

Resistivity and Microearthquake imaging of Krafla Geothermal Field, NE Iceland

Stephen Onacha, Dan Kahn; Peter Malin, and Eylon Shalev
Nicholas School of the Environment and Earth Sciences
Department of Earth and Ocean Sciences
Duke University, NC USA

Keywords: Geophysical Imaging, resistivity structure, shear-wave splitting, anisotropy

Abstract

The main objective of this study is to contribute to the continued development of Joint Geophysical Imaging (JGI) methods for the combined use of seismic and electrical resistivity measurements to guide the drilling of high-production geothermal wells. For competitive production of geothermal power, it is essential to develop well-targeting techniques that maximize production with minimum drilling. This paper presents the preliminary results of developing joint geophysical imaging methods map that couple seismic, magnetotelluric (MT), and other geophysical measurements such as Transient Electromagnetics (TEM). The results show a good correlation between resistivity, location of microearthquakes postulated volcanic activities, fluid flow, and structural anisotropy. Analysis of the resistivity data shows high anisotropy close to the boundaries of low and high resistivity anomalies which are also associated with the location of microearthquakes. Preliminary data indicates that most of the earthquakes occur at the boundary between a deeper low zone resistivity (interpreted as a heat source) and a shallow high resistivity zone.

Introduction

Krafla is a high-temperature geothermal field which lies in an active caldera that formed 100,000 years ago (Armannsson et al. 1987) in the rift zone in NE-Iceland. This area has experienced repeated volcanic activity. The last volcanic period started at the end of 1975 and ended in September 1984 with 21 tectonic events and 9 eruptions (Gudmundsson 2001). This volcanic activity occurred along a fissure and released volcanic gases into the geothermal reservoir. From studies of S-wave shadows, it has been postulated that a cooling magma chamber exists at shallow depth of 3-8 km below the geothermal field (Einarsson 1978).

The geothermal field and power generation have been developed in different phases since the commissioning of a 60MWe power station in 1975 (Gudmundsson 2001, Armannsson et al. 1987). The main drilling strategy was to intersect fractures and intrusive boundaries. The historical development of the Krafla and Olkaria show that the high production wells were drilled at the end of the production drilling program. The purpose of this paper is to contribute to the development of Joint Geophysical Imaging (JGI) methods of microearthquake and electrical resistivity measurements to guide the drilling of high-production geothermal wells. We carried out a Joint Geophysical Imaging (JGI) of microearthquake and magnetotelluric (MT) to develop methods of siting high production geothermal wells. This paper presents the preliminary results of this project.

Geological Setting of Krafla area

The Krafla volcanic system is transected by a fissure swarm, which is 4-10 km wide and trends in a near north-south direction (Björnsson, 1985). The geothermal manifestations are

controlled by tectonic fractures and faults. The drilling of production wells focused mainly on intersecting known fractures and intrusion boundaries at a depth of 800-2100 m. Additional geothermal exploration was carried out between 1984 and 1996 to locate fluid with low magmatic gases and also find replacement wells for some of the wells damaged due to tectonic movements. Although some of the wells were targeted in the known upflow zone, the production was still low. This highlights the problem of variability in production of geothermal wells even in modeled upflow zones. Analysis of drill cuttings from the wells has facilitated the evaluation of the distribution of individual lithological units, correlation of aquifers with lithology, and the degree of hydrothermal alteration. Intrusive rocks are the dominant features below 1200-1300 m depth.

The Krafla geothermal reservoir

A total of 34 wells have been drilled in Krafla within an area covering 3-4 Km². The initial output from the wells ranges from 2.3 to 19.7 MWe (Gudmundsson, 2001), reflecting the variability in permeability. Two wells in the Krafla geothermal field account for over 50% of the steam required to power the installed capacity of 60MWe. Similar well output variability exists in the Olkaria Geothermal field in Kenya where two wells produce 19 MWe for a power station of an installed capacity of 45 MWe. The Krafla geothermal area is divided into three fields (Figure 1): Leirbotnar, Sudurhlídar and Hvíthólar fields.

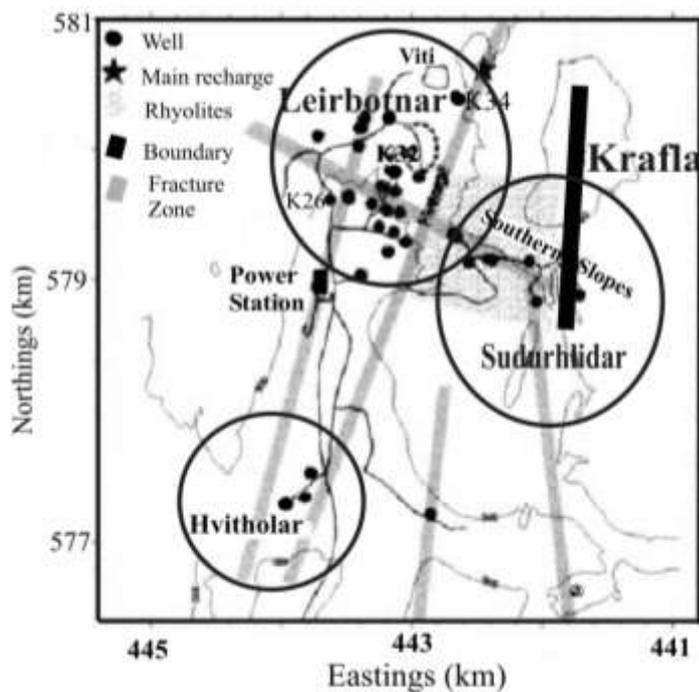


Figure 1 Location of Krafla Geothermal fields

Although the sectors are within a caldera, the drilled wells show a great variability in reservoir characteristics. The Leirbotnar geothermal system is divided into an upper and a lower zone (Stefánsson and Steingrímsson, 1980). The upper reservoir to a depth of 1000 m is water saturated with a mean temperature of 205°C. The main aquifers in the lower zone are associated with fissures and intrusives. This lower zone is boiling with temperatures ranging from 300 to 350°C. The Sudurhlídar field is a boiling system while the Hvíthólar field exhibits boiling characteristics down to 700 m depth with a temperature reversal (Armannsson et al. 1987).

Background and Objectives

The first stage of the Krafla project was funded by US Department of Energy (DoE) and covered the area around the geothermal field. This provided adequate data to map the heat source. We recorded seismic waves from microearthquakes, and added transient electromagnetic (TEM) data collected by the Icelandic Geological Survey (ISOR) to our resistivity data analysis. The TEM data was used to correct for static shifts inherent in MT methods. We also seek to include shear wave splitting in our joint mapping methods research.

The seismic network and magnetotelluric studies in the Krafla geothermal field area were carried out for the purpose of:

- examining induced seismicity from injection and locating microearthquakes
- establishing the value of MT measurements in demarcating the reservoir size and depth, and the heat source which can not be resolved by TEM methods
- locating faulted and fractured zones that could have enhanced permeability
- locating the heat source postulated to be at a depth of 3-8 km from previous studies
- evaluating parameters that can be used in the joint inversion of seismic and resistivity data to map high permeability zones.
- As a pilot study to guide future field expansion and development of a conceptual model

Data Acquisition

During the month of July and August 2004, Duke University deployed twenty (20) three component seismographs (Figure 2). A complimentary array of 20, 3-component seismic stations was deployed around the Krafla geothermal field by the University of North Carolina

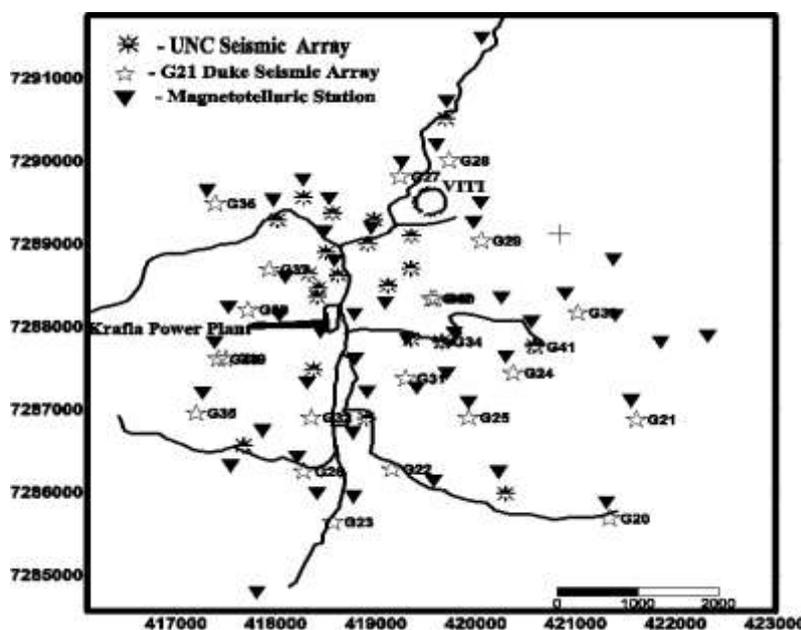


Figure 2 Location of MT soundings and seismic arrays by Duke

at Chapel Hill (Chuanhai et. al 2005). The data loggers were set for 500 samples per second with data recorded on flash cards. The array deployed by Duke University continuously recorded all the local seismicity. The seismic array was deployed to record natural and induced seismicity from re-injection and exploitation of the geothermal field. Injection into well K-26 was stopped on July 15 and restarted on July 26. Microearthquake activity was monitored between the July 15, and the August 5, 2004.

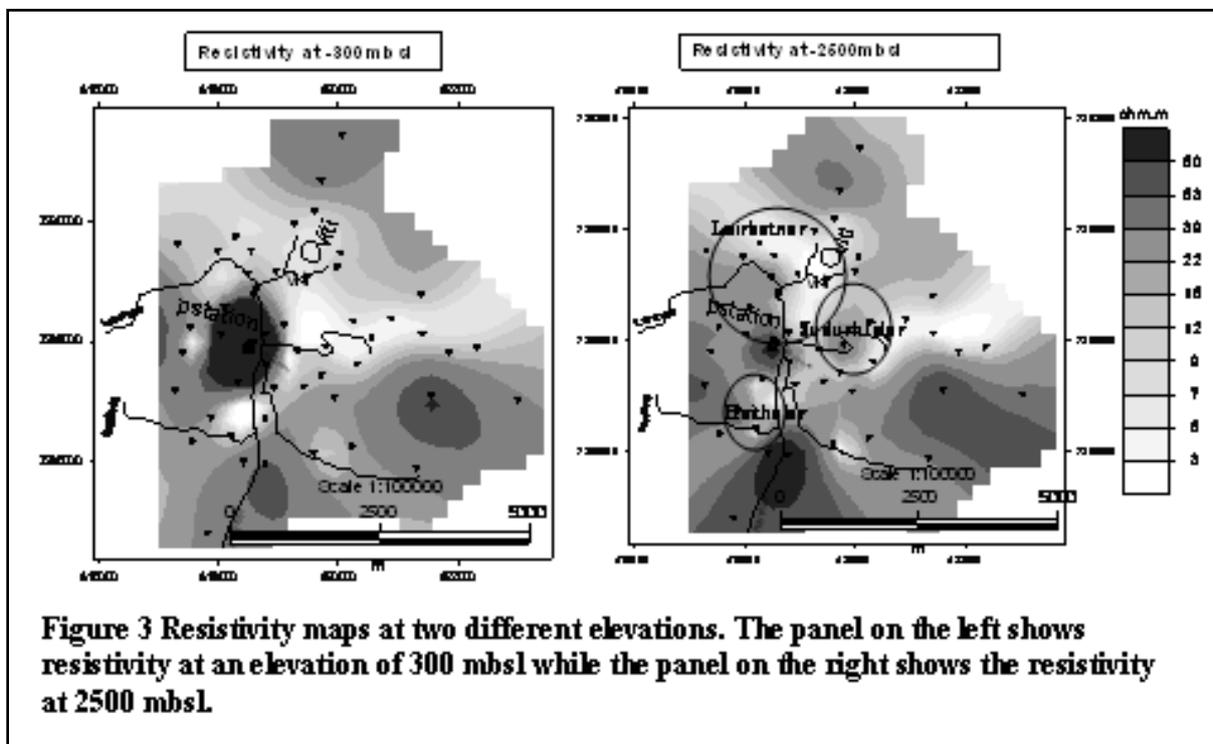
Resistivity Studies

Previous studies in Iceland show that resistivity methods have been the most reliable in estimating the size and structure of geothermal fields (Knútur et. al. 2000). These studies have shown that the resistivity structure can be correlated with the alteration mineralogy which is an indicator of existing or relict thermal conditions in the geothermal field. The interpretation of detailed transient electromagnetic measurements in Krafla (Knútur and Ingvar 2001) postulates that the low resistivity anomalies are associated upflow zones of the geothermal fluids. The conceptual model of the best targets for geothermal development consists of a near surface low resistivity underlain by a resistive layer. The near-surface low resistivity is correlated with clay alteration and marks the temperature isotherm of 180-200°C.

Magnetotelluric Studies

In magnetotelluric method, the impedance tensor, linking the horizontal components of electric and magnetic fields in the frequency domain, reflects the conductivity distribution in a volume of rock below the measurement point. In this paper we present the initial results of 1-D and 2-D inversion. The inversion was carried out after the analysis of the impedance tensor in order to understand the basic electrical properties of the Krafla geothermal field.

The initial results have been plotted as maps and cross-sections to show the variability in resistivity in the Krafla geothermal field. The closely spaced measurements confirm the demarcation of the production area into three distinct regions (Figure 3). The maps from 1-D interpretation have been plotted at different elevations to show the areal variability of resistivity. At shallow depths, the resistivity distribution coincides with the surface hydrothermal alteration. The map at 300 mbsl shows linear low resistivity anomalies with NW-SE and NE-SW trends that may be structurally controlled. These trends do not coincide with the NS trending fissures swarms. This may indicate that the structures that control geothermal fluid circulation trend in the NW-SE and NE-SW directions. The resistivity map at 2500 mbsl shows distinct low resistivity in the three production zones in Krafla. The boundaries of the fields are not well defined because of scant data coverage beyond the developed geothermal field.



We have analyzed the variability of resistivity measurements across three NE-SW 2-D profiles (Figure 4). Profiles NE1 and NE2 shown on the left panels show a deeper low resistivity which we interpret as a confirmation of the heat source which has been postulated to be at 3-8 km. The third (bottom right panel) profile does not show this low resistivity which shows that the heat source is deeper in this area and therefore a lower priority area for geothermal development. We show later that this area shows no microearthquake activity. The northern boundary of the interpreted heat source is not well defined because of poor data coverage in this area. The near surface low resistivity which corresponds to hydrothermal

alteration of 180-200 °C covers a wider area within the Krafla geothermal field. The resistivity rotated to the principal directions show anisotropy which might be related to both structure and the heat source. The anisotropy is highest at the boundaries of the deep low resistivity and high resistivity (Figure 5). We will investigate this relationship further to establish whether it is significant in mapping structures that control the productivity of geothermal wells

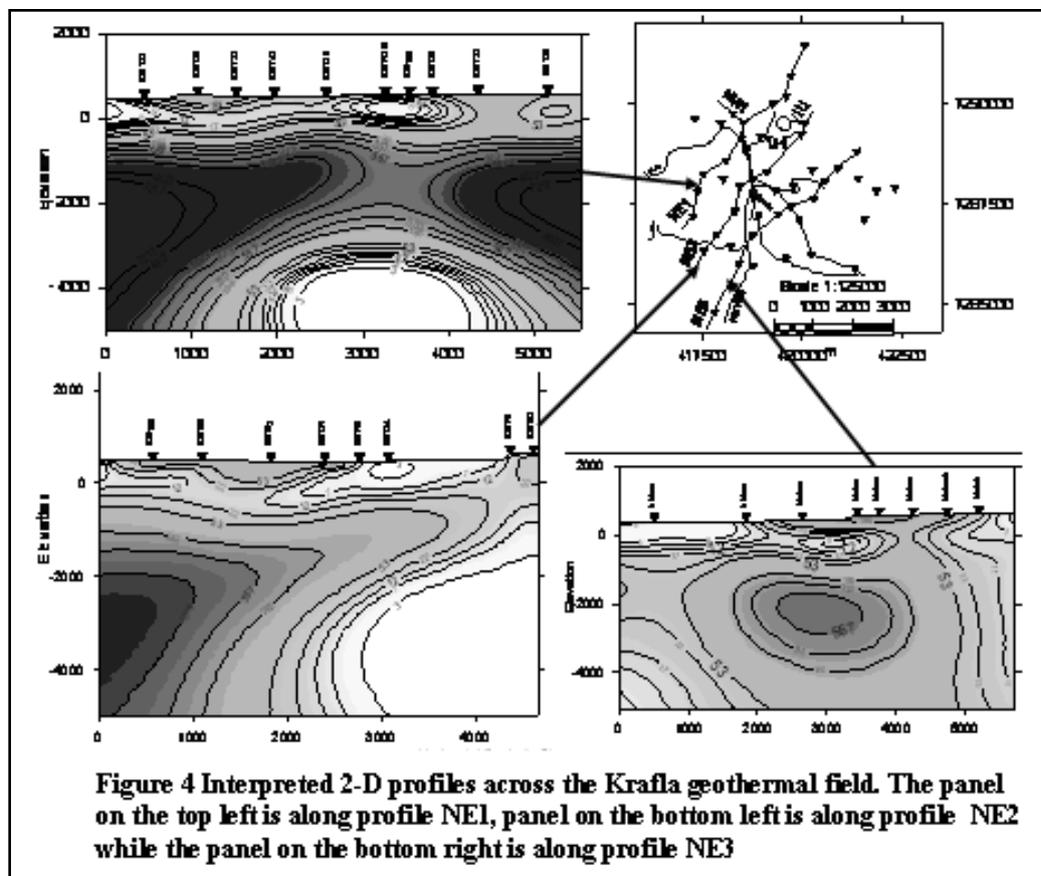
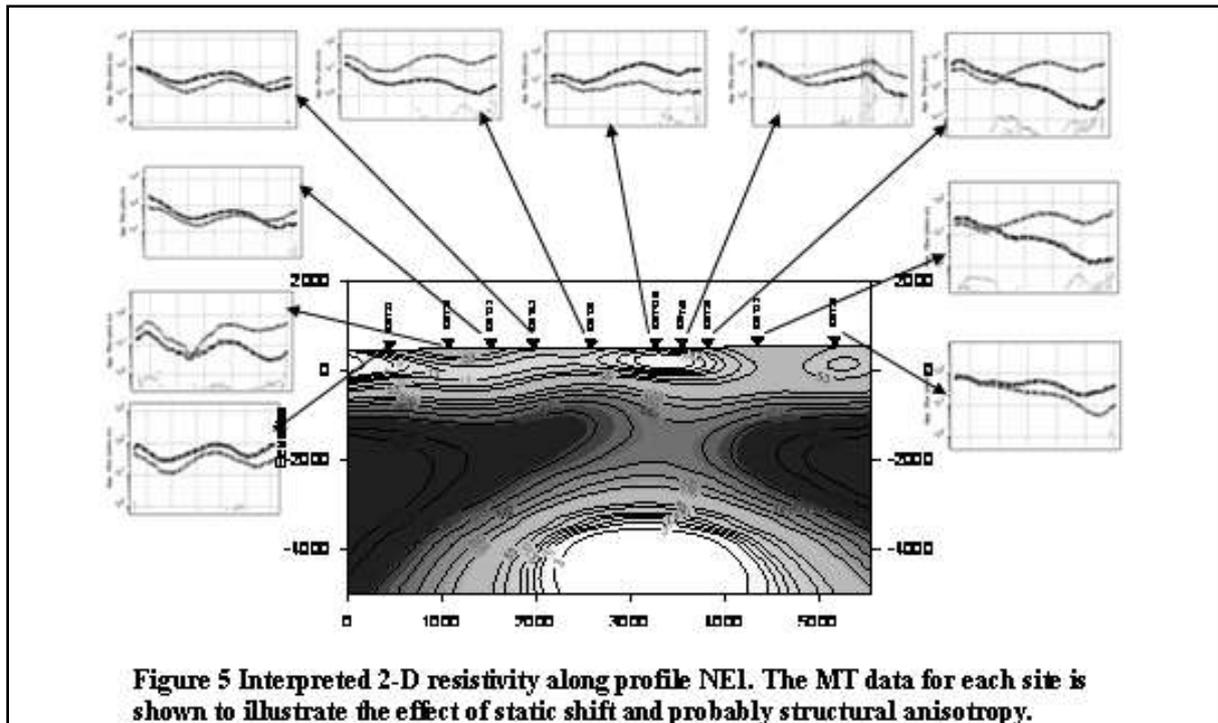


Figure 4 Interpreted 2-D profiles across the Krafla geothermal field. The panel on the top left is along profile NE1, panel on the bottom left is along profile NE2 while the panel on the bottom right is along profile NE3



Microearthquake Studies

The major factors that affect seismic velocities are density of the rocks, porosity, degree of fracturing and temperature. All these factors also affect the bulk resistivity of rocks. In this study, the focus was on seismic shear-wave splitting which is similar the most diagnostic, informative, and easily observable feature of azimuthal seismic anisotropy (Crampin, 1981). Azimuthal anisotropy can be interpreted in terms of stress-aligned, fluid-saturated microcracks of *in situ* rocks (Crampin and Zatsepin, 1997)

The microearthquake data was acquired using 20 new Geospace GS-1 3-component, 24-bit, 4-channel seismometers. This new equipment was designed for microearthquake exploration in a variety of terrains with emphasis on utilisation in the East Africa Rift system. The equipment was designed under a grant from the Global Environmental Facility (GEF) as part of the Joint Geophysical Imaging Project (JGI) aimed at increasing the probability of drilling high production wells and therefore reducing risks and costs of developing geothermal energy (Onacha. et. al., 2003).

The seismometers were designed with a natural frequency of 1 Hertz (Hz), well suited for optimal response to microearthquakes. The GS-1 seismometers at this time run on lead chloride batteries which were recharged every two days. The seismometers were firmly anchored to the ground by securing them with a 70cm auger which couples the seismometer acoustically to the ground. The GS-1 was design specifically to provide added security against vandalism in the field during the data acquisition for the JGI project. Another important feature of this new equipment is that there are no exposed cables and the battery is integrated into the equipment. The GPS is also fixed on the data acquisition logger.

Preliminary Results

The data from the Geospace GS-1 seismometers were used to determine the location of the

epicenters by analyzing P-wave and S-wave arrival times. Data from the twenty seismometers were manually inspected and the signatures of likely events handpicked. The hypocenters were determined from microearthquake events observed at more than four stations. On average four microearthquakes were observed per day, with somewhat fewer occurring when injection was stopped. The locations of the earthquakes were determined and plotted on maps. In our preliminary results, we have combined maps of microearthquakes and resistivity (Figure 6).

The clustering of the microearthquakes in the NW-SE direction suggests structural control aligned in this direction. The location of earthquakes in the near vicinity of the injection well shows a correlation with the injection of geothermal fluids. The depth of these epicenters at approximately 2500-3500 m occurs at the boundary of the low and high resistivity. This boundary dips to the southeast correlating well with the deeper earthquakes. There are no earthquakes recorded in the region where we do not have the low-high resistivity interface. The analysis of polarization directions for MT data at high frequency corresponding to shallow depths shows very similar orientation to the polarization determined by shear wave splitting (Figure 7) by the University of North Carolina at Chapel Hill (Chuanhai et.al., 2005).

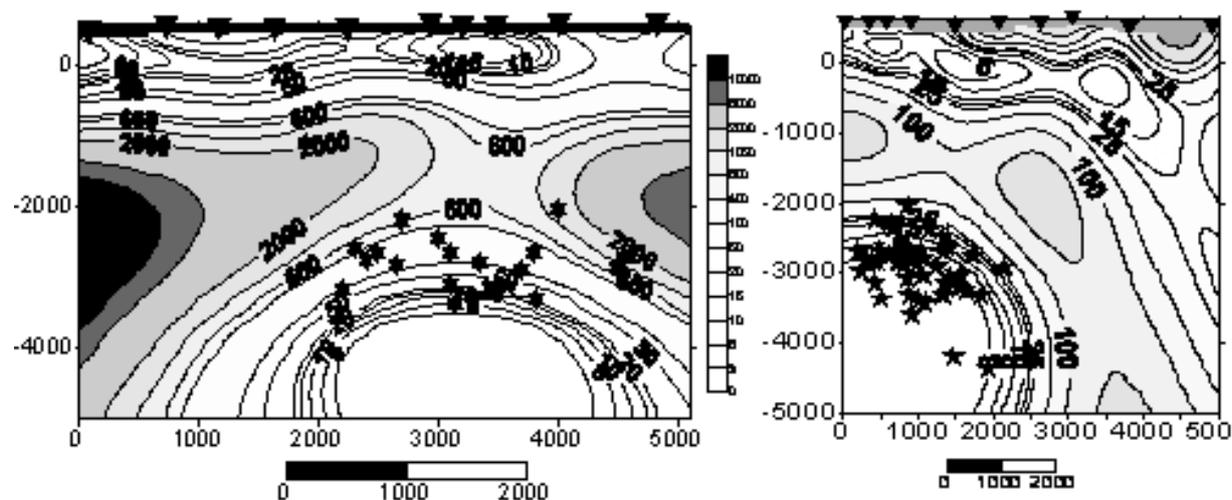


Figure 6 Depths and location of microearthquakes along 2-D resistivity profiles. The panel of the left shows earthquakes along profile NE1 while the panel on the left shows earthquakes along profile NW1.

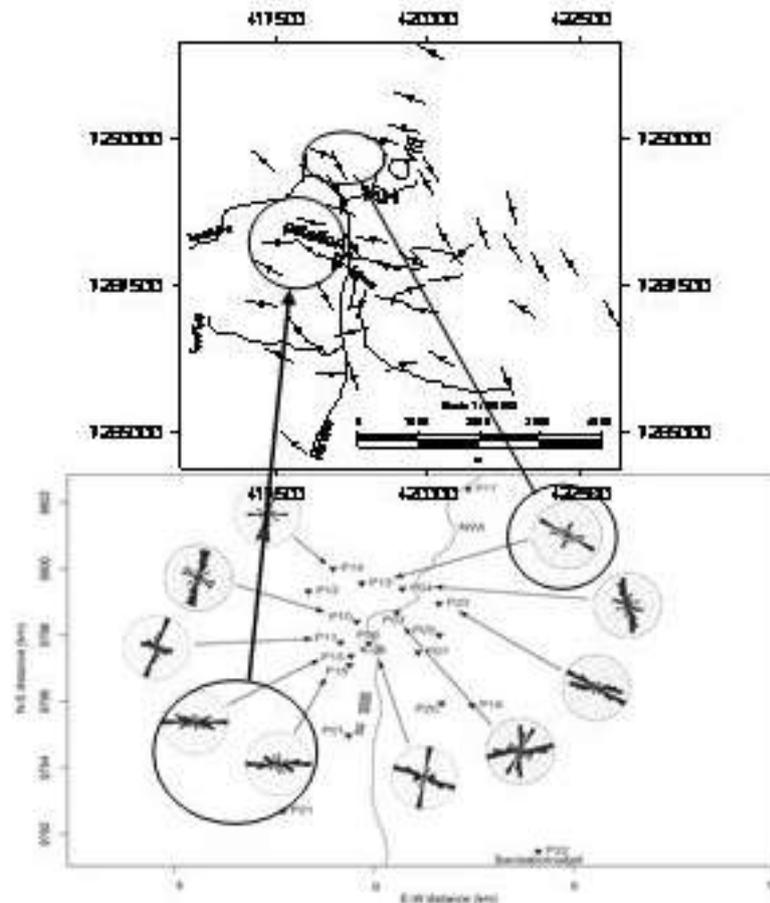


Figure 7 Comparison of the polarization directions derived from MT and shear wave splitting data. The top panel shows MT polarization at 200HZ at each of the sounding stations. The bottom panel shows shear-wave splitting direction computed by the University of North Carolina at Chapel Hill (Chuanhai et. al. 2005)

Conclusions

The new coincident MT and microearthquake data has provided information on structural anisotropy. This anisotropy is related to fractures and cracks that might be filled with geothermal fluids. This study clearly shows the relationship between the resistivity contrasts and location of microearthquake epicenters. The earthquakes occur at the boundary between zones of low and high resistivity. The deeper low resistivity is interpreted as the heat source for the geothermal system. This study has therefore contributed to the mapping of the heat source which could not be resolved by TEM methods. The new conceptual model for the highest potential in Krafla area is the existence of a shallow low resistivity due to low temperature alteration, followed by a resistive layer due to high temperature mineralogy and then low resistivity that is interpreted as the heat source

Acknowledgement

The authors would like to thank GEF/UNEP for funding to design and purchase new equipment for JGI. DOE provided the funding for the Krafla field data acquisition in collaboration with Landsvirkjun, the Icelandic Cower Company. We are grateful to KenGen

Best Geophysics Paper, 2005 Geothermal Resources Council Annual Meeting, Reno, NV

for providing the equipment and personnel for the project.

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