Geophysical joint inversion applied to deep geothermal exploration.

Jean-Michel Ars[1,2], Pascal Tarits[1,3], Sophie Hautot[1,3],Mathieu Bellanger[2], Marcia Maïa[1], Olivier Coutant[4], Jean-Luc Auxietre[2].

[1] IUEM, UMR 6538 Laboratoire Domaines Océaniques, Plouzané, F29280, France

[2] TLS-Geothermics,Saint-Genies-Bellevue , F31180, France

[3] IMAGIR sarl, Brest, F29200, France

[4] Université Joseph Fourier, UMR 5275 ISTerre , Grenoble, F38041, France

jean-michel.ars@univ-brest.fr

Keywords: geothermal exploration, joint inversion, magnetotelluric,gravity, seismic noise tomography, Massif-Central.

ABSTRACT

A geophysical joint inversion approach of magnetotelluric, gravity and seismic noise tomography is developed to attempt imaging deep geothermal reservoirs targets in the Massif-Central, France. These techniques allow us to image complex geology, with water filled fractures, down to several kilometers. We carried out magnetotelluric, gravity surveys and seismic noise tomography in the Sioule valley, West of the Chaîne des Puys volcanoes.

We obtained a 3-D 30km deep conductivity model from the 3-D inversion of the full tensors from all MT sites . The conductivity structure is highly heterogeneous in depth with a north-south trend. The full Bouguer anomaly shows a regional West/East gradient . A large negative anomaly is correlated with deep resistive structures, while positive anomalies are correlated with conductive structures. Surface wave dispersion curves were obtained from the seismic noise processing , then were inverted to obtain a shear wave velocity model down to 12-15 km depth. In spite of the cross shaped layout of the seismic network, the location of the sources of the seismic noise allowed only a final 2-D velocity model across the studied area. Shear velocity increases from 2.9 km/s at the surface to 4km/s in depth. A low velocity region 12 km in depth is located beneath the volcanoes of the Chaîne des Puys then the deep velocity increases westward. The preliminary results of the joint inversion of these three data sets are presented and discussed.

1. INTRODUCTION

Deep geothermal energy has become an highly profitable source of renewable energy for the future. Global resources are mainly spread out over America, Europe, the East African Rift and South-East Asia. According to previous studies (BRGM), France might have exploitable resources in Alsace, Auvergne, Midi-Pyrénées and Rhônes-Alpes. These resources are in complex geological environment and several kilometres in depth. A geophysical joint inversion approach of magnetotelluric (MT), gravity and seismic noise tomography is developed to attempt imaging these deep geothermal reservoirs targets. Magnetotelluric technique provides information on the electrical conductivity structures. Gravity analysis reveals the density variation in depth and seismic noise processing leads to shear wave velocity models. These techniques are used in geothermal exploration of deep fractured basement because they are sensitive to water, temperature and fractured rock. All three techniques are passive methods used to image the geological structures down to several kilometres.

2. DATA ACQUISITION

We carried out a MT survey in the Sioule valley, West of the Chaîne des Puys volcanoes (Massif-Central, France) covering an area of 14x12 km2 (Figure 1). We carried out 45 broadband MT soundings (0.001-1000 Hz). We also acquired 40 gravity measurements. The later are combined with an additional 123 data set available at the International Gravimetric Bureau. For seismic noise tomography, we deployed a preliminary cross shaped network of 11 tri-axial broadband seismometers CMG-40 during 4 months of winter 2015/2016. This acquisition layout records seismic noise at a sampling frequency of 100 Hz.

3. MAGNETOTELLURIC INVERSION

Data processing was carried out with the BIRRP code (Chave and Thompson, 2004) to compute the impedance tensors for each site. Most of the data show a substantial 3D behaviour with variable resistivity and phase for the 4 components of the tensor from short to long periods. Off-diagonal apparent resistivity values are generally above 100 Ωm and split, the largest approaching 1000Ωm at the longest periods (figure 2, site042).

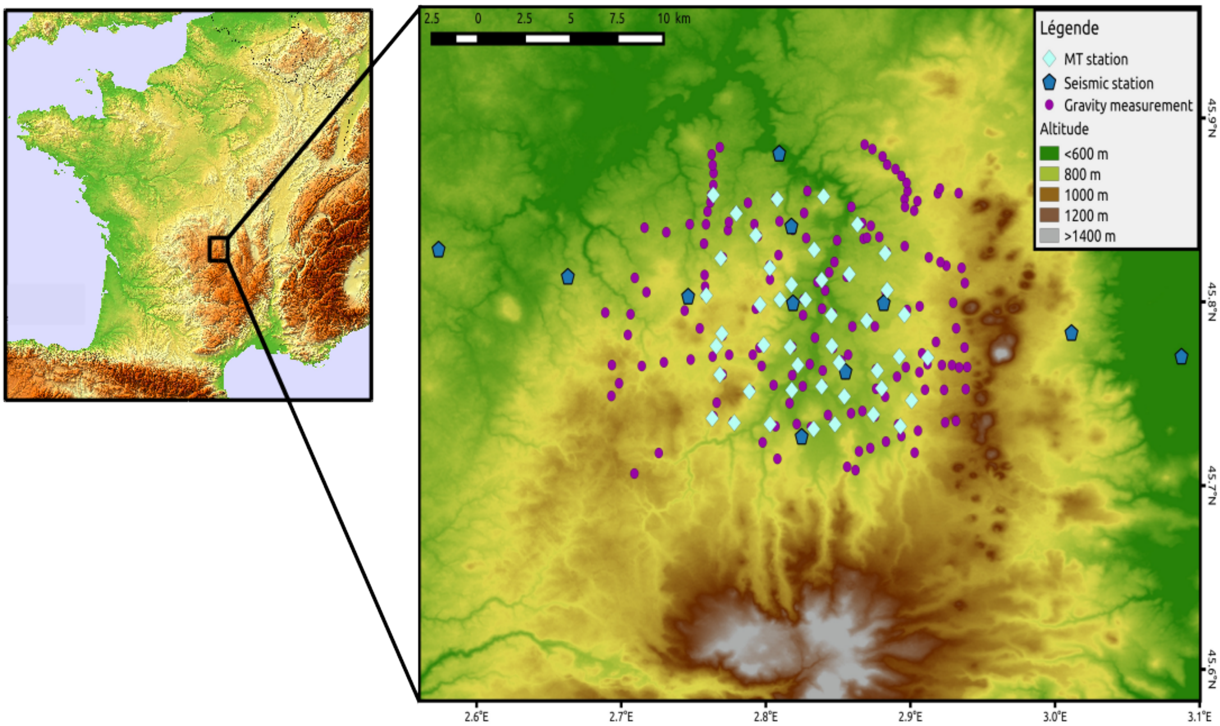


Figure 1: Map of the Sioule valley, west of the Chaine des Puys volcanoes and North of Mont Dore . Magnetotelluric sites are represented as light blue diamonds. The purple dots are the gravity points (measurement and BGI data set). The seismic stations are represented as blue pentagons.

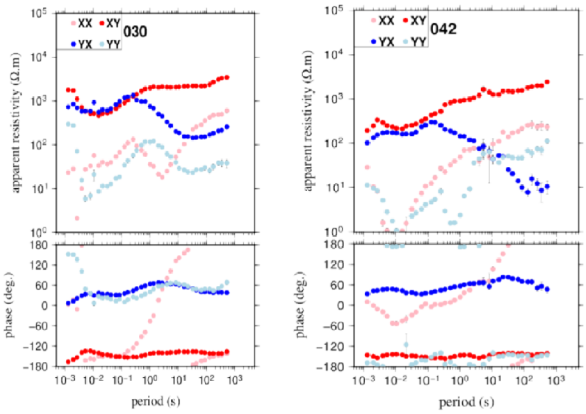


Figure 2: Impedance tensor expressed as apparent resistivity and phase for the MT sites 030 and 042. Off-diagonal components are dark blue and red while diagonal components are light blue and pink.

The diagonal components resistivity may be larger than the off diagonal terms at some sites (figure 2, site030). We run a 3D-inversion of the full tensor from all MT site on a flat grid using the minim3D code (Hautot et al., 2000, 2007). The first 30 km of the 3-D resistivity model is presented in Figure 3.. The resistivity structure is heterogeneous at all depths with a north-south trend .

3. PROCESSING OF GRAVITY DATA

The 40 gravity measurements have been processed together with the 123 existing measurements of the Bureau Gravimétrique International. The complete Bouguer anomaly have been calculated from absolute gravity values subtracting the ellipsoid, the free-air correction and the topographical Bouguer correction computed from a DEM with a constant density of 2670 kg/m3.

5. SURFACE WAVE TOMOGRAPHY

Surface wave dispersion curves were obtained from the seismic noise processing. For each pair of stations, seismic noise recording are cross-correlated. We estimated a group velocity dispersion curve for each correlation using an automatic Frequency-Time Analysis (Levshin et al., 1989). Those curves are first inverted into 2D group velocity map for periods from 2.5 seconds to 10 seconds (figure 5 - Left). Then for each cell of the maps, we interpolate a dispersion curve which is vertically inverted to obtain a 1D shear wave velocity model down to 12-15 km depth. The final 3D model is constructed by stacking all the 1D models (Barmin et al., 2001). In spite of the cross shaped layout of the seismic network, the location of the sources of the seismic noise gives heterogeneous reconstructed dispersion curves, sometimes defined by less than 10 periods. We choose to only invert well defined curves with more than 15 periods, this reduces the available data to a profile to the East of the cross (figure 5 - Right). This approach allowed only a final 2-D velocity model across the studied area. Shear velocity increases from 2.9 km/s at the surface to 4km/s in depth. A low velocity region 12 km in depth is located beneath the volcanoes of the Chaîne des Puys then the deep velocity increases westward.

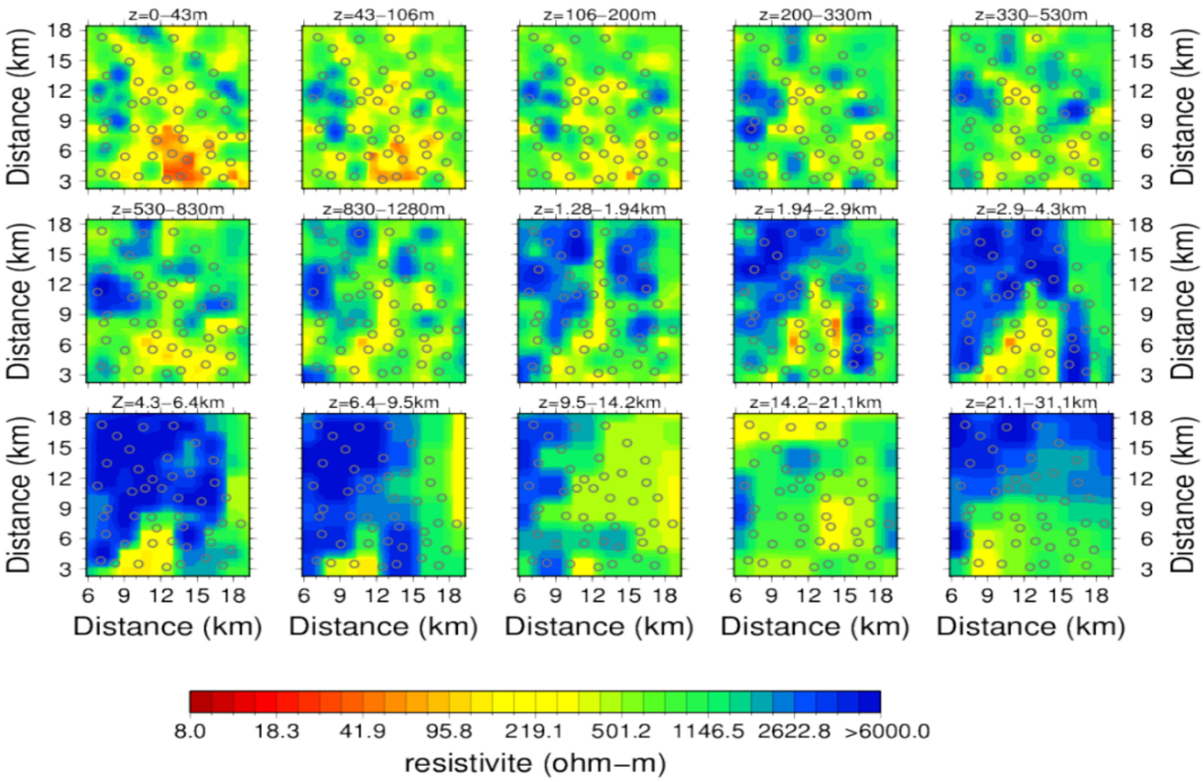


Figure 3: Layers of the final 3D magnetotelluric model.

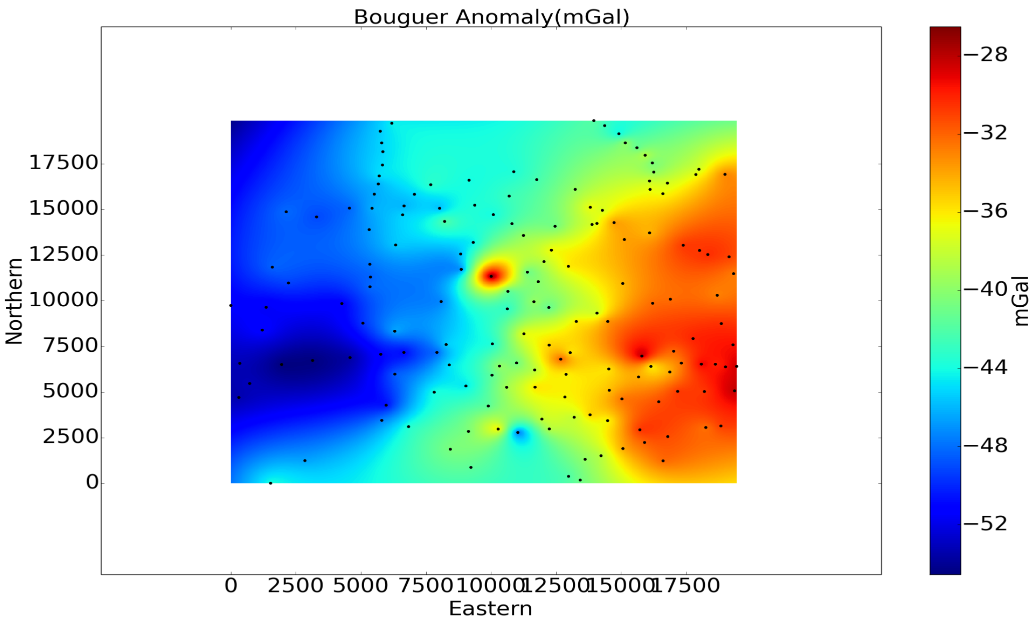


Figure 4: Map of the Bouguer anomaly. Blacks dots are the gravity data points (measured and BGI).

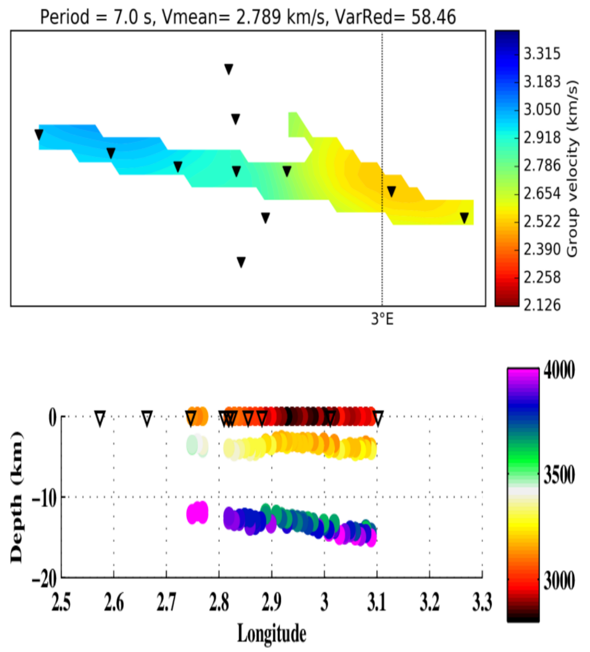
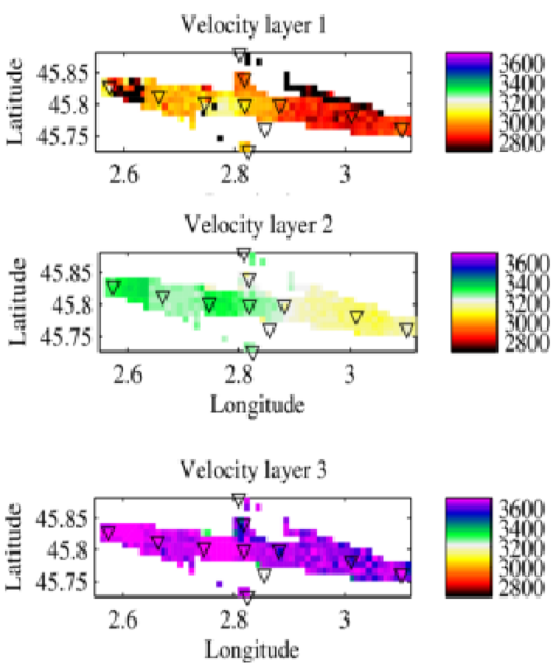


Figure 5: Left – 2D group velocity map for a period of 7 second. Right – 2D final velocity (m/s) model reduced to a profile along the east part of the cross.

A new 3D inversion was computed with the same data set but dispersion curves with less than 15 periods were also inverted to obtain 1D model for every cell of the grid. This allowed us to extend the coverage of the ambient noise tomography but the constraint on the 3D model is weaker. (figure 6). Nevertheless we still notice constant trend, velocity still increases going westward on every layer and the top of the third layer is also shallower on the East of the model.



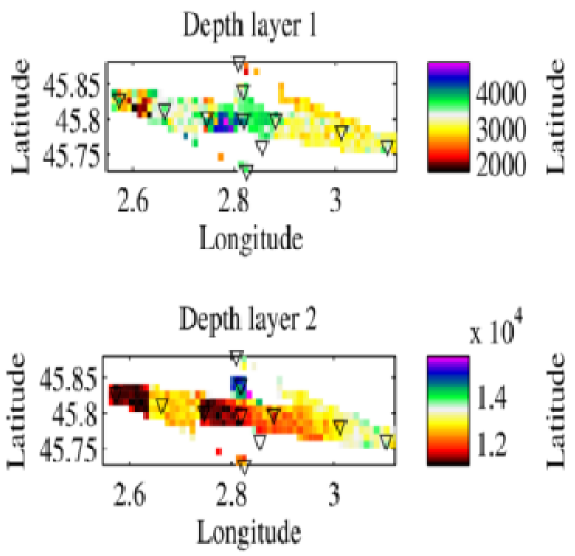


Figure 6: 3D shear wave velocity model. The model is composed of three layers of variable depth and velocity.

6. DISCUSSION

Shallow resistivity distribution in the MT model is heterogeneous with scattered conductive and resistive structures. From 2 km deep, the West part of the model displays a massive resistive structure down to 14 km depth. The East part of the model is composed of a conductive body for the same layers, its size increases laterally with depth. The full Bouguer anomaly shows a regional West/East gradient (figure 4). A large negative anomaly is correlated with deep resistive structures, while positive anomalies are correlated with conductive structures . For the 2D seismic model, the shear velocity is lower on the east part than on the west. Also the layer 3 dives to a depth of 15km on the west of the model. This model indicates that slower rocks are present deeper underneath the volcanoes. The 3D model from all the dispersion curves is more heterogeneous than the 2D model (figure 6) with artefacts such as leap of depth on the west of the layer 2. This is due to the lack of constraint on this model. However increasing of the shear velocity is a robust structure of the model.
The MT resistivity model and the Bouguer Anomaly are correlated which is confirmed by seismic results, to the extent of the coverage of the tomography model. The eastern part of the area, composed by the Chaines des Puys volcanoes presents conductive structures, lighter and slower rocks while the western part, composed by the plateau above the Sioule valley, is resistive, denser and faster.

7. CONCLUSIONS

The analysis of the three different data sets shows a strong correlation . It supports the hypothesis of a deep geological anomaly on the East part of the survey area, between the Sioule valley and the Chaines des Puys volcanoes. This anomaly may be a heat source related to a geothermal network. Next We will first jointly inverse the MT and gravity data sTo improve the geological model. With additionnal seismic results, the joint inversion will be extended to MT, gravity and dispersion curves.

REFERENCES

Barmin, M. P., M. H. Ritzwoller, and A. L. Levshin: A fast and reliable method for surface wave tomography, Pure Appl. Geophys, (2001), 158, 1351 – 1375.

Chave, A. and Thomson D.J.: Bounded influence magnetotelluric response function estimation, Geophysical Journal International, 157, (2004), 988-1006.

Gallardo, L.A., Meju, M.A.: Joint two-dimensional cross-gradient imaging of magnetotelluric and seismic traveltime data for structural and lithological classification. Geophys. J. Int 169 (3),(2007), 1261e1272. http://dx.doi.org/10.1111/ j.1365-246X.2007.03366.x.

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 magneto-telluric imaging: Implications for rift evolution, Journal of Geophysical Research, 105, (2000), 23493-23518.

Hautot, S., R. Single, J. Watson, N. Harrop, D. A. Jerram, P. Tarits, and K. A. Whaler.: 3-D magnetotelluric inversion and model validation with gravity data for the investigation of large igneous provinces, Geophysical Journal International, 170(3), (2007), 1418-1430.

Levshin, A. L., T. B. Yanocskaya, A. V. Lander, B. G. Bukchin, M. P. Barmin, L. I. Ratnikova, and E. N. Its: Seismic Surface Waves in a Laterally Inhomogeneous Earth, edited by V. I. Keilis-Borok, Springer, New York, (1989).

Acknowledgements

We would like to acknowledge Aurelien Mordret, Florent Brenguier for the seismic data processing and their explanations about the surface wave tomography. We also wish to acknowledge Yassine Abdelfettah, Sebastian Held for their help in providing the MT equipment lent by KIT in Karlsruhe and all the inhabitants of the Sioule valley that lend us a basement, a field or a hangar to achieve the data acquisition.