Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Integrated Geophysical Study of Lake Bogoria Basin, Kenya: Implications for Geothermal Energy Prospecting

Josphat Mulwa[1], Justus Barongo[1], Derek Fairhead[2], Nicholas Mariita[3] and Jayanti Patel[4]

[1]University of Nairobi, Department of Geology, P.O. Box 30197, Nairobi, Kenya, [2] University of Leeds, Department of Earth Sciences, Leeds, LS2 9JT, United Kingdom, [3]Kenya Electricity Generating Co. Ltd., Olkaria Geothermal Project, P.O. Box 785, Naivasha, Kenya, [4]University of Nairobi, Department of Physics, P.O. Box 30197, Nairobi, Kenya

[1]josphat_mulwa@yahoo.com, [1]jbarongo@uonbi.ac.ke, [2]jdf@getech.com, [3]nmariita@kengen.co.ke, [4]jayanti@uonbi.ac.ke

Keywords: Lake Bogoria basin, geothermal, constrained interpretation, gravity, magnetotelluric, two-phase.

ABSTRACT

The Lake Bogoria basin, here in referred to as the study area, is located in the greater Baringo-Bogoria basin (BBB), about 100 km to the north of Menengai geothermal prospect on the floor of Kenya Rift Valley (KRV). It is bound by latitudes 0° 00' and 0° 30'N and longitudes 35°45'E and 36°15'E within the rift graben. The study area is characterized by geothermal surface manifestations which include hot springs, spouting geysers, fumaroles/steam jets and mud pools. The area is overlain by Miocene lavas lavas, mainly basalts and phonolites, and Pliocene to recent sediments and pyroclastics such as tuffs, tuffaceous sediments, superficial deposits, volcanic soils, alluvium and lacustrine silts. The terrain is characterized by extensive faulting forming numerous N-S ridges and fault scarps.

Gravity and magnetotelluric (MT) surveys were undertaken in the area to determine the heat source, characterize the geothermal reservoir, and evaluate the geothermal resource potential of the basin.

Gravity survey results indicate Bouguer anomaly having an amplitude of ~40 mGals aligned in a north-South direction and interpreted to be due to a series of dyke injections and hence the heat source in the basin. The interpretation of Bouguer anomaly has been constrained by using previous seismic results. The MT survey results show three distinct layers in the basin. The first layer, overlain by high resistivity thin layers, is ~3 km thick and has resistivities ranging between 4-30 Ω-m. This layer is interpreted to be due to a combination of saline sediments and circulation of high temperature geothermal fluids. The second layer is ~10 km thick and resistivity values range between 85-2500 Ω-m. This layer is interpreted to be fractured basement metamorphic rocks hosting a steam reservoir where circulating fluids are heated by underlying dyke injections. The substratum is characterized by resistivities ranging between 0.5-47 Ω-m and is interpreted as hot dyke injections which are the heat sources for this geothermal prospect. The magnetotelluric results in this study are consistent with results of previous microseismic study in Lake Bogoria basin by Young et al. (1991).

On the basis of gravity and MT results, the heat source in Lake Bogoria basin is due to cooling dyke injections occurring at depths of ~6 – 12 km in the subsurface. Gravity method however favours depths of ~3 – 6 km. The geothermal reservoir is probably two-phase and is attributed to condensation of high temperature steam from the underlying fractured basement metamorphic rocks.

1. INTRODUCTION

Kenya is dissected longitudinally by the East African Rift System (EARS), here in referred to as the Kenya Rift Valley (KRV) where medium to high temperature (>140°C) geothermal fields and prospects are located (Figure 1). These geothermal fields are associated with Quaternary volcanic centers and fissures/fault related to the rift floor fault systems (Riaroh and Okoth 1994; Omenda 2001). Only a few of these geothermal fields have been studied in detail for the purpose of mapping the heat sources and characterizing the reservoirs for the purpose of geothermal power generation.

Gravity and magnetotelluric surveys were undertaken in Lake Bogoria basin. The purpose of the geophysical surveys was to map the heat source in the basin and characterize the geothermal reservoir. In this paper, we present the results of gravity and magnetotelluric surveys undertaken in the basin as part of an intensive geothermal resource exploration programme in Kenya.

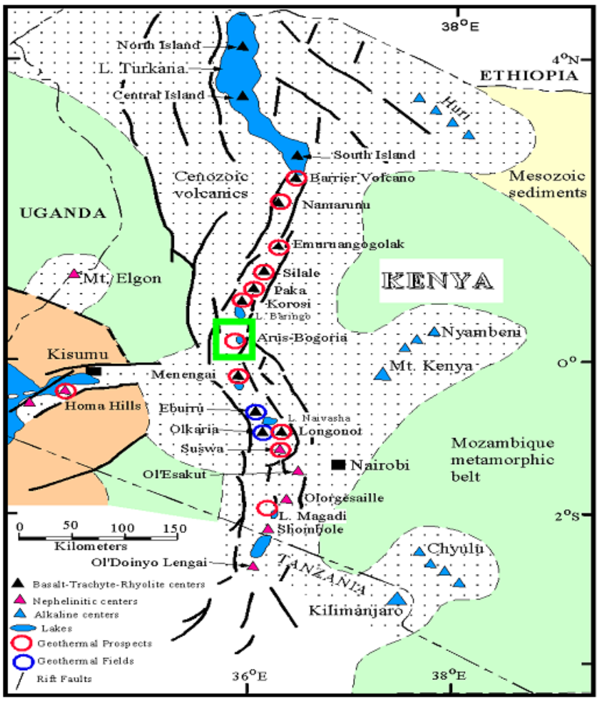

Figure 1: Location of Lake Bogoria basin (outlined by green box) within Kenya Rift Valley (modified from Mariita, 2003).

Lake Bogoria basin geothermal prospect is located in Baringo-Bogoria basin (BBB), about 100 km to the north of Menengai geothermal field on the floor of central Kenya Rift Valley (KRV). It is bound by latitudes 0° and 0°30' N and longitudes 35°45' E and 36°15' E (figures 1 and 2). The geothermal prospect is characterized by spectacular geothermal surface manifestations which include hot springs and spouting geysers on the shores of L. Bogoria, fumaroles/steam jets and mud pools which extend for several hundred meters on the east bank of Molo river. The prospect area is overlain by Miocene lavas and Pliocene to recent sediments and pyroclastics. (Baker and Wohlenberg 1971; Smith and Mosley 1993).

Extensive faulting accompanied by block tilting characterize the terrain and these form numerous N-S ridges and fault scarps. According to Baker and Wohlenberg (1971) this complex network of faults and fractures suggests that tensional strain oblique to the primary rift axis is still occurring.

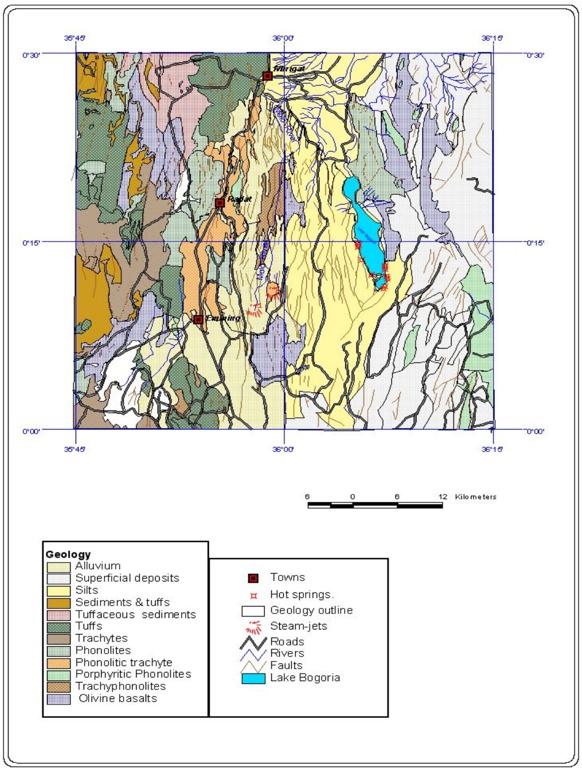

Figure 2: Geology and geological setting of Lake Bogoria basin.

2. PREVIOUS WORK

Generally, the central Kenya rift valley and particularly the Lake Bogoria basin has been the target of a number of geophysical and geological investigations summarized in two special volumes (Prodehl et al. 1994, 1997). Other geophysical investigations include those by Simiyu and Keller (1998, 2000, 2001); Simiyu (1990); Mariita (2003); Swain et al. (1981, 1994); Swain (1992), Fairhead (1976); Hautot et al., (2000); Rooney and Hutton (1977); Young et al. (1991); Tongue (1992); Tongue et al. (1992, 1994) among others. Regional gravity analysis by Simiyu and Keller (2001) and Mariita (2003) indicate no existence of volcanic heat sources in Lake Bogoria basin. Gravity analysis by Simiyu and Keller (2001) along an axial rift profile show a series of positive gravity highs at Menengai, Eburru, Olkaria and Suswa geothermal fields (Figure 1). The gravity highs have been modeled as resulting from volcanic centers underlain by discrete mafic bodies having a density of $2.9x10^3$ kg m^{-3} which are presumed to be the heat sources for these geothermal fields. Cross-rift gravity model by Mariita (2003) at latitude 0.6° N just to the north of Lake Bogoria basin geothermal prospect shows that this area is underlain by about 2-4 km thick of low density ($2.3x10^3$ kg m^{-3}) Miocene lavas and sediments but there no evidence of volcanic intrusives which could be possible heat sources. According to Fairhead (1976), the Kenya rift valley is characterized by localized positive anomalies due to dyke injections. Magnetotelluric studies by Rooney and Hutton (1977) show that the Kenya rift conductor is probably due to high temperature and water saturation. Hautot et al., (2000) have identified a thick succession of well defined tectonostratigraphic units in Baringo-Bogoria basin and downward continuous layer related to dyke injections.

Young et al. (1991); Tongue (1992); Tongue et al. (1992, 1994) and have identified the basin as area as an area of relatively high seismic activity in comparison to other geothermal areas along the KRV, and a 12 km depth defining the brittle–ductile transition zone.

Recent geochemistry work by Karingithi (2006) indicates that a geothermal reservoir exists in Lake Bogoria basin. The reservoir temperature ranges between 115 to 425°C and the upflow zone may be located in the area close to arus steam jets, between Molo river and longitude 36° E (figure 2).

3. METHODOLOGY

The principal aim of this study was to determine the variation in physical parameters that are associated with heat sources and, attempt to delineate and characterize the geothermal reservoir in Lake Bogoria basin. In order to achieve these objectives, the present study involved utilization of integrated geophysical methods namely magnetotelluric (MT) and gravity. Integrated methods are useful in geothermal resource studies since they complement each other and provide a subsurface image that can be used for delineating geothermal reservoirs and mapping the associated heat sources. Standard gravity and magnetotelluric (MT) techniques were utilized in an attempt to map the heat source and, delineate and characterize the geothermal reservoir in Lake Bogoria basin.

Figures 3 and 4 show the gravity and magnetotelluric station coverage in Lake Bogoria basin acquired for the purpose of this study.

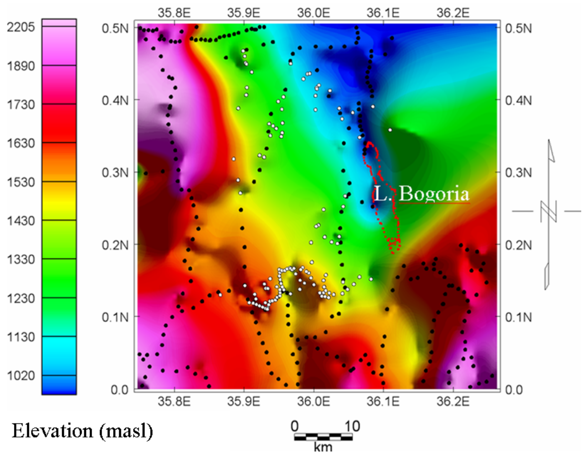

Figure 3: Gravity station coverage in Lake Bogoria basin.

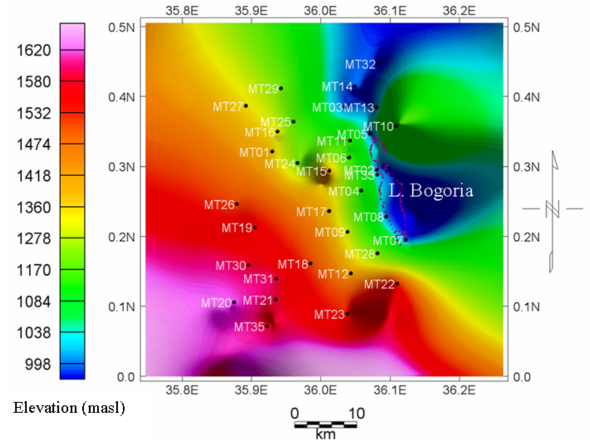

Figure 4: Magnetotelluric station coverage in Lake Bogoria basin.

4. RESULTS

Gravity survey results indicate a Bouguer anomaly having an amplitude of ~40 mGals aligned in a north-South direction (Figure 5). This gravity high has been modeled and interpreted to be due to a series of dyke injections (Figures 6 and 7) having a density of 2.90 g/cc, and hence the heat source in the basin. The modeling of Bouguer anomaly was constrained by using previous seismic results by Simiyu and Keller (2001); Keller et al., (1994a) and Braile et al., (1994). Seismic velocities were converted to densities using the expression by Gardner et al. (1974). The calculated densities were considered as the initial density values for the modeling of the Bouguer gravity anomaly but could however be varied within certain limits.

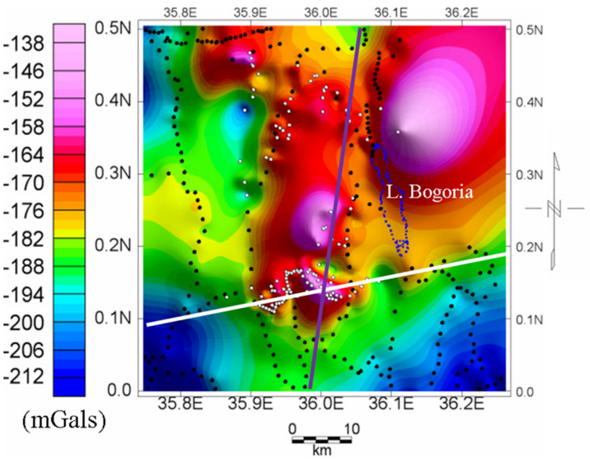

Figure 5: Complete Bouguer anomaly in Lake Bogoria basin.

The results of MT data modeling along N-S and E-W profiles (Figures 8 and 9) show three distinct relatively thick layers in the basin. The first of these layers, which is overlain by high resistivity thin layers, is ~3 km thick and has resistivities ranging between 4-30 Ω-m. This layer is interpreted to be due to a combination of saline sediments and circulation of high temperature geothermal fluids. The second layer is ~10 km thick and resistivity values range between 85-2500 Ω-m and is interpreted to be fractured basement metamorphic rocks probably hosting a steam reservoir where circulating fluids are heated by underlying dyke injections. The substratum is characterized by resistivities ranging between 0.5-47 Ω-m and is interpreted as hot dyke injections which are the heat sources for this geothermal prospect.

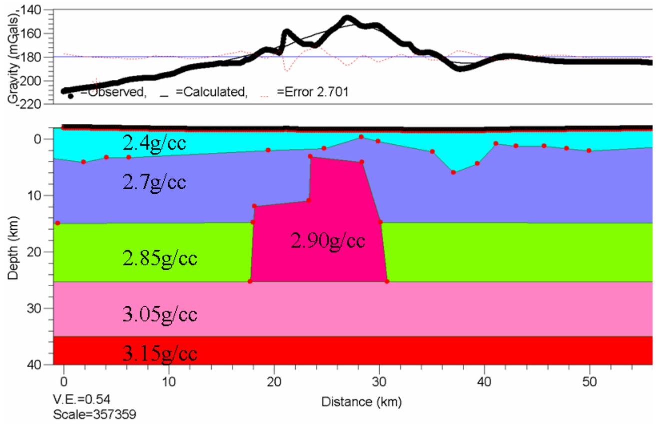

Figure 6: East-West gravity model.

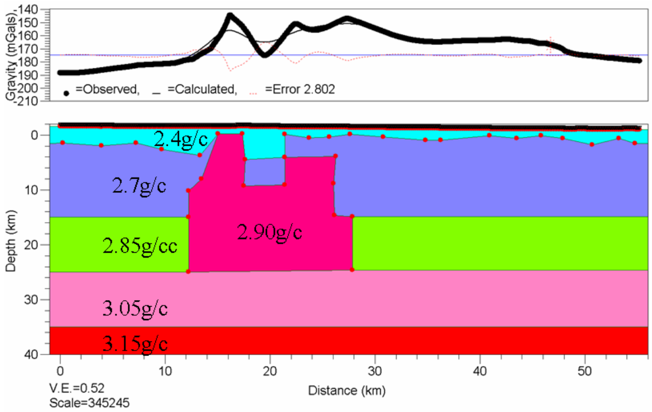

Figure 7: North-South gravity model.

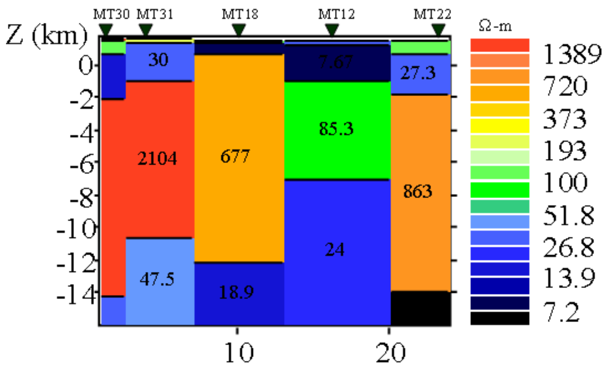

Figure 8: East-West magnetotelluric resistivity model.

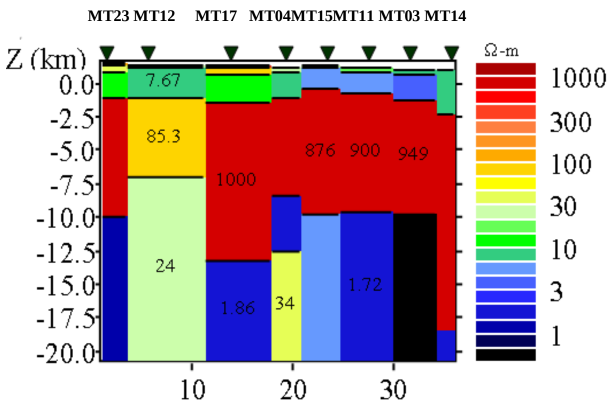

Figure 8: North-South magnetotelluric resistivity model.

5. CONCLUSION

An axial gravity high is evident in Lake Bogoria basin. The gravity high is characterized by an amplitude of ~40 mGals and is the heat source in the basin. The gravity high is presumed to be due to cooling dyke injections.

One dimensional full inversion of the MT data along East-West and North-South profiles indicates existence of three distinct layers. The first layer, overlain by high resistivity thin layers, is ~3 km thick and has resistivities ranging between 4-30 Ω-m. This layer is interpreted to be due to a combination of saline sediments and circulation of high temperature geothermal fluids. The second layer is ~10 km thick and resistivity values range between 85-2500 Ω-m. This layer is interpreted to be fractured basement metamorphic rocks probably hosting a steam reservoir where deeply circulating fluids are heated by the underlying dyke injections. The substratum is characterized by resistivities ranging between 0.5-47 Ω-m and is interpreted as cooling dyke injections which are the heat sources in the area.

REFERENCES

Baker, B.H., and Wohlenberg, J.: Structure and evolution of the Kenya rift valley, *Nature*, **229**, (1971), 538-542.

Braile, L.W., Wang, B., Daudt, C.R., Keller, G.R., and Patel, J.P.: Modeling 2D seismic velocity structure across the Kenya rift. In: Crustal and Upper mantle structure of the Kenya Rift, Eds. Prodehl, C., Keller, G.R. and Khan, M.A., *Tectonophysics*, **236**, (1994), 251-270.

Cagniard, L.: Basic theory of the magneto-telluric method of geophysical prospecting. *Geophysics*, **18**, (1953), 605-635.

Fairhead, J.D.: The structure of the lithosphere beneath the eastern rift, East Africa, deduced from gravity studies, *Tectonophysics*, **30**, (1976), 269-298.

Hautot, S., Tarits, P., Whaler, K., Le Gall, B., Tiercelin, J., and Le Turdu, C.: Deep structure of the Baringo Rift Basin (Central Kenya) from three-dimensional magnetotelluric imaging: Implications for rift evolution, *J. Geophys. Res.*, **105**, (2000), 23, 493-23, 518.

Karingithi, C.: The geochemistry of Arus and Bogoria geothermal prospects, *Proceedings*, 11th conference of the Geological Society of Kenya, Geology for Industrial Growth, Wealth Creation and Poverty alleviation, (2006).

Keller, G.R., Mechie, J., Braile, L.W., Mooney, W.D., and Prodehl, C.: Seismic structure of the uppermost mantle beneath the Kenya rift, In: Crustal and Upper Mantle Structure of the Kenya Rift, Eds: Prodehl, C., Keller, G.R. and Khan, M.A., *Tectonophysics*, **236**, (1994a) 201-216.

Mariita, N.O.: An Integrated geophysical study of the northern Kenya rift crustal structure: Implications for geothermal energy prospecting for Menengai area, PhD dissertation, (2003), University of Texas at El Paso, USA.

Omenda, P.A.: An update on the status of geothermal resource exploration and development in Kenya, *Proceedings*, Commercial development of geothermal power projects in Kenya, (2001), Unpubl.

Phoenix Geophysics Ltd.: Data Processing User Guide: SSMT2000, SyncTSV and MTEdit, Version 2, (2003), Victoria Park, Toronto, Canada.

Phoenix Geophysics Ltd.: V5 System 2000 MTU/MTU-A user guide, Version 1.4, (2004), Victoria Park, Toronto, Canada.

Prodehl, C., Keller, G.R. and Khan, M.A., (Eds).: Crustal and Upper mantle structure of the Kenya Rift, *Tectonophysics*, **236**, (1994), 2-483.

Prodehl, C., Ritter, J., Mechie, J., Keller, G.R., Khan, M.A., Fuchs, K., Nyambok, I.O., and Obel, J.D.: The KRISP 94 Lithospheric investigation of southern Kenya-the experiments and their main results, In: Stress and stress release in the Lithosphere, Edited by Fuchs, K., Altherr, R., Muller, B. and Prodehl, C., *Tectonophysics*, **278**, (1997), 121-148.

Riaroh, D., and Okoth, W.: The geothermal fields of the Kenya rift, *Tectonophysics*, **236**, 1994), 117-130.

Simiyu, S.M., and Keller, G.R.: Integrated geophysical analysis of the East African plateau from gravity and recent seismic studies, In: Stress and stress release in the lithosphere, Eds: Fuchs, K., Altheer, R., Muller, B., and Prodehl, C., *Tectonophysics*, **278**, (1997), 291-314.

Simiyu, S.M., and Keller, G.R.: An integrated geophysical analysis of the upper crust of the southern Kenya rift, *Geophys. J. Int*., **147**, (2001), 543-561.

Smith, M., and Mosley, P.N.: Crustal heterogeneity and basement influence on the development of the Kenya Rift, East Africa, *Tectonics*, **12**, (1993), 591-606.

Swain, C.J.: The Kenya rift axial gravity high: a re-interpretation, *Tectonophysics*, **204**, (1992), 59-70.

Swain, C.J., Khan, M.A., Wilton, T.J., Maguire, P.K.H., and Griffiths, D.H.: Seismic and gravity surveys in the Lake Baringo-Tugen Hills area, Kenya rift valley, *J. Geol. Soc. Lond.*, **138**, (1981), 93-102.

Swain, C.J., Maguire, P.K.H. and Khan, M.A.: Geophysical experiments and models of the Kenya rift before 1989. In: Crustal and Upper Mantle Structure of the Kenya Rift, eds. Prodehl, C., Keller, G.R., and Khan, M.A., *Tectonophysics*, **236**, (1994), 23-32.

Tongue, J.A.: Tomographic study of local earthquake data from the Lake Bogoria region of the Kenya Rift Valley, *Geophys. J. Int*., **109**, (1992), 249-258.

Tongue, J., Maguire, P., and Burton, P.: An earthquake study in the Lake Baringo basin of the central Kenya Rift, *Tectonophysics*, **236**, (1994), 151-164.

Tongue, J.A., Maguire, P.K.H., and Young, P.A.V.: Seismicity distribution from temporary earthquake recording networks in Kenya, *Tectonophysics*, **204**, (1992), 71-79.

Vozoff, K.: The magnetotelluric method, In: Nabighiam, M.N. (Ed.), Electromagnetic methods in applied geophysics, Vol. 2, (1992), SEG, pp. 641-712.

Young, P.A.V., Maguire, P.K.H., Laffoley, N.d'A., and Evans, J.R.: Implications of the distribution of seismicity near Lake Bogoria in the Kenya Rift, *Geophys. J. Int.*, **105**, (1991), 665-674.