Joint Geophysical Imaging – Results and Future Development

(3 back-to-back presentations on Joint Geophysical Imaging are summarized in this paper)

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1. JOINT GEOPHYSICAL IMAGING – RESULTS AND FUTURE DEVELOPMENT

2. FRACTURE DENSITY MAPS FROM SHEAR WAVE SPLITTING OBSERVATIONS

3. MAPPING HYDROTHERMAL FRACTURES USING EARTHQUAKES AND RESISTIVITY

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SUMMARY – We have been developing geophysical data collection and analysis methods for the combined use of seismic, electrical resistance, and potential field measurements to guide the drilling of geothermal wells. The aim is to guide drilling with a single, "joint", map that couples (not superimposes) such geophysical measurements through the material and structural properties controlling their characteristics. Our data collection methods include borehole sensors, which combine both high temperature seismometers and electrical sensors. Our previous studies, on which our current Iceland and Hawaii studies are based, were conducted at Coso, Geysers, Long Valley, Olkaria, and the Parkfield San Andreas Fault. The 3 talks we present at this meeting summarize all these studies, highlighting our newest results. We also propose that a facility to develop both JGI field measuring and analysis techniques be jointly established by a collaborative industry, government, and academia program.

1. INTRODUCTION

The objective of our research is the combined or "joint" use of geophysical data for mapping and evaluating hydrothermal zones for geothermal drilling. The current focus of our study is the use of electrical and microearthquake data to determine the depth, orientation, and number of the hydrothermal fractures. By combining such data and constraining them with the geological features that they should hold in common, we aim to better locate and resolve permeable zones.

As described in our 3 presentations, we are making progress toward this goal by incremental developments in "Joint Geophysical Inversion" theory and application. In theory development for example, we have studied combining seismic refraction and MT data, finding that when velocity and resistivity layers coincide, only joint inversion retrieves correct models (Fig.1).

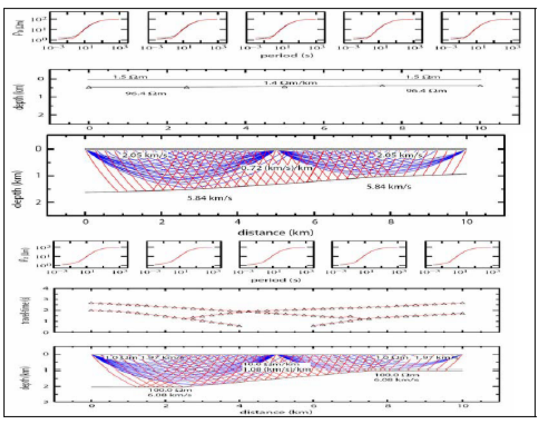

Fig. 1. Three inverse calculations of the depth to a dipping interface using seismic travel time and resistivity. Top and middle frames show independent inversions. The bottom shows the joint inversion of both data. The joint inversion found the correct model.

Likewise, in real applications such as those we have completed at Coso, Geysers, Long Valley, and Olkaria, we have found that successful joint imaging studies begin with, and depend on, the collection of numerous data points over relatively large areas. At Iceland, for example, we used 20 portable seismographs and 3 MT profiling systems to record more than 250 earthquakes and 100 resistivity soundings.

In a potentially significant finding, we have observed that the directions of MT polarization and MEQ S-wave splitting appear to correlate in areas of high fracture density and uniform orientation. Standard interpretation of aligned polarizations in MT data is the presence of either a lateral discontinuity in resistivity or 3-D resistivity structure. For S-wave splitting it is fractures. However, in Iceland both MT polarization and S-wave splitting directions align with geothermally-productive fault zones in uniform rocks and otherwise homogeneous geology. This and equivalent observations in other data sets suggest that some correlations between MT polarizations and MEQ splitting may be related to fractures.

We conclude our talks by suggesting that Government, Industry, and Academia join to acquire instruments to continue this work.

2. JOINT GEOPHYSICAL IMAGING

The seismic and electrical measurements used in our research come from portable microearthquake (MEQ) monitoring networks and closely spaced (MT) and transient electromagnetic (TEM) observation campaigns. The TEM data has been used to correct the MT data for static shifts at collocated measurements. The MEQ records were examined for S-wave splitting and 1-D and 2-D inversions of the shifted MT data were carried out to determine the resistivity structures. The strike direction and splitting in the MT data were recorded and compared to the results of the S-wave splitting study at collocated MT and earthquake measurement sites. In the following sections we describe these data and our analysis and interpretation of them.

2.1 S-wave Splitting and MT Polarization Data

One analysing approach we take to our seismic data is to study the splitting of the S-wave into slow and fast components by fracture induced anisotropy. An example of a split shear wave from our current work in Hawaii is shown in Fig. 2

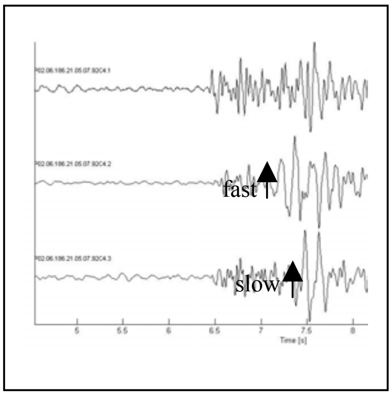

Fig. 2. Three component borehole seismogram from a geothermal area in Hawaii showing very clear S-wave splitting, which we interpret as resulting from a strongly oriented system of large fractures.

To overcome the time consuming job of picking the time difference between fast and slow S-waves for use in fracture studies, we have developed computer code to assist in this task. Given an S-wave travel time pick, the code finds the direction of the fastest S-wave. It accomplishes this by searching for the angle that maximizes the amplitude ratio of the 2 horizontal component S-waves. After rotating the horizontal parallel and perpendicular to this angle, the code finds the time difference by cross correlation. We will present a fracture orientation and density map of a geothermal fracture system we have produced using this code.

In an effort to understand the combined effects of 1-2-3-D geological structure and anisotropic electrical resistivities, we have also collected MT data across a known fracture zone in Iceland. Data were collected in tightly spaced profiles that gave several sounding in each section of the fracture zone: its core, damage zone, and transition to relatively intact rock. Since the entire study area consisted of a uniform set of basaltic flows, the fracture zone can be considered as primarily a structural feature with no lateral lithological contacts. Examples of these data are shown in Fig. 3, illustrating the polarizations modelled here.

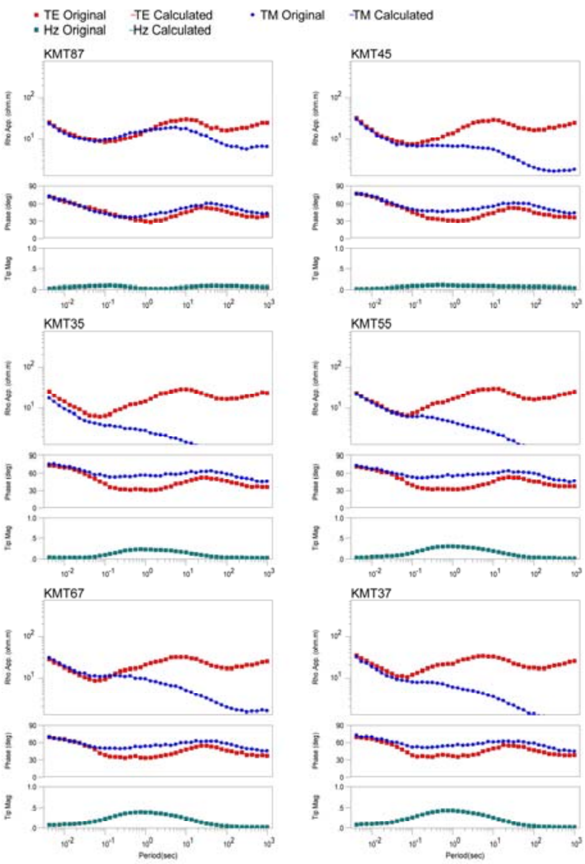

Fig. 2. MT response for several sites within and outside of a known fracture zone in Iceland. The splitting in the MT data is attributed to the resistivity contrasts between the lower resistivity in the fracture zone and the postulated heat source and the higher resistivity in the host rock.

2.2 Combining Seismic and MT Data

One of the preliminary findings in our work at Long Valley and in Iceland is that both S-waves recordings and MT soundings appear to show correlated splitting and polarization effects. This correlation is illustrated in Fig.s 4, 5 and 6.

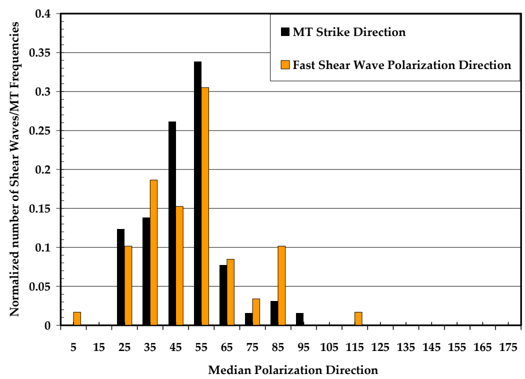

Fig. 4: Plot of normalized fast shear wave splitting direction and MT strike direction for a fracture zone site in Iceland. The dominant polarization directions for both fast S-wave splitting and MT strike directions are between 20 and 60 degrees from the geographical north

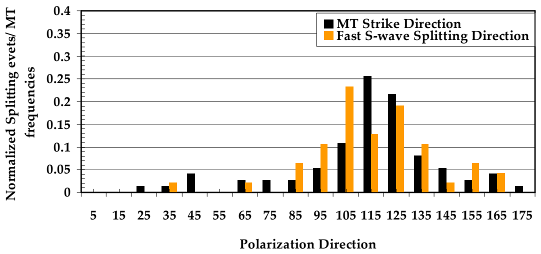

Fig. 5: Polarization of the fast S-wave splitting and MT data for another Iceland site. The dominant direction is between 100 and 130 degrees.

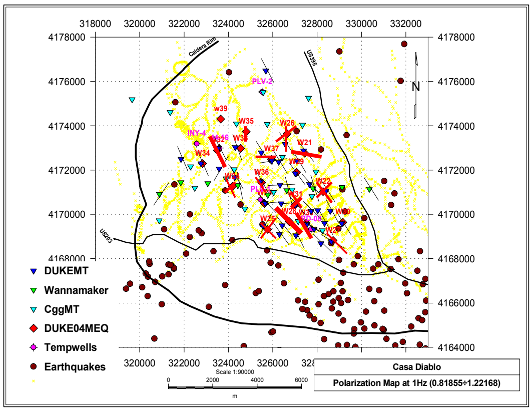

Fig. 6: Map showing both MT polarization (black lines) and S-wave splitting (red lines) directions in Long Valley. The S-wave splitting line lengths and thickness are proportional to the number of events showing splitting. Fault traces are shown in yellow while the locations of earthquakes are shown in brown.

The coupling of the seismic splitting and resistivity polarization measurements to yield a joint image is based on a fractured rock model. The relation of resistivity and fracture related permeability assumes the double porosity model as shown below.

$$f(\Phi)=\frac{1}{\rho}+\frac{022}{\rho_w}\left[1-(1-\Phi_f)^{2/3}+\frac{(1-\Phi_f)^{2/3}}{1+(1-\Phi_f)^{1/3}+(1-\Phi_f)^{1/3}49x10^3}\right]+\frac{\Phi_f^2}{b}$$

Once fit to the MT data, the porosity function is then used to solve for the relationship between P-wave velocity and porosity. The P-velocity model that was found from the resistivity based porosity model was then use to locate the MEQ recorded at the study site. A cross section showing the relationship of the resistivity and event locations found this way is given in Fig. 7.

Resistivity is lowest within the heat source and core of the fracture zone and increases towards the host rocks. Low resistivity near the surface is attributed to a low temperature clay zone. The fracture zone is defined by resistivity (5-70Ωm). The higher resistivity is attributed to lower temperatures and fracture permeability.

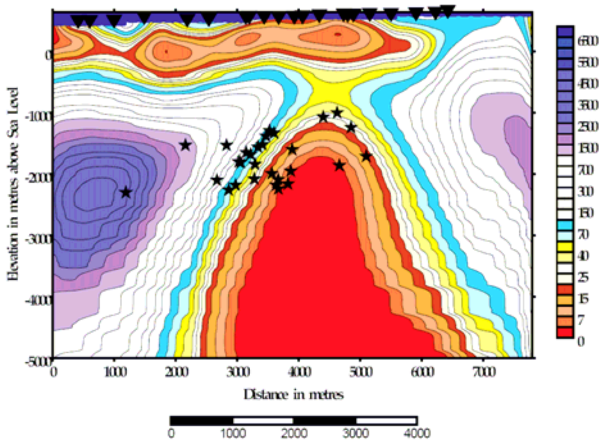

Fig. 7: Plot of smooth 2-D MT resistivity section from Krafla. The mapped fracture zone occurs above the heat source. Microearthquake locations mapped based on a resistivity derived velocity model are shown by stars. These occur at boundaries between high and low resistivities.

3. CONCLUSIONS

The correlation of S-wave splitting and MT polarization directions has been observed at Long Valley and Iceland.

1. Microearthquakes in the Iceland hydrothermal system occur where the heat is shallow and on the boundary between high and low resistivity.

2. Resistivity is lowest within the heat source and core of the fracture zone and increases towards the highly resistive host rocks. A low resistivity near the surface is attributed to a low temperature clay zone. The fracture zone is defined by resistivity values between 5-70Ωm.

3. Fracture permeability based on a double porosity modelling varies between 5-45%. The higher resistivity outside the fracture zone is interpreted as an area of lower temperature and low fracture permeability. This region also has higher P-wave velocity corresponding to that of the rock matrix saturated with water.

4. We suggest that a consortium be assembled to construct a seismic and electromagnetic instrument pool for facilitating further work on joint imaging of New Zealand and other geothermal prospects. The goal of this consortium will be to improve the targeting of high productive wells and lower geothermal exploration and production costs.

3. ACKNOWLEDGEMENTS

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