Three-dimensional geophysical modelling of the Alalobeda geothermal field

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Geological setting

- The **Alalobeda** geothermal field is located along the western margin of the Tendaho Graben (Afar, Northern Ethiopia).
- In this region, the Red Sea Rift, the Gulf of Aden Rift and the Main Ethiopian Rift form the Afar triple junction.
- The Tendaho Graben (TG) is a branch of the Red Sea Rift.
- The TG shoulders are constituted by the Afar Stratoid Basalts (ASS).
- The age of the ASS in Alalobeda is about **1.2Ma**.
The survey area

- In Alalobeda, the intersection of the NW-trending TG faults with the NNE-trending Main Ethiopian Rift (MER) structures, yields intense rock fracturation
- Several geothermal manifestations are present, among which the Alalobeda hot springs
- A geoscientific study was funded by ICEIDA/NDF through the Geothermal Exploration Project (GEP)
- Detailed MT/TEM and gravity surveys have been accomplished between December 18, 2014 and March 10, 2015 as part of the GEP
The gravity survey

- The gravity survey consisted of 300 gravity stations, located on a regular 750 m grid
- A Lacoste-Romberg G-series gravity meter has been employed, with an estimated measurement errors of 0.024 mGal (1 σ)
- The station positioning has been done by means of differential GPS, allowing for an average of the vertical component error of 11.6 cm (1 σ)
- Standard scale factor, Earth's tides, drift, latitude, free air, Bouguer and topographic corrections were applied

Gravity processing

- Gravity data have been tied to an absolute gravity point in Semera (978127.31 mGal)
- Density estimation for Bouguer anomaly done by Nettleton method and 3D forward modelling (calculated value: 2485 kg m\(^{-3}\))
- Bouguer map shows a wide positive anomaly (4.3 mGal) over the graben shoulder, while a large negative belt characterises the plain (-5.1 mGal)

2D fwd modelling of the complete BA revealed an anomalous density body (+300 kg m\(^{-3}\)) in the ridge sector
The 3D gravity inversion was carried out by means of the Geosoft GMSYS-3D software.

The model is defined by stacked surfaces defining layers with fixed density.

The top surface defined by the 150 m-resolution topographic Aster DEM.

The hidden bedrock surfaces set as the topography shifted 100 m downward.

Initial anomalous density body lateral extension from 2D modelling.
3D gravity inversion results

- The inverted bedrock surface beneath the graben sediments, knitted with the topographic surface, gives a clear imaging of the bedrock structures.

- Main faults (MF1, MF2) and hidden horst-graben structures revealed from bedrock topography horizontal gradient.

- Anomalous density body in the ridge depicted.

- Transversal faults inferred.

The MT/TEM survey

- **104** MT stations acquired, on a 1 km-grid
- Previous (2013) **26** MT survey stations included in processing
- Three Phoenix V5 System MT equipments acquired EM data in the 1000-0.0001 Hz range, **26** hrs mean rec. length
- Robust MT processing performed with remote reference, with resulting very good data quality

- **130** TEM stations acquired by Zonge GDP and Phoenix V8 systems, with central loop configuration
- Loop size ranged from **100** to **200 m**, current from **10** to **20A**

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TDEM/MT joint inversion

- MT static shift effect corrected by means of TDEM/MT phase joint inversion
- Effective, $xy$ and $yx$ MT impedance corrected

Shift values on the Alalobeda plain are close to 1

Higher values on the ridge sector (likely topographic effects)

MT 3D inversion discretization

- MT 3D inversion has been carried out by ModEm software (Egbert et al., 2012, Kelbert et al., 2014, Meqbel, 2009)

- 92 x 92 x 55 cells; width: 300m x 300m x 25m, thickness increases with depth

- Starting model: 1D-interpolated model

- Inversion of full-tensor MT impedance and geomagnetic tipper in the 300-0.001 Hz band

- Error floors of 5 % for the impedance components, and 0.03 for the tipper
MT 3D inversion model

- Normalized total RMS 1.7 after 62 iterations
- Equal smoothing in the x-y-z direction
- Manual masking of bad data points
- Good fit for most of the sites

- Very conductive sediments in the plain
- The ASS basalts show low resistivity values in the ridge sector
- MER faults have an electrical signature at depth
• Very conductive anomalies (1-5 Ohm m) in the ASS basalts in the ridge sector: one very shallow (ASS-CL1) and one deeper (ASS-CL2)

• The ASS-CL2 anomalies are elongated along NNE trending lineaments and associated with less conductive belts at depth (FZ1-FZ3)

• The FZ1-FZ3 anomalies are limited to NE by one of the graben's main faults (MF1)

• Southernmost anomaly (FZ0) prosecutes into the plain and is not related to any known structural trend
The graben steps beneath the sediments are delineated.

Increase of the thickness of the conductive zone in the ridge sector (where positive gravity anomaly is located).

Three conductive anomalies located in correspondence of the MER faults visible from topography.

One deep conductive anomaly.
Integrated interpretation

- The low resistivity in the ridge indicates that it is extensively affected by alteration at depth.

- The NE limit of this area is a main fault detected by gravity (MF1), that may have acted as deep fluid paths toward surface; the same is observed at SW for MF0 up to FZ3.

- The transversal FZ1-FZ3 zones could have served as preferred paths for fluid to come to shallow depths, due to the enhanced permeabilty given by the MER faults.

- The gravity positive anomaly is related to the MF0 and MF1 and can indicate an increase of the bulk ASS density due to alteration minerals or thermo-metamorphism (Barberi et al., jvolgeores, 1991).
We image the deep resistivity structures by means of the 30 Ohm isoresistive surface, from which a main down doming zone is apparent (FZ0).

FZ0 is not related to surface geology or structures inferred from the gravity modeling; its trend and genesis are then enigmatic.

It has similar characteristics to the deep conductive anomaly South of Dubti, described by Didana et al. (jvolgeores, 2015), and attributed to hot fluid upward migration from a deep hot zone.
Conclusions

- The structure of the Alalobeda geothermal field is governed by three main faults, two of which inferred by 3D gravity inversion (MF1, MF2)

- Along MF0 and MF1, thermal updoming and/or enhanced hydrothermal circulation/alteration has produced a positive density anomaly and a widespread conductive zone

- MER faults have created as enhanced permeability fracture zones, along which exceptionally low resistivity in the ASS basalts has been observed; the Alalobeda hot springs are located in correspondence of FZ2

- FZ0 is a possible deep upflow path, not related to any geological/geophysical evidence. Its depth is such that it could be related with pre-ASS formations (Dahla Basalts) and ancient hidden structures
Thank you for your attention!