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Aluto-Langano Geothermal Field, Ethiopia: Multiscale Image of Trans-crustal Magmatic System by Combining Local 3D and Regional 2D Magnetotelluric Soundings

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ABSTRACT

Geothermal energy has the potential to support Ethiopia in its attempt to overcome energy poverty and provide sustainable energy for all. The formation and distribution of geothermal energy resources in Ethiopia is associated with magmatic activity along the Main Ethiopian Rift (MER). Until now, geothermal exploration mainly concentrated on shallow magmatic-hydrothermal systems underneath volcanoes in the central part of the MER. At the geothermal field of the Aluto volcano local 3-D magnetotelluric (MT) surveys successfully imaged the geothermal reservoir leading to the placement of productive geothermal wells. However, due to the limited aperture (15 km) of the surveys it was not possible to image the lower crustal magmatic plumbing system of the volcano. A regional MT study along a 120 km long profile transecting the rift and Aluto volcano was conducted within the project RiftVolc. They imaged an off-rift axis magmatic system in the Silti-Debre Zeyit Fault Zone (SDFZ) west of the central rift. However, the feeding zone of Aluto's magmatic system remained enigmatic. In this study we combined the two existing datasets, resulting in a selection of 165 stations located at Aluto and 26 stations along the 120 km long RiftVolc cross-rift profile. The preliminary 3-D model revealed the existence of a deep conductor in about 35 km of depth on the western side of the rift, indicating that partial melt is present.

1. INTRODUCTION

Geothermal energy in the East African Rift (EAR) holds a huge potential for sustainable socio-economic development of the countries situated along the EAR. However, to deploy geothermal power plants successfully, knowledge of the geology and the formation of the hydrothermal system is crucial. High enthalpy geothermal systems in the EAR form in the context of active continental rifting and magmatism. Hence, knowledge about rifting-related volcanism and how it leads to the emplacement and distribution of magma in the crust is key to understand the formation of convective volcanic geothermal resources.

The new project "Magnetotelluric Investigation of Active Rifting and the Formation of Geothermal Energy Resources" (MIRIGE), aims to obtain this knowledge by conducting MT-surveys that will cover the central part of the MER, complementing existing data from local and regional MT-surveys. Doing so, it aims to answer the questions: (1) how magma is spatially distributed beneath the MER, (2) what controls magma transport and emplacement under rift-aligned segments and (3) how this influences the formation of geothermal resources.

Here we present a magnetotelluric study, that investigates the deep routed magmatic system of Aluto volcano by imaging it from the surface down to the upper mantle. The only existing geothermal power plant in Ethiopia is situated at Aluto, where geothermal power with a capacity of 7.3MWe is produced (albeit intermittently) since 1990 (Hochstein et al., 2017). Expansion work to increase the production to 70 MWe is currently ongoing. Two MT-studies were conducted in this region: (1) A regional cross-rift 2D MT-study across Aluto (Hübert et al., 2018) using data collected by the RiftVolc project and (2) a local 3D-inversion of MT-data in the region of Aluto (Samrock et al., 2020) using data collected by ETH Zürich (Samrock et al. 2015) and the Geological Survey of Ethiopia (Cherkose and Mizega, 2018) (Fig. 1). Both studies added to the understanding of geothermal systems and melt-distribution in the MER. Samrock et al. (2020) were able to image Aluto's the high enthalpy geothermal system and its magmatic heat source for the first time in detail and Hübert et al. (2018) could confirm the existence of a high-conductivity anomaly in the Silti-Debre-Zeyit fault zone (SDFZ), that has previously been indicated by tipper data (Samrock et al., 2015). However, the three-dimensional extent of the high conductivity anomaly in the SDFZ and the depth of Aluto's transcrustal magmatic system and the deep asthenospheric zone of melt generation remains poorly imaged.

In this study we combine those two MT-datasets by Hübert et al. (2018) and Samrock et al. (2020). Namely, the 120 km long crossrift profile and the local high-resolution dataset from a 15 km by 15 km wide area at Aluto. Doing so, we aim to model the extent of the feeding zone of Aluto's magmatic system and examine it extent into the deeper crust and upper mantle.

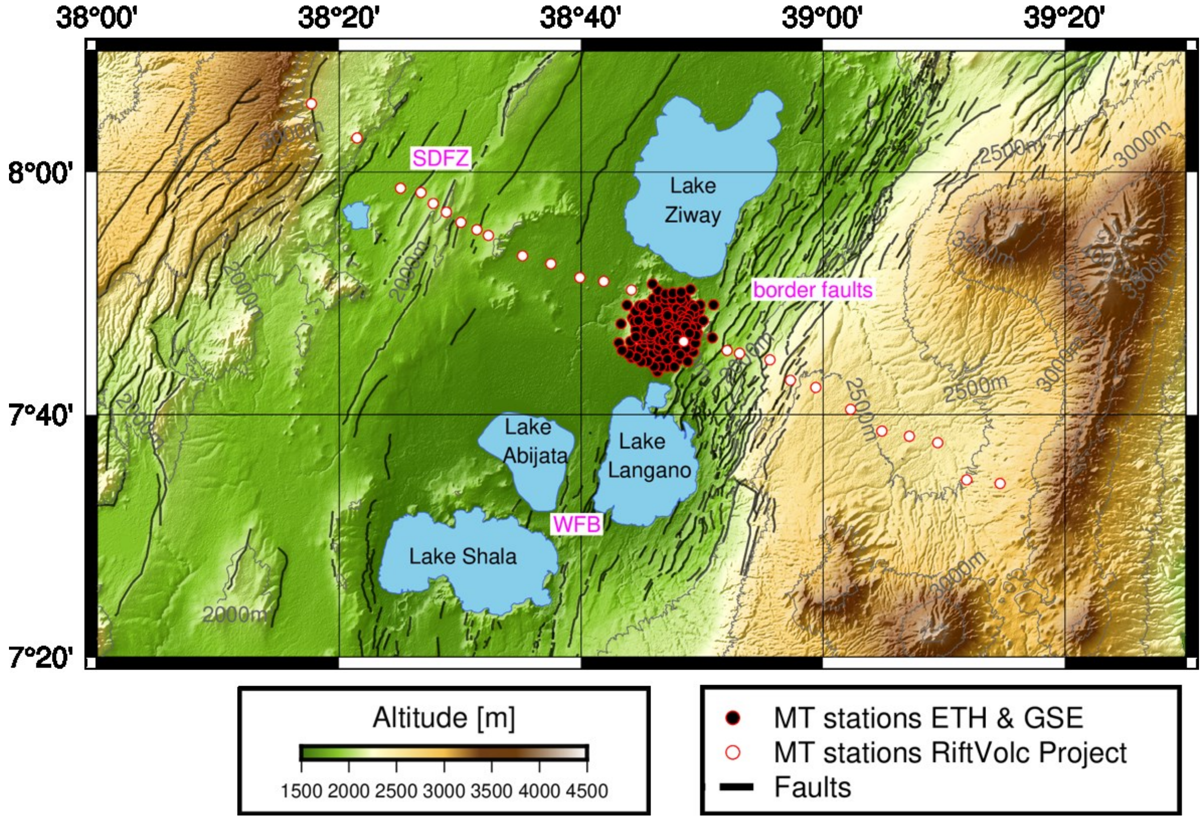

Figure 1: Map showing the area of our study with Aluto volcano at its center. MT-stations from different projects are colored accordingly. All shown MT-stations (191 in total) were used for the 3D inversion performed in this study. Faults on the eastern rift border are named Asela-Langano border faults and faults closer to the rift-axis belong to the Wonji-fault-belt (WFB) (Corti et al., 2020). Faults in the western part of the rift belong to the southern part of the Silti-Debre-Zeyit fault zone (Woldegabriel, 1990).

2. METHOD

Magnetotelluric measurements use natural electromagnetic field variations to measure the induced electromagnetic field in the subsurface. Electric ($\overrightarrow{E}(\vec{r},\omega)$) and magnetic field ($\overrightarrow{H}(\vec{r},\omega)$) variations measured by MT are related by a transfer function called the impedance tensor $\vec{Z}$: $\overrightarrow{E}(\vec{r},\omega) = \overrightarrow{Z}(\vec{r},\omega)\ \overrightarrow{H}(\vec{r},\omega)$, where ω is the angular frequency and $\vec{r}$ the location of the measurement station. The impedance tensor contains the full information about the 3-D subsurface electrical conductivity (σ) distribution that can be recovered by solving a 3-D numerical inversion problem. However, if small scale electric scatterers, that are too small to be resolved, are present the impedance tensor will be affected by frequency-independent galvanic distortion (Simpson and Bahr, 2005). This makes inversion for the impedance tensor quite cumbersome. To solve this inherent difficulty of MT, Caldwell et al. (2004) and Bibby et al. (2005) introduced the phase tensor ($\vec{\phi}(\vec{r},\omega)$). The phase tensor is defined as the ratio of real and imaginary parts of the impedance tensor ($\vec{\phi} = Im(\vec{Z})/Re(\vec{Z})$), and it is free of galvanic distortion effects. It has been shown, that phase tensor inversion can be superior over impedance tensor inversion if site spacing is smaller than the sensitivity radius of the measurements (Tietze et al., 2015; Samrock et al., 2018).

To interpret the MT data (Fig. 1) we choose the following inversion approach: (1) starting with a homogenous model with the median apparent resistivity of all data ($\rho_{app} \approx 35\ \Omega m$), (2) performing a phase tensor inversion, (3) defining the phase tensor inversion result as the new starting model, (4) performing an impedance tensor inversion. Inversion is performed using the 3-D modelling and inversion code GoFEM (Grayver, 2015; Grayver and Kolev., 2015). GoFEM allows for the incorporation of topography, which is crucial as the altitude difference in the investigated are is about 1500 m (Fig. 1) (Käufl et al., 2018).

We chose to perform 3D-inversion, as it has been shown that a 3-D inversion approach is superior over a 2-D inversion approach, even if MT site locations are along a profile line (Siripunvaraporn et al., 2005), as it is the case for the cross-rift profile (Fig. 1). We analyse local data that comprise 165 MT stations on Aluto measured by ETH Zürich and the Geological Survey of Ethiopia (Cherkose and Mizunaga 2018; Samrock et al., 2015 and 2020) together with 26 stations on a 120 km profile crossing Aluto volcano measured by the RiftVolc project (Hübert, et al. 2018) (Fig. 1). The combined MT-dataset comprises periods from T = 10^{-2} – 10^{3}s.

We assigned a row-wise error (e) of 5% of the maximum impedance element of the respective row to the impedance tensor elements, so that the variances are: $\delta Z_{xx}^2 = \delta Z_{xy}^2 = \left[e * max\left(\left|Z_{xx}, Z_{xy}\right|\right)\right]^2$ and $\delta Z_{yx}^2 = \delta Z_{yy}^2 = \left[e * max\left(\left|Z_{yx}, Z_{yy}\right|\right)\right]^2$ (Käufl et al., 2020). This error was then propagated to the respective phase tensor elements. The inversion mesh is shown in Fig. 2, note, that the cell size accounts for decreased resolution beneath the profile “arms” and increased resolution below Aluto.

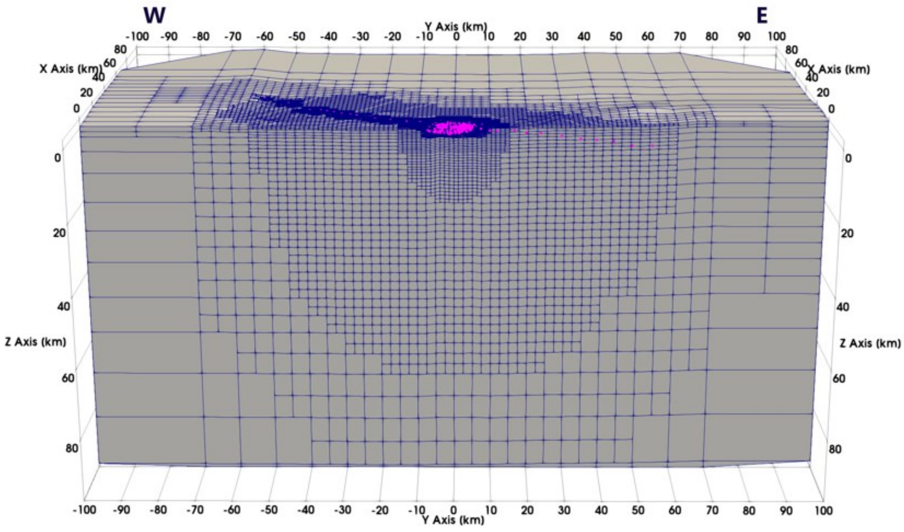

Figure 2: The inversion mesh accounts for higher resolution below Aluto and for the decreasing resolution with depth. MT-stations are shown in pink.

3. RESULTS AND INTERPRETATION

The phase tensor inversion converged from an initial rms-misfit of 2.78 to 0.8 for the best fitting model and the following impedance tensor inversion converged from 5.05 to 0.72. The final residuals were uniformly distributed, indicating that the obtained inversion model fits the data well and a geological interpretation of the obtained model is justified.

Figure 3 shows a vertical slice through the preliminary model along the cross-rift profile. The central part of the model under Aluto volcano is, in terms of electrical resistivity values and structural features, in overall good agreement with the model from Samrock et al. (2020). They interpreted the shallow conductor C1 under the volcano to be the clay cap, which was confirmed by geothermal well data. The clay cap is underlain by a more resistive zone of hydrothermal alteration (R1) and a deeper (5 km below surface) conductor (C2). C2 was interpreted to be a highly-crystalline rhyolitic melt reservoir with a melt fraction in the range of 4.5-15vol% (Samrock et al., 2020). This melt reservoir is connected to a westward-dipping conductor (C3), which can be interpreted as the feeding zone of the magmatic system imaged as C2 under Aluto. The dipping conductor C3 is oriented along the dominating fault plane of the so-called Artu Jawe fault, that intersects the Aluto volcanic complex (Hutchison et al. 2015).

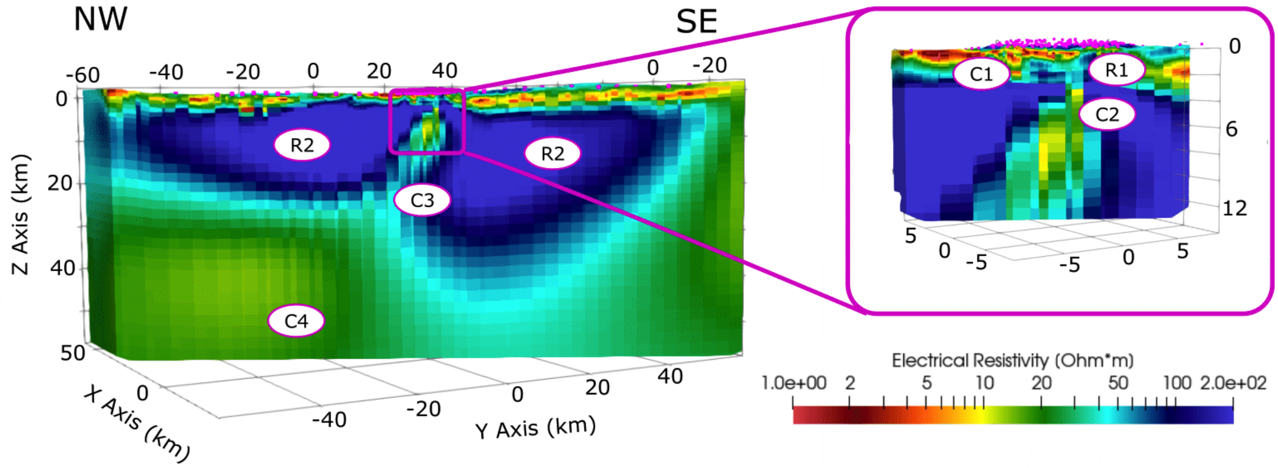

Figure 3: Slice through the model along the profile line of the MT-stations, as well as a detailed view of the model underneath Aluto volcano in the pink box Resistivity anomalies were interpreted to be (C1) argillic alteration (clay cap), (C2) shallow melt reservoir, (C3) magma ascent channel, (C4) asthenospheric melting, (R1-3) resistors, (R1) propylitic alteration.

Due to the limited aperture of the dataset analysed by Samrock et al. (2020), they were not able to constrain the extent of this mush column in depth and laterally to the west. Adding the cross-rift MT stations from the RiftVolc project by Hübert et al. (2018) It is now possible to better constrain the size and the shape of C3 to greater depths. C3 extends to a depth of about ~ 30 km, following the dip angle of the faults from the WFB. At a depth of $z \approx 30$ km C3 merges with a wider zone of reduced resistivities (C4). Resistivities of this deep conductor C4 reach from $\rho \approx 2 - 10\ \Omega$m in a region from $z \approx 30 - 50$ km.

We propose that the low resistivity anomaly (C4) can be explained by the presence of electrically conductive basaltic melt (Shankland and Waff, 1977). However, it should be noted that although the conductor C4 is required by the data its precise size and location are not well constrained as it is located south of the profile line. A better spatial coverage is necessary to reliably estimate the extent of this anomaly. The resistive zones R2 and R3 in the model (Fig. 4) are asymmetric with respect to the rift axis, with the eastern resistor R3 reaching deeper.

4. CONCLUSION

Multiscale imaging of existing MT data-sets has proven that 3D inversion of regional and local MT data is a promising tool for imaging rifting-related magmatism and, as a consequence thereof, the formation of high-enthalpy geothermal reservoirs. The obtained model (Fig. 3) delineates the geothermal system of the Aluto-Langano geothermal field, where heat from a shallow melt reservoir (C2) drives a hydrothermal system (R1), which led to the formation of a clay cap (C1). Furthermore, the model indicates that the shallow magmatic system under Aluto (C2) is connected via C3 to a deeper zone of asthenospheric melting (C4). This is an important finding for the assessment if a recharge of C2 with melt and hence heat is plausible, which will influence the future development of the Aluto's geothermal system.

The findings prove that MT is a powerful geophysical tool for investigating volcanic high-enthalpy geothermal prospect. Further MT-studies in the MER are planned to be conducted within the framework of the project MIRIGE and will play an essential role in further unravelling rifting-related magmatic processes and the formation of attractive geothermal prospects. Results that may support geothermal exploration are of great value in a country that suffers from energy poverty, while at the same time facing an immense increase of energy demand. Detecting more exploitable geothermal resources in the central Ethiopian rift, might support a sustainable development in Ethiopia, ensuring energy access for all. Hence, the question how geothermal systems similar to Aluto volcano, like Tulu Moye or Corbetti volcano, are related to the regional distribution of melt will be the central objective of future studies. Obtaining more MT-data in this region of the MER will also allow for reliably constraining the extent of the asthenospheric melting zone.

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