Geothermometry of hot springs in the Malawi Rift

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ABSTRACT

The Malawi Rift is located in the Western Branch of the East African Rift System (EARS), which has potential for geothermal energy generation. Previous geothermal studies in Malawi focused on the geochemistry of hot springs and recognized that the hot fluids are not related to mantle sources but rather to heat from elevated geothermal gradient and deep fault circulation. The Mesozoic shear zones intersecting with Quaternary rift faults are controlling the emplacement of the major hot spring clusters in the Malawi Rift Valley. This study is focused on the estimation of silica and cation geothermometry of geothermal systems to better characterize the geothermal resources in Malawi. The composition of the 27 hot springs can be classified as 1) sodium bicarbonate, 2) sodium sulfate, or 3) sodium chloride and sulfate. The sodium bicarbonate water type is associated mainly with meteoric waters from shallow aquifers and poor content of admixture of thermal waters at deeper depths. The quartz conductive silica geothermometer, which is used to estimate temperatures in shallow aquifers with immature rock-water equilibrium, indicate temperatures from 40 °C to 130 °C. Major ion analysis indicate that the Na-SO4 and Na-Cl waters are related to deeper geothermal aquifers, heated by steam, and where partial rock-water equilibrium has occurred. The Na-K geothermometer shows the highest reservoir temperatures of about 190°C and highest chloride concentration were measured in the Chiweta and Mphizi hot springs. The stable isotopes of hydrogen (δD) versus oxygen ($\delta^{18}O$) show that most of the hot springs lie on the Local Meteoric Water Line. This meteoric water is infiltrated at depth through faults where water-rock interactions occur between ascending geothermal water and shallow colder groundwaters take place. Our results indicate that some of the hot springs in Malawi have geothermal energy capabilities of medium enthalpy. The most promising area to continue exploration work is the north region of the country. In addition, structural studies should be conducted to better understand the hot fluid storage, and pathways through faults.

LOCATION

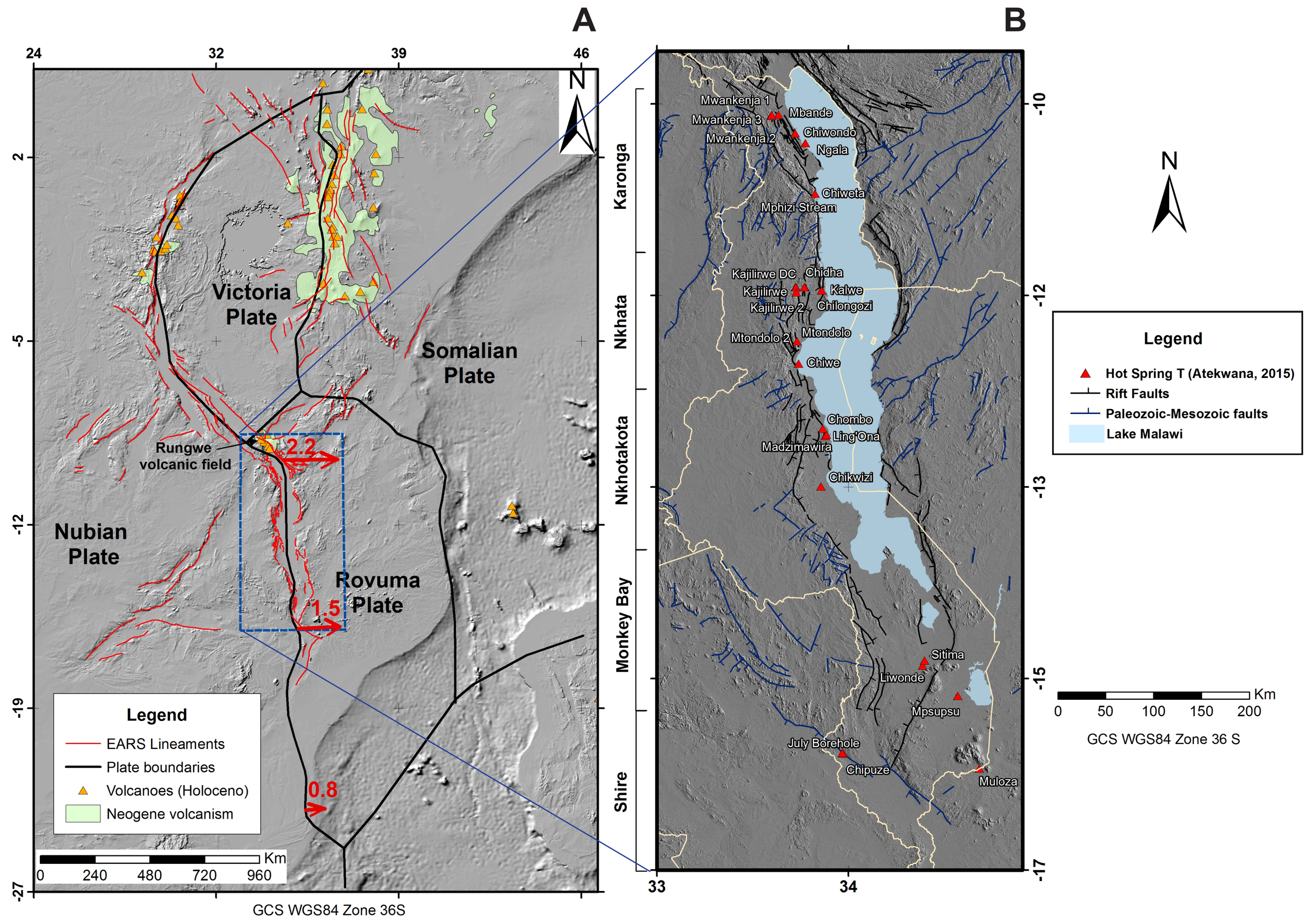

Figure 1 A. Tectonic setting of the East African Rift System showing the Eastern and Western branches and Neogenic volcanism including the Rungwe volcanic field, which is the only volcano in the Malawi Rift of Late-Cenozoic age (Ebinger, 1989). Relative motion vectors mm/yr to the Nubian and Rovuma plates reported by Saria et al. (2014). The average extension rate is 2.2 mm/yr in the north and 0.8 mm/yr in the south of the Malawi Rift. **B.** Structural map showing 27 hot springs (Atekwana et al., 2015) across the Malawi Rift with Quaternary and Mesozoic faults (Modified from Laó-Dávila et al., 2015). Labels on the left of Figure 1B. represent the rift segments zones proposed by Ebinger et al. (1987).

MOTIVATION

Problem:

Despite the occurrence of geothermal resources in Malawi, geothermal energy is undeveloped because of a dearth of exploration data to classify and quantify the resources.

Hypothesis:

Malawi has geothermal potential areas of at least medium enthalpy (Dulanya et al., 2010; Gondwe et al., 2015). The geothermal systems are related to meteoric waters that are infiltrated at depth through faults and heated by an anomalously high geothermal gradient (e.g. Dulanya et al. 2010; Atekwana et al., 2015).

Objective:

The goal of this study was to calculate geothermometers to estimate temperatures in geothermal reservoirs at depth and identify the most promising geothermal areas to continue exploration in the future.

METHODS

Sampling:

- Atekwana et al. (2015) provided geochemical data of 27 hot springs along the Malawi Rift collected in 2013.

Analysis:

- The pH, surface temperature, electrical conductivity, and total dissolved solids (TDS) were measured in the field.
- The hot springs were analyzed for the major cations and anions (Na, K, Ca, Mg, Cl, SO4, and HCO3/CO3) and stable isotopes ($\delta^{18}O$ and δD).
- The Powell and Cumming (2010) spreadsheets were used to generate graphics, ternary diagrams, and cross-plots from water chemistry data. The diagrams include silica and cation geothermometry calculations (e.g., Fournier, 1981; Fournier & Potter, 1982; and Giggenbach, 1991), fluid composition (i.e., piper diagram), and trend characterization of different parts of geothermal systems.

GEOCHEMISTRY OF GEOTHERMAL SYSTEMS

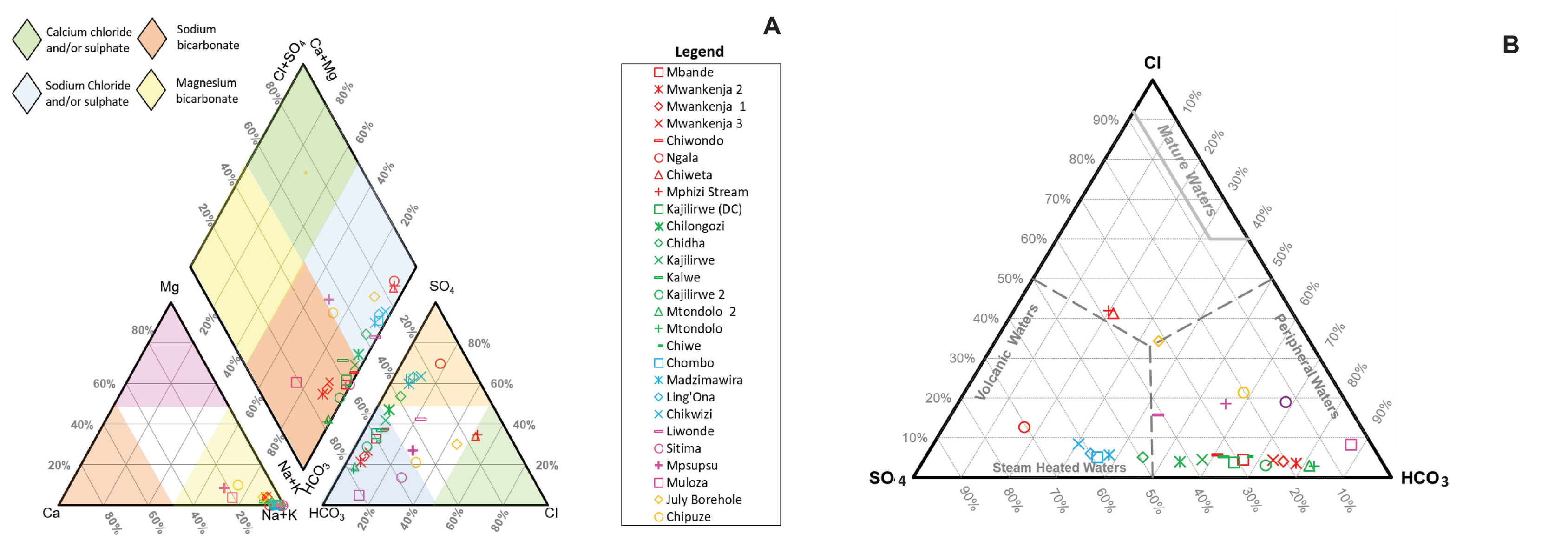

Figure 2 A. Piper ternary diagram showing that cations Na^{+}, Ca^{+} and HCO_3^{-}, SO_4^{-}, and Cl^{-} anions are the main ions of Malawi's hot springs. **B.** The Cl-SO4-HCO3 ternary diagram showing the proportions of major anions of geothermal waters and their relation with different parts of geothermal systems.

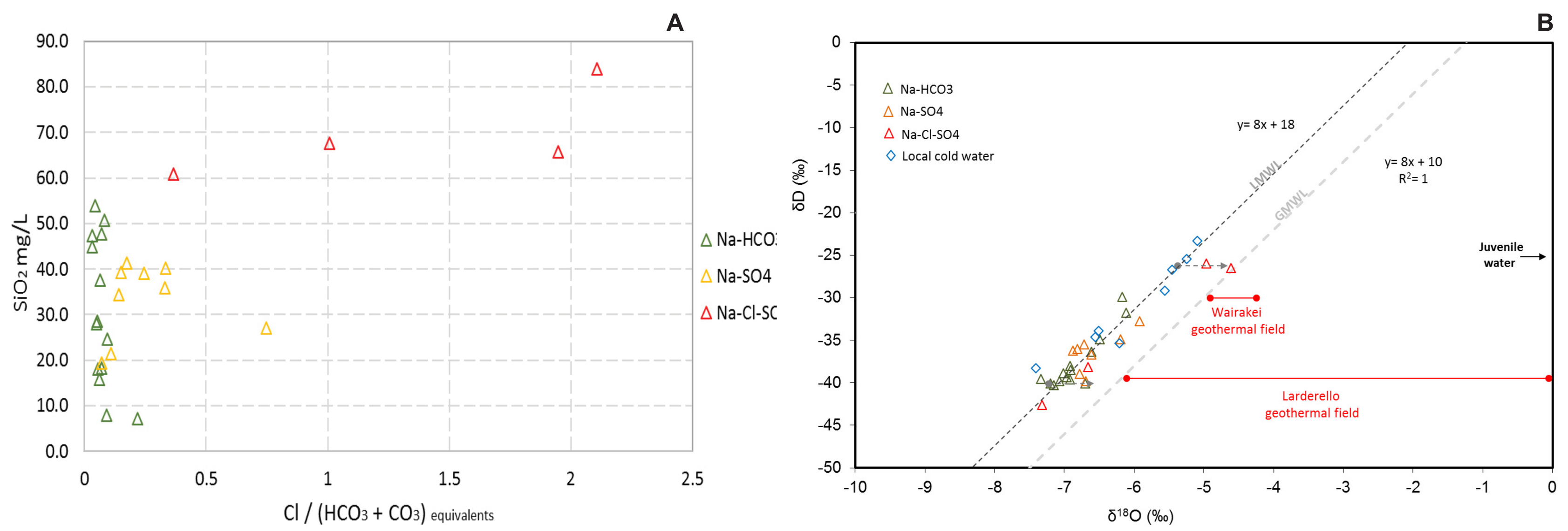

Figure 3 A. Scatter diagram showing Cl / (HCO3 + CO3) ratios plotted against silica for the three types of water composition in Malawi's hot springs. The Cl / (HCO3 + CO3) ratios are useful to identify waters from different aquifers (Fournier & Truesdell, 1970). Higher ratios of Cl / (HCO3 + CO3) suggest hotter aquifers (Fournier, 1977). **B.** Stable isotopes δD versus $\delta^{18}O$ plot of hot springs in the Malawi Rift and their relationship with the Local Meteoric Water Line (LMWL) generated in this study and the Global Meteoric Water Line (GMWL; Craig, 1961). The plot also shows the relationship in Larderello, Italy and Wairakei, New Zeland geothermal fields.

GEOTHERMOMETRY

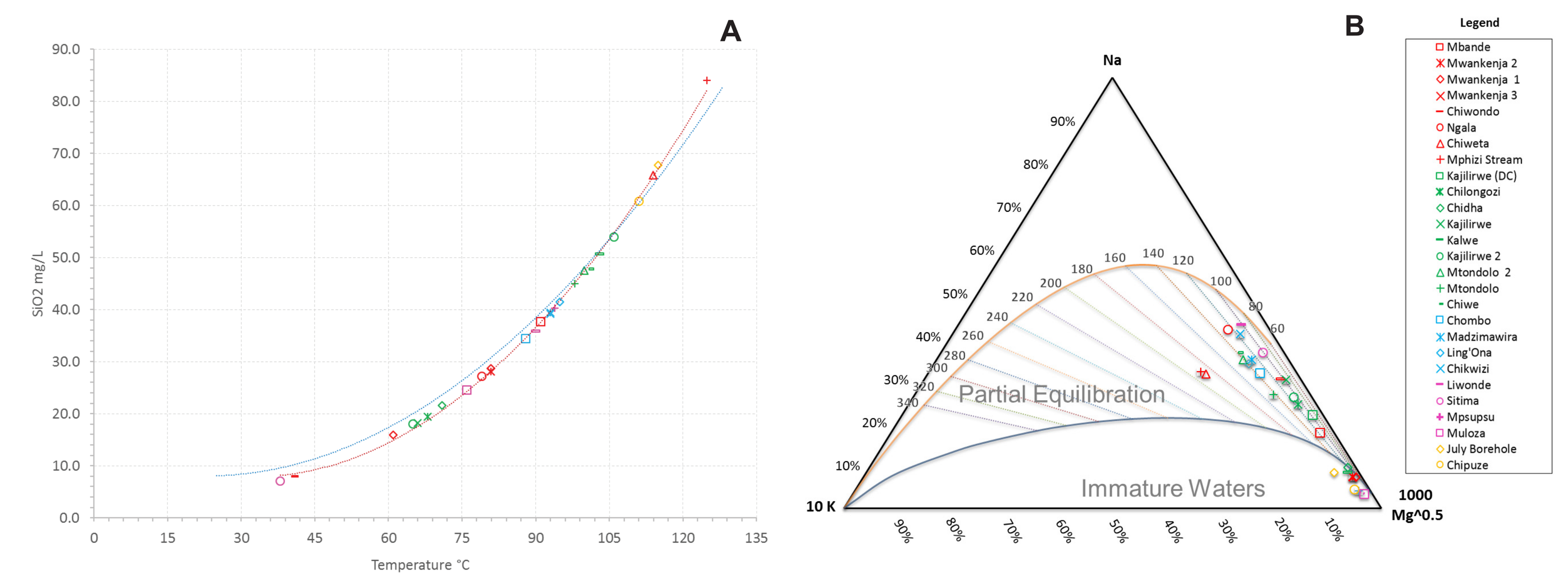

Figure 4 A. Scatter diagram plotting silica concentration against quartz geothermometer temperatures for waters cooled by adiabatic expansion (red trend) and waters cooled by heat conduction (trend blue). **B.** Ternary diagram K-Mg-Na geothermometer by Giggenbach (1988) showing estimated reservoir temperatures and the immature or partial equilibrium water fields.

GEOINDICATORS

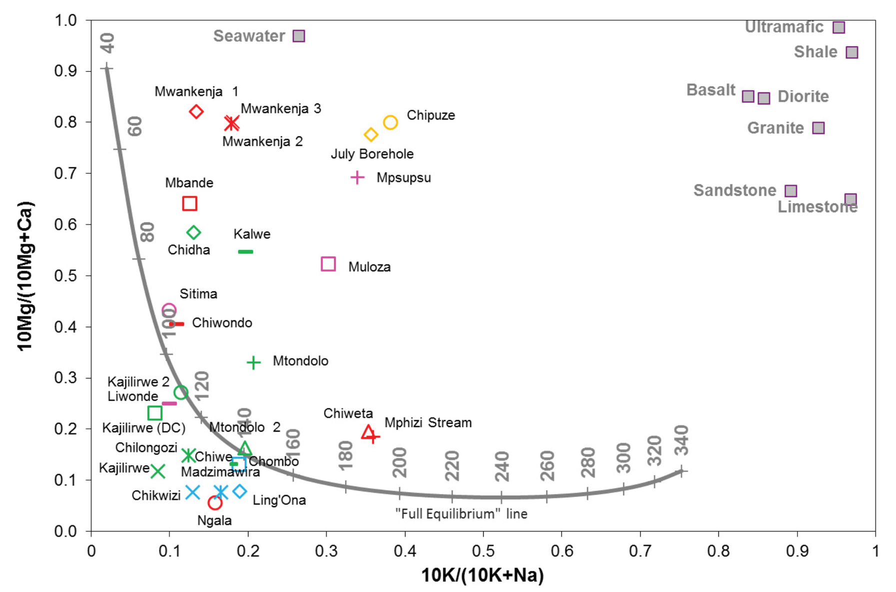

Figure 5. The Na-K/Mg-Ca diagram plot by Giggenbach and Goguel (1989), is a "geoindicator" used to determine the influence of shallow, low temperature processes, mixing meteoric waters, and steam heating (e.g. Powell and Cumming, 2010; Giggenbach & Glover, 1992) that may be hidding the geochemical signature of deeper waters. The "Full equilibrium line" is showing reservoir temperatures (Giggenbach & Glover, 1992).

GEOTHERMAL CONCEPTUAL MODEL

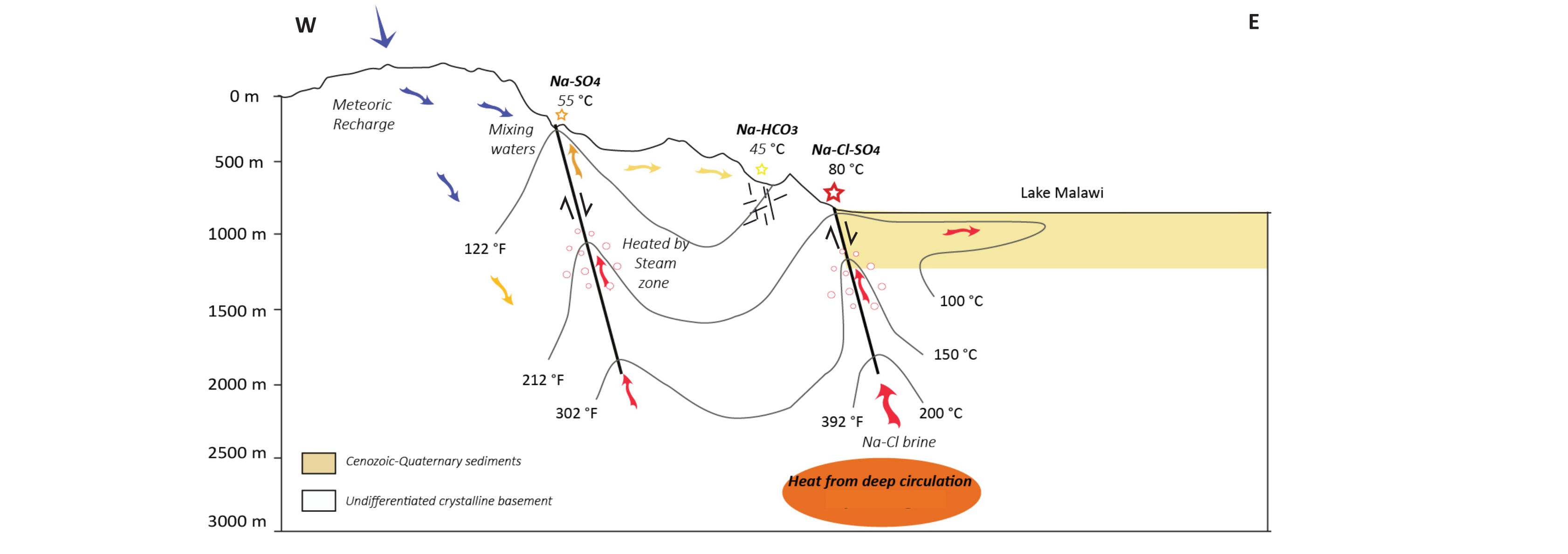

Figure 6. Geothermal conceptual model of the northern part of the Malawi Rift. The meteoric water is infiltrated at depth and is heated by elevated geothermal gradient or magma intrusions. The geothermal fluid (Na-Cl) rises through faults and processes such as water-rock equilibrium, boiling, heating by steam (Na-SO4), and mixing with shallow aquifers (Na-HCO3) ocurring during the ascent.

DISCUSSIONS

- The Na-SO4 waters in Malawi may be related to groundwater in partial equilibrium with the rock and heated by steam from deeper reservoirs. Similar to those found in the Basin and Range Province of the U.S., which are controlled by geological structures.
- The Na-Cl-SO4 waters from Chiweta, Mphizi, Chipuze and July borehole springs are related to geothermal fluids from deep aquifers with full or partial water-rock equilibrium. These types of water could be the result of mixing waters heated by steam due to boiling and/or volcanic waters heated by intrusions at depth.
- The stable isotope of δD against $\delta^{18}O$ show that 93% of the hot springs lie on the LMWL, except Chiweta and Mphizi hot springs which show enrichment of $\delta^{18}O$, similarly to other geothermal fields caused by high reservoir temperatures and water-rock equilibrium (e.g. Wairakei, Larderello).
- The Na/K geothermometers show the highest reservoir temperature results. The Chiweta and Mphizi (Na-Cl-SO4) hot springs in the northern part of Malawi are the hottest (190 °C) and they are in partial equilibrium with the rock. On the other hand, July borehole and Chipuze hot springs in southern Malawi also show reservoir temperatures around 190 °C. However, July borehole and Chipuze hot springs have immature waters, which cause geothermometer results reading accuracy to become unreliable.

CONCLUSIONS

- The northern part of the Malawi Rift has the most prominent areas (Karonga) to develop a geothermal field due to the high reservoir temperatures.
- The results indicate that Chiweta hot springs area in Malawi have geothermal energy capabilities of high to medium enthalpy.
- The geothermal systems in Malawi are related to meteoric water infiltrated at depth through highly permeable and deep faults. The meteoric water is heated by elevated geothermal gradient or volcanic waters related to rifting processes. The geothermal fluid (Na-Cl) rises through faults and processes such as boiling, heated by steam (Na-SO4), and mixing with shallow aquifers (Na-HCO3) ocurring during the ascent.
- Structural geology analysis should be conducted to better understand the hot fluid storage, and pathways through faults in order to find the best exploratory wells targets.

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