

Joint geophysical imaging of fluid-filled fracture zones in geothermal fields in the Kenya Rift Valley

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Abstract

We present the application of joint geophysical imaging (JGI) and interpretation of seismic shear-wave splitting and electrical resistivity polarization due to aligned, fluid-filled fracture zones as targets of drilling exploration and production wells. The method included coupling of physical properties as well as geological structures. The joint imaging scheme has been used to obtain the orientation of fracture zones in two geothermal areas in Kenya using microearthquake (MEQ) recordings, Transient Electromagnetic (TEM) and magnetotelluric (MT) soundings. Joint imaging results show two main polarization directions aligned both with younger fractures and tectonically activated older fracture systems. The complex interconnection between these fracture zones causes heterogeneity and anisotropy which determines geothermal fluid movement. The JGI results have been used to successfully target higher production geothermal exploration and production wells.

Our experience from the geothermal fields in Kenya suggests that the best targets for drilling geothermal production wells can be found on fracture zones that are aligned with the old tectonically activated fractures. Intersections of NE and NW trending fractures also form important fluid up-flow channels. The alignment of fractures has been used to successfully determine the direction of drilling deviated wells. This result shows that due to heterogeneity and anisotropy, it is difficult to determine and predict fluid flow paths and therefore routinely drilling across interpreted surface fractures does not always guarantee success. The most successful wells should be drilled either along NW trending fractures or intersections of fractures which form zones of enhanced permeability.

Introduction

High-temperature geothermal prospects in Kenya occur in the tectonically active Kenya Rift Valley and have an estimated potential of over 3,000 MWe. The Rift Valley has experienced repeated volcanic activity and is associated with crustal upwarping and volcanism of mostly Rhyolitic and Trachytic rocks that started 20 Ma (Clarke et. al., 1990). Existing geophysical models indicate that the upwelling of the asthenosphere provides the driving mechanisms for the lithosphere uplift and extension (Clarke et. al., 1990). Seventeen volcanic centers have been identified in the Kenya Rift Valley, but only eleven are associated with geothermal activity (Figure 1). There are also geothermal areas around lakes Magadi, Arus-Bogoria, and Baringo that are not associated with known volcanic centers. The complex geological, structural and volcanic setting in the Kenya Rift Valley provides a tremendous challenge to understanding, exploring and development of the geothermal systems. In this paper, the Olkaria-Domes and Mt. Longonot geothermal systems were studied to explore and develop the geothermal potential.

Geothermal exploration and development has been carried in various phases since the 1950's

but the challenge has always been to locate high production geothermal wells to reduce the costs of developing geothermal energy. The Greater Olkaria Geothermal Area (Figure 2) covers over 80 Km² and has been divided into several fields of which Olkaria East (Olkaria I), Olkaria Northeast (Olkaria II) and Olkaria West (Olkaria III) have been developed for power production. This paper focuses on the use of JGI methods for locating higher production wells in the Olkaria- Domes and Longonot areas to the east Olkaria I. The results of the JGI project have increased the average well production from 2.5 MWe per well in the older Olkaria I field to over 6 MWe per well in the new Olkaria-Domes area. The higher average production has been achieved by using Joint Geophysical Imaging (JGI) methods of MEQ and electrical resistivity measurements to guide the drilling of high-production geothermal wells to increase productivity in an area that is covered by a thick layer of more than 600m of volcanic ashes and pyroclastics.

Geological Setting of Olkaria-Domes Longonot area

Several geological, geophysical and geochemical studies have been carried out in the Kenya Rift Valley to study and understand the complex geological and tectonic setting of the rift (Karson and Curtis, 1989). Most of these studies have been focused on understanding the deep crustal structure and therefore are not relevant to evaluating the reservoir properties of the hydrothermal systems. The significant finding of most of the studies is that the structure of the rift valley varies both along and perpendicular to the rift. Seismic tomographic studies through Longonot have shown low P-wave velocities in the crust that are interpreted as zones of partial melt. These studies indicate significant variations in magmatism and tectonism both with depth and along the Rift Valley (Karson and Curtis, 1989). These variations could significantly control the structures and the fluid flow mechanisms in the geothermal systems. This area of the Rift Valley is dominated by Rhyolitic and Trachytic lava flows.

Background and Objectives

The JGI project was aimed at increasing productivity from the Greater Olkaria Geothermal Area and indentifying exploration drilling targets in the Longonot geothermal field. Over 400 regional DC Schlumberger measurements and over 300 TEM (Onacha, 1998) measurements previously acquired by the author while working at the Kenya Electricity Generating Company were re-interpreted and integrated to provide the regional resistivity (Figure 3) structure as a basis of acquiring detailed MT measurements and deploying MEQ loggers. From previous studies in the Longont area (Shalev et. al., 2000, Simiyu et. al., 2000), and experience in Krafla in Iceland and Mammoth Lakes in California, inappropriate deployment of MEQ can lead to the wrong conclusion that geothermal systems are not seismically active. The TEM data was used to correct for static shifts inherent in MT method by generating an equivalent 1-D MT model from the TEM data. The data analysis and interpretation includes shear wave splitting (S-Wave splitting) and MT polarization which we have postulated that is caused by aligned fluid-filled fractures. The major of objective of the JGI studies are:

- locating MEQ and examining their association with possible fluid-filled fracture zones
- locating faulted and fractured zones that could have enhanced permeability
- evaluating parameters that can be used in the joint inversion of seismic and resistivity data to map high permeability zones.
- Determining drilling locations and directions
- Determining the extent and depth of accessible reservoirs with a view of increasing productivity of an existing field

Data Acquisition

During the months of October to December 2004, Duke University and KenGen deployed fifteen (15) three component new seismographs in Olkaria and Longonot. The MEQ data was acquired by 15 new 3-component, 24-bit, 4-channel seismometers designed to record low frequency data with sampling rate of 250 samples per second. The new seismographs consist of a data logger module, geophone module, and an anti-theft “lockout lock-down” ground auger assembly. The tri-axis on which the geophones are mounted also contains an opening for a J-hook which anchors onto a ground auger. This mechanism couples the geophones acoustically onto the ground and also provides security against vandalism. The electronics and battery are located inside the logger module, and the GPS antenna is located on top of the logger. Another important feature of this new equipment is that there are no exposed cables and the battery is integrated into the equipment. 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, 2005, 2006 and 2007).

The 3 Phoenix MTU-5A data loggers were used for MT data acquisition in the frequency range of 400-0.001HZ. A total of 123 MT stations were acquired in Olkaria-Domes area and 84 MT soundings in Longonot. 132 TEM soundings acquired by KenGen in various stages between 1998 and 2004 in Olkaria-Domes were used for static shift correction (Pellerin, L., and Hohmann, G., 1990) while 84 TEM soundings were used in Longonot. The TEM measurements were acquired using the central loop configuration with square loops of 200-300m. The DC Schlumberger resistivity measurements used for the regional resistivity structure were acquired with current electrode spacing of up to 6000m.

Resistivity Studies

In most high temperature geothermal fields, the resistivity structure can be correlated with the alteration mineralogy which is an indicator of existing or relict thermal conditions in the geothermal field. In many high temperature geothermal fields, for instance Krafla (Onacha, et. al., 2005; Arnasson and Ingvar 2001, Arnasson et. al. 2000), the low resistivity anomalies are associated with up-flow zones where geothermal fluids flow along high permeability fracture zones. 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.

All the regional DC Schlumberger data was re-interpreted to evaluate the regional resistivity structure of the Suswa-Longonot-Olkaria area. The regional DC resistivity map at 1000masl derived from 1-D models (Figure 3) shows that the Olkaria and Longonot geothermal areas are defined by a low resistivity anomaly while the Suswa field has a higher resistivity anomaly may be due to a lower degree of hydrothermal alteration and lower permeability. The resistivity structure shows distinct NE and NW linear trends that are most likely due to alteration caused by geothermal fluid circulation along aligned fluid-filled fractures. The DC resistivity measurements are however, only reliable in indentifying the shallow geothermal resource boundaries but not adequate imaging deeper structures that could be targets for drilling high production wells.

MT data analysis and results

In MT 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 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. The 2-D interpretation was done by inverting for both the Transverse Electrical (TE) and Transverse Magnetic (TM) modes and the vertical magnetic transfer functions (HZ). The near surface resistivity was fixed using the 1-D TEM smooth models.

1-D models from TEM data were used to generate equivalent 1-D MT models at the same site. The synthetic 1-D MT models were then used to correct for static shifts (Pellerin and Hohmann, 1990) for the TE and TM modes of the MT data. Resistivity maps were prepared from the results of 1-D Occam's models to show the spatial distribution of resistivity at fixed elevations. 1-D interpretation was carried out both for layered and Occam's inversion using the entire MT data set after rotation to the principal axes. These maps together with the 1-D sections have been used as the basis for the 2-D modeling. 2-D forward and inverse modeling was carried out on NE-SW trending profiles using WinGlink program (Rodi and Mackie, 2001) to determine which features in the inversion models were important.

At shallow depths, the resistivity distribution coincides with the surface geothermal alteration. The isoresistivity map at 1600masl (Figure 4) shows linear low resistivity anomalies with NW-SE and NE-SW directions are structurally controlled. This may indicate that the structures that control geothermal fluid circulation are in the NW-SE and NE-SW directions. The JGI project provided new data that identified a new area of about 6 Km² for increased productivity in the existing Olkaria I field and defined the targets and depths of drilling production wells in the Olkaria-Domes area earmarked for production drilling for a new 70MWe power plant. We have analyzed the variability of resistivity measurements across one 2-D profile in Olkaria-Domes and one 2-D profile in Longonot (Figure 5 and 6). The profiles show a deeper low resistivity which we interpret a possible heat source which has been postulated to be at 6-8 km. The best target for deep drilling is the interface between the deeper low resistivity and the higher intermediate layer high resistivity.

Analysis of polarization directions and the splitting in the principal resistivities at each site after correction for static shifts using collocated TEM data can be used as a measure of anisotropy caused by the response of the MT signals to aligned fluid-filled fractures. The amount of splitting varies depending on the proximity resistivity contrasts at depth (Figure 7). This gives additional useful information that can be used to locate fluid filled fractures. In areas close to the fractures, the principal resistivities "split" into 2 distinct values. Our experience at Krafla in Iceland, Mammoth Lakes in California, and Olkaria and Longonot in Kenya indicate that areas with high resistivity and minimal splitting in the frequency range of 10 – 0.1 Hz are not good targets for drilling.

Microearthquake data analysis and results

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, we focus on use of seismic shear-wave splitting which is 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-filled microcracks in rocks (Crampin and Zatsepin, 1997; Crampin, 2005). S-wave splitting was done by searching for the angle that maximizes the amplitude ratio of the horizontal components of the S-waves. After rotating the S-waves to the direction parallel and perpendicular to this angle, the time delay was obtained by cross correlation of the amplitudes.

Locating earthquakes was done by first picking P and S phases with the associated errors. The locations of the MEQ stations required to locate earthquakes were determined from the internal GPS measurements. The MEQ are located at a reference datum which is the average of the stations. Station corrections were incorporated to account for the elevation differences with respect to the average elevation. Station corrections are computed by locating many earthquakes with zero corrections and then assigning the average time errors as station corrections. The location MEQ was carried by the Hypoinverse- 2000 code (Klein, 2000) with a parameter input interface in Matlab. The initial velocity model was obtained from the velocity structure previously used to locate events in the area of Longonot (Simiyu and Keller, 2000). After deploying the MEQ data loggers for 26 days in domes, only 41 earthquakes were located.

Joint geophysical imaging and well targeting strategy

The analysis of polarization directions for MT data in the frequency range of 10-0.1 HZ corresponding to shallow depths shows very similar orientation to the polarization determined by S-wave splitting at collocated sites for both Olkaria-Domes (Figure 8) Longonot (Figure 9). The dominant MT polarization and S-wave splitting directions are in the NE and NW directions. This demonstrates the value of JGI even if few MEQ are recorded. The additional data provided by both MT and MEQ in response to anisotropy and heterogeneity caused by fluid-filled fractures is important in determining drilling targets, depths and directions.

The depth of MEQ epicenters at approximately 1500-4000 m occur at the boundary of the low and high resistivity (Figure 10 and Figure 11). The clustering of MEQ in the NW and NE directions which also along with resistivity anomaly suggests structural control aligned in this direction. The recorded earthquakes were too few to carry out tomography modeling. From the results of this study, the drilling targets, depths and directions can be optimized for high production wells by an integrated and joint interpretation of the geophysical data that takes into account the effect of heterogeneity caused by systems of aligned fluid-filled fracture zones. The results from the JGI project indicate that it is preferable to drill along fractures that coincide with polarization from MT data and MEQ shear wave splitting. The electrical polarization and S-wave splitting respond to spatial variations in the density of high permeability fluid- filled zones.

Conclusions

The new coincident MT and MEQ data has provided information on structural anisotropy. This anisotropy is related to fractures and cracks that might be filled with geothermal fluids. This study shows the relationship between the resistivity contrasts and location of MEQ 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. The new conceptual model for the highest potential in the geothermal areas 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 lower resistivity that is interpreted as the heat source.

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