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**WORKSHOP ON ELECTRICAL METHODS
IN GEOTHERMAL EXPLORATION**

**U.S. Geological Survey
Contract No. 14-08-0001-G-359
January, 1977**

TABLE OF CONTENTS

Summary Report: Electrical Methods in Geothermal Exploration.	1
List of Participants	11
Introduction	15 ✓
Team Report, Rock Properties	16 ✓
Team Report, Modeling	36 ✓
Team Report, Self Potential	59
Team Report, Data Processing	79
A Group Assignment	81
Group 1 Report, Nov. 5, 1976	85
" 2 " " " " 	87
" 3 " " " " 	90
" 4 " " " " 	92
" 5 " " " " 	94
" 6 " " " " 	95
" 7 " " " " 	98
" 8 " " " " 	99
Summary of Evening Discussion, Nov. 5	101
Team Report, Applications, Limitations, Instrumentation; IP, Resistivity & EM	103 ✓
Team Report, Applications, Limitations, Instrumentation; Tellurics and MT/AMT	107 ✓
Team Report Downhole-to-Surface	112 ✓
Introduction to Group Discussion, Nov. 6, 1976	128 ✓
Group 1 Report, Nov. 6, 1976	131
" 2 " " " " 	132
" 3 " " " " 	135

Group 4 Report, Nov. 6, 1976	137
" 5 " " " "	140
" 6 " " " "	142
" 7 " " " "	145
" 8 " " " "	149
Summary of Evening Discussion, Nov. 6	151
Team Report Case Histories	152 ✓
Recommendations, Team I	160
" " II	162
" " III	163
" " IV	164
" " V	166
" " VI	167
" " VII	169
" " VIII	170
Other Recommendations	171
Final Session Review of Recommendations for Required Research	173
Appendix	
- A simple almost exact method of MT analysis by F. X. Bostick, Jr.	174

SUMMARY REPORT:

ELECTRICAL METHODS IN GEOTHERMAL EXPLORATION

By

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University of Utah, Salt Lake City, Utah

ELECTRICAL METHODS IN GEOTHERMAL EXPLORATION

Introduction

A workshop on *Evaluation of Electrical Methods in the Geothermal Environment* was held at Snowbird, Utah, November 4 through 7, 1976. The workshop was financed by the U. S. Geological Survey under a grant to the University of Utah. S. H. Ward, Chairman of the Department of Geology and Geophysics, University of Utah, aided by a steering committee consisting of William Dolan (Amax), Frank Frischknecht (ex officio, USGS), George Keller (Group 7), Tsvi Meidav (Geonomics), Frank Morrison (U. C. Berkeley) and Sulhi Yungul (Chevron) arranged to invite 50 participants while the USGS arranged the attendance of four federal program managers as observers. Balanced representation of industry, government, and academia was stressed during the invitation process. Will Forsberg and Mary DeWitt of the University of Utah arranged accommodations and provided workshop management. R. L. Christiansen, F. C. Frischknecht, and D. W. Klick of the U. S. Geological Survey were very generous with their time in helping me to organize and edit this report.

Objectives

The objectives of the workshop were:

- ✓ 1) to disseminate case histories of the application of electrical methods in the geothermal environment;
- 2) to disseminate information from theoretical and field studies bearing on the relative merits of the reconnaissance electrical methods such as

MT/AMT
Tellurics,
Bipole-dipole, and
self-potential;

- 3) to disseminate information from theoretical and field studies bearing on the relative merits of the detailed electrical methods such as
 - downhole-to-surface methods,
 - Schlumberger resistivity,
 - electromagnetics;
- 4) to make studies of the cost-effectiveness of reconnaissance versus detailed electrical methods;
- 5) to analyze the preferred location and/or locations of electrical methods in typical exploration architecture;
- 6) to develop goals for specific theoretical and field comparisons of the cost-effectiveness and resolution of the various electrical methods;
- 7) to develop goals for advances in (a) equipment (b) data processing; and (c) data interpretation of electrical methods applied in the geothermal environment; and
- 8) to discuss the advantages and limitations of electrical methods in the search for geothermal resources.

Procedures

Teams of specialists were preassigned to prepare state-of-the-art presentations on each of:

- 1) electrical rock properties,
- 2) forward and inverse models,
- 3) the self-potential method,
- 4) data processing,
- 5) applications, limitations and instrumentation for resistivity induced polarization, and electromagnetics,

- 6) applications, limitations and instrumentation for tellurics and MT/AMT,
- 7) down-hole-to-surface methods, and
- 8) case histories.

Eight *groups* were formed by random selection on each afternoon of the first two days of the workshop for the purpose of debating the team presentations and the ensuing discussion. Group leaders submitted oral reports each of the two evenings which, naturally, led to frequent animated discussion. Written summary reports were later submitted by the group leaders and team leaders.

The workday was long but effective in stimulating discussion and in bringing out all viewpoints.

Observations

The presentation, discussion, and reporting procedures described above permitted me to draw the following observations.

The electrical properties of rocks occurring in the geothermal environment are functions of the parameters porosity, crack and pore geometry, pore fluid salinity, temperature, pressure, mineralogy and alteration products, and hydraulic pressure gradients. Given such a broad spectrum of functional dependence, it is not surprising that surface electrical methods of exploration cannot given a clear picture of the subsurface distribution of the parameters nor can our usual imperfect knowledge of the subsurface distribution of the parameters permit us to predict the results of a surface electrical survey. Input from geological, geochemical, and other geophysical observations can help us reduce the uncertainty in the functional relationships, but research in this area is in its infancy.

Electrical geophysical methods historically have suffered from a lack of capability for interpretation. Analytic solutions for simple bodies in a whole-space and solutions obtained by means of scaled model experiments have proven useful but limited in application. However, in the past few years, previously intractable electromagnetic boundary value problems have begun to yield to numerical solutions; large computers are essential for cost-effective application of these techniques. Much research remains, however, to obtain practical interpretation methods applicable for complex geological structures. The numerical solutions are divided into solutions of a) the forward problem, and b) the inverse problem. Success has been achieved, in a limited way, in solving the forward boundary value problem of a single three-dimensional body in the field of a three-dimensional source. For the inverse problem, only a two-dimensional body in the field of a three-dimensional source has been solved, and then only in a limited way. Not all of these limited achievements have yet found their way into the literature. One needs both forward and inverse solutions for multiple two- and three-dimensional bodies in the fields of three-dimensional sources. How applicable these modeling solutions will be in the complexity of real world geology will need to be demonstrated subsequently.

Self-potential anomalies have been observed over some geothermal environments and over heat fronts in thermal flooding of oil reservoirs. In most cases the source mechanism is unknown but could be streaming fluids, thermo-electric effects, geochemical variations occurring both near surface and at reservoir depths, oxidation of semi-conductive minerals, and possibly by colloid deposition in convective hydrothermal systems. Given the uncertainty of the source mechanism and frequently low signal-to-

✓ noise ratio, it is not surprising that the self-potential method has not yet demonstrated its general applicability in geothermal exploration.

✓ Processing of data from electrical surveys is mostly of concern in magnetotelluric, telluric, and geomagnetic deep sounding methods - the passive techniques. Good progress has been made in recent years in producing processed data which can readily be interpreted in terms of simple and complex earth structures. More work on suppression of noise and recognition of useful signal is required. The science and art of the subject is in such a state of flux that it is difficult to provide a consensus of the preferred procedure. However, this preferred procedure appears to be on the horizon. It is sophisticated.

The availability of new inexpensive computer programs for model calculations in resistivity and electromagnetics has permitted a much more quantitative approach to the interpretation of surveys using these techniques. Combined sounding-profiling with both resistivity and electromagnetics is essential if one is to provide sufficient data for interpretations which describe the geoelectric section with any assurance. Controlled source electromagnetics ✓ offer advantages over resistivity in the following ways: a) sounding without lateral separation thus minimizing the effects of lateral resistivity variations that are a problem in large separation resistivity surveys, b) electrical contact does not have to be made with the ground, and c) less sensitivity to local inhomogeneities. However, one should not pit resistivity against electromagnetics for both are required to delineate any geoelectric section; they excite different modes. In some instances, the electromagnetic survey can be an integral part of the resistivity survey, e.g., transient analysis of the square wave used in conventional resistivity survey. Many

participants felt that controlled source electromagnetic methods were not adequately treated during the workshop. The induced polarization method may offer advantages in geothermal exploration, but almost no use of this method has been made.

Magnetotellurics, audio-magnetotellurics, tellurics, geomagnetic deep sounding, and various combinations of these methods have been employed with varying degrees of success in the geothermal environment. No clear understanding of the applicability of these methods has emerged. On the other hand, one of the most significant discoveries resulting from application of the magnetotelluric data is the widespread observation of highly conductive zones at depth in the range 2 to 20 km. In many geothermal regions of the western U.S. these conductive zones (> 1 mho/m) occur shallower than 10 km. For instance, depths are less than 5 km in Yellowstone, 2 to 7 km at Fallon, Nevada, 5 km at Coso Hot Springs, California, 7 km at Darrow Hot Springs, Nevada, and 3-15 km at Roosevelt Hot Springs, Utah. Study of non-minimum phase behaviour in tensor magnetotelluric data from some of these areas suggest that the boundary between the conductive zone and the resistive material above is a very sharp one. The widespread occurrence of shallow buried conductors in geothermal regions suggests that the mapping of these zones may be the most powerful technique available for geothermal exploration over large areas. Unfortunately, the cause or causes of the buried conductors is not yet known but could be a brine-filled and clay-altered thermally fractured zone above a magma, or it could be the magma itself. Supplementary geological, geophysical, and geochemical data may help to solve this puzzle. We are yet sufficiently bold to obtain the answer by drilling!

The workshop was dedicated to surface electrical surveys and borehole logging was specifically excluded in order to keep the scope within

reasonable bounds. However, a survey of downhole-to-surface electrical methods was included. The participants in the workshop concluded that application of these well-known and fairly well-developed methods ought to be stressed more in geothermal environments.

Five case histories of application of geophysical methods in geothermal exploration were presented at the workshop. The areas discussed were Animas Valley, N.M.; a negative prospect east of the Imperial Valley, Ca.; Salton Sea geothermal field, Ca.; Raft River, Id.; and Roosevelt Hot Springs, Ut. As expected, but unfortunately, industry released very little information which would relate to discoveries.

Controversies

Controversy centered on the following topics:

- 1) should electrical methods ever be used in the reconnaissance phases of geothermal exploration,
- 2) which electrical method is best suited to reconnaissance,
- 3) should the self-potential method be used at all in geothermal exploration until its basis is better understood,
- 4) should the ambiguity of the bipole-dipole resistivity method preclude its use in geothermal exploration,
- 5) is the magnetotelluric method best used in reconnaissance or detail phases of geothermal exploration,
- 6) would a deep-probing (3 to 10 km) active electromagnetic system largely replace MT and resistivity or should it supplement them,
- 7) is the dipole-dipole method less preferable than the Schlumberger method for geothermal exploration,
- 8) has two-dimensional or three-dimensional numerical modeling ever

been of help in understanding a geothermal system, are the inherent ambiguities too great, or can modeling only be applied reliably when constrained by complementary geological, geochemical, and geophysical data,

9) can we ever sensibly apply electrical methods in geothermal exploration until we understand better the electrical properties of rocks as functions of porosity, crack and pore geometry, pore fluid salinity, temperature, pressure, mineralogy and alteration products, and hydraulic pressure, and

10) the various forward and inverse modeling algorithms are not consistent, one-to-another, nor is it obvious which inverse algorithm is best.

No attempt was made to reach a consensus on these controversies, rather a large number of research projects was suggested which are expected to resolve many of them.

Recommendations

In excess of 50 specific recommendations concerning required research were endorsed by a consensus of the participants. We shall review some of these recommendations here.

Most strongly endorsed was a need for comprehensive, high quality, laboratory studies of the electrical properties of rocks under temperatures, pressures, and solution chemistries pertinent to the geothermal environment. Unless we can move off square one in this basic area, the very foundations of electrical methods are in question.

Interpretation of data from the various electrical methods is in a poor state of health on account of our poor understanding of rock properties, but also because we need to refine, expand, and extend our forward and inverse algorithms to permit solutions for scattering from two- and three-dimensional objects in the fields of three-dimensional sources. The cost-effectiveness

of the various algorithms must be established by objective comparison. Computer interactive one-, two-, and three- dimensional inversion schemes are almost totally lacking and require early establishment. Linear and non-linear mathematical, geological, and multiple data set constraints need to be imposed on these schemes. The design of experiments by linear and non-linear inversion needs much effort.

Research into the origins of self-potential anomalies is essential before the method can be applied with any degree of reliability.

A fascinating current achievement permits us to move MT/AMT preliminary data processing into the field and so permit us to provide objective criteria for evaluating noise and signals in real time. Much more effort in this area is warranted. New innovative techniques of MT/AMT data processing should be encouraged.

Rather than set resistivity methods in contest with electromagnetic methods, extra effort is required to assure that the two methods are integrated in the field and in data processing and interpretation. One can readily envision that multiple data set inversion of MT/AMT, resistivity/induced polarization, and controlled-source electromagnetics may well be the optimum means of describing a 1D, 2D, or 3D geoelectric section. Geologic and other data input are readily introduced as constraints on these inversions. Development of deep-probing controlled-source electromagnetic and ultra low-frequency induced polarization systems therefore appear mandatory.

There seems to be considerable justification for combining the telluric and magnetotelluric methods in some optimum combination for reconnaissance purposes. Research is needed to develop this optimum combination. However, it is clear that simultaneous recording at one or more MT/AMT stations and at

several telluric stations ought to be pursued with dispatch. The role of ✓ geomagnetic depth sounding in geothermal exploration is uncertain. However, its role clearly is dependent upon development of enhanced methods for processing and interpreting G.D.S. data.

An unexpected recommendation of the workshop was the unanimous desire to inventory and catalogue all available computer programs pertaining to processing and interpretation of geoelectric data. All participants in the workshop join me in encouraging you to write Walter Anderson, U.S.G.S., Denver Federal Center, to facilitate this task.

We had a good time and learned a lot at the workshop. We expect that the true fruits of our efforts will appear in the literature in the next few years.

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Introduction

The Workshop was organized around the team presentation matrix of Figure 1. The team presentations were made in the mornings and early afternoons. In the late afternoons, study groups were arranged by random selection. The groups gave short, oral presentations in the evenings. Much discussion ensued the group presentations and the discussions were recorded by five U of U graduate students, Wm. Pelton, Wm. Petrick, Don Pridmore, Luiz Rijo, and Alan Tripp.

Written reports following, then, were made by team leaders group leaders, and the students. A purposely provocative presentation by Stan Ward and a creative piece of interpretation theory by Frances Bostick are included to round out the report.

The recommendations made by each team and a final session review of these recommendations constitute the real fruits of the workshop -- a plan to reduce our state of ignorance of the subject area.

The report itself is a working document, not a polished manuscript. We do this in an effort to preserve the integrity of the workshop.

ROCK PROPERTIES TEAM REPORT

T. Madden, Team Leader

R. McEuen

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ROCK PROPERTIES

Relevant to Geoelectric Measurements

Introduction

Electrical properties of rocks are a function of many parameters some of which are important factors in any evaluation of a potential geothermal reservoir. These parameters include:

- porosity
- crack and pore topology and width distribution functions
- pore fluid salinity
- temperature
- pressure
- mineralogy and alteration products
- hydraulic pressure gradients

The factors that are related to these parameters of special interest to evaluations of geothermal reservoirs include:

- rock type
- temperature
- permeability
- porosity
- pore fluid salinity
- presence of convection
- long-term effects of forced convection

The geometric distribution of these parameters is equally important, but this is a problem in interpretation which is outside the scope of this section.

The role of our understanding of rock properties in geothermal exploration is thus two-fold; first, the prediction of the electrical properties, given the parameters of the situation; and secondly, the inverse problem of inferring the parameters, given the electrical properties. The second problem can never be done just on the basis of electrical measurements, but must involve other geophysical measurements as well as geologic and geochemical inputs, and even perhaps some divine guidance.

Our understanding of the functional relationship of electrical properties

to the rock parameters is still developing and runs from adequate to marginal.

Most of the parameters fall into three groups,

- ✓ geometric properties of cracks, pores and fissures
- ✓ electrical properties of the interstitial fluids
- ✓ electrical properties of rock minerals and alteration minerals

and we wish to review briefly where we stand in our understanding of these parameters.

1. Geometric Factors

The most useful relationship involving the geometric factors of the pore fluid distribution in a rock is Archie's Law, an empirical relationship between

✓ porosity and electrical resistivity. For a saturated rock the law can be expressed as

$$\rho_{\text{rock}} = \rho_{\text{fluid}} \phi^{-n} \quad (1)$$

≈ 2

where ϕ is the porosity and n , although not exactly a universal constant, is often very close to 2 as shown in Figures 1 and 2. If the pore fluids are very dilute, the predictions of this expression would have to be modified because of the surface conductivity contribution from the mineral-solution interfaces. The parameters of this phenomenon are given in Table 1. The magnitude of this effect as shown in Figure 2 was probably overestimated due to salt contamination in the rock samples, and it is not important in high salinity, high porosity environments. The presence of clay minerals and zeolites in the pores, however, does introduce important surface conduction effects.

The fact that n is close to the value 2 represents a considerable inefficiency for conduction in low porosity rocks. This inefficiency is a property of relatively simply connected networks when the conductances of the individual

Fig. 1: Relationship of the formation factor, P_p , to the coefficient of porosity, k , for carbonate (limestone) sedimentary rocks in the USSR and the USA: (1) limestones from Kazakhstan (from Sigal), (2) limestone from the Kuibyshev area, Bashkiria (from Kachurina), (3) carboniferous limestones from the Saratov Basin (from Eidman), (4) devonian limestone from Crosset, Texas, (5) oolitic limestone, Smackover formation, (6) Permian limestone, San Andreas Basin, Texas (from Archie). (from Parkhomenko)

Fig. 2: Conductivity at 4kb as a function of pore porosity in tap water and in salt solution. (Brace et al., 1965)

Table 1

Surface Conductivity Parameters

Critical Width and Conductivity Multiplicative Factor

conc(Normality)	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^0	10^1	
Debye length (μ)	.03	.01	.003	.001	--	--	
(mv)							multiplicative ⁺ factor
10							1.09
15							1.19
20							1.34
30							1.81
50	.125	.040	.0125	.004	.001	--	3.76
75	.311	.099	.031	.010	.003	.001	10.07
100	.632	.200	.063	.020	.006	.002	27.31
150	2.04	.646	.204	.065	.020	.006	201.7
200	5.77	1.83	.577	.183	.058	.018	1490.5

zeta potential

critical crack width in microns (μ)
(width at which surface conductivity = crack
volume conductivity)

+ Multiplicative factor is $\frac{(\sigma_{\text{surface}} + \sigma_{\text{volume}})}{\sigma_{\text{volume}}}$ in limit
of infinitesimal crack width

network elements have a wide range of values. A reasonably accurate prediction is obtained by replacing each element with an element whose conductance is the geometric mean of the original conductance distribution. Thus, in analogy with this network property, if one knows the number density distribution (number x length) of the rock crack and pore widths, one can predict its conductivity, as shown in Figure 3. Archie's Law seems to reflect an increased widening of the pore width distribution function as the porosity decreases.

These results must be modified if a wide range of crack lengths are involved, and if the cracks of each length scale are interconnected among themselves, as well as intraconnected with neighboring scales. Such a situation greatly increases the conductivity relative to the geometric mean estimates. It can be responsible for important differences between large scale field measurements and laboratory measurements on the same rocks. It also helps explain large conductivity increases that are caused by stress damage to a rock. Unfortunately, the information needed to take this factor into account is difficult to come by.

Since the permeability of a rock involves the same channels as those determining the electrical conductivity, one should expect a functional relationship between the two. When the geometric mean estimate is a good predictor of electrical conductivity, the permeability should be proportional to the product of the conductivity and the square of the geometric mean crack width.

$$k \text{ in darcies} = \frac{(\text{geometric mean width in } \mu)^2}{(12 \times \text{formation factor})} \quad (2) \checkmark$$

figure 3 also shows permeability data. There is considerable scatter between observations and predictions for the more permeable rock samples, which may indicate a sampling problem for these measurements.

Pore Fluid Conductivity

Conduction in moderately saline water is due to the ion drift driven by the electric field. The conductivity is therefore proportional to the ionic

Q1 1 Pore widths 10μ

Number Density Distribution

Por = 15.7% FF = 48 $k = 27$ md
predicted FF = 41 $k = 1.5$

Por = 6.2% FF = 193 $k = 0.6$ md
predicted FF = 106 $k = 0.4$

Por = 21.6% FF = 17 $k = 18$ md
predicted FF = 15 $k = 7$

Por = 23.2% FF = 14 $k = 2.6$ md
predicted FF = 8.3 $k = 3.8$

Por = 14.8% FF = 42 $k = 61$ md
predicted FF = 31 $k = 8.6$

Por = 12.1% FF = 83 $k = 4.4$ md
predicted FF = 34 $k = 7.0$

Por = 15.7% FF = 38 $k = 9$ md
predicted FF = 14 $k = 65$

concentration and inversely proportional to the water viscosity. The mobility of the ions is also involved, but the spread of ionic mobilities is not very great (excluding H^+ and OH^-). For very concentrated solutions, interactions between ions reduce somewhat the ionic mobilities. Temperature has an exponential effect on viscosity. Since the activation energy of viscosity is quite small, however, the magnitude of the temperature effect is modest. The single most important factor is the ionic concentration which can vary in natural waters by four orders of magnitude.

As the temperature approaches the critical temperature of water, dramatic changes in the fluid properties take place. An important change is a large decrease in the dielectric property of water due to the thermal agitation counteracting the tendency of the water molecules to be polarized by the electric field. This reduction decreases the shielding effect that water has on the ions in solution and causes the ions to recombine into neutral molecules. High pressures can offset this effect, but these pressures would not be present in the upper crust. Tables II and III show the viscosity and dielectric properties of water, and the resulting conductivity changes are shown in Figure 4. This effect is modified by very concentrated solutions, as shown in Figure 5.

Using laboratory measurements on the effect of pressure on the electrical properties of saturated rocks and the above data on the temperature and pressure effects on the fluid, one can estimate the range of resistivities that could be expected within the upper crust. There are some questions concerning whether or not the crack distribution of near-surface rocks would be representative of deeper rocks. There is also the problem of the presence of deep seated fissures and faults affecting these predictions. Also, eventually as the temperature continues to increase with depth, the rock minerals can contribute to the conductivity. Estimates of these effects are shown in figure 6 for a variety of heat flow conditions.

Table II

Viscosity of Water above 100°C and 0.1 kbar^(2, 8, 279, 484, 565, 597, 613, 737, 768, 893, 1034, 1068, 1105)Viscosity, $\mu\text{N sec m}^{-2}$

P , kbar	at T														
	100°C	150°C	200°C	250°C	300°C	350°C	400°C	450°C	500°C	550°C	600°C	650°C	700°C	750°C	800°C
0.1	287	185	137	110	89.5*	23.6	25.4	27.2	29.2	31.2	33.2	35.2	37.2	39.2	41.2
0.5	296	194	148	121	101	84.8	68.8	52.0	42.0	39.8	40.0	41.0	42.1	43.5	44.9
1.0	308	205	162	132	113	98.6	86.7	76.0	66.9	60.4	56.1	53.3	52.1	51.9	52.3
1.5	320	216	175	145	124	109	98.0	87.0	79.0	72.5	—	—	—	—	—
2.0	333	227	184	155	133	117	105	95.0	86.0	81.0	—	—	—	—	—
2.5	346	238	192	163	141	124	111	100	92.0	87.0	—	—	—	—	—
3.0	359	249	199	171	148	130	116	105	96.0	91.0	—	—	—	—	—
3.5	372	260	206	178	155	135	121	109	100	95.0	—	—	—	—	—
4.0	385	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5.0	415	—	—	—	—	—	—	—	—	—	—	—	—	—	—
6.0	446	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7.0	477	—	—	—	—	—	—	—	—	—	—	—	—	—	—
8.0	510	—	—	—	—	—	—	—	—	—	—	—	—	—	—
9.0	544	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table III Static Dielectric Constant of Water above 100°C and 0.1 kbar⁽¹⁰³⁴⁾

P , kbar	Static dielectric constant								
	at $T = 100^\circ\text{C}$	200°C	250°C	300°C	350°C	400°C	450°C	500°C	550°C
0.1	55.7	34.8	27.1	20.2	—	—	—	—	—
0.25	56.2	35.4	28.1	21.5	14.8	2.7	1.9	1.7	1.5
0.5	67.0	36.4	29.4	23.0	17.7	12.5	6.5	3.7	2.7
0.75	57.8	37.3	30.5	24.2	19.3	14.9	10.2	7.0	4.9
1.0	58.4	38.0	31.4	25.3	20.5	16.5	12.5	9.3	7.0
1.5	59.6	39.5	32.8	27.0	22.4	18.7	15.0	12.0	9.9
2.0	60.8	40.8	34.1	28.4	23.8	20.0	16.6	13.0	11.6
2.5	61.9	41.9	35.1	29.5	24.9	21.1	17.7	15.1	12.9
3.0	62.9	42.8	36.0	30.5	25.9	22.1	18.7	16.1	13.9
3.5	63.8	43.7	36.8	31.3	26.7	22.9	19.5	17.0	14.8
4.0	64.7	44.5	37.5	32.0	27.4	23.5	20.3	17.7	15.5
4.5	65.5	45.2	38.2	32.7	28.0	24.1	20.9	18.3	16.1
5.0	66.3	45.8	38.7	33.2	28.5	24.6	21.5	18.8	16.6

Resistivity of .001 N NaCl

Model SEMI-LOGARITHMIC 46 4970
1 1/2 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.

Fig 5 Salinity modification of temperature effect on conductivity of saline solutions

Fig 6 Hypothetical conduct resistivity depth profile taking into account T,P effects on pore fluid resistivity and rock matrix resistivity for different temperature gradients

Rock Mineral and Alteration Mineral Conductivities

Normally we do not think that the rock matrix is important electrically until we reach the temperatures of the lower crust or even the upper mantle. In truth, however, our knowledge of mineral conductivities as a function of temperature and chemical environment is still too limited for us to make definitive statements. Most of the early laboratory measurements on mineral conductivities are quite worthless because they were made in oxidizing environments. Since the conductivity is mostly impurity conduction, the chemical influence on conductivity is enormous. Through Al Duba's work we are familiar with the importance of the oxygen fugacity on the conductivity of olivine, as shown in Figure 7, but work is needed on many other minerals and other chemical factors besides oxygen fugacity. Basalts show a great range of conductivities, but our understanding of their properties is extremely limited.

Some recent measurements on hornblende (G. Olhoeft, personal communication) have shown them to have quite high conductivities at modest temperatures, which could considerably alter conductivities at those depths where hornblende should be a stable and common alteration product. Figure 8 shows some possible conductivity profiles based on such an effect. Much more work is needed, however, before we can feel reasonably sure about the mineral conductivity contribution to the electrical properties of the crust.

Melt properties are also still relatively little studied. Reports of large conductivity increases on melting are sometimes given, but the few published figures on melt conductivities are often quite in line with the extrapolated behavior of the temperature effect on the solid phase. A partially melted rock also raises many of the same problems that arise in conduction in porous media, although as pointed out by Harvey Waff, the wetting relationships can make the partially melted rock have a more systematic "pore" geometry than a typical porous rock.

Log₁₀ electrical conductivity vs $10^4/T$ for San Carlos olivine and the Red Sea peridot. Lines labelled A through E are for the San Carlos olivine and are discussed in the text.

Fig. 7: Effect of oxygen fugacity (f_{O_2}) on conductivity of olivine (Duba and Nicholls, 1973)

Fig. 8: Possible effect of hornblende alteration on conductivity profile (Olhoeft, 1976)

Despite our ignorance on the full range of mineral conductivities, one can predict reasonably well that the rock matrix will not be important in the near surface (excepting those situations where liquid magmas are near the surface). Alteration products, on the other hand, in the near surface often are of considerable importance for the electrical properties. This is the result of the special electrical properties of clays which are common alteration products in the near surface. Clays are really unconsolidated porous rocks, but on a microscopic scale, so that surface phenomena control many of their properties. Thus their conductivities represent extreme examples of surface conductivity effects. One measure which is related to these surface properties is the ion exchange capacity. Simple models have been proposed which can predict reasonably well the clay conductivity given the porosity, fluid salinity, and ion exchange capacity of the clay (Waxman and Smits, 1968), but more work is probably needed. These models show that in many realistic situations the clay conductivity contribution is more important than pore fluid contribution. This factor becomes even more important at elevated temperatures apparently due to a slightly higher activation energy for the surface conduction than for the pore volume conduction. It is important, therefore, to recognize the conditions that lead to clay alteration, especially the high ion exchange clays such as montmorillonite, since their presence in the rock pores may completely dominate the electrical properties of the rock. Fig. 9 shows the strong influence of clay minerals on the apparent fluid resistivity. The strong linear trend with ion exchange capacity is partly the result of circular arguments using determinations of surface conductivity to estimate the ion exchange capacity, but these estimates correlated fairly well with the clay content.

Sulphide minerals may play a similar role although their concentrations may not be as high as is often the case with clay minerals. Induced polarization

✓ measurements may help identify the presence of both sulphide and clay minerals.

Since clay alteration zones (sometimes accompanied by sulphides) are common to many geothermal areas, I.P. measurements can be an important exploration tool.

* Sulphide mineralization, however, is usually much more effective in producing I.P. effects than the clays.

The Inverse Problem

Determining Rock Parameters from Rock Properties

In most situations it is not the electrical properties, but rather it is certain parameters that influence the electrical properties that are of direct interest. In geothermal applications the parameters of most interest are temperature, permeability, porosity, and the chemical nature of the interstitial fluids. Attempts to determine such parameters from the electrical measurements obviously must contend with a non uniqueness problem. Thus it is very important to bring in other information that could help narrow the range of possible interpretations. Geologic, geochemical, and other geophysical data can all make important contributions, but to make proper use of such data requires expanding our knowledge and understanding of rock properties.

As an example of the potential of such analysis consider the possibility that seismic data could also give determinations of porosity. From Archie's Law the combined electric and seismic data would give the pore fluid conductivity. If a valid relationship between porosity and thermal conductivity existed, and if it was known that convection was not occurring, heat flow data combined with the seismic data would determine the temperature profile. Combining all this information we should know the temperature, porosity, and the pore fluid salinity. Such correlative studies are often used in oil exploration, but much more work is needed to bring out the full potential of these methods.

Fig. 9: Apparent fluid resistivity determined from rock sample resistivity, using Archie's Law, as a function of ion exchange capacity determined by clay content (and by surface conductivity determinations)

O core samples from clay alteration zone at Roosevelt Springs
 X artificial samples with montmorillonite (true Q_v)
 (Sill and Ward, 1976)

Since seismic data is one of the richest sources of other geophysical data, an understanding of rock elastic properties is of special importance. Porosity: velocity relationships has been observed for a long time, but the theoretical understanding of these relationships is still a bit thin. Figure 10 shows such a relationship involving velocity and electrical properties that can lead to estimates of the pore fluid resistivity. Considering the fact that most of the past work has concentrated on sedimentary rocks which are not typical of the rocks in geothermal areas, it is clear that further studies are needed. The great interest in physical property changes associated with earthquake phenomena has spurred studies of such relationships in igneous and metamorphic rocks where crack porosity becomes an important factor. These studies too are far from complete, but very useful results have been obtained. Of special interest here are the effects of partial saturation on P wave velocities and the effects of pore fluids on Poisson's ratio and on seismic wave damping. (Direct detection of gas-liquid interfaces from seismic reflection data has been one of the most significant recent developments in oil exploration.) There is a need for a better understanding of the effect of clay alteration on these elastic properties, however.

Other areas of interest include strain damage in rocks, its effect on electrical conductivity and permeability, and its association with microearthquake activity and the parallel problem of fracture healing by mineral precipitation.

Porosity also plays a role in thermal conductivity, and permeability is an important parameter in convective heat transport. We have already mentioned the possibility for unique determinations of porosity from combined seismic and electrical measurements. Permeability is a special problem. It not only plays a role in establishing the thermal conditions in existence but it is also an

Fig. 10: Seismic: Resistivity relationship that can be used to estimate pore fluid resistivity

important factor in dealing with the problems of extracting geothermal energy from a reservoir. Developing methods to estimate permeability would be a significant step for geothermal exploration. Some inputs will come from self potential measurements which can detect the presence of pore fluid convection, and these studies will be dealt with separately in this symposium. Permeability, since it is proportional to the cube of the channel widths, is very scale sensitive. Channel ways that do not influence the electrical conductivity to any great extent, can monopolize the permeability. Obviously non electrical data is also needed to predict permeabilities. Geologic data, especially quantitative evaluations of surface faulting and fault geometry, will be especially important.

Geochemical data can also be very helpful in sorting out parameters from the geophysical data, as well as providing direct input such as in geothermometry. Because alteration minerals often have significant effects on the electrical properties, it is important to understand the conditions that lead to the development of these alterations. Knowledge of phase equilibria, while necessary, is not sufficient, and some understanding of rate processes is also needed.

The scope of the subject matter of this section is so wide it is understandable that much development is still needed. (It also helps explain the sketchiness of our presentation) Such developments will benefit not only geothermal exploration, but other resource exploration as well as general geophysical studies.

MODELING TEAM REPORT

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INTRODUCTION

Electrical geophysical methods traditionally have suffered from a lack of interpretation capability. Analytic solutions for simple bodies in a whole space and scale model experiments are useful, but severely limited. However, in the past few years previously intractable electromagnetic boundary value problems have begun to yield to numerical solutions using large computers. Much work remains, though, to make practical interpretation methods for complex geological structures widely available.

Forward Solutions

Four main techniques have been used to achieve numerical solutions to two- and three-dimensional problems:

- ✓ (a) Finite difference,
- ✓ (b) Network analogy,
- ✓ (c) Finite element,
- ✓ (d) Integral equation.

All of these techniques use the method of moments (weighted residuals) to solve an equation of the form:

$$L(f) = g, \quad \text{where } L \text{ is a linear operator, } g \text{ is a source term, and } f \text{ is the unknown.} \quad (1)$$

where L is a linear operator, g is a source term, and f is the unknown.

The unknown is approximated by

$$f = \sum_n \alpha_n f_n, \quad (2)$$

where the α_n are constants, and the f_n are basis functions. Substituting (2) into (1),

$$\sum_n \alpha_n L(f_n) = g. \quad (3)$$

An inner product $\langle f, g \rangle$ and a set of weighting functions, W_n , are defined for the problem. Then taking the inner product of (3) with each W_m ,

$$\sum_n \alpha_n \langle W_m, L(f_n) \rangle = \langle W_m, g \rangle \quad (4)$$

yields a matrix equation

$$[l_{mn}] [\alpha_n] = [g_m] \quad (5) \checkmark$$

to be solved for α_n , which are substituted into (2) to give the unknown f .

For methods (a), (b), and (c), L is a second-order differential operator, while for method (d) it is an integral operator. The finite difference and network analogy methods are similar in that the differential operator is approximated by a finite difference operator. In each method one must choose effective basis and weighting functions. The particular choice, $W_n = f_n$, is known as Galerkin's method.

For purposes of comparison, the numerical techniques may be divided into two groups: differential equation (a,b,c) and integral equation (d). The differential equation solutions are simpler to set up, and they result in large banded matrices. Because the entire earth is modeled on a grid, differential equation methods are preferable for modeling complex geologic structures. Of the differential methods, the finite difference and network solutions are easier to program, while the finite element solution can handle more complex geometries. Integral equation formulations involve more difficult mathematics, but their advantage is that unknown fields or potentials must be found only in anomalous regions. Thus integral equation solutions are better for modeling one or a few small bodies, because the matrices, though full, are smaller than those for differential equation solutions.

* The state-of-the-art in forward solutions for electrical geophysical problems is shown in the matrix below:

	<u>Forward Solutions</u>		
	<u>2D</u>	<u>2D-3D</u>	<u>3D</u>
Finite Difference	0 ● <i>elec- mag</i>	0 [●]	[●]
Network	0 ●	0	
Finite Element	0 ●	0	[0 ●]
Integral Equation	0 ●	0 [●]	0 [●]

The open circles stand for resistivity, or zero-frequency solutions, while the solid circles stand for electromagnetic (time-varying) solutions. The brackets indicate numerical solutions that have been reported but are not substantiated by adequate cross checks. In the 2D problem, both the model and the source are two dimensional; in the 2D-3D problem the model is two dimensional, while the source is three dimensional (e.g., short grounded wire); and in the 3D problem both model and source are three dimensional. The lack of good solid numerical solutions for 2D-3D and 3D EM problems and for 3D resistivity problems is startling in view of the money and effort spent collecting field data over complex geology. High priority must be assigned to research aimed at filling in this matrix, so that good solutions with adequate cross checks are available.

Gaps in the matrix are due to mathematical complexity and to computer time and storage limitations. The EM problems that remain unsolved are vector problems requiring three unknowns for each node or cell. Even though the 2D-3D EM problem is solved on a two-dimensional grid in Fourier transform space, a large amount of computer time is required to compute the many solutions needed for an inverse Fourier transform.

To compare numerical solutions, Figure 1 shows a comparison of finite element and integral equation results for a pole-dipole resistivity survey over a simple cube. Where the results differed by more than two ohm-meters, the difference is shown in parentheses. The finite element solution employed 6300 nodes, while 8 cubic cells were used for the integral equation solution.

Both solutions were computed on a UNIVAC 1108 computer; the finite element solution, computed by D. Pridmore, required 10 minutes cpu time, while the integral equation solution, computed by G. Hohmann, required only 4 seconds. Pridmore used an iteration solution to conserve storage, and hence had to solve separately for each source position, while Hohmann, having only a 24 x 24 matrix, used a direct solution. This, then, is the type of problem where an integral equation solution is better than a differential equation solution.

On the other hand, Figure 2 shows the type of model that is more amenable to a differential equation technique. It is taken from J. Coggon's thesis and shows dipole-dipole, resistivity-^{Induced Pole}IP results for a complicated two-dimensional model. Very complicated models such as this are difficult or impossible to model using integral equations because of the extremely large matrices that result.

Topographic effects are best modeled by the finite element method because of its geometric flexibility. Another problem that has hardly been studied is that of transient EM responses. All EM modeling discussed above refers to steady state; time-domain modeling involves another order of complexity. Nevertheless, it is an important modeling problem that should be attacked.

Data Interpretation

The purposes of theoretical modeling are survey design and data interpretation. The matrix below shows the state-of-the-art of data

$p = 100 \Omega M$

POLE-DIPOLE-APPARENT RESISTIVITY (6300 NODES)

Fig 1

THEORETICAL INDUCED POLARIZATION ANOMALIES

APPARENT RESISTIVITY
 ρ_a IN OHM-M
CONTOURS AT 10, 14, 19, 27, 37, 52, 72, etc.

ARRAY: DIPOLE-DIPOLE
ELECTRODE INTERVAL: 200 ft

PERCENT FREQUENCY
EFFECT P.F.E.
CONTOUR INTERVAL 1.0

MODEL: JAN 3N-5A
MESH: W9
DATE COMPUTED: 5 Aug 74
DATE DRAWN: 5 Aug 74

STRUCTURE

0 200 400
FEET

FEET
0
200
400
600

FIG. 122

JAN 3N-5A

Fig 2

interpretation for the three methods used. Again, open circles pertain to resistivity and solid circles indicate electromagnetic methods, while the brackets denote rudimentary or unsubstantiated techniques.

✓ State-of-the-art

	<u>Data Interpretation</u>			
	<u>1D</u>	<u>2D</u>	<u>2D-3D</u>	<u>3D</u>
Comparison with Simple Numerical Models	0 ●	0 ●	0 [●]	0 [●]
Trial and Error Data Fitting With Complex Numerical Models	0 ●	0 ●	0	0
Inversion	0 ●	[●]	[0]	

Gaps in the first two rows of this matrix reflect a lack of forward solutions, while gaps in the last row are due both to a lack of forward solutions and to the great difficulty of inverting data when forward solutions are numerical. If electrical methods are to be successful in geothermal exploration, these gaps must be filled.

Simple numerical models are essential for proper survey design, for rough field interpretations, and for insight in more sophisticated interpretation schemes. Trial and error data fitting with complex models is very useful, but those who have used it for 2D and 3D structures recognize the following difficulties:

- (1) Many time-consuming iterations required.
- (2) Difficult to choose next model.
- (3) Does not generate a range of acceptable models.

Inversion, on the other hand, has significantly enhanced the science of 1D interpretation, and must now be applied to 2D and 3D interpretation.

Initial efforts have been made, but these efforts should be pursued. It is doubtful, however, that strictly automated inversion can be applied to the latter cases, because of non-uniqueness, geological noise, and the large computer time involved. Furthermore, good initial estimates of model parameters are crucial for the success of nonlinear inversion, but they are difficult to obtain for complex geology. Probably some combination of trial-and-error fitting and inversion -- call it interactive inversion -- is optimum.

One-dimensional Inversion ✓

There are three applications of inversion methods to geothermal exploration problems. These are:

- 1) obtain a realistic set of earth model parameters which explain a given set of geophysical observations,
- 2) provide an estimate of the resolution of the earth model parameters and
- 3) yield estimates of the parameter resolution in designing proposed field measurements.

Inversion methods can be broadly classified as follows:

- 1) exact methods,
- 2) approximately exact methods,
- 3) linear or derivative methods and
- 4) approximate methods.

There are certainly other ways in which inversion methods could be classified but the above is a convenient one for the purpose of the following comments. Examples of specific methods which fall into the four categories illustrate why this particular classification has been used. Exact methods generally directly or indirectly use an integral equation formulation for the inverse scattering problem commonly employed in small particle physics. The general integral equation approach has been developed by Russian workers (Agranovich

and Marchenko, 1966) and Gel'Fand and Levitan (1955). Though the methods have been employed to interpret main magnetic field variations there has been no implementation of the method for electrical sounding methods. Becher (1968) implemented the method for a plane wave source and suggested that the results could also be applied to line source problems. An example of inversion using synthetic data is shown in Figure 3. The interesting point demonstrated by this figure is that the inverse solution is capable of yielding a continuous variation in conductivity with depth. Another interesting but academic point is that the method yields a unique estimate of model parameters if the observations are made over an infinite frequency range with no error.

Approximately exact methods are those which use a parameter relationship between model layer parameters and the geophysical data. Two prime examples are the methods developed by Bostick and by Zohdy (1975). Figure 4 demonstrates an output from Adel's program.

The third type of inversion method, the linear or derivative type, is based on linearization of a nonlinear functional relationship between model parameters and computed points. Glenn et.al. (1973) and Inman (1975) have published results of using this method for controlled source and resistivity sounding methods respectively. Figure 5 is an example from Inman (1975) for a resistivity sounding; a major advantage of linearized inversion is that there is an estimate of the resolution of model parameters.

✓ The fourth type of inversion method, approximate inversion, consists of methods which are based upon curve matching principles. Since this has been a rather standard method we will not go into details.

Table 1 gives a summary of the general advantages and limitations of each inversion method.

With this preamble we can now examine some areas where more work needs to be done. Broadly speaking these are:

- 1) integration of interpreted values of model parameters with petrophysical measurements,
- 2) a greater emphasis on the design of field experiments in terms of optimizing parameter resolution,
- 3) simultaneous inversion of different but complementary sets of geophysical data.

A few examples will illustrate the nature of these problems.

The first example is from horizontal loop-loop soundings conducted in the Kilauea Iki Caldera on Hawaii. Figures 6 and 7 demonstrate the sounding data from one distance and the data fit. The computed values for combined parametric and geometric soundings are based upon model parameters shown in Figure 8, which also shows the error bars for each parameter not held constant. VLF measurements of apparent resistivity along traverses across the crater, at a frequency of 18.6 khz, yielded values around 150 ohm-meters. One problem encountered in interpretation of the electrical measurements is that the mutual agreement of resistivity values for the approximately 600 ohm-meter layer above the melt (~ 2 ohm-meters) is poor for the various sounding interpretations. The interpreted values were 600 Ω -m from loop-loop EM and 200 Ω -m from VLF. One possible cause of the discrepancy between the interpreted values is shown in Figure 9, which compares laboratory values of resistivity as a function of frequency and the interpreted values from the sounding data. One of the important points of this comparison is that the intrinsic physical parameters of rocks are an important component in the inverse interpretation of electrical data.

The second and third problem areas have been investigated by a few workers but not very extensively. Table 2 demonstrates a comparison between the resolution of parameters for a crustal sounding model by three sounding methods. Such data could be used to evaluate each individual method in conducting sounding experiments. Of particular note here is the lack

GENERALIZED PROS AND CONS

A) EXACT AND ALMOST EXACT

PROS

- 1) CHEAP-FAST
- 2) NO APRIORI PARAMETER ESTIMATES
- 3) UNIQUE
- 4) ARBITRARY MANY LAYERS

CONS

- 1) AMPLIFICATION OF NOISE
- 2) CAN NOT COMBINE DATA SETS
- 3) NO RESOLUTION ESTIMATE
- 4) LIMITED THEORY (PLANE WAVE RESISTIVITY)

B) LINEARIZED

PROS

- 1) RESOLUTION ESTIMATES
- 2) COMBINE DIFFERENT DATA
- 3) FILTERS NOISE
- 4) EXPERIMENT DESIGN

CONS

- 1) MORE EXPENSIVE
- 2) COMPLEX MODELS NOT RESOLVED
- 3) ESTIMATE OF MODEL REQUIRED
- 4) NOT UNIQUE

C) APPROXIMATE

PROS

- 1) CURVES GENERATED ONCE
- 2) NO COMPUTER

CONS

- 1) NO ESTIMATED RESOLUTION
- 2) NO ESTIMATE OF FIT
- 3) MORE THAN 2-3 LAYERS USUALLY IMPOSSIBLE

TABLE 1.

3
FIGURE 1

FIGURE 8

Fig 6

-52-

FIGURE 7

KILAUEA IKI SOUNDING MODELS

FIGURE 6

FIGURE 7.

PARAMETER STANDARD DEVIATION

METHOD	ρ_1	ρ_2	t_1	t_2
AMT ρ_a	7%	U.R.	77%	9%
AMT ρ_a	59%	U.R.	U.R.	35%
DIPOLE - DIPOLE	7.2 %	U.R.	U.R.	U.R.
VES	4%	U.R.	21%	U.R.
COMBINED AMT ρ_a, ϕ	6%	U.R.	58%	7%

Table 2

of resolution of model parameters by phase measurements. Of course a more natural approach is to use two or more complementary geophysical methods.

Table 3 shows that the combination of MT-AMT and dipole-dipole soundings yields an estimate of the middle layer resistivity and thickness-the objective of this particular sounding problem. The moral here is that a study of the combination of different sounding methods can mean the success or failure of a sounding experiment.

PARAMETER	PERCENTAGE STANDARD DEVIATION	BOUNDS	
		LOWER	UPPER
$\rho_1 = 2000$	12%	1780	2240
$\rho_2 = 1 \times 10^6$	45%	6.4×10^5	1.5×10^7
$\rho_3 = 100$	92%	40	251
$t_1 = 2000$	11%	1770	2260
$t_2 = 2.5 \times 10^4$	2%	2.46×10^4	2.54×10^4

PARAMETERS	CORRELATION
$\rho_1 \rho_2$	0
$\rho_1 \rho_3$	0
$\rho_1 t_1$	+
$\rho_1 t_2$	0
$\rho_2 \rho_3$	0
$\rho_2 t_1$	0
$\rho_2 t_2$	-
$\rho_3 t_1$	0
$\rho_3 t_2$	0
$t_1 t_2$	0

TABLE 3 COMBINED DIPOLE-DIPOLE AND MT-AMT DATA
RESOLUTION

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SELF POTENTIAL TEAM REPORT

M. Dorfman, Team Leader

Don Hoover

Dave Fitterman

Bob Corwin

Charles Zablocki

INTRODUCTION

The Self-Potential Team presented results of various field studies, and presented the theory for the calculation of SP anomalies generated by cross-coupling phenomena. There appears to be SP anomalies over many geothermal sites, but the specific source mechanism has not been determined. In addition, background potentials often are sufficiently large so as to mask readings from potential geothermal reservoirs. Recommendations for future work are included at the end of this report.

Charles Zablocki presented the results of field tests in Kilauea, Hawaii. He reports that surface measurements of self-potential (S.P.) on Kilauea Volcano appear to be the single most useful geophysical method for identifying and delineating thermal anomalies related to concealed magma reservoirs and still-hot intrusive zones. Positive potentials, as high as 1600 millivolts across lateral distances of a kilometer or less, are developed not only over known fumarolic areas and recent eruptive fissures but also in areas that have no surface thermal manifestations. The S.P. method excels because of: 1) the higher surface resolution of the causative heat sources, 2) the smooth distribution of the measured potentials (i.e., insignificant short-wave length "noise" potentials), and 3) the simplicity and relative speed of measurement.

Evidence supporting an electrokinetic origin for the large anomalies is that: 1) top-of-source-depth determinations of the S.P. anomalies are shallow, coinciding with local water tables (<500 meters), and may result from the horizontal divergence of the cooling, convective water rising above the deeper heat sources; 2) lateral boundaries of an S.P. anomaly above a suspected magma reservoir coincide with the epicentral distribution of earthquakes at depths of 2 and 3 km and can be explained by collimation of the hydrothermal

fluids by vertical gravitational forces: 3) all anomalies have a positive polarity over known or inferred hot zones, suggesting preferential adsorption of anions or other means of effecting the differential displacement of cations from anions; and 4) small negative potentials associated with some anomalies are thought to reflect the descent of cooler waters in the convective system.

Figure 1 shows the area map (a), the S-P map (b), earthquake epicenters and S-P anomalies (c), and S-P profile along the Chain of Craters Road (d).

Don Hoover discussed background noise problems associated with S-P profiling. These include 1) effects due to watering the probes, 2) junction potentials, 3) variations in the water content of the soil, 4) topographic effects (capillary pressure potentials), 5) man made effects, 6) streaming potential.

Fig. 2 shows the variations that occur due to watering electrodes. Figs. 3-6 indicate errors that may be caused by other effects. Hoover also reported on recent S-P profiles taken at Adak, Alaska. S-P readings as high as 2700 mv. at the volcano were noted; however, these appear to be directly related to changes in elevation and are probably a function of streaming potential, according to Hoover.

Bob Corwin reported as follows:

A. Case histories of SP surveys

Four SP surveys in geothermal areas are briefly summarized below:

1) Leach Hot Springs, Grass Valley, Nevada

Fig. 7 shows SP contours around the hot spring area. This was the only large-scale SP anomaly found in Grass Valley (several anomalies of similar amplitude but less than 100 m width were measured over obvious fault scarps). This survey was done very carefully, using a common reference electrode for all readings, and subtracting long-period telluric variations (which were independently recorded). Although the data is noisy (Fig. 8

shows the data along line AA'), the anomaly is easily distinguishable. A great deal of geophysical work has been done in this area, with no obvious indication of a large-scale reservoir.

2) Los Humeros Caldera, Mexico

Fig. 9 shows results of an SP profile run across part of a caldera which appears to have very high temperatures very close to the surface (the area of surface geothermal activity is at Station 0). There is not sufficient data to determine where the true zero level is (i.e. whether the fumarole area is positive relative to background, or the rim area negative), but a gradient of 550 mV in 13 km certainly is of interest.

3) Paoha Island, Mono Lake, CA

Fig. 10 shows a gradient anomaly obtained by towing a pair of SP electrodes, separated by 20m, about 15m offshore of Paoha Island, Mono Lake, Ca. Anomalous activity is clearly seen off a large hot spring area located on the shoreline. While the amplitude of the anomaly is small, it must be kept in mind that the lake water is very conductive (about 0.1 ohm-meters) and that the background noise also is low.

4) Kyle Hot Springs, Buena Vista Valley, Nevada

Fig. 11 shows the SP line run through the hot springs area. A very large anomaly begins just east of the hot springs and continues for some 6 km. Similar anomalies have been recorded up to 15 km to the north and south of the hot springs, and appear to be caused by conductive mineralization rather than geothermal activity. (Drill holes in the anomaly have shown conductive minerals, but heat flows are not high).

B. Cost effectiveness of SP surveys

Effectiveness is not yet established but costs are low. Cross-country in the Nevada desert, one man can survey up to about 8 km at 250 m spacing in a day. Equipment cost probably is less than \$1,000. Increasing spacing increases

survey speed but reduces resolution.

C. Location of SP in exploration architecture

From the very preliminary data available so far, SP may be useful as an initial reconnaissance method as it is fast and cheap and may give broad-scale anomalies of reservoir dimensions. SP also may be useful in detailed surveys, for locating faults along which water is flowing or small areas of high heat flow.

D. Goals

Future work in geothermal SP should include:

- 1) Dissemination and compilation of field data and case histories- as at this conference. This is especially important for a method such as SP, where field input is needed to check theoretical mechanisms.
- 2) Research into generation mechanisms of geothermal SP anomalies. At this time we are confident that anomalies exist, but don't know whether observed anomalies are caused by thermoelectric coupling, streaming potentials, geochemical effects, conductive minerals, or other unknown sources. Theoretical modeling and laboratory methods are available; they only need to be applied to the problem.
- 3) Research into the standardization of field techniques. The quality of SP data is strongly affected by the manner in which it is measured. It is easy to obtain bad data, and difficult to tell it is bad. Field and laboratory research into the effects of geology and cultural activity on SP readings and methods to eliminating telluric current effects is needed. Published SP data should include a description of equipment and field procedure.

- 4) Research into response of electrodes to changes in soil moisture, chemistry, temperature, etc. (Figure 12) is needed.

Myron Dorfman presented results of laboratory experiments in which a point heat source was embedded in a limestone block, resulting in an instantaneous generation of S-P readings at the surface of the block. The phenomenon was attributed to thermo-electric effects related to conductivity contrasts within the inhomogeneous media. Field tests were carried out in an artificial geothermal reservoir - a steam flood of a petroleum reservoir. These tests indicate that strong signals may emanate from the heat front. Successive tests over the field area indicate movement of the heat front with time, and appear to show temperature distribution behind the front. Dorfman noted that various methods have been developed to reduce background potentials to within the range of 5-10 mv.; that one reference point is preferable to successive step-wise progressions in elimination of error. He stressed the need for additional lab and field tests to confirm these data.

David Fitterman presented a review of the mathematics governing the generation of SP anomalies caused by cross coupling effects. The same mathematics is applicable whether the driving force is hydraulic pressure, temperature, or Eh potential. The theory shows that the magnitude of the anomalies for a streaming potential source is controlled by the product of the dynamic pressure and the contrast of the streaming potential coefficient at boundaries. Further, surface anomalies can not be produced without a subsurface interface between regions of different cross-coupling coefficient, and there must be a gradient of the driving force parallel the interface. Presently anomalies for the following cases can be calculated:

- 1) Layer over a half-space for a point pressure source
- 2) Vertical dike and vertical stock with a $1-e^{-kz}$ source dependence
- 3) Two-dimensional variations of pressure source over a layer

above a half space.

The calculation of anomalies for 2-D interface geometry with arbitrary source and is presently being pursued.

Fitterman suggests further laboratory work on measurement of streaming potential and thermo-electric potential. Every effort should be made to combine laboratory measurements of cores from geothermal areas where SP anomalies have been measured. This information can then be used as input to model studies with the goal being to explain field observations. Additionally, the results of geothermal convection calculations should be sought and used in 2-D SP models when programs become available.

✓Conclusions:

Observed SP anomalies occur over both geothermal areas and heat fronts in thermal floods, but in some cases the source mechanism is unknown. Potentials may be generated by streaming fluids, thermo-electric effects, geochemical variations occurring both at near surface and reservoir depths, conductive mineralization due to the proximity of magmatic material, and possibly by colloid deposition in convective hydrothermal systems. In order to better understand these mechanisms, recommendations for additional laboratory studies and 2-dimensional models based upon streaming and thermo-electric coupling effects were made. Improvements in field techniques are needed and these include development of better probes, and better methods for elimination of ground noise.

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VARIATIONS IN SELF POTENTIAL DUE TO WATERING OF
ELECTRODES SEPARATED BY 200 METRES, RAFT RIVER,
IDAHO

CAPILLARY EFFECT POTENTIAL (LOOSJES)

SUSPENSION EFFECT POTENTIAL

DIAGRAM ILLUSTRATING TWO POSSIBLE SOURCES OF ANOMALOUS SELF POTENTIAL WHEN ELECTRODES ARE PLACED IN THE SOIL

CAPILLARY PRESSURE POTENTIAL MILLIVOLTS

CAPILLARY PRESSURE POTENTIAL MEASURED ON

DIAGRAM ILLUSTRATING TWO SOURCES
OF SELF POTENTIAL DUE TO WATERING
OF ELECTRODES

**COMPARISON OF SELF POTENTIAL AND TOPOGRAPHIC
VARIATIONS AT STEAMBOAT HILLS, NEVADA**

FIG. 7

SELF-POTENTIAL

LEACH HOT SPRINGS AREA

GRASS VALLEY, NEV. SEPT. 1975

SEPT. 1975

LINE 001 GRASS VALLEY NEVADA

FIG. 15A

JAN 1976

R. Clymer

mV

FUMARoles

↓ CALDERA RIM

2W

0

2E

4E

6E

8E

10E

12E

14E

16E

2

0

1

2

3

4

5

6

7

8

STATION

KM

PALOHA IS., MONO LAKE, CA

0.2 mV → ←

↓
1 min
↑

1203
summers
~50' off

~50'
shore

Swings

seeps (2)

CHART NOS-2193
INDIANAPOLIS IND U.S.A.
ESTERLINE ANGUS
CHART NOS-2193
INDIANAPOLIS IND U.S.A.

BUENA VISTA VALLEY Line B-B'

XBL 7512-9824

XBL7411-8267

Potential Between Cu-CuSO_4 Electrodes vs Concentration Change.

DATA PROCESSING TEAM REPORT

John F. Hermance, Team Leader

William M. Adams

Marvin Bloomquist

Walter F. Hernandez

James O'Donnell

Harold W. Smith

Richard Thayer

Overview

The objectives of this team's presentations are to review state-of-the-art techniques for processing natural electromagnetic data, to describe innovative techniques which are presently being developed, and to offer recommendations concerning future developments in magnetotelluric, telluric and magnetic variation data processing.

One must keep in mind that a common ground exists for calculating the coefficients describing the cross-coupling of various electromagnetic components.

Marvin Bloomquist described conventional band-averaging techniques to obtain these cross-coupling coefficients.

Jim O'Donnell reviewed techniques employed by the U.S. Geological Survey in their telluric-magnetotelluric program for evaluating KGRA's.

Skeet Smith outlined a simplified data processing technique that while abbreviated to the point of being able to be utilized on a small programmable calculator, still retains much of the power of more sophisticated data processing techniques.

Richard Thayer discussed the handling of noise in MT data, and suggested several simple techniques for evaluating and minimizing their effects. Subtraction of measured instrument noise spectra from data autospectra was proposed as a way to overcome the problem of bias in impedance estimates; use of standard confidence limit estimation after empirical correction for data non-stationarity was also presented.

Walter Hernandez introduced some of the innovative techniques being developed at ENSCO. He emphasized the usefulness of employing a quantitative analysis of errors introduced by noise contamination and recommended the cost-effectiveness of using multiple-coherency and partial-coherency techniques.

GROUP ASSIGNMENTS

Friday, November 5, 1976

1. Discuss, criticize, & prepare 10 min. oral presentation on one or more topics discussed today.
2. Recommend procedure for disseminating computer programs.
3. Answer Dave Williams problem.

Do one or more of the above

A Problem Posed

by

Dave Williams

ERDA's Division of Geothermal Energy is in the process of planning a resource assessment project at one of the high Cascade volcanoes. The project will necessarily begin in a reconnaissance phase with the objective of identifying promising targets for drill sites. The most attractive targets will be carefully studied and, if warranted, one or two deep confirmation holes will be drilled. Because of budgetary restrictions, I must limit the number of field surveys; our first priority will be to assess a resource, not to assess techniques.

I look at electrical methods as one of our primary exploration tools in both the reconnaissance phase and the detailed studies. I would like this workshop to help design an electrical exploration strategy. I am primarily interested in advise on which electrical techniques would be the most effective in each phase, but comments on the need for supporting surveys are welcome.

The volcano we are looking first at is Mt. Hood. It is a range cone made up of various types of volcanoes (lavas, ash, mud flows, etc) which presumably are quite resistive. Beneath these are roughly 1/2 kilometer of Columbia River basalts. Access and topography can limit exploration work but helicopters will be available.

If possible I'd like a brief explanation of why the surveys recommended are being recommended over other techniques.

Land is mostly Nat'l Forest and most has
filed on by non-competitive geothermal leases. Sales
should be completed in 1977 & 1978??

First Field Season - Reconnaissance

1. heat flow (up to 1 km deep holes)
2. aeromag.
3. gravity
4. geochemistry
5. geologic mapping & dating
6. electrical?
7. microearthquake (several months)

Second Field Season

Detailed surveys at prospects identified during first field season
including intermediate depth drilling if appropriate.

Third Field Season

Deep drilling, if indicated by detailed surveys.

Group I Report

Friday, November 5, 1976

Group I discussed three primary areas: 1. Rock properties, 2. Dave Williams' Mt. Hood problem, and 3. Inversion techniques. The major discussion effort centered on rock properties.

The group discussed topics in the general categories as presented in the morning session. Additional work is needed on geometric problems in porous media; however, the problem probably does not require a national effort.

A major effort should be initiated to compile data on conductivity and induced polarization-effect for alteration-product minerals. The group feels that thermal conductivity as a function of electrical conductivity should also be studied. Particular effort should be concentrated on the relationship for metamorphic rocks. A spin-off of the lab work on thermal conductivity could yield theoretical relationships such that with an appropriate suite of logs (for example, neutron activation, electrical conductivity, sonic and neutron logs) it might be possible to calculate thermal conductivity in situ.

Additional measurements should be made to provide data to facilitate the integration of seismic and electrical field data.

In summary, group I encourages lab and theoretical studies of complex aggregates of minerals in the intermediate temperature range (200-600°C).

A brief discussion of inversion techniques resulted in the statement that a judicious choice of constraints was necessary. A judicious choice of constraints would result when geologic controls, and multiple data sets were integrated.

A preliminary discussion of the Dave William's Mt. Hood problem resulted in two primary approaches. One of these approaches would involve the use of SP and AMT for reconnaissance. The other approach would use heat flow,

and seismic data (microearthquakes, attenuation and delay data), and would use electrical techniques only if the others were positive.

Jim Applegate for
Art Lange
Dave Fleming
Dal Stanley
Jerry Hohmann
John Hermance
Ted Madden
Don Pridmore
Bill Petrick

Group II Report

Friday, November 5, 1976

Self potential (SP) surveys have been made in many geothermal areas in the western United States and Hawaii. In Hawaii the SP surveys often provide a direct indication of anomalous concentration of heat; however, in the western United States the relation to geothermal systems is not clear. With the possible exception of the Steamboat Hills, Nevada no examples have been presented indicating that SP data have contributed to an understanding of a geothermal system outside of Hawaii.

Research designed to provide a better understanding of the source of the measured SP anomalies in geothermal areas is needed. Until a better understanding of source of SP anomalies is obtained and methods of interpretation are developed, extensive new SP surveys are not justified.

Recommendation procedure for dissemination of electrical-methods computer Programs.

As a start, we propose that an inventory of all available working computer programs be undertaken by all conference participants using the following inventory format (see attached form):

The type of documentation may include: published, internal documentation, or undocumented programs. Walt Anderson of USGS agrees initially to collect all program inventory forms completed after the meeting. The combined total inventory will be collated and a current tabulation mailed to all conference members. To make the inventory comprehensive, a 100% voluntary contribution is requested from all members. A continuing effort to update the inventory with new and/or improved programs is desirable. However, it appears that this should be the function of some software systems group (e.g. a University) rather than the USGS.

Further, future published programs (suggested NTIS) should follow some

minimal program documentation standards as follows:

- (1) Use ANSI Fortran coding standards, where possible. Avoid machine dependent and/or assembly language code.
- (2) Define all program parameters, data, and all data files (include format description where applicable).
- (3) Include a typical input and output sample problem listing, complete with all machine operating system control statements used to run the sample. The CPU time for the run should be reported.
- (4) Attach the complete source program listing, including all called subprograms (exclude standard Fortran library routines)
- (5) State a program availability statement, e.g: "The current or updated source code for this program and related subprograms may be obtained by writing directly to the author. A magnetic tape copy of the source code will be sent to requestors to be copied and returned to the author. This method of releasing the source code was selected in order to provide requests for the latest updated version of this program. The magnetic tape will be recorded in the following mode (unless otherwise requested):

Industry compatible: 9-track, unlabeled, EBCDIC mode, odd-parity, 800 b.p.i. density, 80-character records (unblocked card images), and contained on 1-file followed by at least 1 end-of-file tape mark."

With respect to resource assessment of volcanoes in the high Cascades the group wanted to bring to the attention of Mr. Williams the rather extensive report that was written for the Washington Public Power Supply System entitled "Geothermal Resource Potential of Central Washington State". This report presents a "predictive regionalization of geothermal resource potential" scheme which is used to delineate areas within the Cascades deemed to have above average geothermal potential. The regionalization map is based on all available

geophysical data. Although the southern portion of the study area stops at the Columbia River the regional tectonics discussed can be applied to the Mt. Hood area. In particular the important suggestion is made that Mt. Hood may reside along the southern margin of an alocugen. The report also includes an exploration program designed for the Cascades and gives approximate costs. With respect to electrical methods the report recommends the rise of tensor magneto-tellurics.

Walter Anderson for
Bill Adams
Larry Ball
Frank Frischknecht
Don Mabey
Bob McEuen
Stan Ward

Group III Report

Friday, November 5, 1976

We primarily worried about the preservation, storage, transfer, and documentation of datasets, particularly MT data. The methods and techniques of MT are currently changing too rapidly to allow for a standard format for data set construction. Such a standard format would tend to be too stifling of future development. When techniques become more fully developed and procedures standardized, then something like the SEG seismic data format standards might be in order.

Right now, in order to facilitate the transfer of data between groups as well as the proper storage of data for analysis and comparison years later, it only seems feasible to recommend a standard way of properly documenting the data. For MT data we recommend that

- 1) the demultiplexed raw data should be stored, along with
- 2) the appropriate instrument response and/or a dataset with the instrument response removed, and
- 3) an explicit and detailed documentation of the measurements, the tape storage format, and the algorithm (or program example) to read the data tape.

Note: The Geoscience Advisory Panel of CODATA (Committee on Data of the ICSU) is very interested in this general type of problem (dataset presentation, storage, documentation, etc.), and they are very interested in receiving suggestions and recommendations, particularly with regard to time series data. These suggestions may be sent through the IUGG or directly to CODATA through the Geoscience Advisory Panel

The other prime topic of discussion was MT with regard to Dave William's Mt. Hood problem (which will be covered separately by F. Bostick). Also, the topic of topographic correction in MT came up as there is the extreme 11,000 ft. of relief in the Mt. Hood area.

Gary Olhoeft for
John Bailey
Marvin Bloomquist
Francis Bostick
Aldo Mazella
Dave Williams

Group IV Report

Friday, November 5, 1976

Group 4 members expressed concern that whereas numerical modeling techniques may provide a reasonable fit of parameters to observed data, they may also lead to preposterous subsurface models which may have limited bearing on geology. More geological inputs are needed to help us understand what the surface electrical observations represent. At this time insufficient work has been done in petrophysics to understand what effects pressure, temperature, water-rock interactions and clay-mineral formation have in controlling resistivity at depths of 0.5 to 3 km. Until we have reasonable understanding of this problem we will not and should not attempt to read too much into resistivity data unless there is supporting geology.

It was also agreed that more than one geophysical method is mandatory in order to help synthesize a subsurface model. Sometimes two methods alone may be insufficient, as in the case where gravity and resistivity may show completely different depths to basement if abundant clays occur in the upper portion of the basement rocks. Mutual inversion of these data may yield poor estimate of basement depth.

The group deferred discussion on specific forward and inverse modeling techniques, but felt it would be an illuminating exercise to compare methods. One suggestion was to submit a proposal to the workshop that various workers model the identical electrical data (e.g. dipole-dipole), taken in an area of good geological control, and compare results to geology in order to determine the variance that can result from different approaches and to find out why the variance if any, exists.

On the subject of how to disseminate computer programs, the group agreed that it is a worthwhile endeavor. It was recommended that one central clearing house be found (ERDA, USGS, NSF were mentioned) should assume

this responsibility to establish a standard form on which program authors could fill out all important information about their program; and to distribute the entire compilation to interested people who could write directly to the authors for copies of their programs.

Norman Goldstein for
Gunnar Bodvarsson
Richard Geyer
Walter Hernandez
Tsvi Meidav
Bill Sill
Darrall Word

GROUP V

Friday, November 5, 1976

The group discussed only the Mt. Hood problem posed by Dave Williams.

Discussion of this problem was deferred until Saturday night.

Group VI Report

Friday, November 5, 1976

- I. Group 6 has the following comments on the Team reports from Friday, November 5, 1976:

Team 1 - Rock Properties

This very important data should be more widely distributed,
e.g. published.

There is a gap between the field investigators and the laboratory researchers.

Strongly recommend more petro-physical studies with appropriate variables, e.g. temperature, pressure, alteration chemistry, well-defined.

The seismic-resistivity correlation may be useful in specific areas but does not appear to have broad application.

Team 2 - Models

The group agreed with the problems and recommendations summarized by the team.

Topographic effects were not reported on by the team.

We look forward to a real breakthrough in the efficiency of calculating 2-D and 3-D modeling. Such a breakthrough in D.C. resistivity 1-D modeling is the convolution technique.

Electrical/EM methods may find their most important application in detailing reservoirs, e.g. depth to top and bottom and lateral extent; this will require 2-D and 3-D models.

Total-field modeling should be more extensively pursued.

Team 3 - SP

There is general concern over the measuring techniques and interpretation of SP data.

Main Concerns are:

Measuring Techniques

1. Telluric corrections using one base station for long profiles.
2. Reference electrode(s) requirements.
3. Electrode preparation.
4. Topographic effects?

Interpretation

Controlled laboratory and field studies are needed.

The group felt that federal support, e.g. USGS, ERDA, should be extended for comprehensive laboratory/field investigations rather than more case history results. Industry would probably not support such activity since SP is not cost-effective at present.

The Heber geothermal field may be a good place for S.P. field tests since other very comprehensive data will soon be released.

Team 4 - Data Processing

The group generally agreed with the team's recommendations.

In particular, the group felt that on site processing of MT data should be encouraged. This assures good data and aids in subsequent site locations.

II. General discussion of dissemination of computer programs.

The group suggested:

1. Extended use of NTIS
2. Possible special issue of Geophysics
3. An availability list of appropriate computer programs should be compiled at the WEEMGE meeting.

George Jiracek for
Jim Combs
Don Plouff
Harold Smith
Charles Swift
Adel Zohdy
Roger Phillips

Group VII Report

Friday, November 5, 1976

In our discussion, Group 7 concluded that the IUGG/IAGA efforts to provide standard test cases for electromagnetic induction models, should be supported. In particular, it is essential that these test cases include geologic structures representative of geothermal targets.

Recommendations for the design of an exploration program to establish the geothermal resource associated with Mount Hood resulted in a general discussion of electrical survey design. The members of Group 7 agreed that a helpful technique in geothermal survey design would be use of a set of idealized models, representative of geothermal targets to compute, SP, electric and EM response prior to planning field efforts. A properly chosen set of such models might facilitate the early participation of geologists in the survey design. Clearly, for such a hypothetical model suite to be useful, it must include 3D models.

William Dolan for
Myron Dorfman,
Dave Fitterman
Alan Ramo
Richard Thayer
James Towle

Group VIII

Friday, November 5, 1976

We came up with some recommendations for the dissemination of computer programs. A list of undocumented programs was assembled. Walt Anderson's evening presentation covered many of our suggestions (e.g. test examples with programs, publish programs in NTIS, maintain a current listing of programs, tape copy procedure, machine, source code, etc.).

Dave William's problem was discussed and much time was spent on the effective application of various electrical techniques depending on the geoelectric setting of Mt. Hood. We suggested to Dave Williams that we needed this information prior to an assessment of techniques. We questioned his presumption that the surficial rocks were resistive and suggested that the ash and mud flows probably were conductive and consequently would modify the effectiveness, particularly of high frequency induction methods. The following techniques were considered for the initial reconnaissance part of the program: AMT, Telluric profiling, MT, S.P., VLF, aeromagnetism, airborne EM. Also brought up the availability of Bonneville Power Authority's large D.C. generator that could be used for D.C. or time-domain resistivity surveys.

Three members of the group were from the S.P. team and some time was spent explaining techniques and procedures on the application of S.P. to the other members. The need for a systematic study of the phenomenological mechanism, or mechanisms, responsible for the large magnitude potentials observed in many geothermal environments was stressed. Such an understanding is essential for attempting to quantify the configuration of a hydrothermal system. If studies should support an electrokinetic process (thermally-induced ion displacement) then a new dimension in studying the dynamic aspects of geothermal systems might be attained.

Charles Zablocki for
Arnold Farstad
Robert Corwin
Donald Hoover
Mark Landisman
I. K. Reddy
Bruce Smith

Summary of Evening Discussion

Friday, November 5, 1976

Forward problems:

Research should be directed towards making the 2D and 3D solutions faster and cheaper.

Inverse problems:

Although it was agreed that multidimensional inversion was desirable, it was thought that complementary geological and geophysical data was necessary for satisfactory implementation. An objection was raised to the basic philosophy of model dependent inversion. (An alternative method of inverting to current distribution was suggested). Other direct, cheaper inversion techniques should be investigated. To gain confidence in the various 2 & 3D interpretational techniques it was suggested that the same psuedo section be sent to the different groups working on the problem and a comparison of their results be made.

SP

There was considerable controversy over the effectiveness of the self potential method in the geothermal environment. Although the source mechanism is not well understood, interesting field results over geothermal prospects have been obtained. As a consequence it was felt that further research into the source mechanisms of SP is essential.

There was some question about the ability of the method to detect long wavelength features through the background noise or anomalies due to near-surface features.

Rock Properties

More correlation between laboratory rock sample measurements and field results is needed. Field samples should be carefully collected in order to preserve their insitu properties. According to Gary Olhoeft, further lab measurements will be published anually by the USGS.

Don Pridmore, reporter
William Pelton
William Petrick
Luiz Rijo
Al Tripp

**Applications, Limitations and Instrumentation;
Resistivity, and E.M. Team Report**

**H. Frank Morrison
James Applegate
Jim Fleming
Frank Frischknecht
Dallas Jackson
George Jiracek
William Sill
Adel Zohdy
Walter Anderson**

Applications and Limitations

The availability of new inexpensive computer programs for two dimensional, and to a more limited extent 3 dimensional, model calculations in resistivity and EM has permitted a much more quantitative approach to the interpretation of surveys using these techniques. In the case of resistivity, questions regarding the effects of lateral variations on soundings, the effects of shallow features, and more general studies regarding uniqueness and non uniqueness of resistivity interpretations are now possible. For many resistivity surveys it can be readily shown that very simple models will not fit the field data. There is general concern, however, that ever more complicated models may only reflect individual bias, or even chance.

For geological situations for which horizontal layering may be assumed inversion schemes are now generally accepted as the fastest and most objective interpretation techniques. Most of these schemes now incorporate statistical estimates of the variability of the resulting model parameters. As a practical matter many of these techniques still demand an experienced first guess by the user. This can be overridden by using a two stage process involving either the Dar Zarrouk multilayer estimation or a process which inverts to a continuous resistivity vs. depth function. A very important result of inversion studies with both resistivity and EM sounding methods is that joint inversion can lead to much improved estimates of the electrical section.

In some situations the total field resistivity survey (roving dipole, bipole dipole) may be of use in defining major structural factors and pronounced conductivity inhomogeneities close to the surface; it may also be used to determine field direction and hence to assist in determining the uniformity of assumed subsurface structure.

The electromagnetic methods fall into three groups; grounded electric dipole sources, long wire sources, or current loop sources. All of these may be operated in either the frequency or time domain and whichever is chosen depends more on practical considerations of instrumentation, noise characteristics or availability of interpretation techniques.

In general the artificial source electromagnetic techniques offer the following advantages: a) sounding without excessive lateral separation thus minimizing the effects of lateral resistivity variations that are a problem in large separation resistivity surveys; b) in the case of loop sources contact does not have to be made with the ground; c) apparently less sensitivity to local inhomogeneities; d) complimentary information to resistivity soundings.

Until recently EM techniques have found application at relatively high frequencies (>10 Hz) and at shallow depths. With new very sensitive magnetic field detectors and digital signal averagers arbitrarily low frequencies can be used and depths of exploration to over 10 km can be realized with available equipment. These sorts of surveys could be made even more easily with very high power pulse generators although at the present time the cost of these systems may more than offset the long signal averaging times required for the less expensive, lower power, conventional systems.

Many detailed problems remain to be resolved with EM methods. Possible inherent advantages of grounded dipole systems in certain geologic situations, quantitative evaluation of the effects of near surface inhomogeneities, and basic questions regarding the resolution and uniqueness of em techniques compared to dc resistivity must now be addressed. The potential advantages should encourage these studies.

The recommendations for future research in this area are summarized below:

- 1) Faster and hence less expensive forward solutions for 2D or 3D

problems will encourage more studies on the basic problems of interpreting and comparing resistivity and EM surveys in non layered situations.

- 2) More combined EM and resistivity surveys should be undertaken.
In some cases the EM survey can be an integral part of the resistivity survey: e.g. transient analysis of the square wave used in conventional resistivity surveys.
- 3) Field experiments with both time domain and frequency domain systems will resolve the accuracy of claims made by proponents of each.
- 4) I.P. offers potential advantages in geothermal exploration that has not been studied. The scale of the experiment indicates that source EM coupling can be anticipated so that very low frequencies must be used. As shown the discussion of EM, I.P. experiments at low frequencies (.1 to .001 Hz) are feasible and could be made part of a conventional resistivity survey.
- 5) Innovative techniques such as magnetometric resistivity should be evaluated.
- 6) Continuing development of improved equipment is required especially in controlled source electromagnetics.
- 7) Controlled source experiments for very deep electromagnetic probing should be undertaken.

Application, Limitations, and Instrumentation;

Tellurics and MT/AMT Team Report

Dal Stanley, Chairman

John Bailey

Gunnar Bodvarsson

Arnold Farstad

Richard Geyer

Mark Landisman

Aldo Mazella

I. K. Reddy

Darrell Word

Tellurics: Current variations in practice

i. Measurement of gradients in the telluric field using colinear electric dipoles is the most popular telluric variation for geothermal exploration. This method has proven to be rapid, instrumentally simple, and offer interpretable results in the field. When combined with MT calibration points, quantitative two-dimensional modeling may be reasonably used to interpret the data. Main limitations are the need for prior knowledge of geologic strike and continuous profile coverage to insure small cumulative errors on long survey lines.

Measurements are generally made at relatively narrow frequency bands around .05

ii. A slightly more sophisticated telluric technique consisting of measuring phase diagram areas at pairs of orthogonal electric field measurement sites is not used as much as the colinear technique because of the need to record recognizable ellipses at base and roving stations, ruling out any signal averaging techniques and the need for timing between base and rover.

iii. When the time series of telluric fields at orthogonal base and roving stations arrays are recorded, the telluric transfer function may be determined by techniques similar to those used in determining the MT transfer function or tensor. This is a quantitative reconnaissance technique, which, when combined with a tensor magnetotelluric base station for calibration may be applied to reconnaissance surveys to depths of several kilometers over large areas. The main limitation is the additional instrumentation and data processing required and lack of interpretable data in the field.

MT and Geomagnetic Sounding

Magnetotelluric methods covering frequencies of 0.0001 to 1000 Hz are now in wide use for geothermal exploration. Most operations use digital recording and home-office processing of data to obtain tensor resistivity soundings.

The majority of field systems now employ either induction coils or SQUID (superconducting quantum interference device) magnetometers as magnetic sensors. A minority of systems in use allow on-site processing though combined analogdigital techniques, but several systems controlled by mini-computers could be readily adapted to on-site processing. New developments and price reductions in the field of LSI (large scale integration) electronics suggest that full digital processing of MT data should be more common in the near future. One variation currently in use is the combination of narrow-band scalar MT measurements and colinear telluric measurements. Still another contractor service offered involves use of an array of scalar MT equipment (single axis measurement) employing fluxgate sensors combined with a tensor base station with a three-axis SQUID sensor. Main application of MT are to study of specific geothermal areas in the depth range of 1 to 10 km where the station spacing may be from 1 to 5 km and for 20-30 km depth studies of crustal electrical structure over large regions to define broad areas of geothermal potential.

The main limitations are the scatter observed in measured data for short records and the accompanying decrease in model resolution. In addition, tensor MT equipment sells for more than \$50,000, typically. Severe interpretation problems are caused, in some instances, by three dimensionality in the geology, current channeling and current dumping effects in the telluric fields, and equivalence in models. Also, the technique has poor resolution on resistive zones in the crust. No other technique, however, allows sounding to large depths and permits the directional detection of conductivity anomalies at a distance from the sounding site. New research stimulated largely by geothermal exploration is leading to vastly improved data processing methods to decrease scatter, 3-D presentation and interpretation of the sounding information, arrays

of MT stations, and on-site processing and interpretation of data. Geomagnetic sounding techniques are being used by government and universities to look at very broad conductivity anomalies of geothermal significance, for instance the Rio Grande graben region. The main limitation of this technique as commonly employed centers around requirements for long periods of deployment, typically a minimum of 7 days. Better instrumentation and data telemetry techniques may reduce this to as little as 2-3 days (apart from setup time). Such techniques are within state-of-the-art but are not employed yet.

AMT

AMT applications differ from MT only when this higher frequency technique is implemented with strictly analog techniques for processing sensor inputs. Several organizations now use AMT extensively for preliminary reconnaissance of geothermal areas. Equipment can be highly portable, although most systems in use are capable of only scalar measurements. Highly portable tensor AMT receivers, when they come into routine use, will prove to be a valuable tool for geothermal exploration. The main limitations are the scatter in measured and the interference caused by nearby thunderstorms in the spring and summer. Double conversion superheteordyne analyzers now being used in AMT receivers seem to offer one of the best approaches to AMT measurement. Controlled source excitation for AMT surveys is very feasible and should offer improved accuracy for exploration of small regions, but is not being utilized much at present. The chief limitation of the latter method centers around deployment of the source and dependence of measurements on geology at the source and azimuthal effects on surface impedances.

Significant Field Findings

One of the most significant discoveries resulting from geothermal geophysical exploration, other than direct geophysical detection of hydrothermal systems, is the widespread observation of highly conductive zones at sub-basement

depths in the range 2-20 km. In many geothermal regions of the western U.S. these conductive zones (resistivities less than 1 ohm-m) occur shallower than 10 km. For instance depths are less than 5 km in Yellowstone, 2-7 km at Fallon, Nevada, 5 km at Coso Hot Springs, California, 7 km at Darrow Hot Springs, Nevada, and 1-5 km at Roosevelt Hot Springs., Utah. Similar conductive regions in the crust and upper mantle have been observed elsewhere in the U. S., for instance at a depth of 10 km in the Black Hills, S. Dakota and at depths of about 100 km in central Texas. Study of non-minimum phase behavior in tensor data from some of these areas suggest that the boundary between the conductive zone and resistive material above is a very sharp one. The widespread occurrence in geothermal regions suggests that the mapping of these zones may be the most powerful technique available for geothermal exploration over large areas and to define the total geothermal resource, and in fact may provide more understandable results about the real potential of geothermal systems than many times the additional shallow geophysical effort. A full understanding of the relationship of this conductivity phenomena awaits the integration of the MT results with seismic data, petrophysical measurements, heat flow data, and deep drilling data.

xx

DOWNHOLE-TO-SURFACE TEAM REPORT

by

S. H. Yungul

This is a brief survey intended for those who are familiar with the electrical methods of exploration. It constitutes the outline of an invited talk at the Geothermal Workshop, sponsored by the University of Utah under funding from the U.S. Geological Survey, to be held on November 5-7, 1976, at Snowbird, Utah.

The "Mise-à-la-masse" Method

This method was developed by Schlumberger (1920). Figure 1 schematically shows the principle. If ρ_1 is very small, one would obtain the same equipotential contours no matter where the downhole electrode A is placed, because there would be no appreciable potential drop within the conductive body. In geothermal work ρ_1 is not likely to be very small, and, therefore, two or more different maps may be obtained by placing A at different positions in one or more boreholes. This procedure would lend itself to higher resolution through numerical modeling.

Figure 2 shows a survey over a sulphide mass. This was done in one day. First two potential profiles were obtained and then equipotentials were traced at steeply descending values. The two closures correspond to high regions of one continuous mass. Otherwise there would be only one closure around A'.

If several development boreholes are available, a subsurface mise-à-la-masse survey can also be made in addition to the surface survey. Figure 3 shows an example. Thus, one can have a plurality of data sets: a number of surface maps, and a number of subsurface cross sections, each for a different location of A.

Parasnis (1967) and Ketola (1972) describe the surface and subsurface techniques and give several case histories.

The Lee Methods

Figure 4 schematically shows one of the methods developed by Lee (1948). The objective is to determine the proximity of a missed oil sand or the extension of one that has been intersected. V_1 and V_2 yield two apparent resistivities that are plotted on a polar diagram. The $C_1P_1P_2C_2$ line is rotated to different azimuths and one polar diagram is completed. The depth of the borehole electrode and the C_1C_2 spacing are varied and several polar diagrams are obtained. These yield the depth and direction of a missed oil sand which is supposed to be more resistive than the surrounding rocks.

Bipole-Dipole Surveys

A surface-to-borehole transmitter bipole and surface receiver dipole are used. Having the transmitter electrode in the borehole and the receiver electrodes moving at the surface saves labor in electrode planting and enables one to obtain large amperage. This arrangement has another advantage in that the small dimension of the receiver dipole is less sensitive to the telluric noise. On the other hand, having only the receiver dipole in the borehole would require substantially smaller capital outlay in the field operations in terms of cable and winch.

Hauck (1970) made an extensive feasibility study by scale modeling and reviewed the past literature. Figure 5 has been reproduced from his work. It shows the response of a conductive sphere along three radial dipole resistivity profiles. It is clear that the downhole-remote (D-R) bipole transmitter yields substantially better indication than the other two transmitter bipole configurations (surface-remote, and surface-downhole).

Figure 6 has also been reproduced from Hauck (1970). It shows a dipole resistivity profile across a flat-lying conductive body. The surface-remote measurements yield a resistivity anomaly of about 10%, whereas the downhole-

remote anomaly is about 56%.

Hauck concludes that the maximum anomalous response is obtained if the downhole electrode is placed below the conductive mass.

Merkel and Alexander (1971) published numerical modeling results for a conductive sphere. In their model the downhole transmitting electrode is on the vertical z-axis passing through the center of the sphere. An analytical solution was obtained and the equation was solved numerically. Figure 7 shows the model for which the results shown in Figure 8 [reproduced from Merkel and Alexander (1971)] were computed. It is seen that when the downhole electrode is half-way to the sphere ($n=0.5$) there is hardly any anomaly, and the response becomes quite large when the electrode is very close to the sphere ($n=1$).

Figure 9 has also been reproduced from Merkel and Alexander (1971). It shows the numerical and scale modeling results for the case in which the downhole electrode is inside the sphere.

Ultra-Long-Spaced-Electric-Logging (ULSEL)

If a borehole is outside an anomalous body, the flank of the body can be delineated by performing "resistivity sounding" laterally from the borehole, without surface measurements. Figure 10 shows the principle schematically. A-B is the transmitter bipole and M-N is the receiver bipole. B is fixed at the surface, and the rest of the electrodes are lowered into the borehole in the same way as electrical logging is done. This is a modified long-normal tool. A multiplicity of electrodes provide measurements from $\overline{AM} = 75$ ft. to 2000 ft. The results are interpreted by two-dimensional numerical modeling to yield the configuration of the flank. This tool was developed primarily for salt flank mapping. Such surveys are available through a service company. Figure 11 [reproduced from Runge et al. (1966)] schematically shows the working principle. The curve to the extreme right is a conventional induction

log. The dashed curves are theoretical ULSEL logs computed from the induction log, assuming that the subsurface is made of a large number of horizontal discrete layers of infinite extent. The deviation between a dashed curve and a measured ULSEL curve, that indicates the presence of an anomalous body, can be used for approximate interpretation, but two-dimensional numerical modeling uses only the measured curves, once the layers have been obtained from the induction log.

Inter-Well Bipole-Dipole Surveys

Figure 12 schematically shows the principles of surveying and interpretation. Two development wells may supply a large amount of data, some independent and some redundant, by keeping AB fixed at certain depths in one well, and logging the other well by means of the sensor dipole MN for each position of AB, and by transposing AB and MN from one well to the other.

It seems that the interpretation has to be done by numerical modeling, that is, approximate or qualitative interpretations would be very susceptible to yielding misleading results.

Downhole Transmitter Cables

The unit price (\$/ft) of the cable depends on length (4000-10,000 ft), ambient temperature (200-400°F), and amperage (5-100 amps). Using copper conductors, steel strength member, and neoprene, or silicone rubber, or teflon for insulation, the price varies from about \$2/ft to about \$10/ft.

Sophisticated coded-signal generators and processing techniques (e.g., Vibroseis type) may not necessitate large amperages and therefore expensive cables.

A metal well casing may, under favorable conditions, approximate a line electrode without the usage of a downhole cable. This is possible if the resistivity of the borehole environment is high, perhaps higher than about 20 ohm-m. Otherwise, the current density around the casing would drop rapidly

FIGURE 1
"MISE-A-LA-MASSE"
SURVEY (SCHEMATIC)

FIGURE 2
"MISE-A-LA-MASSÉ" SURVEY

Fig. 3

Fig. 3. Misc-à-la-masse measurements in boreholes. Vindfall area, central Sweden. (After Parasnis, 1967.)

(A)

(B)

(C)

FIGURE 4

LEE METHODS

FIGURE 4

DOWNHOLE
RESISTIVITY
SCALE MODEL CASES

Fig. 5

[Hauck (1970)]

Fig. 6

FIGURE 7
SPHERE AND EPICENTRAL BOREHOLE

Fig. 8

Fig. 4: Resistivity variations over spheres of different conductivity for various electrode depths τ . [Merkel and Alexander (1971)]

Fig. 9. Superposition of analog and digital results for a model with the buried current electrode in the sphere. The dashed section denotes negative apparent resistivity. The analog sphere was made of a salt saturated gelatine solution in a porous sponge-rubber sphere. [Merkel and Alexander (1971)]

FIGURE 10
ULSEL
2D NUMERICAL MODELING

Fig. - 11. ULSEL

FIGURE 12
INTER-WELL BIPOLE-DIPOLE,
2D NUMERICAL MODELING

Introduction to Group Discussion

Saturday, November 6, 1976

The Role of Electrical Methods in Geothermal Exploration

by

S. H. Ward

The following straw-man comments are offered to stimulate discussion.

A logical, but not necessary, exploration architecture for convective hydrothermal systems in the eastern Basin and Range is shown in Table 1. This architecture assumes that electrical methods have not proven their cost-effectiveness in reconnaissance!

This architecture, if adopted, would lead to the uses of the electrical methods in a manner depicted in Table 2.

Perhaps more staunch defense of the "not used" methods of Table 2, a defense based on factual presentation of their advantage/disadvantage ratios, would cause me to re-evaluate their uses.

TABLE 1

EXPLORATION ARCHITECTURE - CONVECTIVE HYDROTHERMAL SYSTEMS

PHASE I

- Office Study
- Collection and Analysis of Thermal Water Samples
- Age Dating of Silicic Intrusives & Extrusives
- Geologic Reconnaissance
- Thermal Gradient Measurements in Available Holes
- Hydrology
- Aeromagnetic Survey

PHASE II

- Drill about 20 thermal Gradient Holes to 40m
- Measure Thermal Gradients & Calculate Heat Flow

PHASE III

- Resistivity Survey
- Detailed Geology
- Alteration Studies on Cuttings from Drilled Holes
- Gravity Survey

PHASE IV

- Drill Model Testing Holes to 600m
- Temperature Log, Electrical Log
- Measure Pressures
- Determine Chemistry of Water
- Study Alteration of Cuttings
- Describe Lithology
- Estimate Fracture Porosity

PHASE V

- Production Test

TABLE 2

USES OF ELECTRICAL METHODS IN GEOTHERMAL EXPLORATION

<u>METHOD</u>	<u>USE</u>
Dipole-dipole	Mapping shallow resistivity and IP in detail.
Schlumberger	Mapping shallow and deep resistivity in detail
MT/AMT	Mapping deep resistivity in detail
Active EM	Mapping shallow to deep resistivity in detail
Bipole-dipole	Not used
Tellurics	Not used
SP	Not used
Downhole-to-Surface Methods	Speciality applications

Group I Report
Saturday, November 6, 1976

1) Mt. Hood problem - Define model properties

1.1 Limit range of geoelectric models and their parameters -

1.1.1 Portable AMT -Tensor MT measurements best suited to rough terrain.

1.1.2 Recon Dipole-dipole methods with dipoles on the order of 1/2 to 1 km with 15 km spread.

1.1.3 logistics problems

1.1.4 spectral measurements useful

1.1.5 Structure control and alteration for geothermal areas in Phillippines mapped well by dipole-dipole methods.

1.2 If some interesting areas do more precise sounding methods

1.2.1 Controlled source sounding methods

1.2.2 Resistivity sounding and bipole-bipole

2) Controlled source methods team report:

2.1 Argued over standard methods but did not mention new instrumentation and data aquisition.

2.2 No mention of determining frequency behavior of rocks from surface measurements - that is I.P. measurements.

3) Borehole methods

3.1 Should have some more insitu measurements

3.2 Need some instrumentation advances in logging tools for high temperatures.

Bruce Smith for
John Bailey
Marvin Bloomquist
John Hermance
Ted Madden
Frank Morrison
I. K. Reddy

Group II Report

Saturday, November 6, 1976

The prime impetus of the group was a discussion of the Mt. Hood problem. The group first reviewed the outline provided by Dave Williams and considered the topics individually. Special emphasis was put on the electrical techniques.

Heat flow was rejected as a reconnaissance tool due to the complex hydrologic conditions suspected. Heat flow could be used as a later stage if hydrologic conditions were found not to be as complex as anticipated.

We felt that there were significant logistical problems associated with aeromagnetics, particularly flight height problems. It was also felt that the wavelength of the Curie point magma anomalies, if they existed, would be of the same order as the structural features. The group did recommend the utilization of any existing data.

A regional gravity survey with a station approximately every 10 km^2 was recommended. This data could be useful for basic structure, and perhaps location of the magma chambers.

Geochemistry, geologic mapping, and dating were considered of primary importance. We felt areas of most recent activity should probably be looked at first. However, techniques for unraveling the relationships of the shallow magma system to the deeper systems may make this approach misleading. (Reporter's comment - An integration of deep-looking controlled-source EM data with MT data would provide some very good control on the vertical geoelectric section so as to define the configuration of the magma system, and some physical properties of the system). In this context, the characteristics of the suspected reservoir were briefly discussed. Three basin reservoir-types were defined: 1. A hot water system impounded in a tuff layer, 2. hot dry rock, and 3. the magma-correlated system.

Geologic mapping should concentrate on structural information. Thus aerial reconnaissance and extensive utilization of available imagery (conventional vertical photos, U2 photos, Landsat, thermal IP and IR) should be utilized. If this data is not available, it is inexpensive enough that it should be acquired. Additional data might be acquired for structural control such as low sun-angle photography. Geothermometry should be conducted on all available spring waters.

The group felt that a microearthquake survey would be useful. The survey could yield data not only on the hypocenter locations, but perhaps on attenuation, and delay times. A severe velocity problem was anticipated which might minimize the results of this survey.

The remainder of the discussion catered on the utilization of electrical methods for exploring the area. The first phase as recommended by the group would include multiple MT sites around the base. This data coupled with the regional data (gravity, microearthquakes etc.) and particularly the geologic data would perhaps reduce the area to be detailed to an area several hundred square kilometers.

A prime objective of the second phase is to provide maps to direct further studies. The group felt that AMT (or perhaps tellurics) would be most efficient for this. Bipole-dipole, dipole-dipole, and Schlumberger techniques were rejected primarily because of logistics and/or the specific geologic setting. If the data suggested reliable results, shallow-to-intermediate-depth heat flow holes would be drilled on judicious locations.

The third field season would include controlled source EM soundings over the areas of interest. The EM would provide good resolution of the geoelectric section. In addition the group supported active seismic techniques to attempt to evaluate the reservoir. The active seismic could be also coupled with some semi-permanent microearthquake stations which would be run continuously during the active seismic survey. The active seismic-survey would concentrate on S/P

velocity ratios, attenuation, and delays. Fan-type shooting arrangements could be beneficial.

In conclusion, the group felt that if any deep holes were drilled, borehole to surface techniques should be tried to define the reservoir configuration. Along this line the group suggested experiments to attempt to define reservoir configuration in known reservoirs such as Raft River, and Roosevelt.

Jim Applegate for
Walter Anderson
Norman Goldstein
Alan Ramo
Harold Smith
Dal Stanley
Sulhi Yungul

Group III Report

Saturday, November 6, 1976

Group III considered the Mt. Hood problem and several points relating to the morning team reports.

Our approach to the MT. Hood problem was guided by the following considerations which were brought to our attention by Dave Williams:

- 1) Shallow temperature gradient measurements are ruled out by abundant ground-water flow, and
- 2) Geochemistry can not provide very much information because of the few springs in the area.

With the constraints in mind we developed the following generalized exploration sequence:

- 1) Evaluation of existing geochemical, geophysical and geological information,
- 2) Acquisition of additional geological, geochemical and aeromagnetic data where needed (and where possible) to supplement existing data,
- 3) Selection of several subareas for more detailed study with electrical methods,
- 4) Application of AMT or Tellurics in conjunction with a few MT soundings in order to select targets for drilling of several deep heat flow holes. A minority of one (Fleming) thought that controlled source EM would be faster and just as effective as the natural field methods in this role.
- 5) Deep (~1Km) heat flow holes should be drilled on apparent conductivity anomalies found by the electrical surveys. Some or all of these holes should be logged to provide feedback on the interpretation of preceeding surveys.

SP was considered and rejected for application to this area because of the streaming potential expected from the abundant ground-water flow (Dorfman). The possibility was also raised that a modified INPUT system which is to be tested as a reconnaissance method might be applied to this area (Ball).

We did not consider the second and third year programs.

Some general comments which were made are:

- 1) Some speakers should take more trouble with their slides (Plouff),
- 2) Two-dimensional modeling of single profile data could be very misleading (Dorfman).
- 3) More attention should be given to investigation of large-scale structures in exploration, and also more research should be done on the physics of geothermal systems (Bodvarsson).

Dave Fleming for
Larry Ball
Gunnar Bodvarsson
Myron Dorfman
Arthur Lange
Don Plouff
Dave Williams

Group IV Report

Saturday, November 6, 1976

The group originally decided to discuss the presentations of team 5 and 6 in addition to the Mt. Hood Survey Problem. Due to shortage of time only the team 5 presentation and Mt. Hood were discussed.

1. Team 5 Presentation - Application, Limitations and Instrumentation, IP, Resistivity & EM

The group felt that there were interpretation problems with Bipole-Dipole data due to Non Uniform fields & source dependent results

Recommendations

1. Operate receivers further removed from transmitter
2. Use multiple bipole transmitting lines
3. Suggest possible use of Gradient Array Survey

The group discussed the inversion techniques of Zohdy and Bostick and concluded that they were somewhat analagous.

It was agreed that the techniques find the solution - however several of the group members felt that further work with generalized inversion techniques be used to further clarify the interpretation.

These techniques offer big improvement over curve matching

There was some question expressed about how realistic some of Bill Sill's models were. It was felt that a more objective means of questioning the elements of the model is needed.

Luiz Rijo suggested that a big improvement in Schlumberger sounding data could be obtained if the survey were allowed to overlap more. This will help resolve some of the lateral inhomogeneities.

It was also suggested that Controlled Source EM could also aid in the near surface interpretation of the Schlumberger Soundings.

The group felt that the use of MHD generators is impractical for Geothermal Surveys - That it would be easier and more cost effective to lower the electrode impedance at the transmitters to achieve the desired current. The group felt that more effort should be directed to finding a way to invert magnetic field data and map the current distribution in the ground, sometimes called magnetometric resistivity. This will help resolve some of the lateral inhomogeneities. The use of SQUID detectors should aid in obtaining the necessary magnetic field data.

The group also agreed to endorse the team 7 effort - indicating that follow-on research should be undertaken

2. Discussion of MT Hood Survey

The group agreed that the survey sequence for the first season was out of order. A recommended survey sequence is as follows:

1st Season

1. Geologic Mapping & Dating
2. Geochemical Analysis - Groundwater Studies
3. Aeromag and Gravity
4. Begin AMT/MT in frequency range 10^{-3} - 10^3 Hz (orientation survey)
5. Check for existing seismic networks and acquire data. (microseismic implementation not recommended)

Helicopter should be employed for mobility

2nd Season

1. Detailed MT/AMT
2. Controlled Source EM (Possible use of Bonneville Trailer Mounted Transmitter as a source)
3. Heat Flow measurements

3rd Season

1. Deep Drilling

Arnold Farstad for
David Fitterman
Frank Frischknecht
Roger Phillips
Luiz Rijo
Stan Ward
Charles Zablocki

Group V Report

Saturday, November 6, 1976

The group discussion initially touched on a number of questions that resulted from the team reports of the day. None of the questions tended to any "hang-ups" in the discussion so the discussion ranged fairly widely. The groups impressions are listed below.

- 1) It was felt that some resolution or edification was desirable relating to the discussion between Zohdy and Morrison during the team report.
- 2) That it would be interesting to submit a given data set; i.e., a Schlumberger sounding profile, MT sounding profile; to various groups for inversion and interpretation to get a better feeling for the possible variations. This would be similar to the study published in Geophysics on magnetic interpretation by P. Jacobson 1961
- 3) It was felt that insufficient geologic constraints were imposed on some of the interpretive models presented, particularly the 2-D models. Or if such constraints were used it was not so indicated. This is the old problem of effectively relating the geophysical data to the geology.
- 4) The problems of base station selection in telluric or MT-telluric surveys didn't receive enough discussion during the team presentation some felt.
- 5) Better criteria for making a first guess in data inversion techniques were felt to be desirable.
- 6) All questioned the practicality of the MHD generator and a super-conductive generator to serve the same goal was discussed.

- 7) The problem of interpretation of bipole-dipole data was brought up and whether it was an effective reconnaissance exploration tool because of this was questioned. The general feeling was that the technique had not proven its effectiveness as yet although there was some fence sitting on this. The group felt that a discussion of the merits of bipole-dipole vs. MT-tellurics would be a good discussion topic at some future meeting.

The final topic of discussion was Dave William's problem. We agreed in general with the first phase of the program outlined with the exceptions of the proposed heat flow measurements. It was thought that the hydraulic regime probably was not suitable for heat flow until more was known about the region.

Other specific suggestions were to check Landsat imagery for snow-melt patterns and to find out what electrical data Bodvarsson already had.

Following the first stage work but during the first year an orientation survey was considered best covering a small part of the area but with the site of the survey determined by all available information. The orientation survey would be an MT-telluric survey with add-on surveys made in conjunction with the primary MT-telluric survey, i.e. short Wenner or Schlumberger soundings, S.P., VLF, etc. The MT soundings however should not be abbreviated, but full range soundings, to determine the complete geoelectric section.

It was felt that the design of following surveys would then be based on the results of the orientation survey.

Don Hoover for
Bob Corwin
Bill Dolan
Dick Geyer
George Jiracek
Gary Olhoeft
Jim Towle

Group VI Report

Saturday, November 6, 1976.

A) Reconnaissance Techniques

1) We are concerned about detailed interpretations (2D) being made for techniques such as scalar MT and leapfrog tellurics. Such interpretations are not justified by the resolution of the methods.

2) Detailed interpretation of exploration data (as opposed to later surveys related to exploration) may not be justified by the quality of the data. No member of the group could cite an example of an exploration effort in geothermal which had been aided by a two-dimensional model. Can anyone at the meeting cite an example?

3) Geomagnetic Deep Sounding may be a very useful reconnaissance tool because of its ability to point sideways toward a conductive anomaly; although this is sometimes possible with 3 component MT tensor soundings.

4) Presently, we expect that detailed information is not needed to encourage exploratory drilling. Would industry comment?

5) Reconnaissance methods have little place in the determination of exploitation strategy as detailed models must be used. However, single frequency leapfrog tellurics at ~20-25 sec. may be used for a first estimate of the spacing of MT stations may be determined.

B) Modeling and "inverting" data

1) People presenting interpreted sections must be aware of the non-uniqueness of their inversion due to limited resolution of surveying techniques. We don't need to know the "best" fit to the data (which after all is determined partly by the noise) but some measure of all the fits which are consistent with the data.

2) It is particularly important to communicate the range of models which fit the data. A 2-D section presented by Bill Sill will illustrate the problem. That section had a very narrow buried conductor which Sill acknowledged didn't need to be there. He is aware of the lack of resolution, but others viewing the section are strongly influenced by the appearance of that conductor.

3) The sensitivity resolution matrix and estimation statistics for parameters are useful for communicating the range of models. Monte Carlo methods have also been used by Thayer to evaluate 1-D MT soundings.

4) More comparisons should be made between 2D sections interpreted using 1D methods in order to assess how misleading 1D analysis can be in complex situations.

C) Design of field work: theory and an example.

1) There is a distinction between exploring for potential geothermal systems and developing and testing new equipment and methods. Different field work will be needed to satisfy those two goals.

2) There is concern that most of the data which are presented comes from experiments which are not designed to find a particular target efficiently. We decided to discuss how to design a geophysical field experiment and then try to apply what we discussed to Mt. Hood. Survey design could start from two approaches:

- a) "Shotgun". We seek an anomaly of anything, so try all methods in order of cost and feasibility.
- b) working model. Try to define an objective, predict its physical properties, and determine which properties can and should be measured. Then design an experiment to answer questions about those properties. Surveys can be designed with the aid of resolution information estimates from forward problems. The

working model is expected to change as more information is learned.

3) We were unable to design a working model for a geothermal system at Mt. Hood with our knowledge of the area, so our approach was the "shotgun" method.

- we assumed we were looking for hydrothermal system
- no consensus on physical properties, of the target, except for high temperature, and probably high electrical conductivity
- uncertain about physical properties of non-geothermal area near Mt. Hood
- detection of location of probable magma body could lead to location of hydrothermal fluid, so we want aeromagnetic vertical gradient measurements to detect Curie Point elevation
- heat flow measurements do measure the relevant property, but hydrology of porous volcanic cone in high rainfall area may be complicated
- major electrical survey should be MT off the mountain and reconnaissance tellurics as easiest on the cone. Landisman suggested using power lines for e.m. source to telluric stations for additional cheap data.
- passive seismic for micro-earthquakes, P delay, and attenuation.

4) We did not discuss how first year's data should be evaluated and how second year's field program should be carried out.

Paul Kasameyer for
Jim Combs
Dallas Jackson
Mark Landisman
Jim O'Donnell
Richard Thayer

Group VII Report

Saturday, November 6, 1976

Our group did not concentrate upon recommendations concerning today's topics (IP, resistivity, EM, Tellurics, MT/AMT, and down-hole), except to comment that:

- 1) in the interpretation of MT cross-sections, both the TE and TM modes should be considered;
- 2) in the application of the roving dipole method, more transmitters per area of investigation should be considered to narrow the wide range of Tx-Rx separations now used;
- 3) the USGS program of using MT and geomagnetic depth soundings to study the regional resistivity structure of the crust is well conceived and potentially useful;
- 4) the application of IP and active source EM should have been discussed; and
- 5) in this workshop in general, more emphasis should be placed upon the geologic target concepts of the geothermal model. In particular, the sessions appear to have driven doggedly on in search of the lowest resistivity zones, while Bill Sill showed at Roosevelt that the hotter K-feldspar stable zone is more resistive than the surrounding clay zones and Dallas Jackson displayed very high resistivity associated with the high heat flow target at Coso Hot Springs. Much emphasis has been placed on the mathematical techniques of experiment design, and effective utilization of these techniques require an understanding of the target.

Our group spent much time discussing the general validity of complex two-dimensional resistivity models resulting from iterative forward modeling. Such modeling is a testing of a hypothesis - when the interpreter finds an acceptable fit to his target concept, he naturally quits. This exercise may result in a very subjective interpretation. Thus we advocate research in ways to objectively consider more than one target concept to obtain a range of possible models. This implies the use of generalized inverse techniques because of resolution information accompanying an inverse technique. Nevertheless we wish Francis Bostick well in obtaining a "little inversion scheme" for direct inversion of 2D data! The group felt that thorough discussions of resolution and equivalence in 2D modeling would be productive.

The group considered the "Mt. Hood Problem" as a hypothetical problem to bypass non-productive discussion of whether an ERDA sponsored program of exploration at Mt. Hood was an appropriate ERDA activity. Although the logistical problems of data collection on Mt. Hood are difficult even with the availability of a helicopter, the geophysical task is simpler than at other geothermal target areas. Mt. Hood is a pile of probably moderately resistive volcanics over a sub-horizontal sequence of Miocene intermediate volcanic rocks and Columbia Plateau basalts. This environment should be more laterally homogenous, at least chemically, than the Basin and Range geothermal environment.

We emphasized the electrical aspects of the exploration architecture for a target of a magma chamber or a hot aqueous zone. We assumed that geologic mapping (including age dating, photography, and alteration mapping) and geochemical work on the waters would be done first. We recognized the importance of heat flow and thermal gradient information, but noted the difficulty of the data acquisition and the probable complexity of the surface hydrologic regime. We then proposed the following geophysical work.

- A) an aeromagnetic survey, with an accompanying depth to Curie Point analysis. Such work has been useful at Shasta.

- B) no gravity survey. Any gravity anomaly remaining after the huge terrain corrections could be explained by a dense flow or a low-density tuff zone, and probably would not provide any meaningful data.
- C) a microearthquake survey, with sufficient coverage for both an adequate epicenter analysis and an accurate attenuation study.
- D) resistivity information, obtained via two techniques
 - (1) a modified bipole-dipole total field survey, "shooting through a mountain as shown below:

This survey would use 6-8 transmitters around the base, with 8 receiver sites opposite each transmitter. This survey should delineate the half or quadrant possessing any resistivity lows. In addition, the leader strongly advocates that the IP response should be measured. Although the high resistivities will minimize the EM coupling contributions, the great Tx-Rx distance will make this a difficult measurement. Nevertheless, hydrothermal systems accompanying subduction-related andesitic volcanism, such as that of Mt. Hood, are frequently accompanied by large volumes of disseminated pyrite. Detection of this zone, if it exists, could direct later electrical surveys.

- (2) a telluric-MT survey, to obtain MT-type data without the

problems of carrying the magnetic field sensor over the mountain. A frequency range of 10^{-3} to 10^2 Hertz, modified if necessary, is recommended and thus AMT equipment may be necessary. Subsequent field seasons should be planned only after the initial data are available.

Charles Swift for
Bob Christiansen
Gerry Hohmann
Aldo Mazella
Tsvi Meidav
Bill Sill

Group VIII Report

Saturday, November 6, 1976

I. Dave Williams Mt. Hood Problem

The team felt strongly that magneto-tellurics/tellurics on a 5 kilometer grid should be applied very early in the exploration program. The consensus was that a ratio of approximately 4:1, telluric versus magneto-telluric stations, would be optimum. The recommendation for application of this technique early in the program was predicated on the assumption that further exploration should only be carried out if in fact there are low resistivities present in the lower portion of the crust. Although topographic effects may be substantial it was felt that they could readily be compensated for.

While highly speculative, the possibility of using the Bonneville 200 amp 3,000 volt current source as an excitation means was discussed. This source might be used should initial surveys indicate that low resistivity conduits exist within the otherwise resistive volcanic pile. The objective would be a mise-a-la-masse survey at Mt. Hood to delineate the configuration of the conductive magma chamber.

II. Resistivity Models

It was felt by the group that all inverse programs should be capable of accepting constraints derived from geologic, well log and surface obtained seismic data.

III. EM Interpretation

Interpreting independently phase and amplitude data obtained by passive and active EM methods clearly has advantage when noise as a function of frequency is not distributed equally between the phase and amplitude data. It was recom-

mended that this be kept in mind when designing methods of interpretation.

IV. Comparison of Modeling Techniques

There was a general desire to head toward a position which would allow comparison of various inverse modeling techniques. The general equivalence problem however appears to frustrate moves in this direction.

Bob McEuen for
Francis Bostick
Walter Hernandez
Don Mabey
Darrell Word
Adel Zohdy

Summary of Evening Discussion

Saturday, November 6, 1976

Inversion

Dissatisfaction was expressed with the 2D interpretations shown by different teams, in particular, the lack of uniqueness of the interpretations.

It was pointed out that certain geological targets, for instance a magma chamber surrounded by resistive steam were difficult targets for resistivity alone and that this and most other models would be better understood by collecting complimentary data sets (eg. resistivity, active source EM, MT).

Rock Properties

It was mentioned that in certain near surface environments the geothermal target may be a resistivity high due to the hydrothermal alteration of clay minerals to feldspar.

In situ borehole measurements are useful to provide physical properties of relatively undisturbed samples.

Seismic

Seismic methods were felt to be useful in providing additional constraints to the geological and electrical models.

MHD Transmitter

The MHD source was considered impractical unless developed and provided by users outside the geophysical community.

Don Pridmore, Reporter
William Pelton
William Petrick
Luiz Rijo
Al Tripp

CASE HISTORIES TEAM REPORT

William Dolan, Chairman

Jim Combs

Art Lange

Don Mabey

Tsvi Meidav

Alan Ramo

Stanley Ward

Animas Valley, New Mexico (Art Lange)

The field was discovered 12-15 years ago by the drilling of wells that produced water as hot as 101°C. Reservoir temperature was estimated by various chemical geothermometers to be between 159 and 165°C.

Available wells were logged for temperature and a short-term microearthquake survey was made, but only 1 local event was recorded. There were no conspicuous delays or attenuations of teleseismic waves. Geology was compiled from published sources; the wells are on the east side of a typical basin range valley. A gravity survey showed evidence of a buried ridge beneath the alluvium, extending south from the area of the hot wells, merging at the south end with the buried extension of the range on the east. An aeromagnetic survey showed a positive anomaly over the buried ridge.

A bipole-dipole survey indicated a resistivity high in the vicinity of the buried ridge, for which a 2D model was interpreted. A telluric survey, calibrated at intervals on MT soundings, was inverted to a 2D Model, also showing a resistivity high. The models were constrained by finding the buried ridge (altered rhyolite) at 30 m in a heat-flow hole.

A heat-flow survey showed a well contoured anomaly, from regional values near 2 HFU to 20-21 HFU over the buried ridge; the anomaly extends southward from the area of the hot wells for about 10 km.

No heat source is evident in any of the geophysical data; the high-temperature area apparently is controlled by basin-range structure buried by valley alluvium. No reservoir has yet been determined, but the area appears to be a good prospect.

Case history of a negative prospect east of the Imperial Valley. (Alan Ramo)

The area selected for prospecting is east of the Algodones Dunes, just west of the Colorado River.

A gravity survey revealed a low in the western part of the area, west of some northwest-trending faults, rising to a high over the Cargo Muchacho Mountains in the eastern part of the area. The gradient bifurcates northward around a secondary low. A ground magnetic survey showed an irregular anomaly near the secondary gravity low. Three dipole-dipole lines were run obliquely to the regional strike. They indicated several low-resistivity anomalies in the basins, including the secondary gravity low.

Modified Schlumberger readings were obtained over the resistivity lows; 1-D models indicated resistivities of 1.5 - 6 ohm meters at about 300m depth. A heat-flow survey of these resistivity lows was made with 500-foot holes. The temperatures were extrapolated to sea level and contoured, but all were relatively low (80-100°F) and showed low temperature gradients.

A reinterpretation, using published geologic data; indicated that the resistivity anomalies reflect Pliocene brackish-water sediments in the lower parts of the basins. The electrical survey was not an effective reconnaissance tool in this blind target area of sedimentary geology.

Salton Sea Geothermal Field (Tsvi Meidav)

A regional resistivity survey has shown a gradient of northwestward decreasing resistivity across the entire Imperial Valley region, with local anomalies superposed on it. Lateral resistivity contrasts clearly delineate many faults including the Brawley and Calipatria faults. Resistivity is lowest west of the Brawley fault.

A sparker reflection survey by the California Department of Water Resources on the Salton Sea has been interpreted to show a complex pattern of faults on the lake bottom, some interpreted as growth faults. A gravity high of 22 mgal exists in the area of the Salton Sea rhyolitic dome field. The highest measured temperatures are displaced southeastward from the dome field. An old ground-magnetic map by Soske and Kelley has been interpreted as showing the extension of a right-lateral fault through the Red Hill dome, perhaps showing progressive displacement of two ages of buried rhyolite. The younger part was dated as 32,000 years; extrapolation of the rate of faulting indicates 170,000 years for the older rhyolite.

Geoelectric sections also show many discontinuities, presumably faults. A resistivity map made from Schlumberger soundings shows low resistivity southeast of the Salton Sea in much the same pattern as the measured high temperatures but including a larger area extending southeastward from the Salton Sea field toward the Brawley geothermal field. Dipole-dipole surveys gave a very complex pseudosection that could not be modelled readily.

A fault map was made from all of this data, showing at least 6 continuous buried northwest-trending faults and a few shorter northeast trending faults. These faults make a block mosaic that prevents much stratigraphic correlation between wells and that controls groundwater flows.

The resistivity low that extends between the Salton Sea and Brawley fields

reflects partly some high temperatures and partly some high salinities in cooler water. This salinity dependence makes interpretation of temperatures from resistivity data quite risky.

Raft River (Don Mabey)

In part, the Raft River area was used as a test area for techniques. Consequently, the program is not an example of a typical exploration program.

The Raft River area is a sediment-filled valley which, from the geophysical evidences is not completely typical of basin-range structure, and probably bears some relationship to the Snake River Plain. Initial studies included water geochemistry, detailed geologic mapping, and age dating. Mapping of surficial geology in the valley was more useful than mapping in the surrounding ranges. Rhyolite domes along the west side of the valley are about 8 my old.

The gravity map indicates a fairly deep valley and a low feature extending SW to The Narrows. The aeromagnetic map permitted mapping the eastward extent of the volcanics found in the Jim Sage Mountains, west of the valley and indicated that volcanics would not be encountered in drilling in the basin.

A conventional telluric survey showed a low which coincided fairly closely with the gravity anomaly, but the lowest ellipse ratios were offset towards the south. An AMT survey showed a low which coincided fairly well with the telluric low. Additional anomalies representing nearer surface features were observed along the west side of the valley. Small self-potential anomalies, which probably reflect shallow hydrologic features, were measured.

A bipole-dipole (roving dipole) map was prepared from measurements at about 300 stations. This map indicated an anomaly in the area of the lowest telluric and AMT values, and also indicated geologic boundaries around the basin. The final map was produced by removing the effects of a layered earth model, as determined from a Schlumberger sounding at the transmitter location. Over 100 Schlumberger soundings were made over the basin and around its edges and interpreted using a 1D model. Basement and several layers were mapped by most soundings.

Detailed seismic refraction measurements located several faults across which significant changes in velocity were measured. The seismic lines were extended far enough to map the depth to basement over much of the area. The seismic method successfully mapped low velocity zones within the basement rocks which could not be detected by the resistivity measurements.

A seismic monitoring program yielded no useful events; perhaps this lack of results is significant.

Thermal IR measurements clearly indicated the presence of a local hot spot on the west side of the valley which is not recognized in the vegetation.

A drill site was selected in the deeper part of the basin, roughly at the intersection of a feature which trends northeast from The Narrows with a north-south trending fault. The hole intersected basement rock at about 1700 meters, which coincided exactly with the depth predicted from the resistivity and seismic measurements. The maximum temperature was about 145°C and flow rate about 900 gals/min. Production is mostly from fracture zones in the Salt Lake formation just above the basement. Two additional deep holes confirmed geophysical evidence that the bridge fault has not displaced these basement rocks in this area. Additional production is available from those holes.

Roosevelt Hot Springs (Stan Ward & Darrell Word)

The University of Utah has spent three field seasons at Roosevelt Hot Springs KGRA conducting integrated geological, geochemical, and geophysical studies.

The geologic aspects of the study have included general mapping volcanic stratigraphy, petrology, joint and fracture mapping, and mapping of hot-spring alteration and deposition. A North-south fault system appears to be the dominant resource control, but east-west and northwest-southeast faults are also abundant. The reservoir occurs in a fractured Tertiary granite. Silicic volcanics lie exposed above the granite and probably relate to intrusive rocks of similar composition at depth; these latter hidden rocks are believed to be the source of heat.

Geochemical studies have included water chemistry, alteration chemistry, whole rock chemistry, water and rock light-stable-isotope analysis, gamma-ray spectrometry, analyses of mercury in soil, and Barringer Air Trace survey and K/Ar dating of the volcanic and granitic rocks. The age range of the volcanics is 500,000 to 700,000 years. Paleomagnetic dating has been used to augment the K/Ar dating.

The geophysical surveys conducted so far include aeromagnetic, gravity, dipole-dipole resistivity, Schlumberger soundings, shallow electromagnetic soundings MT, mise-à-la-masse, regional microearthquakes, temperature gradient and heat flow, and precise levelling & gravity profiling. An active seismic experiment is planned.

The only data presented was an overview of the dipole-dipole data and a preview of the MT data. The resistivity data mapped the shallow part of the convective hydrothermal system as low resistivity zones. The MT method found irregular patches of low resistivity (<1 ohm meter) at depths ranging from 3 km to 15 km.

Recommendations Team I

Rock Properties

We find what seems to be an imbalance between the efforts spent on surface electrical measurements and their interpretation and our understanding of the significance of the resistivity values. We therefore do recommend further physical property studies.

I. Laboratory measurements of electrical properties;

conductivity, I.P.; cross coupling

Such work should be of the highest quality only, as poorer quality work may be harmful rather than helpful. The measurements must carefully control the environment, and proper sample handling must be used. Standard samples should be interchanged between laboratories. We have some specific recommendations that take into account the technical difficulties in making the measurements.

Highest priority

- a) 0-250°C controlling solution chemistry, T,P conductivity, I.P., properties of clays, zeolites, and altered rock samples cross coupling properties of rock samples and altered rock samples.
- b) 250-550°C controlling T,P, P_{H_2O} , solution chemistry conductivity of alteration minerals (within their stability fields) rock samples, and altered rock samples

Lower priority

Conductivity of melts controlling T,P, P_{H_2O} , f_{O_2} , f_{S_2} . Much lower priority for 550°-1100° range.

This work should not be allowed to be hidden from those interpreting electrical measurements.

II. Correlative studies between electrical, seismic, and thermal properties

We have split opinions about recommending new laboratory studies,

but we do agree on

- a) looking more closely at on going work related to this problem, both theoretical work and experimental work.
- b) encouraging in situ measurements of these relationships using bore hole measurements.

III. Permeability

Something needs to be done to better understand fracture permeability.

We do not have specific recommendations about how to go about this but obviously in situ studies are involved.

Recommendations Team II

Models

Following are our recommendations for numerical modeling work aimed at increasing the effectiveness of electrical surveys in geothermal exploration.

- (1) Develop accurate, 2D-3D and 3D, steady-state and transient, EM solutions using different methods to provide cross checks. Solutions are needed for both simple and complex models.
- (2) Make definitive comparisons of different modeling techniques with regard to accuracy, computer time and storage, and capabilities.
- (3) Develop interactive inversion techniques for 2D and 3D, resistivity and EM problems, including linear and non-linear constraint.
- (4) Set up a vehicle for making computer programs widely available.
- (5) Integration of geophysical methods through simultaneous inversion (based on laboratory or petrophysical measurements of rock properties) should be stressed in any geothermal research program.
- (6) Theoretical work should be conducted to integrate advantages of inexpensive inversion methods with more expensive methods which yield estimates of parameter resolution.
- (7) A comprehensive study should be made of the effects of lateral inhomogeneities on one-dimensional inversion methods.
- (8) Aspects of experiment design (e.g. parameter resolution) should be recalculated in light of the non-linear nature of most electrical methods.

Recommendations Team III

SP

Future work in geothermal SP should include:

- 1) Dissemination and compilation of field data case histories - as at this conference. This is especially important for a method such as SP, where field input is needed to check theoretical mechanisms.
- 2) Research into generation mechanisms of geothermal SP anomalies. At this time we are confident that anomalies exist, but don't know whether observed anomalies are caused by thermoelectric coupling, streaming potentials, geochemical effects, conductive minerals, or other unknown sources. Theoretical modeling and laboratory methods are available; they only need to be applied to the problem.
- 3) Research into the standardization of field techniques. The quality of SP data is strongly affected by the manner in which it is measured. It is easy to obtain bad data, and difficult to tell it is bad. Field and laboratory research into the effects of geology and cultural activity on SP readings and methods to eliminating telluric current effects is needed. Published SP data should include a description of equipment and field procedure.
- 4) Research into response of electrodes to changes in soil moisture, chemistry, temperature, etc. (Figure 12) is needed

Recommendations Team IV

Data Processing

- 1) Obtain tensor coupling coefficients if at all possible
- 2) Move computational capability to the field for adaptive modification of the field site locations.
- 3) Establish objective criteria for evaluating and flagging good data in the field.
- 4) Evaluation of system noise characteristics due to:
 - a) instruments
 - b) source
 - c) complex geologic structures
- 5) Digital recording of field data is preferred to analog recording.
 - a) Dynamic range
 - b) Accuracy
 - c) Compatibility to digital computers
- 6) Compatibility of tape formats for exchange of data between groups
- 7) Dissemination of new processing techniques as developed.
- 8) Development of innovative techniques of data processing
 - a) Time domain
 - b) Emphasis on error analysis
 - c) Use of multiple-coherency and partial-coherency techniques
 - d) Multiple simultaneous site coverage (array studies)
- 9) Continuing emphasis on data processing being an integral part of the total geophysical/geological interpretation procedure (pre-planning and post-survey modeling). Should design processing scheme with a view of
 - a) data acquisition systems
 - b) Ultimate model inversion technique

- i) 1-D
 - ii) 2-D
 - iii) 3-D
- c) the total geophysical/geological framework of the field problem.

Recommendations Team V

Applications, Limitations and Instrumentation:

Resistivity, and E.M.

- (1) Faster and hence less expensive forward solutions for 2-D problems will encourage more studies on the basic problem of interpreting and comparing resistivity and EM surveys in non layered situations.
- (2) More combined EM and resistivity surveys should be undertaken. In some cases the EM survey can be an integral part of the resistivity survey: e.g. transient analysis of the square wave used in conventional resistivity surveys.
- (3) Field experiments of both time domain and frequency domain systems will resolve the accuracy of claims made by proponents of each.
- (4) I.P. offers potential advantages in geothermal exploration that has not been studied. The scale of the experiment indicates that severe EM coupling can be anticipated so that very low frequencies must be used. As shown the discussion of EM, I.P. experiment at low frequencies (.1 to 001 Hz) are feasible and could be made part of a conventional resistivity survey.
- (5) Development of better field equipment, particularly for controlled source EM methods.
- (6) Development of a controlled source EM system for very deep probing.
- (7) Study of applications of magnetic resistivity to geothermal investigations.

Recommendations Team VI

Applications, Limitations and Instrumentation:

Telluric and MT/AMT

Telluric: (1) Leapfrog tellurics

- A. Optimization of leapfrog tellurics to utilize side-looking capabilities
- B. Study of geologic significance of sign-reversal in leapfrog components
- C. Integration of leapfrog surveys with strike information provided by tensor MT results

(2) Ratio and Timeseries orthogonal tellurics

- A. Theoretical and field research to justify extension of MT base data to roving telluric sites and study of test methods of handling multiple timeseries.
- B. Modeling and processing research to extract strike parameters at telluric sites.

MT/AMT: (1) MT

- A. Application of generalized body of statistical signal processing techniques to MT
- B. Optimization of noise removal techniques from data
- C. Application research in on-site processing methods
- D. Research into data presentation of 3-D field data and models
- E. Use of MT systems arrays and processing-interpretation
- F. Rock studies for MT analysis
- G. Use both TE (E parallel) and TM (E perpendicular) modes in MT interpretation.

(2) AMT

- A. Research into combined analog-digital processing methods to develop highly portable tensor AMT system.
- B. Study of a rear source effects on AMT measurements.

(3) GDS

- A. Develop more advanced methods for interpretation of geomagnetic depth soundings.
- B. Develop realistic geologic models for GDS data.

Recommendations Team VII
Down-hole to Surface Methods

It is felt that what is needed is application of these well known and fairly well developed methods to the geothermal problems. No specific research is recommended at this time.

Recommendations Team VIII

Case Histories

More documented case histories of geothermal systems should be made available. Particularly, studies incorporating data from industry sources should be encouraged.

Other Recommendations

1. Effort should be directed toward inverting field data in order to map the current distribution in the ground.
2. An inventory & cataloguing of available computer programs should be completed at an early date by the USGS.
3. Because MT is in a rapid state of evolution it seems inadvisable at this time to inhibit the development of novel data acquisition systems based on current practices. Data interchange is, however, encouraged and this can be successful only if all data is adequately documented. All investigators who engage in data exchange should be encouraged to provide complete documentation.
4. Research should be directed towards making the solutions to 2D and 3D problems faster and cheaper.
5. To gain confidence in the various 2 & 3D interpretational techniques the same psuedo section should be sent to the different groups working on the problem and a comparison of their results be made; other direct cheaper inversion techniques should be investigated.

Final Session Review
of
Recommendations for Required Research

Team 1 - (1) Quality control in P.P.

a) two temperature ranges.

b) etc.

STRONGLY ENDORSED!

Team 2 - Gerry Hohmann - Models

Endorsed

Team 3 - Don Hoover -

Endorsed

Team 4 - Jim O'Donnell - Data processing

Endorsed

Team 5 - Frank Morrison -

a) #5 - good equipment needed

b) #6 - Jim Applegate - deep EM

c) #7 - Frank Frischknecht - magnetometric resistivity

ENDORSED

Team 6 - Dal Stanley - MT/AMT

ENDORSED with mods.

Team 7 - Sulhi Yungul - Surface to Borehole

Team 8 - Bill Dolan - More case histories available from industry - make it
easy.

APPENDIX

A SIMPLE ALMOST EXACT METHOD OF MT ANALYSIS

by

F. X. Bostick, Jr.

A simple approximate method of MT analysis based on the asymptotic behavior of the apparent resistivity curves at low frequencies is briefly described. Reference is first made to Fig. 1. In that figure the exact apparent resistivity curve and its low frequency asymptote are plotted for an earth model consisting of a single section of uniform resistivity overlying a perfectly conducting substrate. In a more general context it can be shown that the asymptote depends only on the depth to substrate and is independent of the conductivity of the resistive section even if that conductivity is a function of depth.

Figure 2 shows the apparent resistivity curve together with its low frequency asymptote for an earth model consisting of the same resistive section as in the model of Figure 1, but overlying a perfectly insulating substrate of infinite thickness. It can be demonstrated that the asymptote for this model depends only on the S value defined in Fig. 2.

If Figures 1 and 2 are superimposed the apparent resistivity values at frequencies higher than the one corresponding to the point of intersection of the asymptotes are seen to be little affected by an infinite change in the conductivity of the substrate. Furthermore, at the frequency of the asymptote intersection the corresponding apparent resistivity value appears to be a reasonable single value central estimate of the small range of values over which the exact apparent resistivity varies in response to changes in the substrate conductivity. Expressing each apparent resistivity value in terms of the equations describing the asymptotes intersecting at that resistivity value forms the basis of the approximate MT analysis described here. It is interesting to note that expressed in this fashion the apparent resistivity value depends only on the earth conductivity at depths shallower than D .

Figure 3 shows a plot of the asymptotes discussed above for a sequence of values of both S and D . The equations for these asymptotes are repeated for reference immediately below the plot. The plotted asymptotes form an orthogonal

coordinate system rotated 45° with respect to the logarithmic axes of ρA and ω . The S and D values associated with each point on an arbitrary ρA vs ω curve drawn on this grid can be determined conveniently from the S and D coordinates of the point. In the lower half of Figure 3 it is shown that simultaneous solution of the asymptote equations implies that the MT apparent resistivity at any frequency ω is the reciprocal of the average conductivity to the depth D, where D is uniquely defined in terms of ρA and ω .

Figure 4 presents an example of a forward MT problem worked within the framework of the asymptote intercept approximations. The values of S and a sequence of increasing values of D are computed and tabulated for the three layer earth model shown in the figure. The corresponding ρA and ω values can be computed from the asymptote expressions or can be obtained graphically. To find the values graphically the S and D values are plotted on the combined S,D; $\rho A, \omega$ grid. Such a plot for the example three layer earth model is shown at the top of Fig. 4. Where the resulting approximate ρA curve is also compared with the exact one-dimensional curve computed for the model.

In addition to providing a technique for working the forward MT problem the asymptote intercept approximation also yields a simple direct procedure for the inverse problem. Figure 5 presents the derivation of the additional equation used for the direct inverse. This equation yields well behaved resistivity vs depth estimates when used with ρA vs ω curves theoretically generated. The derivative term does, however, cause the inverse to be sensitive to the scatter inevitably present in experimental curves. This sensitivity can be greatly reduced if the necessary derivative is estimated from phase measurements. As indicated in Fig. 6 the Hilbert transform provides the necessary equations. The zeroth order approximation of the Hilbert Transform provides the particularly simple equation expressing the relationship between phase and the required logarithmic derivative of the apparent resistivity curve.

The approximate MT analysis procedures described above have been used for approximately three years in a wide variety of both theoretical and experimental situations. For the most part the results obtained in those applications have been remarkably accurate. In addition, the simplicity of the technique provides for considerable insight into the inherent capabilities and limitations of the MT method.

FIG 1

APPARENT RESISTIVITY

DEPTH-FEET

PHASE-DEGREES

FREQUENCY-HZ.

FIG 2

$$P_A = \omega \mu D^2 \quad (D\text{-lines})$$

$$P_A = \frac{1}{\omega \mu S^2} \quad (S\text{-lines})$$

Eliminate $\omega \mu$

$$P_A = \frac{D}{S} ; \quad \sigma_A = \frac{1}{P_A} = \frac{1}{D} \int_0^D \sigma(z) dz$$

FIG 3

The Forward Problem - An Example

$\sigma = 10^{-2}$	$z = 0$
$\sigma = 10^{-1}$	$z = 10^3$
$\sigma = 10^{-2}$	$z = 2 \times 10^3$

D	ΔD	σ	ΔS	S
10^3	10^3	10^{-2}	10	10
2×10^3	10^3	10^{-1}	100	110
5×10^3	3×10^3	10^{-2}	30	140
10^4	5×10^3	10^{-2}	50	190

The Inverse Problem

$$S = \int_0^D \sigma dz, \quad PA = W \mu D^2, \quad PA = \frac{1}{W \mu S^2}$$

$$\frac{dS}{dD} = \sigma, \quad \sigma = \frac{\frac{dS}{dW}}{\frac{dD}{dW}}$$

$$\sigma = \frac{1}{PA} \frac{1 + \frac{d \log PA}{d \log W}}{1 - \frac{d \log PA}{d \log W}}$$

The Hilbert Transform
Dominant Operation

$$\phi = \frac{\pi}{4} + \frac{\pi}{4} \frac{d \log p_A}{d \log \omega}$$

$$\frac{d \log p_A}{d \log \omega} = \frac{4}{\pi} \phi - 1$$

$$\log p_A = \frac{4}{\pi} \int \phi d \log \omega + C$$

FIG 6