APPLICATION OF THREE-DIMENSIONAL MAGNETOTELLURIC IMAGING TO GEOTHERMAL EXPLORATION

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Keywords: magnetotelluric, three-dimensional, heterogeneity, geothermal exploration

INTRODUCTION

Eastern Africa geothermal fields are associated with the recent to actual volcanism in the Rift region. As a result, the geometry of the geothermal source is complicated. Water and vapor flow in fractures within the lava flows often interlaced with hydrothermal and/or sediment deposits. How geophysical imaging techniques could provide accurate models of the plumbing system and the nature of fluids circulating in it is a central question in geothermal exploration. Electromagnetic techniques and in particular Magnetotelluric (MT) is one of the geophysical technique used in this domain. The method provides information about the electrical conductivity down to several kilometers in depth.

Electromagnetic techniques complete seismic techniques for oil, gas, mining, geothermal or hydro-geological exploration. These complementary techniques are particularly useful in areas with complex structures such as geothermal regions. Furthermore, although seismic methods provide the best possible reservoir descriptions, they remain poorly informative on fluids properties, MT methods provide reservoirs electrical resistivity information, thus enabling to better describe and understand fluids in the pore space. .

New tree-dimensional imaging (or inversion) tools are now available to improve the accuracy of the conductivity models retrieved from the MT data. For 3-D inversion, it is best to acquire data over a fine 2-D surface grid with a regular spacing. It is in general difficult to acquire MT data on a such a grid over a volcanic geothermal field. In this study, we present results of three-dimensional (3-D) MT inversion for various types of MT sites distribution, including 2-D profiles which show that accurate local 3-D structures can be recovered. We test the approach with synthetic examples and demonstrate the feasibility with a series of 3-D MT studies carried out in Eastern Africa.

THREE-DIMENSIONAL INVERSION

We developed a robust full tensor 3D MT data inversion scheme with a coarse-to-fine lattice parameterization approach (Hautot et al. 2000, 2007). The technique was developed to provide a detailed geological image of sedimentary basins in complicated geological contexts such as thick basaltic screen covers. It is now extended to complex geothermal and volcanic regions. The 3-D inversion technique is based on an iterative procedure to minimize a misfit function between the observed data and the model response using a non-linear steepest gradient method with a regularization term. The data is the MT tensor (the four complex components and tipper when available) at all available frequencies and at all sites.

As MT inversion is a non-linear problem, the misfit obtained for the best-fitting model is not an absolute minimum but is some compromise between all sites, periods, and data quality. Therefore, the parameters of the model may not be equally constrained by the data. The large number of parameters to be processed makes the 3-D inversion procedure complex. In order to limit the number of these parameters, the 3-D model is parameterized by blocks. The size and the initial meshing of the 3D volume are determined according to the MT sites distribution and the depth of investigation of the data. Then the inversion is controlled by increasing the number of parameters treated as iterations on increasingly sensitive areas. This procedure tends to increase the number of voluntary iterations but with shorter and more effective iterations.

The coarse-to-fine approach provides a final grid that reflects the resolution of geological targets in the model. Compared to other available techniques, the number of parameters is much smaller, adapted to the actual number of data and fully flexible in terms of site/frequency distribution, hence providing accurate 3D structures resolution information. The approach makes the technique flexible and allows dealing with unevenly distributed sites, topography or bathymetry (for marine MT) effects and any number of periods. This iterative and incremental parameter approach enables an easy integration of parameters from other sources (drilling) into the procedure to add geophysical information.

SYNTHETIC INVERSION OF COMPLEX RESERVOIR

Figure 1 is the result of 3-D inversion for a synthetic test for a complex structure embedded in a uniform half space. MT data at 100 sites were generated (Miensopust et al., 2008) and inverted with our code. The results for a fairly coarse grid was quite good. The quality of the results may be measured by the fit between the data and calculated MT tensor (Figure 2).

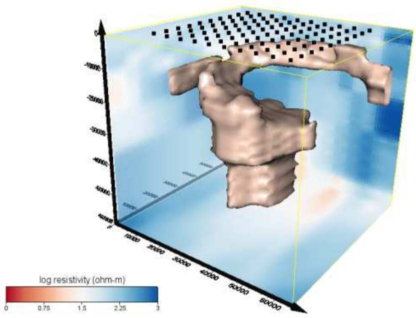

Figure 1: 3-D inversion of complex structures. Dots are the sites were synthetic data were generated.

One the characteristics of 3-D geothermal structures is to generate quite heterogeneous data set with significant diagonal terms in the MT tensor data. The later are difficult to fit but provides a very good constraint on the geometry and conductivity of the 3-D structures.

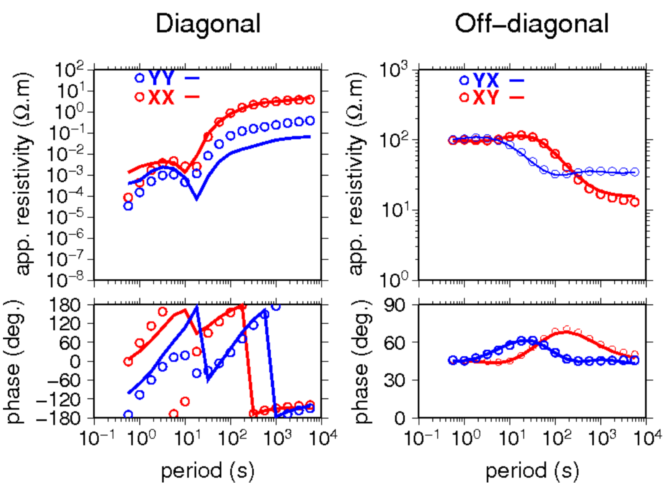

Figure 2: Example of fit between data (circles) and model responses (lines) for all four components of the MT tensor, expressed as apparent resistivity and phases. The term X means North and Y East.

3-D MT IMAGING FROM A HETEROGENEOUS NETWORK

Surveys in difficult areas such as volcanic regions or remote access areas generally leads to very heterogeneous networks of MT sites from which one has to obtain some ideas about the 3-D structures. As an example, we present here a project funded by industry to study the thickness of sediments in the basin of the River Omo in Southwest Ethiopia (Whaler and Hautot, 2007). For political and practical reasons, the actual network of MT sites is not homogeneous as planned (Figure 3).

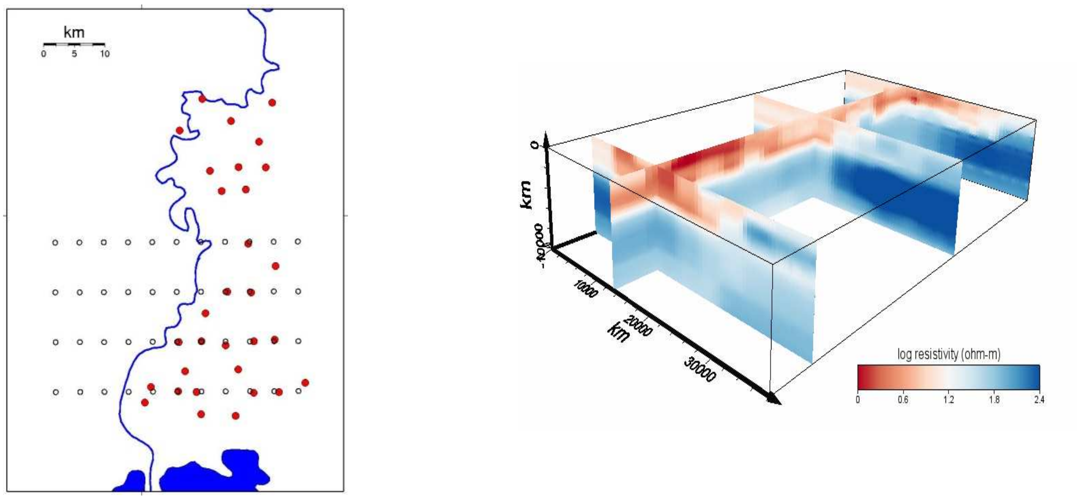

Figure 3: Left: MT network for the OMO basin experiment. The open circles are the original plan while the red dots are the actual 31 sites which were possible to collect. Right: The final 3-D resistivity model obtained from the inversion of the data from the 31 sites.

A total of 31 magnetotelluric (MT) sites were occupied over the Omo basin in South west Ethiopia. The inversion was run on the 31 full MT tensors at 16-33 frequencies depending on the sites, with a total of 6840 data values to recover 1000 resistivity parameters. The final model is shown to the right. In Omo Basin, the structures are fairly smooth and the diagonal terms of the tensor are small and easy to fit at all frequencies. The model indicates a N-S geo-electrical strike, in agreement with the geological strike, with up to 4km of sediments in the southern part of the basin, but no more than 2km in the northern part, underlain by more resistive material, assumed to be the basement.

3-D IMAGING OF A MAGMATIC CHAMBER IN AFAR (NORTH ETHIOPIA)

As part of a major program of research into the processes and controls involved in the break-up of continents and the generation of new oceanic crust, we have collected broadband magnetotelluric (MT) data along a ~50km long profile in the Afar region of Ethiopia (Hautot et al. 2009).

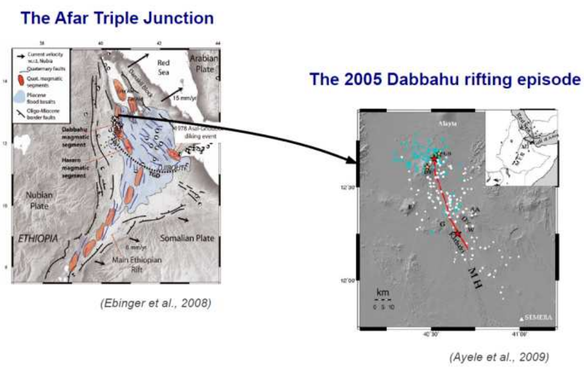

Figure 4: The Dabbahu volcanic event in Afar (Ethiopia)

The Dabbahu rift segment (Figure 4), in Afar is active since 2005 with volcanic eruptions and seismic tremor associated with a 60 km long dike intrusion in major tectono-magmatic episodes along the same segment. MT data have been collected in 2008 at 17 sites along the profile across the Dabbahu segment in order to image beneath the volcanic layers. The method can provide new and additional information on the relationships between the crustal structure and the deep processes that control the deformation of the rift. While the data are broadly consistent with a two-dimensional interpretation, with geoelectrical strike along the segment's axis of rifting, three-dimensional effects are seen primarily at sites beneath the rift axis. We have inverted the data using a 3-D inversion technique (Hautot et al. 2000, 2007) in order to account for conductivity variation along the rift segment (Figure 5).

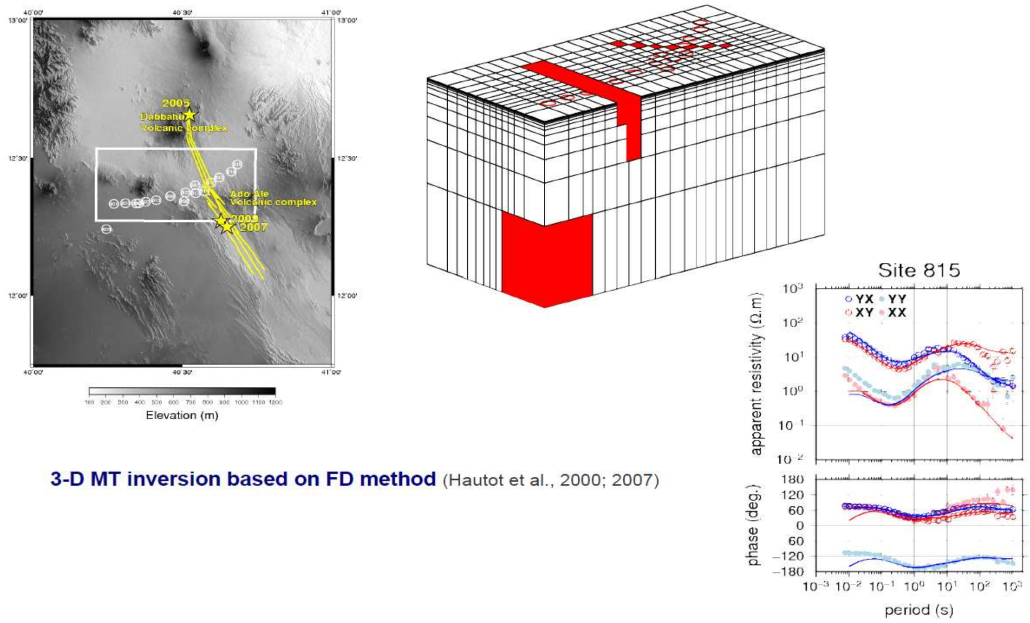

Figure 5: Left: MT profile across the Dabbahu segment. Top right: 3-D parameterization of the model for the Mt inversion. Bottom left: Example of fit for one site showing the significant diagonal MT tensor components.

Significant departure from a 2-D structure are observed in the depth range 5-10 km and in the shallow (0-2 km) part of the model. The 3-D approach refines the observation of high conductivity at depth beneath the segment axis in a zone ~10 km wide close to the surface and in a much broader zone at depths straddling the crust-mantle interface (Figure 6).

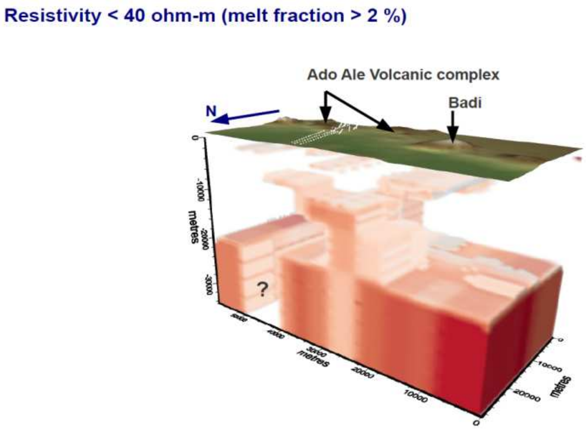

Figure 6: Iso-contour of resistivity values less than 40 Ohm-m that depict a possible limit of partial melting.

CONCLUSION

The 3-D MT inversion is now becoming a tool that may be used to obtain accurate models of the geological structures in complex areas. The 3-D MT is proven to provide useful information even if the network of MT sites is heterogeneous or only along a profile provided the full MT tensor is available. MT surveys for geothermal exploration should make use of these methods to provide the best resistivity models to geologist and geothermal scientists and managers.

REFERENCES

Ayele, A., D. Keir, C. Ebinger, T. J. Wright, G. W. Stuart, W. R. Buck, E. Jacques, G. Ogubazghi, and J. Sholan, September 2005 mega-dike emplacement in the Manda-Harraro nascent oceanic rift (Afar depression), *Geophys. Res. Lett.*, 36, L20306, doi:10.1029/2009GL039605, 2009.

Ebinger, C. J., Keir, D., Ayele, A., Calais, E., Wright, T. J., Belachew, M., Hammond, J. O. S., Campbell, E. and Buck, W. R., Capturing magma intrusion and faulting processes during continental rupture: seismicity of the Dabbahu (Afar) rift. Geophysical Journal International, 174: 1138–1152. doi: 10.1111/j.1365-246X.2008.03877.x, 2008.

Hautot, S., Tarits, P., Whaler, K., Le Gall, B., Tiercelin, J.J, and Le Turdu, C., The deep structure of the Baringo Rift basin (central Kenya) from 3-D magnetotelluric imaging : Implications for rift evolution, Journal of Geophysical Research, 105, 23493-23518, 2000.

Hautot, S., R. Single, J. Watson, N. Harrop, D. A. Jerram, P. Tarits, K. A. Whaler,, and G. Dawes, 3-D magnetotelluric inversion and model validation with gravity data for the investigation of flood basalts and associated volcanic rifted margins, Geophysical Journal International, 170(3), 1418-1430, 2007.

Hautot S., K. Whaler, M. Desissa, G. Dawes, S. Fisseha, N. Johnson, 3-D conductivity structure of an active magmatic segment associated with the final stage of continental break-up: Afar, Ethiopia. Eos Trans. AGU 90(52), Fall Meet. Suppl., Abstr. T43F-07, 2009.

Miensopust, M. P., P. Queralt, A. Jones, and the "MT 3D inversion workshop attendees, MT 3D inversion: a recapitultation of a successful workshop, IAGA WG 1.2 on Electromagnetic Induction in the Earth, 19th Workshop, Beijing, China, October 23-29, 2008.

Whaler, K., and S. Hautot, Final report on the magnetotelluric study of the Omo Valley JSA, report for White Nile Company, RPS Energy, and The Ministry of Mines and Resources of Ethiopia, 2007.