ELECTROMAGNETIC INDUCTION IN GEOTHERMAL FIELDS AND VOLCANIC BELTS

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Abstract. This review covers electromagnetic studies in geothermal and volcanic regions presented in the literature since 1983. It has been arranged by geographical areas, emphasizing where possible the data gathering, the interpretation techniques and the results of each study. The main conclusions of this review are: In all the surveys, people are measuring the complete MT impedance tensor. However, in general, this information is not being used in the interpretation mainly because of the poor quality of the data. This unfortunate situation originates by the presence of strong noise in the surveyed area and generally, by the lack of use of the remote reference technique. Crews with equipment and techniques that can gather data of very good quality, generally perform very detailed interpretations using most of the gathered information. Other groups that collect noisy data oversimplify the interpretation by using only one mode or averaging the resistivity of both modes and interpreting the results using simplified 1-D interpretations. At the interpretation stage, most of the mid-crustal conductors identified are being associated to the presence of trapped water of magmatic origin. In general, magma chambers are not being detected, probably because either they are absent or because there is a lack of resolution of the electromagnetic methods to detect them.

Introduction

This review is intended to cover the period since Berktold's (1983) paper on electromagnetic studies in geothermal regions. He presented a thorough review of the physical characteristics of geothermal fields, and covered technical aspects on the use of electromagnetic methods in these regions. Wright *et al.* (1985) has also reviewed geophysical exploration of geothermal resources. Chave and Booker (1987) gave a complete review on the general subject of electromagnetic (EM).

Since 1983, there has been an impressive improvement in EM instrumentation used worldwide, particularly in the development of better sensors and advances in electronics and hardware. It has become less expensive to have access to portable computer-controlled equipment everywhere. Also, there has been substantial progress in the processing and interpretation of EM data (Booker, 1988). Perhaps due to global economic restrictions, there has also been a tendency for groups to work together and integrate different techniques to study interesting areas in the world. This approach has gained support by funding agencies, both in America and Europe.

I have arranged the presentation by geographical areas. I have tried to emphasize, where possible, the data gathering and the interpretation techniques used, together with the major findings from each area. As it always happens in papers

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of this kind, I may have inadvertently missed some important work. Therefore, I apologize for any omissions I may have made.

North America

Kurtz *et al.* (1986, 1990), collected magnetotelluric MT and geomagnetic depth sounding (GDS) data at 25 locations across Vancouver Island, Canada, over the subducting Juan de Fuca Plate, along the line where the Canadian Lithoprobe Program obtained detailed seismic profiles. A one-dimensional (1-D) inversion of the data shows a conducting layer whose top coincides with a seismic reflector interpreted as the upper surface of the Juan de Fuca Plate. They also present a two-dimensional (2-D) model consistent with the MT and GDS data, and relate the conductor to substantial amounts of sediment filled with saline fluids. Stanley *et al.* (1987) used MT and geomagnetic variation results to map a high conductivity anomaly in the southern part of the Washington Cascades. The MT data were fitted using a 2-D model derived by trial and error using a forward modeling algorithm. The anomaly is located within the triangle formed by the volcanos Mt. Rainier, Mt. St. Helen, and Mt. Adams. The anomaly is associated with conductive strata with resistivities in the range of 1–4 Ω-m and thickness of more than 15 km. These conductive rocks are found 2–8 km beneath the overlying, more resistive, volcanic and sedimentary rocks of the upper crust. This conductive anomaly is interpreted by the authors as a compressed forearc basin/accretionary prism complex of probable Eocene time, caused by the accretion of a large seamount complex (Siletzia).

The Electromagnetic Study of the Lithosphere and Asthenosphere Beneath Juan de Fuca Plate (EMSLAB-Juan de Fuca) experiment was designed to investigate the electrical structure of the entire Juan de Fuca Plate and the adjacent continental section under which it has been subducted. The experiment had a broad international participation from eight countries. Its main phase took place during the summer of 1985. Eighty soundings were measured in 1986 on an E–W 200 km profile, known as the Lincoln line, running across Central Oregon from the Pacific coast to the Basin and Range area, as shown in Figure 1a.

The measurements were made using four wide band MT systems using remote reference and in-field processing, and with long period equipment at several sites. Data from 39 representative sites on this profile have been modeled, inverted and interpreted. Wannamaker *et al.* (1989b), Jiracek *et al.* (1989), Livelybrooks *et al.* (1989) and Martinez *et al.* (1987), gave a full description of the field operation, the data characteristics, and presented 2-D interpretations of the data. In spite of the very careful site selection to place the line across a 2-D structural setting and probably because of finite strike length effects in the N–S TE data, it was not possible to find a 2-D model that would fit both modes in a satisfactory manner. Wannamaker *et al.* (1984) have shown that two-dimensional modeling of TM data across simple, elongated three-dimensional structures yields accurate resistivity cross sections, even when the profile is not close to the center. In Figures 1b and 1c, the 2-D models obtained by Wannamaker *et al.* (1989a, b) and Jiracek *et al.* (1989) are shown. The Wannamaker *et al.* (1989b) resistivity model was obtained by trial and error fitting of the data using a finite element forward algorithm, Jiracek *et al.* (1989) used Rodi's 2-D inversion algorithm (Jiracek *et al.*, 1987). Obviously, there are many similarities in both models. There is a low resistivity layer dipping inland at approximately 20°, extending from 12 km depth under the Oregon Coast to 30–40 km depths under the Willamette Valley (WV). This feature may be the top of the subducting Juan de Fuca plate. The low resistivity may be caused by residual sediments and pore water in them. Other important conductor occurs at depths of 30 km under the very resistive Western Cascades. The contact between the older Western Cascades and the active High Cascades is also conductive. Under the High Cascades and to the east, under the Deschutes Basin, the conductor thickens by a factor of six. These pronounced conductors could represent a concentration of water-rich fluids, that have risen from the surface of the subducted plate. The top of the conductor could be controlled by temperature: mineral hydration and silica precipitation mechanisms of permeability sealing appear to occur at 400–450°C.

Mozley *et al.* (1986) report on the interpreting of telluric and magnetotelluric data gathered around and as close as possible to the Mt. Hood, Oregon, volcano. Each setup consisted of a full tensor MT base, two remote telluric stations and a remote magnetic station. They obtained six clusters of data with the given setup. In order to avoid bias in the calculations of the impedance tensor due to topographic effects, they estimated the topographic corrections at each site. Using a D.C. forward modeling scheme, the electric field over the digitized terrain for each polarization mode was calculated and with this solution, a distortion matrix to remove this effect was estimated. To interpret the MT data, they used 1-D approximations where applicable and three-dimensional (3-D) simulations to understand the shape of the polarization diagrams and the calculation of residual phases, as shown in Figures 2a and 2b. The residual phase is defined as the absolute value of the impedance phase, calculated as a function of rotation angle, minus the minimum phase for all angles of rotation at each frequency. The resulting diagram shows this parameter to be extremely sensitive to conductor strike (Figure 2b). They also used 2-D modeling for a profile perpendicular to strike (Figure 2c), which shows a deep conductor 10 km thick at 12 km depth. Although the use of 1, 2 and 3-D interpretations of the MT data did not yield a complete model for the region, discrete anomalous areas were identified, as shown in the composite model of Figure 2d. Shallow conductors at depths of 500 m probably represent saturated and relatively permeable pyroclastics. Controlled-source EM soundings (Goldstein *et al.*, 1982) support such an interpretation. The lateral boundaries of the shallow conductors were determined on the basis of multidimensional modeling, using tippers and induction arrows in the 1–5 Hz

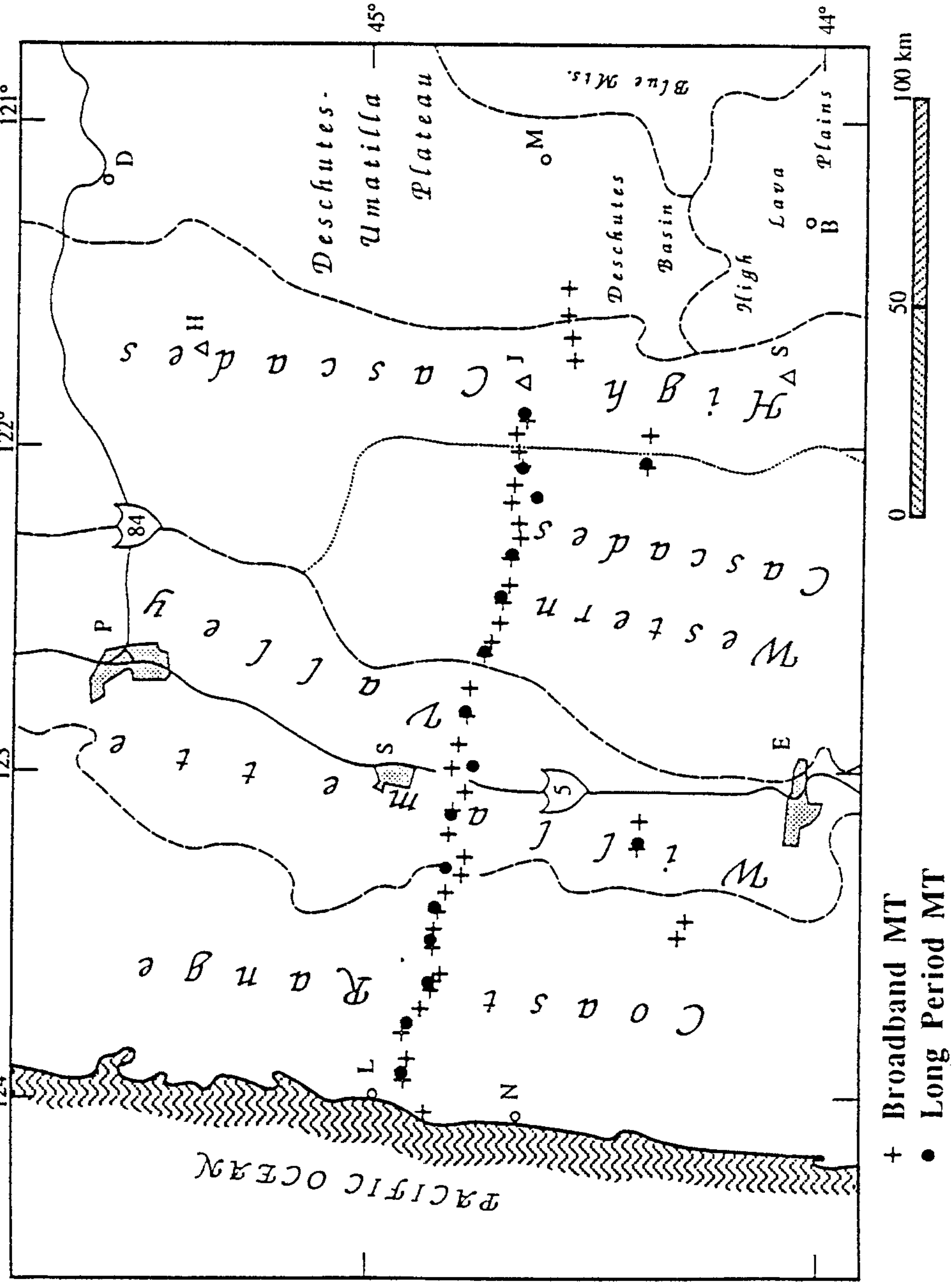

45°
44°
121°
122°
123°
124°
Deschutes-Umatilla Plateau
Blue Mts.
Deschutes Basin
High Lava Plains
High Cascades
Western Cascades
Willamette Valley
Coast Range
PACIFIC OCEAN
84
5
0
50
100 km
+ Broadband MT
• Long Period MT

Fig. 1(a).

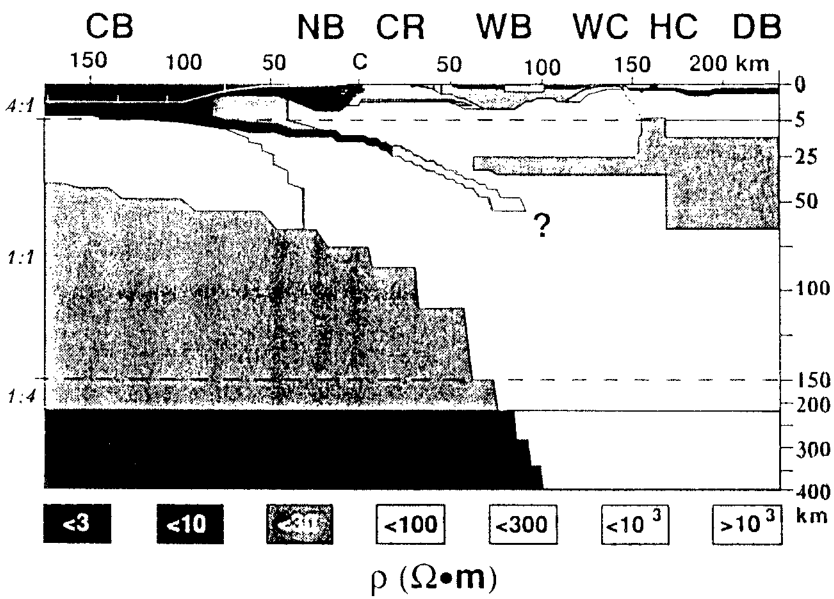


Fig. 1(b).

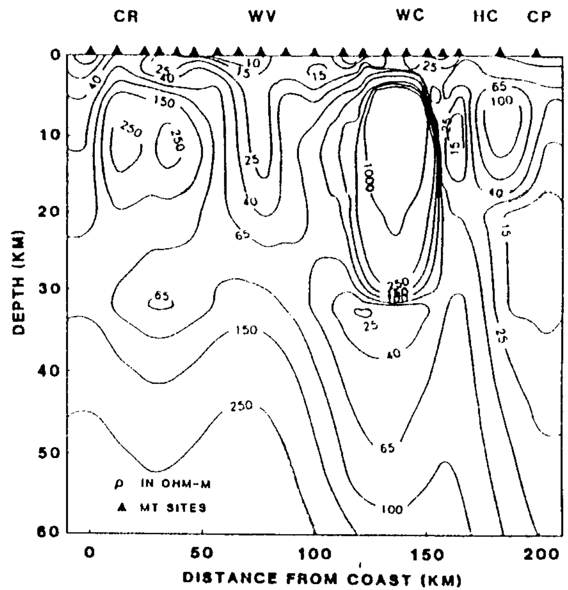


Fig. 1(c).

Fig. 1. (a) Wannamaker *et al.* (1989a). Broadband and long periods MT sounding along the Lincoln line, in the State of Oregon. (b) Wannamaker *et al.* (1989b). Resistivity cross-section derived from forward modeling of the EMSLAB MT data along the Lincoln line. Resistivities have been grouped in half-decade intervals for gray-scale display. Note changes in vertical exaggeration. Important physiographic regions crossed include the Cascadia Basin (CB), Newport Basin (NB), Coast Range (CR), Willamette Basin (WB), Western Cascades (WC), High Cascades (HC), and the Deschutes Basin (DB). (c) Jiracek *et al.* (1989). Smooth, two-dimensional geoelectric model derived from inversion of $\rho_{yx} - \phi_{yx}$ from the 20 odd-numbered land MT sites along the entire EMSLAB Lincoln Line.

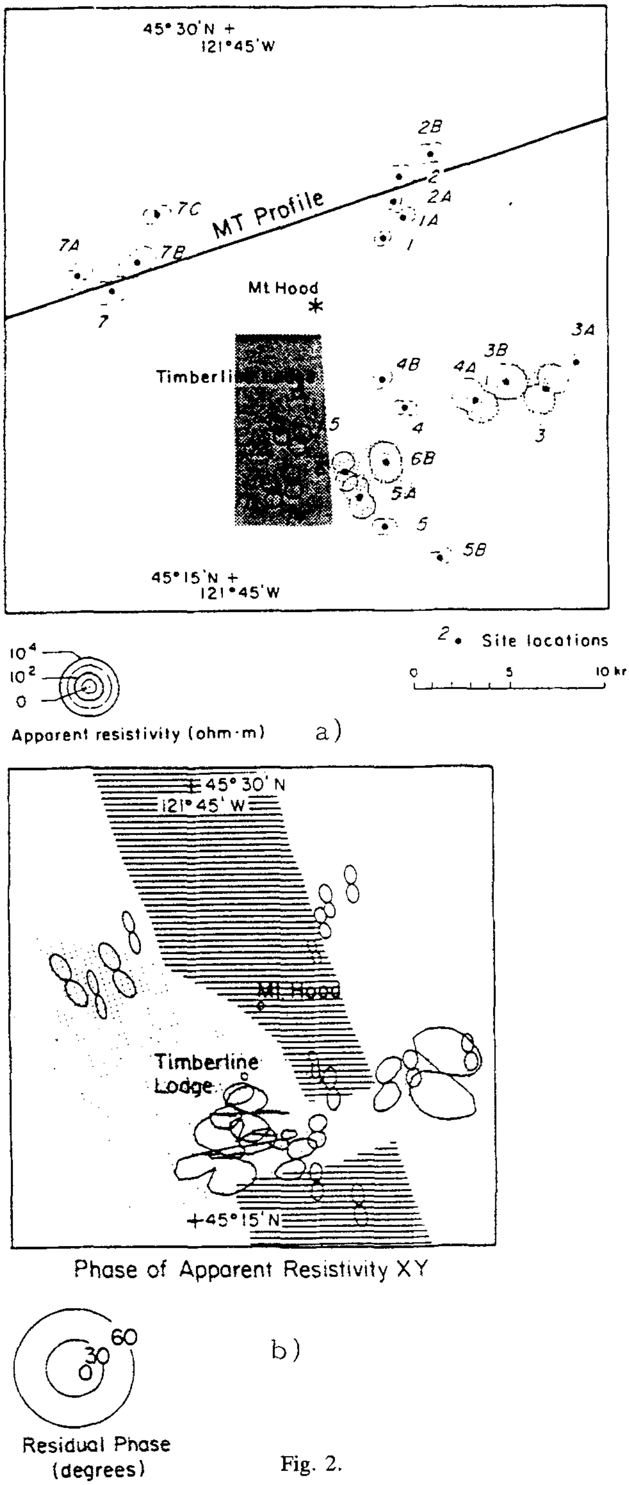
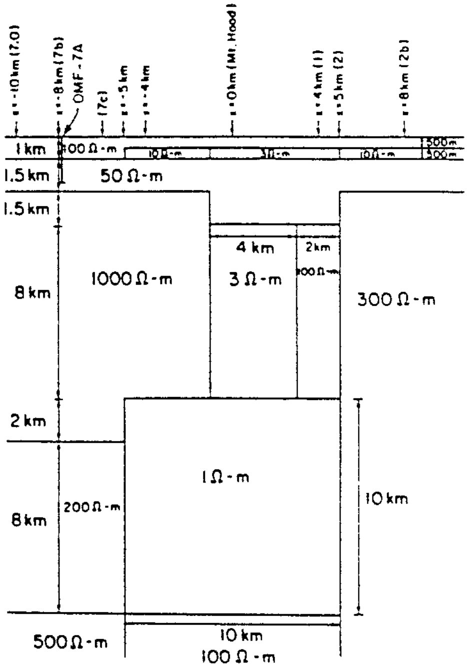
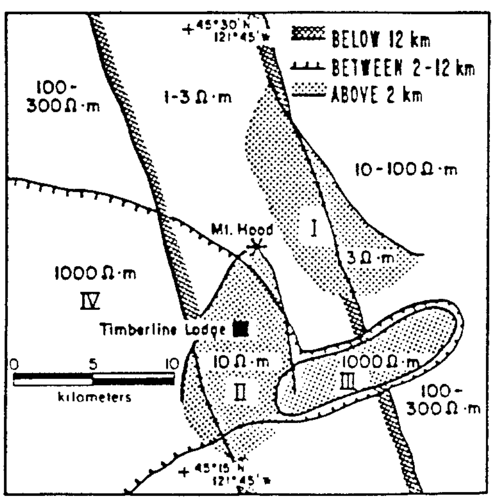

45° 30'N +
121°45'W
MT Profile
2B
2
2A
1A
1
7C
7A
7B
7
Mt Hood
Timberline Lodge
3A
3B
4B
4A
4
3
5
6B
5A
5
5B
45°15'N +
121°45'W
2 • Site locations
0 5 10 km
10^4
10^2
0
Apparent resistivity (ohm·m)
a)
45° 30' N
121° 45' W
Mt Hood
Timberline Lodge
45° 15' N
Phase of Apparent Resistivity XY
60
30
0
Residual Phase (degrees)
b)

Fig. 2.

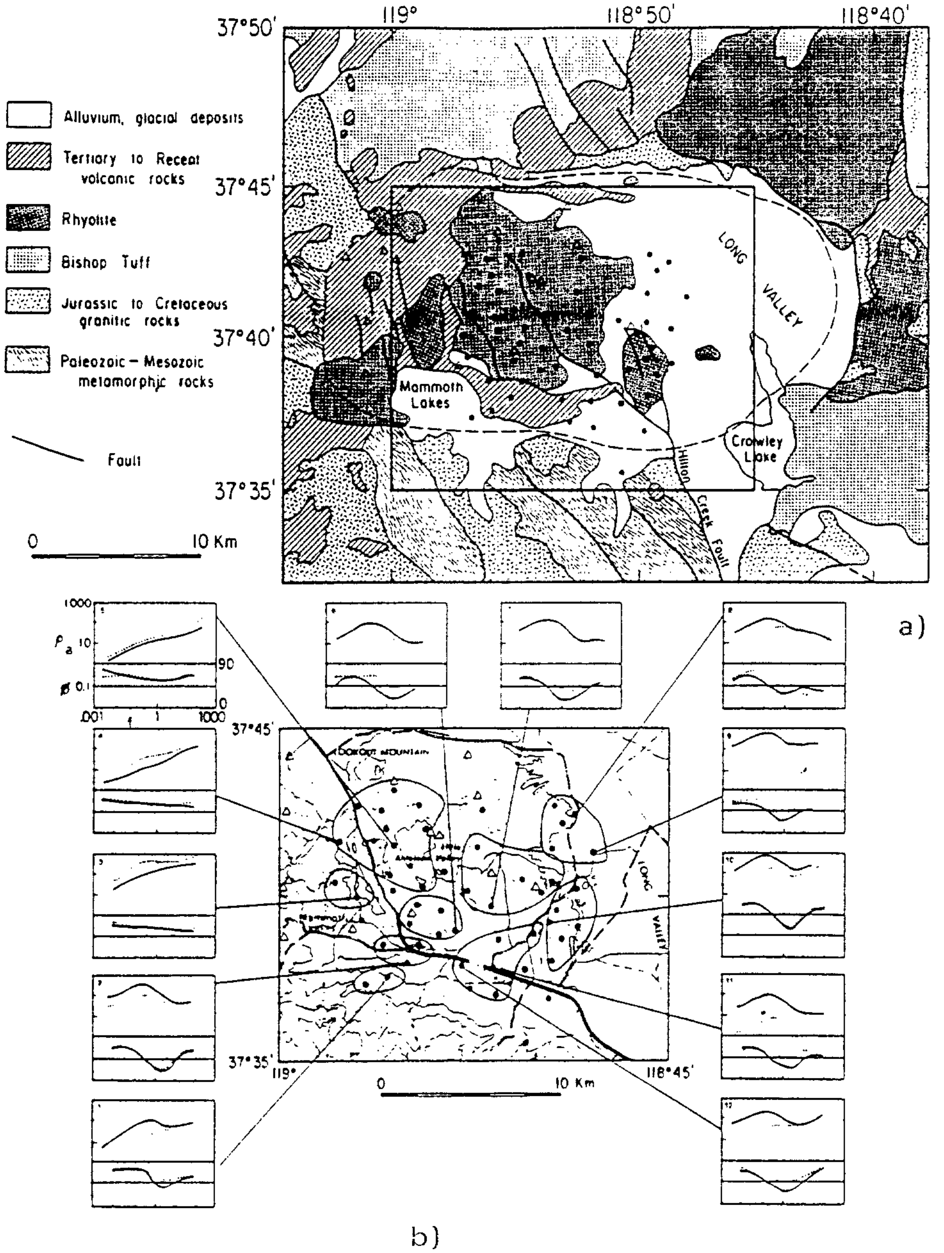


c)



d)

Fig. 2. (a) Mozley *et al.* (1986). Location of the MT station in the Mount Hood area that provided information for this study. Apparent resistivity polar diagrams for the field data averaged over the bandwidth 0.001–0.01 Hz. The dark stippled region is the approximate location of what appears to be a near-surface conductor on the south flank of the volcano. The lightly stippled region indicates the probable region of a near-surface resistive body. (b) Mozley *et al.* (1986). Residual phase polar diagrams for field data in band 4 (0.03–0.006 Hz.) The inferred deep conductor is indicated by the region with banded shading. The shallower resistive region is indicated by the stippled pattern. (c) Mozley *et al.* (1986). The two-dimensional resistivity distribution for the profile shown in Figure 2a. (d) Mozley *et al.* (1986). A composite model of the resistivity distribution around Mount Hood.



37°50'
119°
118°50'
118°40'
37°45'
37°40'
37°35'
Alluvium, glacial deposits
Tertiary to Recent volcanic rocks
Rhyolite
Bishop Tuff
Jurassic to Cretaceous granitic rocks
Paleozoic – Mesozoic metamorphic rocks
Fault
0
10 Km
LONG VALLEY
Mammoth Lakes
Crowley Lake
Hilton Creek Fault
a)
1000
10
0.1
90
0
.001
1
1000
37°45'
37°35'
119°
118°45'
0
10 Km
LONG VALLEY
b)

Fig. 3.

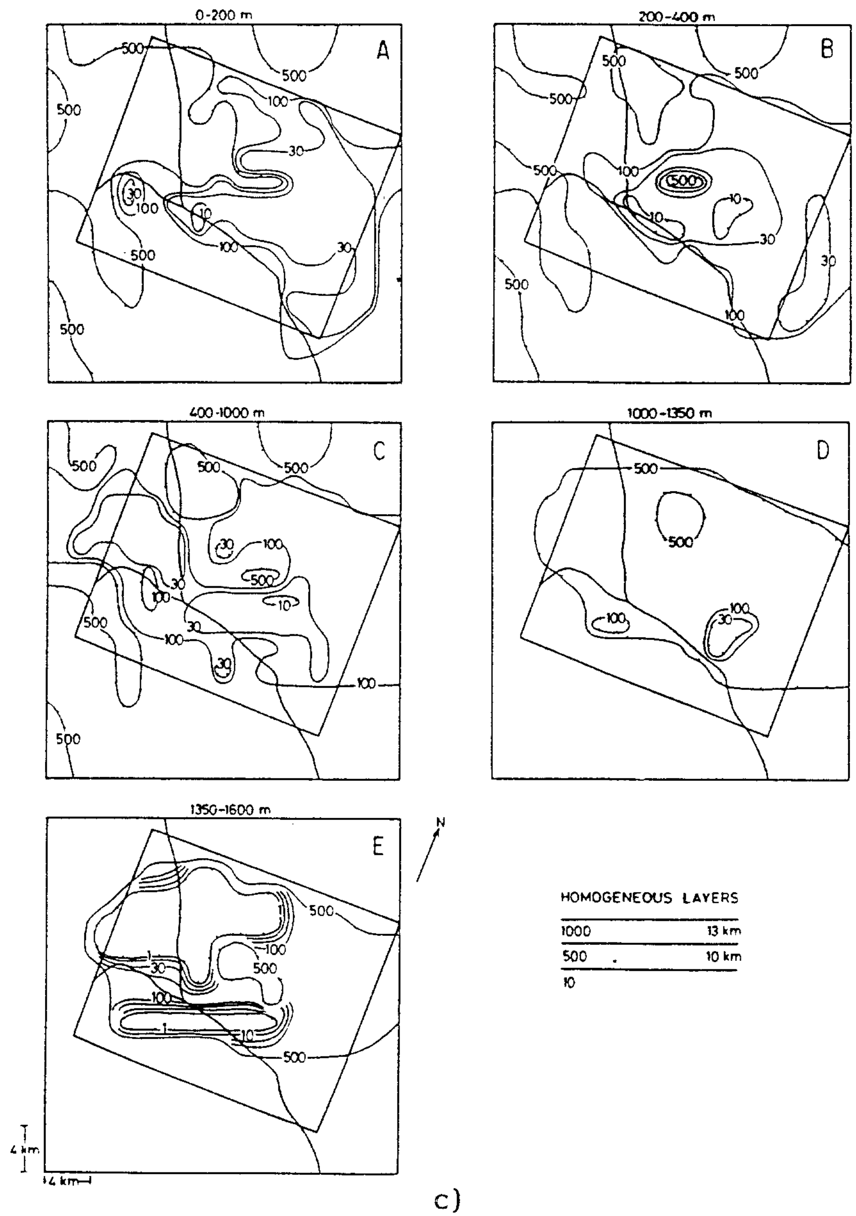


Fig. 3. (a) Park and Torres-Verdin (1988). Magnetotelluric sites from Chevron Resources Company (solid dots) and from Unocal (open triangles) are shown. The rectangular outline is the approximate boundary of the MT survey from Chevron and is the outline on subsequent figures. The resurgent dome is located beneath the large outcrop of rhyolite in the central portion of the caldera. (b) Park and Torres-Verdin (1988). Representative sites from MT surveys. Sites are clustered according to similar responses. Clusters are enclosed in solid lines on map. The tensor apparent resistivities and phases are plotted. The dashed line is used for one polarization, while the solid line is used for the other. (c) Park and Torres-Verdin (1988). Three-dimensional model. Resistivities are contoured at intervals shown in each of five layers at the depths indicated. These five layers compose the heterogeneous portion of the model. Three homogeneous layers underlie the heterogeneous portion, and they are also shown. Thicknesses are in kilometers for this section of the model and resistivities are in ohm meters.

bandwidth. There is a broad area of resistive strata beneath the western flank of the volcano, and the deepest feature is an elongated conductor at a depth of 12 km. Because there is no measurable P-wave velocity anomaly there, it can not be associated to a partial melt zone. Therefore, that conductor could be caused by a brine-filled microfractured crust limited on top by a permeability barrier.

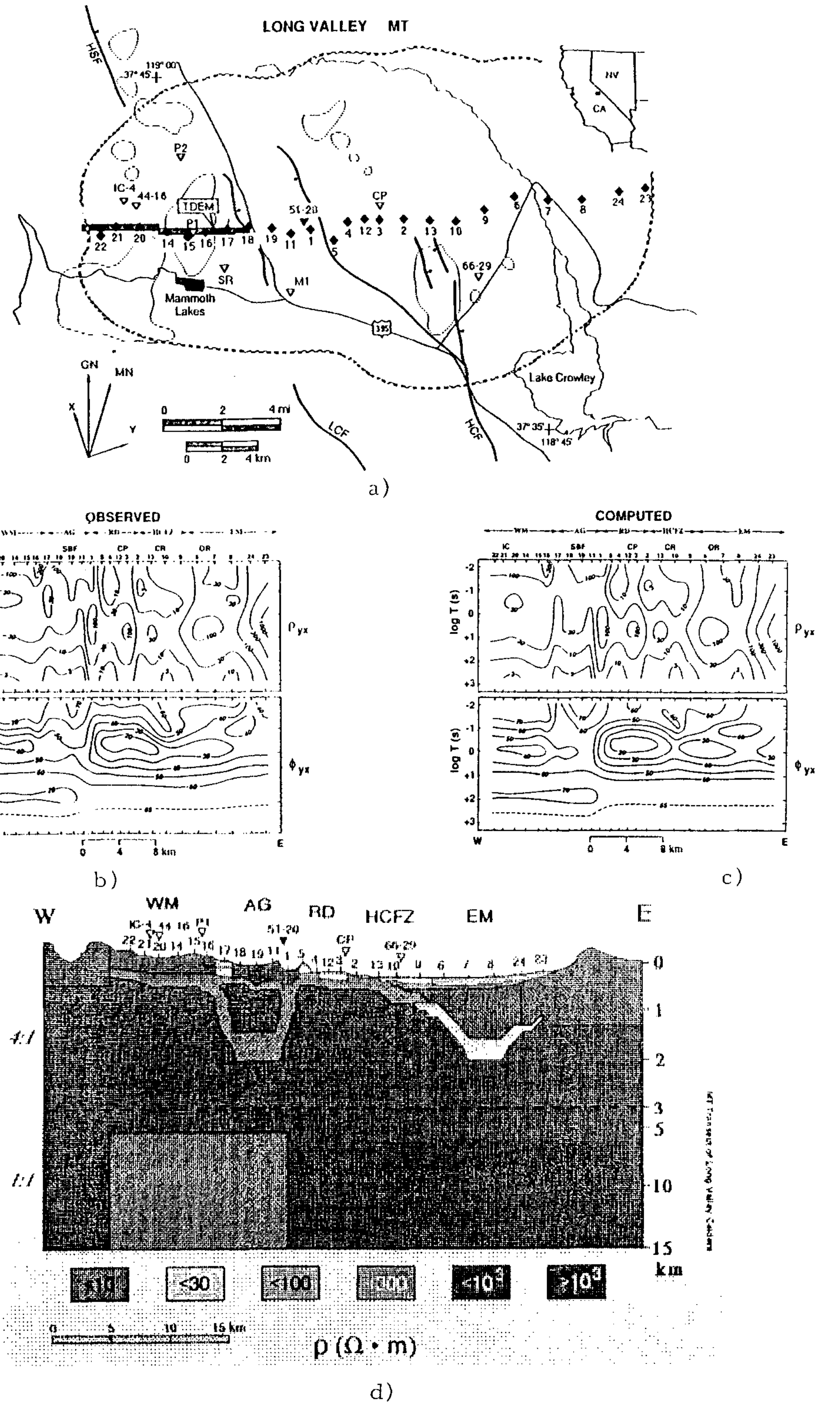
Fitterman *et al.* (1988a, b) report the results of magnetotelluric soundings, together with transient electromagnetic and Schlumberger resistivity data measured at Newberry Volcano, located in Central Oregon. The data were inverted to obtain 1-D models for each of the sites, and these results were pieced together to produce a simple cross section. In general, the data were approximately 1-D in nature. A common distortion in some of the sounding curves was the parallel splitting of the observed TE and TM data. The result shows that Newberry Volcano is separated from the main axis of the Cascade Range by a 5 km deep trough filled with electrically conductive Tertiary volcanics and sediments (Stanley 1982). Pre-Tertiary accreted crust forms a 10 to 15 km thick resistive zone. The contact between the pre-Tertiary material and the underlying lower crustal conductor is downwrapped at the same location as the conductive Tertiary trough. Beneath Newberry volcano, a resistive zone thought to be the result of repeated intrusive activity, sits atop the pre-Tertiary accreted crust.

Park and Torres-Verdin (1988) studied the Long Valley Caldera, in eastern California, where 77 MT stations (shown in Figure 3a) had been measured by two oil companies. The data were of variable quality. One set was collected without a remote reference and was heavily smoothed by the contractor. The other was collected with remote reference, but exhibited problems in the phases. Because of the complex structure in the rocks filling the caldera, the sounding curves shown in Figure 3b, were distorted by the surrounding media. The soundings were classified in groups according to the following criteria: geographical proximity, similarity of the phases, matching in the direction of the maximum and minimum apparent resistivity, and in the tipper strike. A 3-D model was built from the surface downwards. The model incorporated as many constraints as possible from wells, seismic and gravitational data. Park's (Park, 1985) thin sheet modeling algorithm was used. Within the uncertainties in the data, all of the conductive inhomogeneities needed to account for the phase spectra, are confined to the caldera fill, which goes no deeper that 1.6 km, as shown in Figure 3c. A conductive body located from 1350 to 1600 m, masks the structures at intermediate depths. This conductive anomaly is associated with the Bishop Tuffs within the caldera and graphitic metasediments beneath it. At greater depths, the crust appears layered and resistive. On the basis of sensitivity analyses, the authors rule out the possibility of a large, conductive melt (5 Ω-m) at a depth of 8 km. However, they can not rule out the presence of smaller conductive zones with the resistivity of a wet, granitic magma, or larger but more resistive bodies at depths greater than 5 km. Such bodies could not be detected by electromagnetic methods.

In the same area, the combined analysis of 20 s telluric ellipses and gravity data by Hermance *et al.* (1988a, b), revealed NNW elongated conductive bodies both east and west from the center of the caldera, as well as a pronounced but confined conductor in the south. They also interpreted a resistive block across the caldera center from SE to NW. Hermance and his colleagues mapped the gross features of the caldera, while Park and Torres Verdin (1988) concentrated on the fine details of those features.

Using the University of Utah Research Institute's (UURI) MT system, Wannamaker *et al.* (1991) collected 24 MT soundings in an E–W profile across the center of the Long Valley caldera (Figure 4a). The very high quality data, collected at fixed rotation angle with electric field perpendicular to the profile (the TM mode shown in Figure 4b), have been fitted to the finest detail (Figure 4c) with a 2-D finite element modeling algorithm. As shown in Figure 4d, the authors find, by drilling, a shallow (0.5–1 km deep) low resistivity layer which is identified as lower tuffs containing lacustrine clays. Under the Smokey Bear Flat, the Bishop Tuff appears resistive overall and on top of a low resistivity layer 1.5 km deep below the axial graben needed to fit the fine inflections in the resistivity and phase sounding curves. Such a layer could be due to hydrothermal fluids in pre-caldera volcanic strata and it shows in Figure 4d, to be electrically connected to the shallow low resistivity layer. A resistive, probably crystalline basement, is apparent almost everywhere. Low resistivities are modeled at a depth of around 5 km below the western and medial graben, and may represent a zone of hydrothermal fluids released from magma crystallization impeded of upward movement by a zone of low permeability near the 400°C isotherm. The regional resistivity profile shows a 40 Ω-m basalt half-space beneath 30 km of crust. The 2-D analysis has its limitations. The disagreement is obvious between observed and computed TE mode results and specially comparing the vertical field results. These differences are associated with caldera structures of finite-strike lengths in the N–S direction.

Twenty-one MT soundings and DC resistivity data have been integrated to derive a regional geoelectric model of the Salton Trough in southern California. The MT work was performed by the San Diego State University/Centre for Scientific Research and Higher Education of Ensenada (SDSU/CICESE) group and reported in Jensen *et al.* (1990). The data were obtained using two complete MT stations linked by digital telemetry. As a first interpretation, joint 1-D inversions were performed using Schlumberger data and nearby TE MT resistivities. Results of this modeling were combined to construct a smooth 3-D model to have a broad view of the area: the upper 2 km can be divided into three layers: a relatively resistive top layer (1–3 Ω-m, 0.6 km thick), an intermediate conductive one (<1 Ω-m), and a relatively resistive electric basement (>1 Ω-m) of hydrothermally altered sediments. 2-D geoelectric block models were developed by trial and error for three MT profiles across the trough. The TE-TM mode separation in the data, at 20–30 s, is explained by a geologic contrast at the basin boundaries


LONG VALLEY MT
HSF
NV
CA
P2
IC-4
44-16
TDEM
P1
51-20
CP
SR
M1
Mammoth Lakes
66-29
Lake Crowley
GN
MN
LCF
HCF
0 2 4 mi
0 2 4 km
a)
OBSERVED
COMPUTED
log T (s)
ρ_{yx}
ϕ_{yx}
W
E
0 4 8 km
b)
c)
W
WM
AG
RD
HCFZ
EM
E
4:1
1:1
<10
<30
<100
<10^3
>10^3
0 5 10 15 km
ρ (Ω • m)
km
d)

and by lateral heterogeneities between conductive surface blocks, especially near the geothermal zone. The 2-D model on the east side of the trough suggests lower resistivities in the crust beneath the Chocolate Mountains. However, these could also be caused by 3-D effects. The resistive crustal section of the Peninsular Ranges to the west is obvious in the data.

The Mexicali Valley and the Laguna Salada Basin, south of the Salton Sea on the Mexican side of the border, have been studied by Romo *et al.* (1985) and by Martinez *et al.* (1986, 1989). Fourteen soundings have been measured on a SW–NE profile perpendicular to strike. Data were fitted using 2-D forward and inversion modeling algorithms. In the Laguna Salada Basin on the western margin of the Salton Trough, the near-surface resistivities are of the order of tens of Ω-m. In the center of the basin, at depths of 2.5 km, the resistivities fall to very low levels, probably due to sediments saturated with saline water and to a high clay content. These sediments are underlain by a resistive basement (500 Ω-m) followed by an 80 Ω-m conductor at near 25-km depth. The deep conductor shallows towards the east, reflecting a thinning of the crust under the Mexicali Valley. The model for the Mexicali Valley near the center of the Salton Trough presents very low near-surface resistivities, (some near 1 Ω-m). In general, there is a horizontal interface between more and less conductive sediments at around 2 km depth. This contact deepens toward the center of the Valley. The two layers correspond to clay-rich unconsolidated sediments saturated with saline water in the upper zone and consolidated sediments with limited pore space below.

In the Rio Grande rift, Jiracek *et al.* (1983) argue against the existence of partial melt as an explanation for a conductive crust in the region. With 2-D modeling, they found that the crust is less conductive in a profile interpreted by seismic reflection as containing partial melt, than in another profile which appears not to have melt. They suggest that the conductor is direct evidence for the presence of water trapped by an impermeable cap, and that small amounts of magma injected through the cap release the water leaving a resistive zone behind.

In the paper by Biehler *et al.* (1991), the results of a 10 station MT profile across the Española Basin, within the Rio Grande rift, are presented as part of an investigation performed by the SAGE (Summer of Applied Geophysical Experience) geophysical group, together with results obtained using other geophysical techniques. The results of the 2-D MT model show an unusual conductive mid-crustal layer. The zone is modeled as a 1 Ω-m layer a few kilometers thick at

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Fig. 4. (a) Wannamaker *et al.* (1991). Site map for magnetotelluric soundings measured by UURI within Long Valley caldera. Fine dotted line outlines resurgent dome and dashed curve traces caldera outline. (b) Wannamaker *et al.* (1991). Pseudosections of TM mode apparent resistivity ρ_{yx} and impedance phase Φ_{yx} for the profile across Long Valley caldera. Contours of ρ_{yx} are in Ω m and of Φ_{yx} are in degrees. Important landmarks include the Inyo Craters trend (IC), Smokey Bear Flat (SBF), Clay Pit Well (CPW), Cashbaugh Ranch (CR), and Owens River (OR).

a depth of 15 km beneath the entire Española Basin. A suggested explanation for this conductor could be the presence of trapped water near the brittle-ductile transition.

From 1985 to 1988, Japan's International Cooperation Agency (JICA 1989), under contract to the Mexican Electric Power Commission, performed a feasibility study of the La Primavera Geothermal Field in Jalisco, Mexico. Within this project, 54 MT sites were surveyed. The field operation took place on January 1986. They used a two-station, ten component MT system linked by cable, with a maximum separation of 5 km. They performed a 1-D Bostick inversion of the TE apparent resistivity curves and joined together the results to form 2-D cross sections. The interpretation shows a thick (800 m) conductive layer formed by fractured andesites, approximately limited on the top by a few hundred meters of resistive tuffs, and a resistive granitic basement at the bottom.

In 1984, the CICESE MT group measured 21 MT soundings at the Los Humeros Caldera in the border between the States of Puebla and Veracruz, in the Trans-Mexican Volcanic Belt. 2-D modeling (Martinez *et al.* 1985) of three lines across the caldera identified very clearly the resistive surface and the conductive reservoir, lying mainly in fractured andesites. An electrical basement present at a depth of 2000 m was identified geologically as altered limestone. The skew and the polar diagrams at different frequencies indicate large 3-D effects in the data. Constrained by gravity and bore-hole information, a shallow 3-D model was obtained by Resendiz *et al.* (1988, 1990). Using a thin sheet modeling algorithm, the shallow effects were stripped from the MT sounding data. Data at long periods still show strong TE-TM mode separation explained only by the presence of a finite length conductive body at 19 km depth which may also be identified as magmatic in origin.

South America

For more than six years (Schwarz *et al.*, 1984, 1986, 1989, 1990), researchers from the Free University of Berlin working with colleagues from Chile and Bolivia, have measured, interpreted, and reported geophysical results from two long profiles near the Bolivia–Chile–Argentina border, from the Pacific coast to the Brazilian shield. This group also established more than 3500 gravity stations and have over 100 magnetotelluric and geomagnetic depth soundings to study the electrical signature of the Nazca Plate subducting under the South American continent. The instruments included a five-component MT station with a fluxgate magnetometer, for the period range from 15 to 20 000s, and Askania magnetographs for the recording of long period geomagnetic variations. The data at each site were rotated to yield minimum coherency of the orthogonal components of the electric field. Then, the coordinate system of the magnetic field was rotated until the coherence between electric and magnetic fields reaches a maximum. In this way, it is possible to infer the dimensionality of the structure. Induction arrows were used to help in the identification of the TE-TM models. A preliminary model pseudo-section was obtained by joining together the 1-D TE psi Schmucker interpretations $\rho^*(z^*)$ (Schmucker *et al.*, 1975). A 1-D layered model interpretation was then performed over the same polarization mode. They found a 0.5 Ω-m conductor at a depth of more than 10 km, with strike direction parallel to the main crest of the High Cordillera. The Altiplano is underlain by very conductive strata to a depth of 40–50 km. This could be associated with a state of partial melt in the lower crust. Data quality is not very good and, unfortunately, no attempt for a multi-dimensional model interpretation has been made.

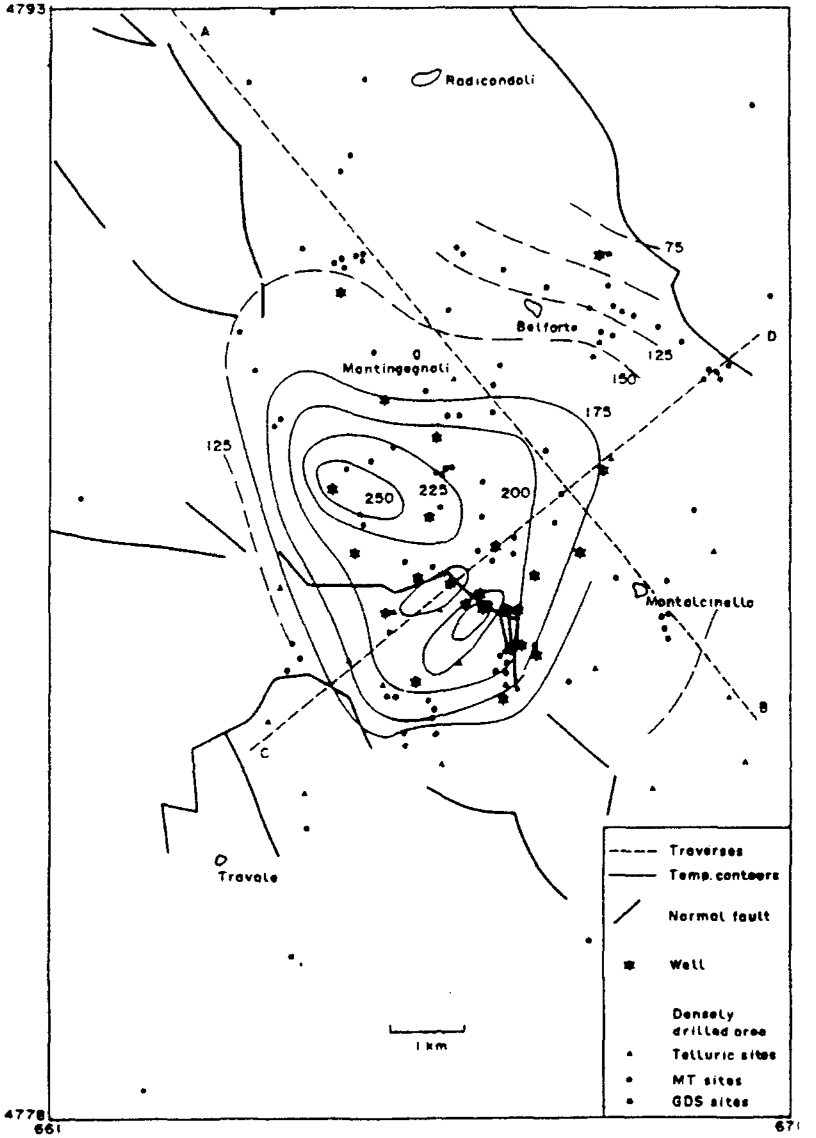
In and around the Villarrica Volcano in Chile, Muñoz *et al.* (1990) obtained four deep MT soundings in a joint program with Argentina. The two resistivity modes obtained at the four sites show very strong distortions. In order to interpret the data, they shifted the TE resistivity curve vertically to fit the geomagnetic global resistivity values of daily periods (Vanyan, 1984). This modified curve was used for 1-D modeling to determine the electrical structure in the study area. The top of the intermediate conducting layer of resistivity 20–60 Ω-m is found at 35–50 km depth. A resistive layer of 600 Ω-m starting at 100 km depth may be resolved in the intermediate conducting layer. A sharp resistivity decrease appears at around 500 km depth.

Europe

In northern Iceland, Beblo *et al.* (1983) interpreted the MT results of 30 sites deployed in a joint project with the University of Munich, Germany and the National Energy Authority of Iceland. For the interpretation of the data, only models of 1-D conductivity distributions vs. depth were fitted to the TE apparent resistivity and phase at each site using the psi Schmucker algorithm. The best fits at all sites were obtained with three-layer models where a good conductor is present for the second layer, with higher resistivities above and below. The 10 Ω-m conductivity layer is thought to depict the transition between crust and upper mantle and is detected throughout the survey area. Its depth increases from 10 km within the zone of present tectonic activity to 20–30 km at 50–100 km distance from the rift axis. The high conductivity layer probably indicates fractured basalt with partial-melt. Once again, only 1-D interpretation has been attempted.

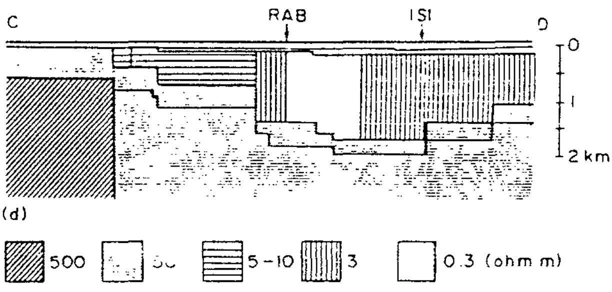
During the past decade and with the support of the European Economic Community (EEC) through the Program of Research into the Potential of Geophysical Techniques for Geothermal Exploration, two targeted geothermal areas have been investigated. During 1980–1983 the measurements were made at the Travale test site, Tuscany in Italy, and during 1986 on the Island of Milos in Greece.

At the Travale test site in Tuscany, Italy, four European Universities from Berlin, Edinburgh, Munich, and Padua undertook complementary electromagnetic induction, MT and GDS studies at more than 100 sites, as shown in Figure 5a. The most serious problem found by all the groups was the presence of noise

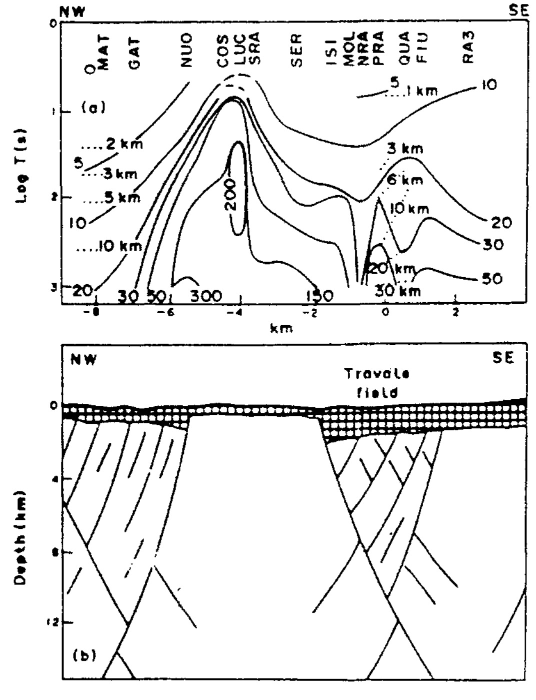

4793
4778
661
671
A
B
C
D
Radicondoli
Belforte
Montingegnoli
Montalcinello
Travale
0
75
125
150
175
125
250
225
200
1 km
Traverses
Temp. contours
Normal fault
Well
Densely drilled area
Telluric sites
MT sites
GDS sites

a)

Fig. 5.



b)



c)

Fig. 5. (a) Hutton, V. R. S. (1985). Site locations in the Travale test site. (b) Hutton, V. R. S. (1985). 2-D model which provides a good fit with well-estimated AMT data and data at 100 s. (c) Hutton, V. R. S. (1985). Pseudo-section along the Travale graben, traverse AB of Figure 5a and a simplified geological section of traverse AB (re-drawn from Schwarz 1984).

(coherent artificial signals) in the bandwidth 1–100 s in the area. Due to the fact that no one used remote reference, they had to spend a great deal of effort trying to clean these signals. The researchers from the Free University of Berlin report their work in a series of papers by Schwarz and Haak (1982), Schwarz *et al.* (1984), and Schwarz *et al.* (1985). Because of the noise present and the very poor quality of the data gathered, some novel editing techniques were applied to reduce the scatter in the data. Apparent resistivities and phases were inverted to yield a 1-D model with Schmucker's psi algorithm followed by simple 2-D modeling. For periods shorter than 1 s, the apparent resistivity curves look 1-D. They appear 2-D in the range from 50 to 100 s, and 3-D for longer periods. All data were compiled in pseudo sections of apparent resistivity for the TE mode (Figure 5c). Strong lateral variations of the apparent resistivity are present. Within the geothermal area, the resistivity is very low, yielding 4 Ω-m at the surface increasing to only 50 Ω-m in the lower crust, but increasing to 100–300 Ω-m north of the geothermal field. Further to the north, they find a poorly conducting barrier. The cause of the high conductivity structures in the geothermal area could be a highly fractured basement which allows the movement of hydrothermal fluids.

The contributions of the University of Edinburgh at the Travale site are presented by Hutton *et al.* (1985) and Hutton (1985). The instrumentation used consisted of an automatic field analysis system S.P.A.M. used for the short period AMT range together with induction coils, torque magnetometers and fluxgate magnetometers, for the wide band MT range. More than 30 sites were measured in the 100 to 10 000 s bandwidth. Since the data at all sites have been found to be either 1-D or 2-D for periods up to about 100 s, a 2-D model study was undertaken. The starting model was constructed on the basis of both the geological section, and 1-D model fitting of the TE apparent resistivity curves. The result that best fits the observed magnetotelluric responses is shown in Figure 5b. It is compatible with the known geological structure of the area and identifies the interface between the highly conductive sedimentary sequences and the more resistive carbonate formation which constitutes the actual reservoir. The 2-D models which fit the long period data are characterized by zones of highly conductive flysch cover formations and by an anomalously conductive basement. The electrical conductivity structure is compatible with the circulation of hydrothermal fluids in a highly fractured basement and restricted to the Travale geothermal field.

The second test site within the scope of the EEC program took place in the known geothermal area in the Island of Milos, Greece. Magnetotelluric groups from the Free University of Berlin, the University of Edinburgh, the University of Braunschweig and BRGM (Orleans, France) participated and arranged jointly a net of measuring sites. Haak *et al.* (1989) report the participation of the Berlin group. They recorded 24 AMT, 12 MT, and 12 LMT sites. In general the data quality is extremely poor. They used robust estimation to eliminate outliers, and also they applied a decomposition scheme to the distorted magnetotelluric tensor, to eliminate the surface distortion effect. After this procedure, the MT curves looked rather uniform, except for those ones at or near the geothermal anomaly which were shifted to lower resistivity values by 3-D effects. One-dimensional inversions were performed in all the AMT curves and on the rotationally invariant MT curves. By mapping ρ^* *and* z^* they show that the AMT results display the shallow expression of the geothermal anomaly characterized by high conductivity. The long period MT data define the boundary of the anomaly. However, within the limitations of data, and from the results obtained, one cannot infer the presence of an anomalous low resistivity zone or body within the crust.

Hutton *et al.* (1985a, b) and Galanopoulos *et al.* (1991) also conducted experiments on the Island of Milos geothermal zone, including 37 MT soundings in the period ranged 0.01–100 s and 12 in the range 30–10 000 s. The instrumention used by the University of Edinburgh is the same as that used at the Travale test site, except that the S.P.A.M. system was modified to handle seven channels to provide remote reference capabilities. Data analysis involved the estimation of the orientation of the polarization ellipse for the electric fields and the Parkinson arrows, at different frequency ranges. From these results, it was possible to infer the lateral variation in the resistivity structure. They also calculated dimensionality indices which show that the curves are 1-D except at the longest periods. They performed a 1-D inversion on the rotationally invariant apparent resistivity and phase data, together with 2-D forward modeling, and found an anomalous region of low surface resistivities ($<1\ \Omega$-m) over the geothermal area consistent with the presence of sea water and the alteration of clay minerals in the rocks. At greater depths, the resistivity of the crystalline basement below the geothermal area is also anomalously low ($<10\ \Omega$-m) for the uppermost part of the basement and does not exceed $50\ \Omega$-m to at least a depth of 10 km. As in the Travale study, these results suggest that the basement is full of fluid-fill fractures. There is also evidence that the geothermal field is bounded by more resistive crustal rocks. As shown by Fytikas *et al.* (1989), the conductivity model complements the information obtained using other geophysical techniques and provides constraints on the integrated model for this geothermal field. It is unfortunate that for the study of the geothermal area of the Island of Milos, so much emphasis is given to the 1-D interpretation. The area is obviously 3-D and we would like to see at least a 2-D interpretation with special emphasis on the fitting of the TM mode.

In two technical reports Dawes (1989b, c) present the results of the application of the S.P.A.M. audiomagnetotelluric system on the Island of Nissyros and on the Island of Koss, also in Greece. The preliminary results of both studies show very low resistivities over the anomalous geothermal area.

Adam *et al.* (1989), obtained a large MT dataset in the Pannonian Basin in Hungary, along a 60 km profile with soundings every 750 m. The soundings were measured with a Phoenix MT system and a GGRI instrument. Using the Bostick inverse, they constructed a resistivity-depth profile which, they say, "unequivocally" confirmed the presence of a conductive layer in the lower crust, at about 18 km, which is in good agreement with the high heat flow of the Pannonian Basin. Also from these results, they estimate that the depth to the conducting asthenosphere is of 47 km. The Phoenix system delivered data of excellent quality and it is unfortunate that only a 1-D Bostick inverse was used for the interpretation. Twenty years of experience in MT shows that 1-D interpretation can be seriously flawed and may result in artifacts at depth.

ASIA

In the Konkan geothermal province in India, a reconnaissance telluric survey is reported by Sarma *et al.* (1983). They carried out the survey in an area of more than 200 km^2 and recorded orthogonal signals in the 0.02–0.05 Hz frequency band. The results indicate a systematic distribution of the telluric field strength which defines a strong anomaly. This anomaly, located on the northwestern part of the area, surrounds the Sapivili–Kopnerek Hot Springs and points to the existence of a subsurface conducting zone. Harinarayana (1984) reports on telluric field investigations in the Tatapani Hot Springs area, Surguha District M.P. Thirty orthogonal telluric field stations were measured in the 0.02–0.05 Hz frequency band. In addition, a split-spread telluric survey was also carried out. The field anomaly detected in the study area is closely related to the hot springs zone.

Guodong (1987) presents the interpretation of more than 200 MT soundings measured in continental China. The longest period employed was 3000 s. In general, a 1-D inversion was performed on the TE apparent resistivity, with the 2-D inversions on some of the profiles to check the validity of the 1-D results. Two conductive layers were found in the upper mantle at some sites. The first is thin, only a few km thick, with resistivities of a few tens of Ω-m. The second one is thicker and slightly more resistive. The depth of the conductive layer is basically consistent with the depth of the upper mantle low velocity zone. Guodong (1987) claims that the origin of the upper mantle conductive layer could be due to partial melting.

Ogawa (1987) carried out a regional 35 MT station survey in the northern Tohoku District, northeastern Japan, in the frequencies 8 to 20 Hz and 17.4 KHz, and at seven sites from 1/4 to 1/265 Hz. Defining the geologic strike to be in a north-south direction, they modeled a 2-D cross section with special attention to the phases of the impedance tensor. The results show a conductor (10 Ω-m) at depths ranging from 20 to 30 km in the lower crust beneath the volcanic region.

Takasugi *et al.* (1989) report the use of an MT system built in Japan to make measurements in the 0.001 to 20 KHz frequency band. The system is equipped with 20 recording channels, hence, four complete MT sounding stations can be recorded simultaneously. In the field, the MT signals from the different sites are transmitted to a central computer through an optical fiber cable. To test the system, they conducted a survey on Hokkaido Island in Japan. The area is particularly interesting because of its geothermal potential. They compared results obtained from simple 1-D analysis of the data between gridded (squares of 50×50 m) and scattered measurements. The scattered measurements were separated by 300 and 400 m. Results of this comparison show that the gridded measurements delineate an anomaly of low resistivity, which cannot be verified by the scattered measurements. The anomaly could represent a fractured system related to the geothermal reservoir in the area.

Pelton and Furgerson (1989) propose a high density MT data gathering scheme in Japan using 16-channel equipment. By combining the measurements of each of the legs of the electric field X-cross, it is possible to obtain up to 48 tensor MT estimates per set up. Their "array" was tested on Hatchobaru, Japan. In 1982, Phoenix Geophysics measured 22 MT soundings on a 200 m grid, and in 1984 38 MT soundings on a 300 m grid. The resulting high density MT data interpreted by Phoenix Geophysics, West Japan Engineering Co. and Kyushu University, resulted in the discovery of another geothermal reservoir and the subsequent construction of an additional 55 Mw power plant.

Also in Japan, several geoelectrical experiments have been performed on Izu-Ochima Island, which is an active volcano along the Izu-Bonin arc about 100 km south of Tokyo. Utada and Shimomura (1990) report a VLF and ELF MT study over the volcano. They used a 17.4 KHz artificial electromagnetic signal for the VLF method and three fundamental Schumann resonance frequencies for the ELF method. Measurements were made in 1984 and 1985 at 57 sites including 30 on the floor of the central caldera. One-dimensional resistivity models were determined from these data. The models indicate the dominance of a reservoir of water beneath the caldera at a depth of a few hundred meters above sea level. Four sites were measured on the crater of the Mihara-yama central cone and the results show the presence of a very shallow conductor with resistivity less than 10 Ω-m. The conducting layer tends to be shallower below the northern and southern sides of the caldera rim. This conducting layer is related to the thermal activity within the central cone of Mihara-yana. There are several fumaroles reported on the crater floor and the pit crater. To further examine the volcano, Yukutake *et al.* (1990) used airborne VLF-EM and ground VLF-MT measurements. In both surveys they used 17.4 KHz as a primary source field. The results revealed that there are clear alignment trends in the resistivity anomalies in many cases. A remarkable resistivity trend was found to run along the fractures through which fountain eruptions occur during volcanic activity. Many of the anomalous belts are related to geological structures; however, other anomalies do not have any such correlation. In the same volcano, Ogawa and Yotakura (1990) carried out a controlled-source audiofrequency MT measurement (CSAMT) across the 1986 C craters. The source was a current bipole with a moment of $8–12 \times 10^3$ using a 25 kw transmitter. The source receiver separation from the transmitter ranged from 3.5 to 7 km. The field measurements were restricted to the TM mode, measuring one electric field parallel to the current bipole and one magnetic field perpendicular to it. The frequency range was from 1 to 2048 Hz. From a 2-D interpretation of the two profiles, they found a deep conductive layer containing thermal waters below the resistive lava, as revealed by nearby drilling. They also found isolated conductive bodies that are related to an old vent and to one of the craters. These bodies were formed in the 1986 eruption period associated with fractured zones containing meteoric water. Away from the profiles, they found a three-layer structure, probably corresponding to resistive lava, a fresh water lens, and sea water.

Oceania

Ingham (1987) presented the results of the interpretation of magnetotelluric data gathered over the last 20 years in New Zealand. He calculates invariant apparent resistivity curves from 11 sites which appear to be representative of different regions. The results of 1-D modeling show the presence of a good conductor in the lower crust and upper mantle in the northwest of the North Island. No conductor is identified south and east of the island. Modeling of one sounding in the Taupo volcanic zone shows indications of the presence of a deep conductor beneath the geothermal region. The quality of his data is not very good and he did not attempt 2-D modeling or to assess the ocean effect.

Bartell and Jacobson (1984) report on the results from a CSAMT survey over the Puhimau thermal area, Kilawea Volcano, Hawaii, where they investigated the nature of a possible magmatic intrusion and estimated the depth to the hot water zone and/or any remaining molten magma. The survey consisted of several profiles using two orthogonal primary field transmitting antennas. The results of the survey show that there is an excellent conductor at a depth of approximately 200 m. Above this conductor, there is a zone which is somewhat less conductive.

Conclusions

In summary, there has been a great number of EM studies performed in recent years on volcanic and geothermal areas around the world. From this review I draw the following conclusions concerning the use of EM techniques in geothermal and volcanic areas:

(1) Most field measurements are of the full MT tensor.
(2) Not all MT research groups have employed the remote reference technique. Extremely good quality data is important. To attempt a detailed interpretation, subtle features in the information can be crucial.
(3) We are witnessing a plethora of EM analysis, reduction, and interpretation techniques with a final oversimplification into 1-D models. Unfortunately, geothermal and volcanic environments have very complex geology, and 1-D or 2-D models may not yield correct results.

(4) Even with the new decomposition techniques, it is still difficult to unmask field information from deep sources that are intermixed with information coming from shallow inhomogeneities.
(5) Mid-crustal conductors are being associated to the presence of trapped water of magmatic origin. The top of the conductor is a low-permeability interphase that divides the fluid regime ductile zone from the brittle crust above.
(6) Magma chambers are not being detected. This could be due to either because they are absent or because there is a lack of resolution of the MT methods, both because of its vertical conductance relative to the integrated conductance of the overburden, as well as its lateral extent relative to its depth.

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References

Adam, A., Landy, K. and Nagy, Z.: 1989, 'New Evidence for the Distribution of the Electric Conductivity in the Earth's Crust and Upper Mantle in the Pannonian Basin as a "Hotspot"', *Tectonophys.* **164**, 361–368.

Beblo, M., Björnsson, A., Arnason, K., Stein, B. and Wolfgram, P.: 1983, 'Electrical Conductivity Beneath Iceland – Constraints Imposed by Magnetotelluric Results on Temperature, Partial Melt, Crust – and Mantle Structure', *J. of Geophys.* **53**, 16–23.

Berktold, A.: 1983, 'Electromagnetic Studies in Geothermal Regions', *Geophys. Surv.* **6**, 173–200.

Biehler, S., Ferguson, J., Baldridge, W. I., Jiracek G. R., Aldern, J. L., Martínez, M., Fernández, R., Romo, J., Gilpin, B., Braile, L. W., Hersey, D. R., Luyendyk, B. P. and Aiken, C. L.: 1991, 'A Geophysical Model of the Española Basin, Rio Grande Rift, New Mexico', *Geophysics* **56**, 340–353.

Booker, J. R.: 1988, 'Geomagnetic Induction Research in the U.S. Status and Goals', Report on the Ensenada Workshop.

Campbell, H. and Schiffmacher, R.: 1988, 'Upper Mantle Electrical Conductivity for Seven Subcontinental Regions of the Earth', *J. Geomag. Geoelectr.* **40**, 1387–1406.

Chave, A. D. and Booker, J. R.: 1987, 'Electromagnetic Induction Studies', *Rev. of Geophys.* **25**, 989–1003.

Dawes, G. J. K.: 1989b, 'Audio-Magnetotelluric Survey of the Nissyros Geothermal Field', University of Edinburgh, Dept. of Geophys. Int. Rep. 30 pp., July.

Dawes, G.: 1989c, 'AMT on Island of Kos, Greece', NECR Geophysical Equipment Pool Loan 104/1088 Final Report, 8 pp.

Elders, A. and Sass, J. H.: 1988, 'The Salton Sea Scientific Drilling Project', *J. of Geophys. Res.* **93**, 12 953–12 968.

Fitterman, D. V.: 1988a, 'Overview of the Structure and Geothermal Potential of Newberry Volcano, Oregon', *J. of Geophys. Res.* **93**, 10 059–10 066.

Fitterman, D. V., Stanley, W. D. and Bisdorff, R. J.: 1988b, 'Electrical Structure of Newberry Volcano, Oregon', *J. of Geophys. Res.* **93**, 10 119–10 134.

Fytikas, M., Garnish, J. D., Hutton, V. R. S., Staroste, E. and Wohlenberg, J.: 1989, 'An Integrated Model for the Geothermal Field of Milos from Geophysical Experiments', *Geothermics* **18**, 611–621.

Galanopoulos, D., Hutton, V. R. S. and Dawes, G. J. K.: 1991, 'The Milos Geothermal Field: Modeling and Interpretation of Electromagnetic Induction Studies', to be published in *Phys. Earth and Planet. Int.* **66**, 76–91.

Goldstein, N. E., Mozley, E. and Wilt, M.: 1982, 'Interpretation of Shallow Electrical Features from Electromagnetic and Magnetotelluric Surveys at Mount Hood, Oregon', *J. Geophys. Res.* **87**, 2815–2828.

Guodong, L.: 1987, 'MTS Studies on the Upper Mantle Conductivity in China', *Pageoph.* **125**, 465–482.

Haak, V., Ritter, O. and Ritter, P.: 1989, 'Mapping the Geothermal Anomaly on the Island of Milos by Magnetotellurics', *Geothermics* **18**, 533–546.

Harinarayana, T.: 1984, 'Telluric and Magnetotelluric Field Studies in Parts of Geothermal Areas of Peninsular India', Ph.D. Thesis submitted to the Dept. of App. Geophys., Indian School of Mines, Dhanbad, India, pp. 162–183.

Hermance, J. F., Newman, G. A. and Slocum, W.: 1988, 'The Regional Subsurface Structure of Long Valley Caldera Fill from Gravity and Magnetotelluric Data', *Geol. Soc. Am. Bull.* **100**, 1819–1923.

Hermance, J. F. and Newman, G. A.: 1988, 'Evidence for Multiple Boundary Faults Beneath the Northwest Moat of Long Valley Caldera: Magnetotelluric Results', *Geophys. Res. Lett.* **15**, 1437–1440.

Hutton, V. R. S., Dawes, G. J. K., Devlin, T. and Roberts, R.: 1985, 'A Broadband Tensorial Magnetotelluric Study in the Travale Geothermal Field', *Geothermics* **14**, 645–652.

Hutton, V. R. S.: 1985, 'Magnetic, Telluric and Magnetotelluric Measurements at the Travale Test Site, Tuscany, 1980–1983: An Overview', *Geothermics.* **14**, 637–644.

Ingham, R.: 1987, 'Lower Crustal and Upper Mantle Electrical Conductivity Contrasts in the Central North Island of New Zealand', *Phys. of the Earth and Planet. Int.* **49**, 304–313.

Jensen, G., Jiracek, G. R., Johnson, K. M., Romo, J. and Martínez, M.: 1990, 'Magnetotelluric Modeling in the Vicinity of the Salton Sea Scientific Drilling Project', to be presented at the Society of Exploration Geophysicists Annual Conference, San Francisco.

JICA: 1989, 'La Primavera Geothermal Development Project in United Mexican States', Final Report. Japan International Cooperation Agency No. 14, MPN CR(3), 89–62.

Jiracek, G. R., Gustafson, E. P. and Mitchell, P. S.: 1983, 'Magnetotelluric Results Opposing Magma Origin of Crustal Conductor in the Rio Grande Rift', *Technophys.* **94**, 299–326.

Jiracek, G. R., Rodi, W. L. and Vanyan, L. L.: 1987, 'Implications of Magnetotelluric Modeling for the Deep Crustal Environment in the Rio Grande Rift', *Phys. of the Earth and Planet. Int.* **45**, 179–192.

Jiracek, G. R., Curtis, J. H., Ramirez, J., Martinez, M. and Romo, J.: 1989, 'Two-Dimensional Magnetotelluric Inversion of the EMSLAB Lincoln Line', *J. of Geophys. Res.* **94**, 14 145–14 152.

Kurtz, R. D., De Laurier, J. M. and Gupta, J. C.: 1986. 'A Magnetotelluric Sounding Across Vancouver Island Detects the Subducting Juan de Fuca Plate', *Nature* **321**, 596–598.

Kurtz, R. D., DeLaurier, J. M. and Gupta, J. C.: 1990, 'The Electrical Conductivity Distribution Beneath Vancouver Island: A Region of Active Plate Subduction', *J. of Geophys. Res.* **95**, 10 929–10 946.

Livelybrooks, D., Clingman, W. W., Rygh, J. T., Urquhart, S. A. and Waff, H. S.: 1989, 'A Magnetotelluric Study of the High Cascades Graben in Central Oregon', *J. of Geophys. Res.* **94**, 14 173–14 184.

Martínez, M., Romo, J. M. and Vega, R.: 1985, 'Magnetotelluric Survey in Los Humeros Caldera', Annual Meeting of the Mexican Geophysical Union, Oaxaca, pp. 16–24.

Martínez, M., Romo, J. M., Herrera, C. and Jiracek, G.: 1986, 'An MT Profile Across the Mexicali Valley', Annual Meeting of the Mexican Geophysical Union, Morelia, Mich.

Martínez, M., Romo, J. M., Fernândez, R., Herrera, C., Jiracek, G. R., Weslow, V. and Miele, M. J.: 1989, 'A Magnetotelluric Profile Across the Western Boundary of the Salton Trough in Northern Baja California, Mexico', *Phys. Earth Planet. Inter.* **53**, 376–383.

Martínez, M., Romo, J. M., Vega, R. and Ramírez, J.: 1987, 'Forward Modeling of EMSLAB

Magnetotelluric Data in the Transition Zone between the Coast Range and the Willamette Valley', I.U.G.G. General Assembly Union Meeting, Vancouver, Canada.

Mozley, E. C., Goldstein, N. E. and Morrison, H. F.: 1986, 'Magnetotelluric Investigations at Mount Hood, Oregon', *J. of Geophys. Res.* **91**, 11 596–11 610.

Muñoz, M., Fournier, H., Mamani, M., Febrer, J., Borzotta, E. and Maidana, A.: 1990, 'A Comparative Study of Results Obtained in Magnetotelluric Deep Soundings in Villarrica Active Volcano Zone (Chile) with Gravity Investigations, Distribution of Earthquake Foci, Heat Flow Empirical Relationship, Isotopic Geochemistry $^{87}Sr/^{86}Sr$ and SB Systematics', *Phys. of the Earth and Planet. Int.* **60**, 195–211.

Ogawa, Y. and Takakura, S.: 1990, 'CSAMT Measurements Across the 1986 C Craters of Izu – Oshima Island, Japan', *J. Geomag. Geoelect.* **42**, 211–224.

Ogawa, Yasuo: 1987, 'Two-Dimensional Resistivity Modeling Based on Regional Magnetotelluric Survey in Northern Tohoku District, Northeastern Japan', *J. Geomag. Geoelectr.* **39**, 349–366.

Park, S. K.: 1985, 'Distortions of Magnetotelluric Sounding Curves by Three-Dimensional Structure', *Geophysics* **50**, 785–797.

Park, S. K. and Torres-Verdin, C.: 1988, 'A Systematic Approach to the Interpretation of Magnetotelluric Data in Volcanic Environments with Applications to the Quest for Magma in Long Valley, Ca.', *J. Geophys. Res.* **93**, 13 265–13 283.

Pelton, W. H. and Furgerson, R. B.: 1989, 'High-Density 3-D MT: Swath MT and Grid MT', 59th Annual SEG Meeting, Dallas, pp. 179–181.

Resendis, M. de L., Martínez, M. and Romo, J.M.: 1988, 'Three-Dimensional MT Modeling of the Los Humeros Caldera in Mexico', IAGA, 9th Induction Workshop in EM, Dagomys, Sochi, USSR, 1988.

Resendis, M. de L.: 1990, 'Magnetotelluric Interpretation of the Los Humeros Caldera', M.Sc. degree thesis, CICESE, Ensenada.

Rodi, W. L., Swanger, H. J. and Minster, J. B.: 1984, 'ESP/UT: An Interpretative System for Two-dimensional Magnetotelluric Interpretation (abstract)', *Geophysics* **46**, 611.

Romo, J. M., Vázquez, R., Fernández, R. and Martínez, M.: 1985, 'MT Transect Juarez – Cucapa', Annual Meeting of the Mexican Geophysical Union, Oaxaca, pp. 94–101.

Sarma, S. V. S., Harinarayana, T., Gupta, M. L., Sarma, S. R., Kumar, R. and Sanker Narayan, P. V.: Sanker: 1983, 'A Reconnaissance Telluric Survey in Northern Parts of Konkan Geothermal Province, India', *Geophys. Res. Bul.* **21**, 91–99.

Schmucker, V. and Weidelt, P.: 1975, Aahrus Lecture Notes, Univ. Gottingen.

Schwarz, G., Martinez, E. and Bannister, J.: 1986, 'Untersuchungen zur electrischen leifähigkeit in den zentralen Anden. *Berliner Geowiss. Abh.* **66**, 49–72.

Schwarz, G., Götze, H.-J. and Wigger, P. J.: 1989, 'The Structure of the Earth's Crust and Upper Mantel in the Central Andes (20°–26° S) as Inferred from Combined Geophysical Studies', 28th IGC 4, Washington.

Schwarz, G., Haak, V. and Rath, V.: 1985, 'Electrical Conductivity Studies in the Travale Geothermal Field, Italy', *Geothermics* **14**, 653–661.

Schwarz, G., Haak, V., Martinez, E. and Bannister. J.: 1984, 'The Electrical Conductivity of the Andean Crust in Northern Chile and Southern Bolivia as Inferred from Magnetotelluric Measurements', *J. Geophys.* **55**, 169–178.

Schwarz G., Chong, G., Krüger, D., Martinez, E., Massow, W., Rath, V. and Viramonte, J.: 1990, 'Crustal Electric Resistivity Structure in the Southern Central Andes', Symp. on Andean Geodynamics, Grenoble, 3 pp.

Schwarz, G. and Haak, V.: 1982, 'Magnetotelluric Measurements in Tuscany/Italy – Evidence for a Geothermal Anomaly. – Geothermics and Geothermal Energy', V. Cermák, and R. Haenel, (eds.), E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 191–195.

Stanley, W. D., Finn, C. and Plesha, J. L.: 1987, 'Tectonics and Conductivity Structures in the Southern Washington Cascades', *J. of Geophys. Res.* **92**, 10 179–10 193.

Stanley, W. D.: 1982, 'A Regional Magnetotelluric Survey of the Cascades Mountains Region', *U.S. Geol. Surv. Open File Rep.* 82–126, 20 pp.

Takasugi, S., Kawakami, N. and Muramatsu, S.: 1989, 'Development of a "High Accuracy MT System and Analysis of Corresponding High-Density MT Measurements"', *59th Annual SEG Meeting*, Dallas, pp. 175–178.

Utada, H. and Shimomura, T.: 1990, 'Resistivity Structure of Izu-Oshima Volcano Revealed by the ELF - VLF Magnetotelluric Method', *J. Geomag. Geoelectr.* **42**, 169–194.

Vanyan, L. L.: 1984, 'Electrical Conductivity of the Asthenosphere', *J. Geophys.* **55**, 179–181.

Wannamaker, P. E., Hohmann, G. W. and Ward, S. H.: 1984, 'Magnetotelluric Responses of Three Dimensional Bodies in Layered Earths', *Geophysics* **49**, 1517–1533.

Wannamaker, P. E., Booker, J. R., Filloux, J. H., Jones, A. G., Jiracek, G. R., Chave, A. D., Tarits, P., Waff, H. S., Egbert, G. D., Young, Ch. T., Stodt, J. A., Martínez, M. G., Law, L. K., Yukutake, T., Segawa, J. S., White, A. and Green, A. W., Jr.: 1989a, 'Magnetotelluric Observations Across the Juan de Fuca Subduction System in the EMSLAB Project', *J. of Geophys. Res.* **94**, 14 111–14 126.

Wannamaker, P. E., Booker, J. R., Jones, A. G., Chave, A. D., Filloux, J. H., Waff, H. S. and Law, L. K.: 1989b, 'Resistivity Cross Section Through the Juan de Fuca Subduction System and its Tectonic Implications', *J. of Geophys. Res.* 14 127–14 144.

Wannamaker, P. E., Wright, P. M., Zi-xing, Z., Xing-bin, Li and Jing-xiang, Z.: 1991, Magnetotelluric Transect of Long Valley Caldera: Resistivity Cross Section, Structural Implications, and the Limits of a 2-D Analysis', *Geophysics* **56**, 926–940.

Wright, P. M., Ward, S. H., Ross, H. P. and West, R. C.: 1985, 'State-of-the-art Geophysical Exploration for Geothermal Resources', *Geophys.* **50**, 2666–2699.

Yukutake, T., Murakami, Y., Nakagawa, I., Yokiyama, Y. and Hamano, Y.: 1990, 'Resistivity Anomalies of Izu-Oshima Volcano Revealed by Airborne VLF-EM Survey', *J. Geomag. Geoelectr.* **42**, 195–210.