Proceedings 5th African Rift geothermal Conference
Arusha, Tanzania, 29-31 October 2014

Guidelines/Templates for full paper

REVIEW OF ISOTOPIC AND FLUID INCLUSION DATA AT TENDAHO PROSPECT - ETHIOPIA

G. Montegrossi[1], G. Ruggieri[1], C. Pasqua[2], G. Magro[3]

1. CNR-IGG, Via G. La Pira 4, 50121 Firenze Italy (montegrossi@igg.cnr.it; ruggieri@igg.cnr.it);

2. ELC-Electroconsult, Via 1° Maggio 41, 20021 Milan, Italy (claudio.pasqua@elc-electroconsult.com);

3. CNR-IGG, Via G. Moruzzi 1, 56124 Pisa, Italy (g.magro@igg.cnr.it)

Keywords: Geothermics, Fluid Inclusion, R/Ra, mixing

ABSTRACT

The Tendaho geothermal system is characterized by the presence of a 50 km wide graben trending NW- SE, dissected on its turn by a series of normal faults which form a sequence of secondary horst and graben. The graben basement is composed of fissural basalts with minor rhyolite of the Afar Stratoid Series, overlain by a 1,200-1,400 m thick sedimentary sequence, consisting of clastic products (mostly siltstone with some sandstone) and intercalated basalt lenses. The occurrence within the graben of continental crust thinning and opening phenomena, accompanied by upward mass and heat transfer, represents a favourable element for the development of important thermal anomalies.

According to surface exploration surveys performed during the 1970s and early 1980s, exploration drilling was carried out in the Tendaho Rift, in Central Afar (Ethiopia), from October 1993 to June 1995. Three deep and three shallow wells were drilled in the central part of the Northern Tendaho Rift to prove the existence of a geothermal reservoir and its possible use for electric power generation. The project was jointly financed by the Ethiopian Ministry of Mines and Energy and the Italian Ministry for Foreign Affairs. Project activities were performed by the Ethiopian Institute of Geological Surveys and Aquater S.p.A.

In this work, a review and reinterpretation of the available fluid inclusion and isotopic data is presented, fostered by the recent Feasibility Study of Dubti prospect (2013) and by the current developments of the scientific investigation and integrated interpretation of Dubti-Ayrobera geothermal fields and by the renewed interest in the Tendaho basin. Data are mostly from core-drilled samples of wells TD1-4, and after having recomputed their isochrones with a new interpretation taking into account the scientific development occurred after the first work in 1999, they provide an insight into the two reservoir model (shallow and deep) with fault-driven circulation. The possible existence of a double reservoir system was proposed by Battistelli et al. (2002), with an hypothesized deep contributing geofluid. Waters discharged from wells TD-1, TD-2 and TD-4 are low salinity, sodium-chloride geothermal types, with reservoir temperature ranging from 220°C to 270°C. Fluid inclusion data, compared with present-day measured temperatures, indicate either heating (well TD-1) or cooling (well TD-3, Gianelli et al. (1998)) and are used in the present work to reconstruct the thermal history of this reservoir.

R/Ra ratios of geothermal fluids discharged from fumaroles, geothermal wells and those trapped in fluid inclusions, suggest a supply of mantle 3He to the geothermal fluids, a mixing between mantle ^{3}He and He of crustal (and/or upper mantle) origin. The ^{4}He/^{20}Ne ratios indicated a moderate or very low input of atmospheric He, except for one sample from Tendaho with the lowest ^{4}He/^{20}Ne ratio both from present-day fluids and paleo-fluids extracted from inclusion in hydrothermal minerals. This low ratio indicates input of atmospheric He from infiltrating water at shallow depths (Ruggieri et al., 1999). In particular, the isotopic signature results support a fault driven circulation model, adding some information on the contributing deep geofluid.

1. INTRODUCTION

The Horn of Africa is characterized by the presence of three active rift systems: the northern portion of the East African Rift System, together with the Red Sea and Aden rifts, forms the Afar triple junction. This marks the transition from continental (southern part) to oceanic crust (northern part). Most of the Afar tectonic and volcanic activity is due to the mechanical interaction of the on-land southern continuation of the Red Sea Rift, with the partly overlapping on-land western continuation of the Aden Rift. This interaction forms an overlapping spreading center, resulting in intense faulting and diffuse block rotations in between. The geology and structural features of Aden propagator into Afar have been widely studied. Conversely, our poorer knowledge of the geology and the structure of the Red Sea propagator is based on general studies, on average several decades old, or confined to sporadic episodes of activity. Of particular interest is the definition of the geology and structural features of the NW-SE trending southern portion of the Red Sea propagator, overlapping with the Aden propagator in Central Afar. The most important structural features of the former include the NW-SE trending Tendaho Graben, the largest depression of Central Afar, and the younger and active Manda Hararo Rift, partly located within Tendaho Graben (Acocella et al., 2008, and references therein).

Several geothermal areas, related to the magmatic activity, occur in the Horn of Africa. There are different possibilities to insert these “mosaic tiles” in the geological-hydrogeological framework of the region. However, considering that the main permeable pathways are controlled by fracturing along major NW-trending tectonic features, it seems likely that the Dubti, Alalobeda, Ayrobera geothermal systems are sustained by separate upflow zones, fed from the same regional recharge. This concept is generally accepted since the first investigation made by Aquater up to recent study (e.g. Seifu et al., 2007; Varet et al., 2012) that conclude “..deep aquifers can be recharged by meteoritic waters due to the vicinity of the high and humid Ethiopian Plateau. Large water basins enable recharge of the fractured and permeable formations located on the western side of the axial ranges where transverse fracture zones offer optimal conditions for geothermal reservoir development”. According to this considerations, many geothermal area present in the triple-junction area may benefit to various extent of this regional recharge, namely from Dallol to Tendaho to Langano geothermal prospects.

Regarding the heat source, namely the Ethiopian plume, the majority of the nowadays models are modifications of the super-plume hypothesis based on global seismic tomography studies. However, the existence of such a continuous hot feature penetrating the whole mantle is highly debated, based on the intrinsic limitations of global tomography studies and on the dependence of seismic velocity on other parameters (composition, phase) in addition to temperature. It is consequently not clear if the vast low-velocity anomaly in the lower mantle results from high temperatures or is controlled by other parameters such as density (see for instance Anderson, 2007; Corti, 2009, and references therein for discussion). In addition, it is also possible that the observed low-velocity structure in the lower mantle represent ‘normal’ thermal fluctuations in a stratified mantle (Ritsema and Allen, 2003). Even admitting the existence of this large scale thermal upwelling, its connection with surface structures, volcanism and the uppermost mantle structure beneath the East African Rift System remain poorly defined. On the basis of simple cooling models, the hot intrusions responsible for the geothermal anomaly cannot be older than 10-100k years and thus related to shallow, recent magmatic events that share a common deep source. The statement that “dykes of recent age are taken as the probable heat source in the Dubti and Ayrobera prospects” is questionable. Actually, it is felt that these dykes constitute an evidence of the existence of an active magmatic chamber, but, in consideration of their relatively small volume, should not represent a direct heat source. These heat sources are associated with phenomena of continental crust thinning and opening, accompanied by outpouring of the upper mantle and upward mass and heat transfer, as well as by partial silicic melting within the crust. The axis of the Tendaho Graben appears to be the preferential structure for the development of such crust oceanization.

In this regional-scale framework we will focus on the Tendhao geothermal prospect pointing out on the fluid inclusions for reconstructing the thermal history of the TD1-6 wells and the behavior of R/Ra and $^4He/^{20}Ne$ ratios to reconstruct a possible deep end-menber for the geothermal system.

2. HELIUM SOURCES AND MIXING

Previous studies documented an extremely variableR/Ra ratio, from 0.035 to 19.6 for the gas extracted from olivines, and piroxenes of the basalts of the Ethiopian volcanic province (Marty et al., 1996; Scarsi and Craig, 1996). Large variation of R/Ra were also found for the geothermal gases of the Ethiopian Rift Valley and Afar depression (Scarsi and Craig, 1996), Isotope Laboratory Scripps Institution of Oceanography, Report 14-77, 1977). This variability were interpreted as a mixing between the atmospheric endmember (ASW), the Ethiopian plume (R/Ra = 19.6) and the crustal source (R/Ra = 0.02). It is noteworthy to point out that Darrah et al. (2012), found an endmember for the Dallol geothermal system with R/Ra = 11.86, that correspond to a mixing of Ethiopian plume with nearly 40% of crustal Helium.

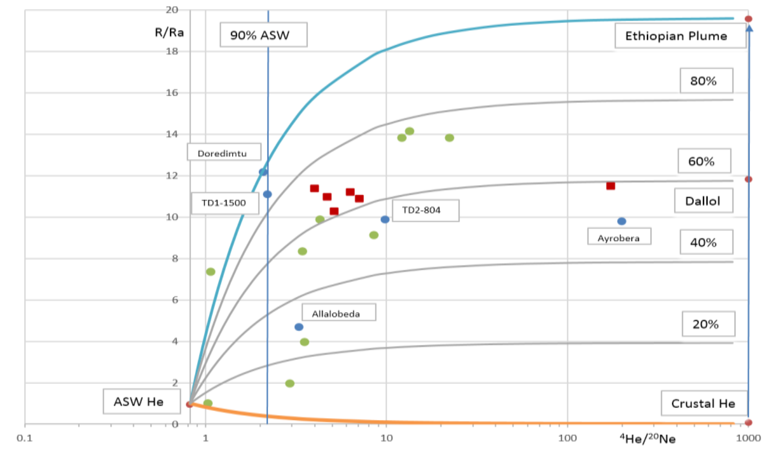

Figure 1: The figure above illustrate the mixing between ASW, Ethiopian plume and Crustal He endmembers. Blue circle are Tendaho samples, red square are Langano samples and green circles are other Ethiopian samples.

In figure 1 the R/Ra *vs* $^{4}He/^{20}Ne$ values for Tendaho and Langano fluid inclusions, as well as selected fluids from Ethiopia rift valley are shown. Values from Isotope Laboratory Scripps Institution of Oceanography, Report 14-77 (1977), Ruggieri et al. (1999), Darrah et al. (2012). We can observe that, while the samples from the Langano system are located along the 30-40% of crustal end-member line, the Tendaho values are more scattered; on the other hand, the Tendaho samples show up to 90% of meteoric water (ASW) while the Langano reach only 80%.

Since this consideration arise mostly from the $^{4}He/^{20}Ne$ ratio, and this ratio could be greatly affected by evaporation/condensation processes in the direction of increase of $^{4}He/^{20}Ne$ ratio, in this contest to infear on the deep system conditions we ought to prefer the lower values. On the basis of the regional settings, we can say that the regional recharge (ASW endmember) reach the Tendaho system and mix with a 10% of a deep end-member, originated by the crustal mixed outpouring upper mantle, responsible for the system heating up.

3. FLUID INCLUSIONS AND WELLS THERMAL EVOLUTION

Previous study on fluid inclusion for the Tendaho geothermal system could be found in Gianelli et al. (1998), and Ruggieri et al. (1999); after a review and reinterpretation of the available fluid inclusion dataset, we present here an discussion of the data under the light of the recent investigations carried out in the Tendaho area. We assume that the mean or average homogenization temperature of fluid inclusions reported by previous fluid inclusion studies are representative of the temperature of the paleo-fluid (T_{past}). The T_{past} was related to the pressure of the paleo-fluid computed from the depth of the samples by using a ‘hot’ hydrostatic pressure-depth curve computed for the system under investigation on the basis of present-day pressure gradient.

In figure 2 the comparison between T_{past} and formation temperature of well TD1 (Amdeberhan, 1998; Seifu 2004) is reported. We could observe that fluid inclusion data are closer to the water boiling curve, while the formation temperatures are lower showing a slight cooling of the well; in particular, the sample showing T_{past} = 285°C is more reliable.

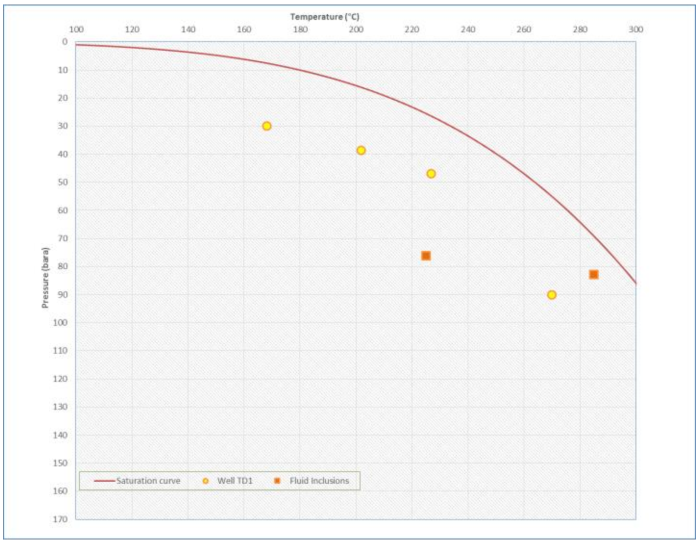

Figure 2: In the figure above are reported fluid inclusion data (orange square) and formation well data (yellow circle) for well TD1.

In figure 3 the same comparison is carried out for well TD3, and the cooling is more evident. It is noteworthy to point out that mineral equilibrium temperature computed by Gianelli (1998), are closer to fluid inclusion temperature for both well TD1 and TD3 (that can be defined a ‘cold’ well). Both well are not productive.

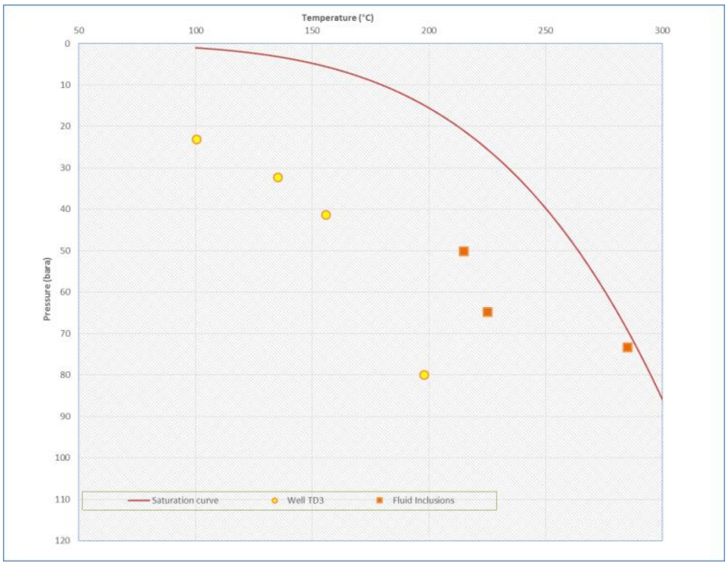

Figure 3: In the figure above are reported fluid inclusion data (orange square) and formation well data (yellow circle) for well TD3.

From the pressure curve of well TD1-4 we could observe a pivot point at a pressure of nearly 80 bar, and this features is present also in well TD3; under the consideration of a common recharge, we can safely assume the pivot point as pressure of the recharging fluid. The temperature corresponding to the 80 bar pressure, with the exception of the TD3 well, is 245°C, and for our purpose we assume this as the heated up recharging water. Thus, the water is infiltrating in the Ethiopian Plateau along a ‘cold’ or standard hydrostatic curve, and after have a pathways that heat up the recharging water up to the ‘pivot point’ conditions.

From this conditions, we could compute a deep end-member (knowing that we need 10% mass of the deep end-member) with an enthalpy (taken as a steam end-member) enough to reach the boiling point of the whole fluid. The results is a steam at 310°C, 90 bar, that generate a boiling fluid at 280°C. The hottest paleo-fluids (well TD1 at 2015m depth and TD3 at 1340m depth) show a temperature distribution centered at 280-290°C (in table 1 reported as 285°C), thus having a good agreement with the present mixing calculations.

In figure 4 are reported the mixing step and the T_{past} of TD1-2-3 wells with formation temperature of wells TD2, TD4, TD5, TD6 from Seifu (2004). We can observe the good agreement of Tpast from fluid inclusions and well temperatures, pointing out that the former circulation at well TD1 and TD3, as well as the former and present circulation at well TD2, and the present circulation at well TD4, TD5 and TD6 are in a similar thermodynamic condition. In particular, the geothermal reservoir is originated by boiling due to depressurization. The difference in hydrostatic curve from the recharging fluid (cold hydrostatic) to the boiling geothermal fluid (hot hydrostatic) will results in a static overpressure at wellhead, like the 4.5 bar found at well TD2 or even higher.

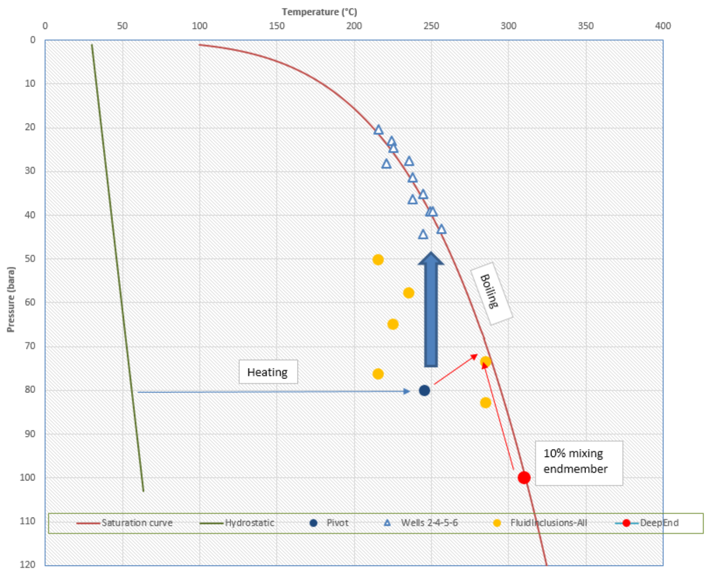

Figure 4: In the figure above are reported fluid inclusion data (yellow circles) for well TD1,2,3 and formation well data (blue empty triangle) for well TD2,4,5,6. Pivot point is blue circle, and the deep end member is red dot. Boiling curve (red line) and cold hydrostatic curve (green line) are present as well.

Since the majority of the previous consideration are on a regional-scale base, we can try to apply our model to another system in the same region; the Langano geothermal system is far enough, but with a similar regional settings. The well-log data for Langano system are from Amdebrhan, (2006) while T_{past} correspond to the average homogenization temperature of fluid inclusions reported in Ruggieri et al. (1999) Pressure of the paleo-fluids was also computed from sample depth and a “hot-hydrostatic” pressure-depth curve. For the Langano system, from figure 1 we could obtain a value of 20% mass fraction for the deep end-member, and with a similar procedure we could found a pivot point at 85 bar and 250°C, and using a 20% mass fraction we have that a steam at 315°C is enough to make the whole fluid reach the boiling point at 315°C. In figure 5, the mixing process is reported from the pivot point to the deep endmember, and the fluid inclusions trace the boiling process up to the shallower two phases reservoir. For comparison, some selected formation temperature from well logs of well LA1-8 are reported.

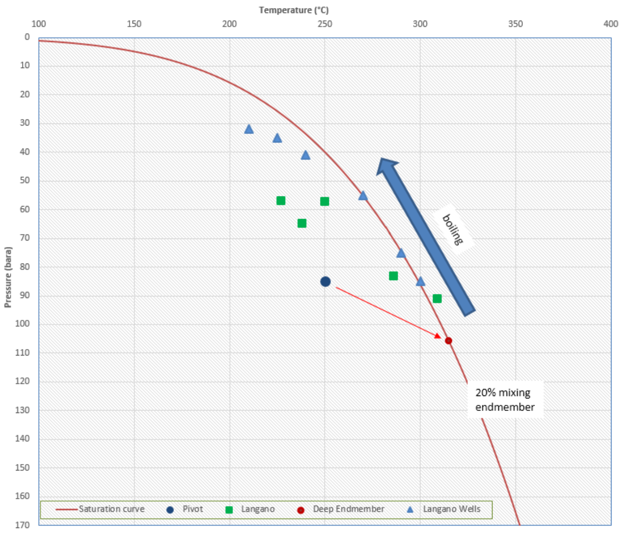

Figure 5: In the figure above are reported fluid inclusion data (green squares) for LA4,7,8 with selected temperatures from well logs (LA1-8). Pivot point is blue circle, and the deep endmember is red dot. Boiling curve (red line) is present as well.

4. DISCUSSION AND CONCLUSIONS

We are aware that this procedure to model the deep input include a possible endless source of errors, mainly in the $^4He/^{20}Ne$ ratio, and later in trying to assess the ‘pivot point’ condition, that in many systems change for each wells. In a true regional-scale recharge, anyway, the inflow pressure should be the same if the wells are close enough.

Concluding, we were able to found a deep inflow end-member for both the Tendaho and Langano systems; we should point out that this deep end-member still contain 30-50% of crustal fluids, that is consistent with the partial fusion of crustal rocks during magmatic events, but could be due also to deep crustal circulation.

The findings are consistent also with precedent ideas of a deep recharge, e.g. Battistelli et al. (2002), but provide a clear description of both thermodynamic conditions and relative mass balance of the deep end member for the Tendaho system, and for the Langano system as well.

The end member found so far, i.e. 310°C for Tendaho and 315°C for Langano, are considered as pure steam along water boiling curve. This is a conservative hypothesis, because latent heat of evaporation account for a large part of the total enthalpy, and considering a two-phase condition would increase the resulting temperature of the end-member, but introduce an unknown that is the steam/liquid ratio. Anyway, the finding of this work seems to be consistent with the previous investigations and the well-log findings.

The developing of the reservoir through boiling stages is justified by the high secondary permeability, and the fluid evolution occur due to depressurization during upraising, developed on a 'hot' hydrostatic curve lying on the water boiling curve. In this contest, it is quite easy to found temperature inversion, occurring as soon as the well exit from the pathways of the upraising hot geothermal fluid. The mixing of the deep end-member with the recharging fluid (i.e. ASW end-member) could occur also locally, but is unlikely to occur due to the scarce rainfall of the region, and left the major recharging contribution to the regional recharge.

REFERENCES

Acocella V., Abebe B., Korme T., Barberi F.: Structure of Tendaho Graben and Manda Hararo Rift: Implications for the evolution of the southern Red Sea propagator in Central Afar, *Tectonics*, **27**, (2008), 1-17

Akalewold: Evaluation of recent temperature and pressure data from wells in Tendaho geothermal field, Ethiopia and from well HG-1 at Hágöngur, Iceland. UNUGTP 2004-15, (2004)

Amdeberhan Y.: A conceptual reservoir model and production capacity estimate for the Tendaho Geothermal Field, Ethiopia. UNU-GTP-1998-1, (1998)

Amdebrhan, Y.: Well testing & reservoir engineering studies at Aluto-Langano & Tehdaho geothermal fields, Ethiopia, ARGeoC1, (2006)

Anderson, D.L.: Is there convincing tomographic evidence for whole mantle convection? (2007) Available at: http://www.mantleplumes.org/TomographyProblems.html

Battistelli, A., Amdeberhan, Y., Calore, C., Ferragina, C., Abatneh, W.: Reservoir assessment of Dubti geothermal field, Northern Thendaho Rift, Ethiopia, *Geothermics*, **31**, (2002), 381-406

Corti, G.: Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa, *Earth-Science Reviews*, **96**, (2009), 1-53

Darrah, T.H., Tedesco, D., Tassi, F., Vaselli, O., Cuoco, E., Poreda, R.J.: Gas chemistry of the Dallol region of the Danakil Depression in the Afar region of the northern-most East African Rift, *Chemical Geology*, (2012)

Gianelli, G., Mekuria, N., Battaglia, S., Chersicla, A., Garofalo, P., Ruggieri, G., Manganelli, M., Gebregziabher, Z.: Water-rock interaction and hydrothemal mineral equilibria in the Tendaho geothermal system, *JVGR*, **86**, (1998), 253-276

Hayward, N. J.,Ebinger, C.J.: Variation in the along-axis segmentation of the Afar Rift system, Tectonics, 15, (1996), 244 – 257.

Isotope Laboratory Scripps Institution of Oceanography, Isotopic Geochemistry and Hydrology of Geothermal Waters in the Ethiopian Rift, Report 14-77, (1977), 1-140

Marty, B., Pik, R., Gezahegn, Y.: Helium isotopic variations in Ethiopian plume lavas: nature of magmatic sources and limit on lower mantle contribution. *Earth and Planetary Science Letters*, **144**, (1996), 223–237

Ritsema, J., Allen, R.M.: The elusive mantle plume. *Earth and Planetary Science Letters*, **207**, (2003), 1–12.

Ruggieri, G., Droghieri, E., Gianelli, G., Panichi, C., Magro G.: Helium isotopic composition of fluid inclusion from two Ethiopian geothermal fields, *Geochemistry of the Earth Surface*, (1999), 535-538

Scarsi, P., Craig, H.: Helium isotope in Ethiopian Rift basalts. *EPSL*, **144**, (1996), 505-516

Seifu, A.: Evaluation of recent temperature and pressure data from wells in Tendaho geothermal field, Ethiopia, and from well HG-1 at Hagongur, Iceland, GTE, 15, (2004), 325-348

Seifu, K., Travi, Y., Asrat, A., Alemayehu, T., Ayenew, T., Tessema, Z.: Groundwater origin and flow along selected transects in Ethiopian rift volcanic aquifers, *Hydrology Journal*, (2007)

Varet, J., Chernet, T., Woldetinsae, G., Arnason, K.: Exploring for geothermal sites in Northern and central Afar (Ethiopia), 4th African Rift Geothermal Conference, (2012)