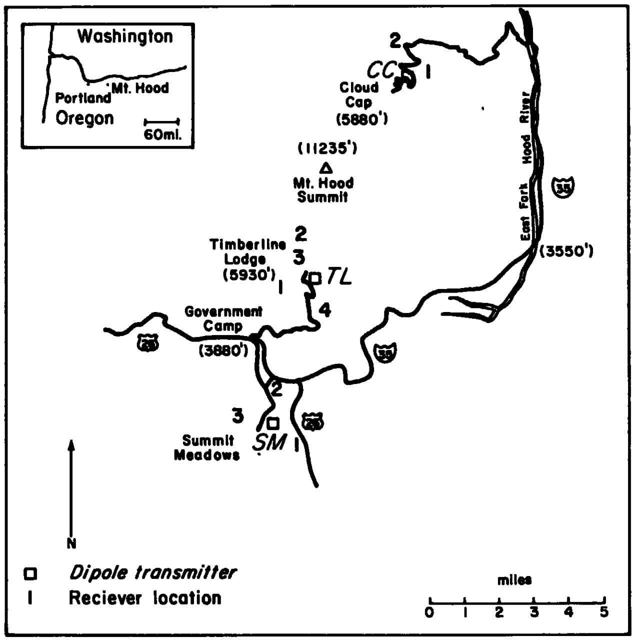

Fig. 1. Project location map, Mt. Hood, Oregon.

## INTRODUCTION

As part of a geothermal research project at Mt. Hood, Oregon, the U. S. Department of Energy, U. S. Geological Survey, U. S. Forest Service, and the State of Oregon have undertaken a series of geological, geochemical, and geophysical studies (Fig. 1). Working for DOE/Division of Geothermal Energy, LBL was responsible for geochemical and electrical resistivity surveys (Wollenberg *et al.*,1979; Goldstein and Mozley, 1978; Goldstein, *et al.*,1978). These and other coordinated studies were designed to evaluate the geothermal resource potential at Mt. Hood and to help formulate an exploration strategy that might be applicable to other volcanoes in the High Cascade Range.

Because of terrain, access, and high surface (contact) resistance, conventional dc resistivity surveys were impractical for deep exploration at Mt. Hood. We therefore embarked on a program of remote reference magnetotellurics in 1977 (Goldstein and Mozley, 1978) followed by a controlled-source electromagnetic sounding program in 1978. This paper will deal primarily with the deep electromagnetic soundings which were conducted with the large-moment, horizontal-coil system developed by LBL and the University of California, Berkeley (Morrison *et al.*, 1978). The system, called the EM-60 because of the 60-kW motor generator that energizes the transmitter loop, was operated at several sites on the flanks of the volcano during August 1978 (Fig. 1).

## GEOLOGY OF MT. HOOD

Mt. Hood is a Pleistocene composite andesitic stratovolcano rising some 2500 m above the surrounding terrain. Development of the main body of the cone was completed about 20,000 years ago (Wise, 1968) and renewed volcanism occurred about 12,000 years ago when several domes were extruded near the surface (Crandell and Rubin, 1977). Further episodes of volcanism caused the collapse of the south rim of the crater roughly 1600 years ago; minor eruptions were reported in 1859 and 1865 (Folsom, 1970).

Mt. Hood is located along a north-south volcanic trend with most of the other Cascade volcanoes of Oregon and Washington. This trend may be associated with a fault zone located along the western edge of the High Cascades (Thayer, 1937; Callaghan, 1933). Allen (1966) believes that Mt. Hood lies within a graben formed by the Hood River/Green Ridge faults on the east and unnamed faults recognized by Thayer and Callaghan to the west.

The predominant surficial material covering Mt. Hood is andesitic clastic debris. The extensive lava flows predating the debris are predominantly horneblende andesite, whereas more recent extrusions on the north and northeast flanks of the volcano are olivine basalt and olivine andesite. Several EM soundings were performed within 3 miles of the summit on clastic debris, which overlie the andesite flows. Other soundings were made in the Summit Meadows area, over lake sediments at the southern base of the volcano.

## FIELD SURVEYS

Three transmitter sites were occupied for the EM experiment: (1) Summit Meadows (SM), immediately south of the warm water emanations at Swim Warm Springs; (2) Timberline Lodge (TL), near the lodge on the relatively accessible south flank; and (3) Cloud Cap (CC), near the eruptive center on the northeast flank where anomalous resistivities were indicated by MT survey results.

Two to four receiver sites were occupied for each transmitter (Fig. 1). In order to create a large dipole moment (greater than $10^6$ MKS), three turns of #6 welding cable were laid out, usually in a square, 100 m on a side. A square-wave current at discrete frequencies between 0.1 and 200 Hz was impressed into the transmitter loop. Peak-to-peak current varied between 150 A at low frequencies to less than 40 A at the highest frequencies where inductive effects limit the current. A schematic of the EM-60 system is shown in Figure 2.

At receiver locations, 1 to 2 km from the transmitter, magnetic fields were detected with a three-component cryogenic magnetometer oriented to detect the vertical or normal field ($H_N$), the radial field ($H_R$), and the tangential field ($H_T$). Signals were amplified and band-passed filtered for anti-aliasing and signal-to-noise improvement. The signals were then field processed by means of a multichannel, microprocessor-controlled wave analyzer that stacked a specified number of cycles and yielded an average "raw" amplitude and an average phase relative to current phase in the loop. Spectral estimates were made automatically at the fundamental frequency and at a specified number of the higher order odd harmonics, usually the third, fifth, and seventh. Although the system can operate to $10^{-3}$ Hz, the lowest frequency conveniently obtained is $10^{-1}$ Hz because of the signal-to-noise, which decreases roughly as $f^2$ at low frequencies.

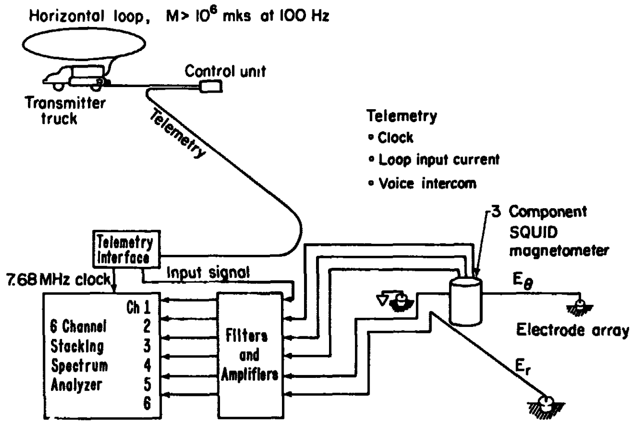

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Fig. 2. System schematic of horizontal-loop electromagnetic system EM-60

Because there is no simple way to calculate an apparent resistivity, as in dc resistivity, basic interpretation must be done by comparing field curves with precalculated curves. Usually amplitude-phase or ellipticity spectra are fit to one-dimensional layer model curves by trial and error or direct inversion.

Field and laboratory processing procedures for the Mt. Hood survey were complicated by cultural EM noise and rugged terrain. High man-made noise at 60 and 180 Hz required use of notch filters whose effect on neighboring frequencies had to be carefully determined before the spectra could be inverted. More formidable was the terrain problem, which forced us to lay out loops TL and CC on an irregular and inclined surface. Because the primary field from these loops has both vertical and horizontal components, it was necessary to rotate the $H_N$ and $H_R$ fields mathematically to find the orientation for which $H_N$ was normal to the plane of the loop. This rotation introduced some error into the spectra, especially into the radial component whose amplitude is normally very small at low frequency. Another approach that we successfully tested was to derive the ellipticity of the observed $H_N$ and $H_R$ components, which are independent of loop inclination, and to invert solely on ellipticity.

## RESULTS

Of the nine soundings made, only four have been successfully analyzed in terms of layered earth models. Two soundings were not interpretable with certainty because the intervening terrain between transmitter and receiver caused distortion of the field curves. The three soundings from loop SM will have to be interpreted in terms of two-dimensional models. Examples of analyzed spectra are shown in Figures 3, 4, and 5 for receiver station TL2 and Figures 6, 7, and 8 for receiver station CC1. Two slightly different interpretations are shown for each receiver site. One is derived from a combined inversion using the four components of amplitude and phase of the normal and radial fields with the amplitudes normalized for the primary field. We also show the inversion based on ellipticity with the ratio of minor to major axes of the ellipse traced out by $H_R$ and $H_N$.

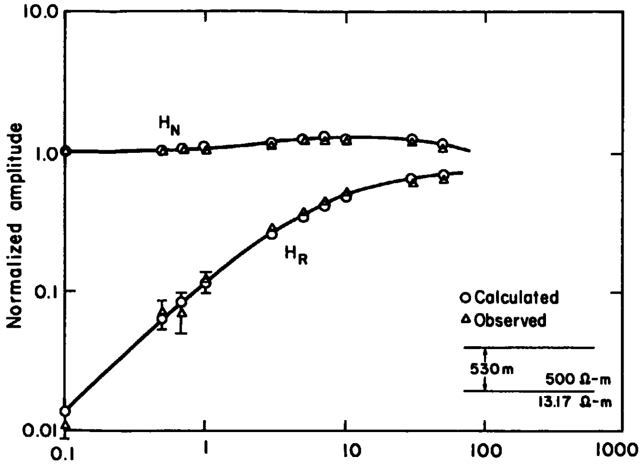

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Fig. 3. Magnetic-field amplitude spectra sounding TL2.

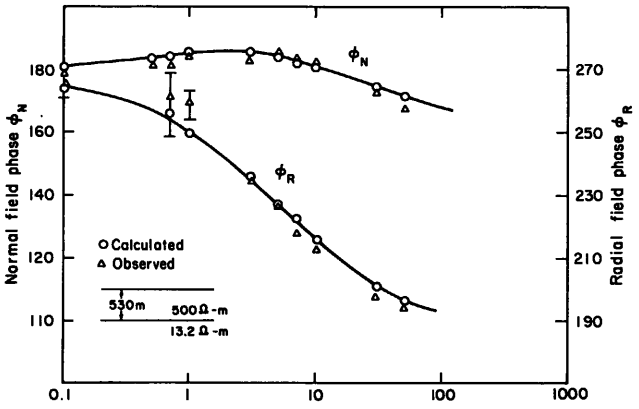

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Fig. 4. Magnetic-field phase spectra sounding TL2.

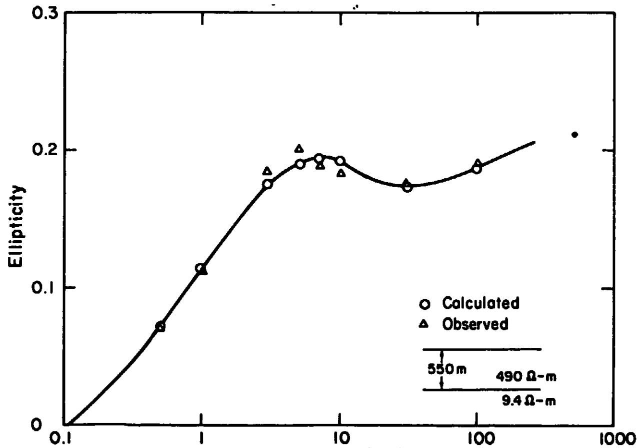

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Fig. 5. Magnetic field ellipticity sounding TL2.

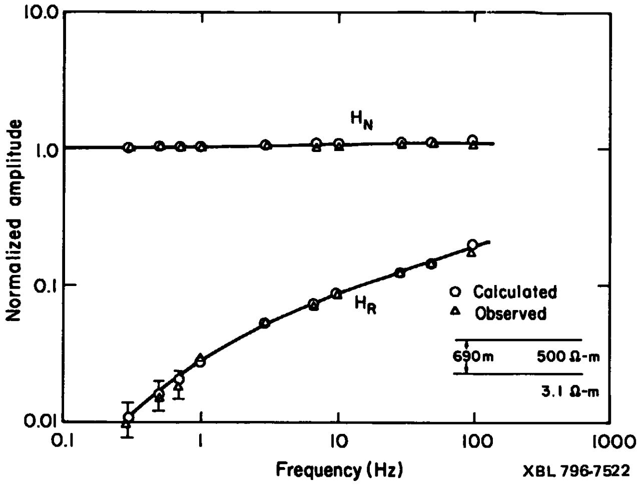

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Fig. 6. Magnetic-field amplitude spectra sounding CC1.

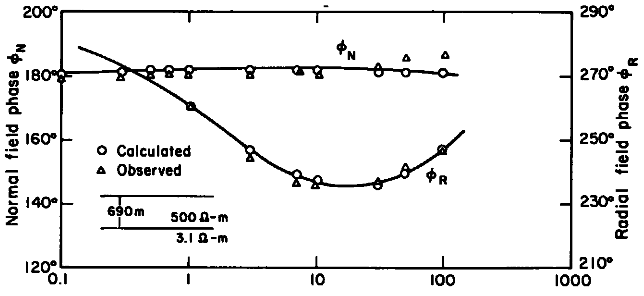

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Fig. 7. Magnetic-field phase spectra sounding CC1.

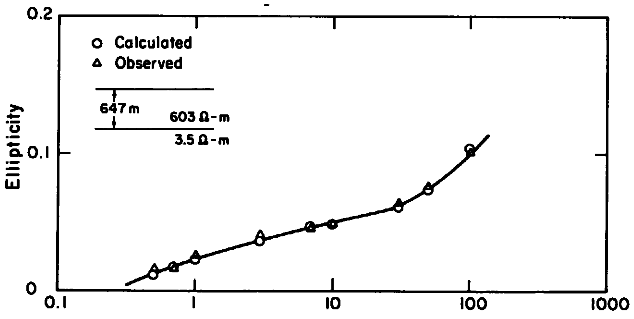

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Fig. 8. Magnetic-field ellipticity sounding CC1.

For each inversion, a two-layer earth is indicated. The inversion program reduced all our initial three-layer models to two layers. A more resistive zone below the second layer, indicated by MT (Goldstein et al., 1978) is not resolved by the technique, mainly because of the relatively small transmitter-receiver separation used.

The models for sounding TL2 are typical of those for the other soundings near Timberline

Lodge. A resistive surface layer exists to a depth of 0.5 km, underlain by a more conductive zone of undetermined thickness. Amplitude-phase and ellipticity results are very similar, implying either that the rotation errors are small or that low-frequency data do not strongly influence the model.

The inversion of sounding CC1 (Figs. 6 to 8) yields a model for the Cloud Cap area that is similar to the Timberline model. The resistive surface layer is thicker, but more important, the second layer appears to be unusually conductive. The results from station CC1 may be compared with a one-dimensional MT interpretation for the same area, shown in Figure 9 (Goldstein and Mozley, 1978). Above 1.0-km depth, MT and EM interpretations show good agreement. Resistivities and thicknesses for the first layer agree particularly well between MT and the EM ellipticity results.

## DISCUSSION

The test of the EM-60 at Mt. Hood has demonstrated that a large-moment controlled-source EM system can be employed successfully in rugged areas and on talus slopes where dc resistivity surveys become difficult to carry out. The good agreement between MT and EM results at Cloud Cap gives us confidence in our ability to interpret the EM data despite imperfect knowledge about the relative orientation of transmitter dipole moment and receiver axis.

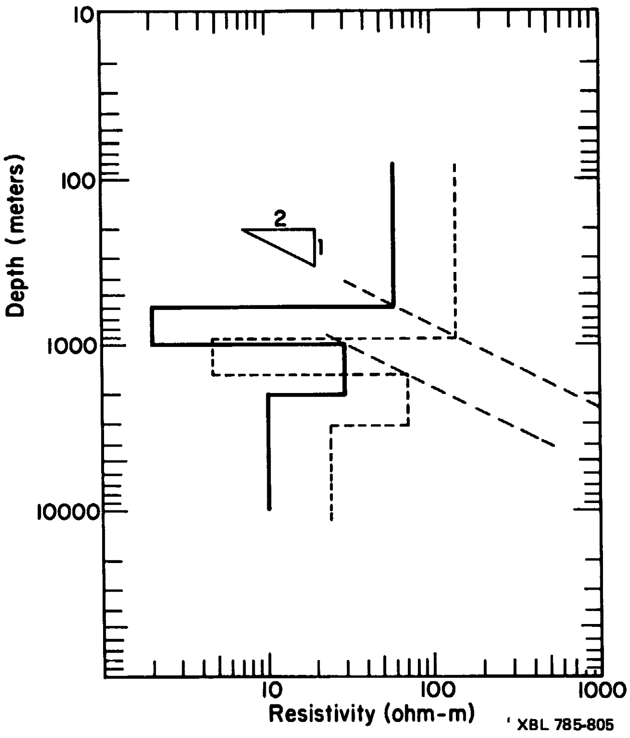

Fig. 9. Range of one-dimensional resistivity models that fit magnetotelluric sounding data for a site near CC1 (from Goldstein and Mozley, 1978).

Because of limited drilling and subsurface temperature information, we can not yet give a substantiated geological explanation for the subsurface resistivities. The high-resistivity surface layer probably represents the shallow zone of cold meteoric water moving downslope through permeable ash and block flows. The low-resistivity second layer may represent a water-saturated zone of higher temperature, containing meteoric water that has been heated high on the mountain. Chemical geothermometers of warm water at Swim Warm Springs indicate that the maximum temperature encountered may be from 150° to 200°C (Wollenberg *et al.*, 1979). The unusually low resistivity of the second layer beneath Cloud Cap (2 to 3 ohm•m) has raised the speculation that the subsurface water temperature may be enhanced by residual heat from the Cloud Cap eruption. A temperature hole is planned for this area in 1979 (J. Robison, USGS, personal communication).

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