Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Structural and Stratigraphic Controls of Malawi's Hotsprings: a Review

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Keywords: Malawi, hotsprings, potential, geothermal

ABSTRACT

Active continental divergent zones such as those in the East African Rift System (EARS) hold significant potential for commercially exploitable geothermal resources. Evaluating these zones and characterizing the structural and stratigraphic controls may give insights of the most favourable locations for geothermal activity in a particular area. Due to the geological setting in the western branch of the EARS, several surface manifestations of geothermal energy mostly in the form of hotsprings have been found throughout Malawi. According to our results it seems that there is a strong correlation between the strike of the hotsprings, rock type, regional faulting and the seismic rupture in 2009. However, the country's full potential has not been evaluated despite these hotspring manifestations throughout this rift segment. Those hotsprings with a high probability of containing easily extractable, commercially viable energy have still to be re-evaluated in order to locate the most favourable areas for geothermal exploration in the area. To achieve this, more local studies are necessary in order to understand better the stratigraphic and structural controls of the hotsprings in the studied area, in order to attract local and international investors. Therefore, the objective of this paper is to give an overview of the geological, structural, geochemical and seismic characteristics in northern Malawi for the exploration of geothermal energy. Once explored, this resource could become crucial in the country's future development and economy.

1. INTRODUCTION

Rift valleys form as a result of divergent tectonic plates i.e. movement of tectonic plates away from each other. The land in between the two plates sinks to form long narrow valleys, as is the case in eastern Africa today. The so-called East African Rift System (EARS) is one of the ideal sites for the study of earth-forming processes related to continental break-up whose development has progressed from north to south and may have been initiated some 40-50 my BP. The EARS comprises two arms the older eastern one which is volcanically active as opposed to the younger western branch with some of the world's oldest and deepest lakes (Rosendahl et al., 1992; Delvaux, 1995; Roberts et al., 2012). For example, the tectonic structures within the Lake-Tanganyika-Rukwa-Malawi rift which forms part of the western branch suggest a probable age of between 12 my - 8 my BP for lakes Tanganyika and Malawi respectively (Cohen et al., 1993; Delvaux, 1995).

Different processes and mechanisms are invoked as being responsible for rifting including lithosphere updoming and mantle convection as it is highly discussed for the EARS (Rosendahl et al., 1992; Ebinger and Sleep, 1998; Stamps et al., 2008). Despite the disagreements in the exact models of rifting (Bosworth, 1985; Ebinger et al., 1987; Stamps et al. 2008; Nyblade and Brazier, 2002), it is recognized that the process of rifting progresses through several stages and involves volcanic eruptions, seismicity and sedimentation. Depending on the stage of rifting, these processes create various igneous and sedimentary environments that favour geothermal activity and the formation of mineral deposits.

The western branch of the EARS is characterised by lack of pronounced magmatic activity in comparison to the eastern branch and other rift zones in the world. The Malawi Rift at the southern-end of the western branch has numerous hotsprings manifestations (Ray, 1975; Dulanya, 2006) without obvious connections to magmatic activity in most areas, and with some Pleistocene volcanics only known from the northern part of the Malawi rift (Ray, 1975). In addition, the area is tectonically active which may favour opening potential fluid pathways for the circulation of geothermal fluids. The geomorphology of the study area consists of wide tilted basins and extremely long faults with the potential for normal-faulting earthquakes of magnitudes around 7 and 8 (Biggs et al., 2010). The most recent damaging events were recorded in December 2009 when a series of earthquakes struck this segment of the rift leading to loss of lives and devastation of several infrastructures (Figure 1).

Figure 1: An earthquake-damaged house in Karonga in 2009.

Despite the widespread occurrence of the geothermal activity (e.g. Dulanya, 2006) in the entire rift segment and absence of any obvious signs of magmatic activity to which the known hotsprings can be related, there is little understanding, to date, of the geological and tectonic processes that control their distribution across the rift segment. Therefore, the goal of this paper is to give an overview of the geological, structural, geochemical and seismic characteristics in northern Malawi for geothermal exploration. Northern Malawi may have a great potential for geothermal energy but more studies are necessary in order to find the most suitable areas for geothermal exploration/exploitation.

2. POPULATION AND INDUSTRY

The EARS is within riparian countries characterized by high population density and rampant poverty. These demographic characteristics have implications on resource use patterns and sustainability and present an interesting linkage between natural and anthropogenic processes. It is interesting to observe how earth-forming processes can shape livelihoods and how livelihood options can change the environment thus providing a unique opportunity to study and appreciate the role of Earth System Sciences at a microcosmic scale.

Malawi is one of the most highly populated countries within the southern Africa sub-region with a population of nearly 15 million residing on a land area of about 90,000 km^2 (Figure 2). Agriculture is the mainstay of the country's economy and is dominated by small scale artisanal farming. The country's manufacturing sector is still in its infancy. These characteristics have implications on natural resources usage and exploitation with severe consequences on land degradation. More than 80% of the rural population use wood fuel for their domestic usage in comparison to less 10% of the population have access to hydroelectricity. In the recent times, severe environmental degradation within catchment basins of rivers where electricity is generated have hampered electricity supply efforts and it is imperative that alternative energy sources be found to widen access while curbing environmental degradation at the same time.

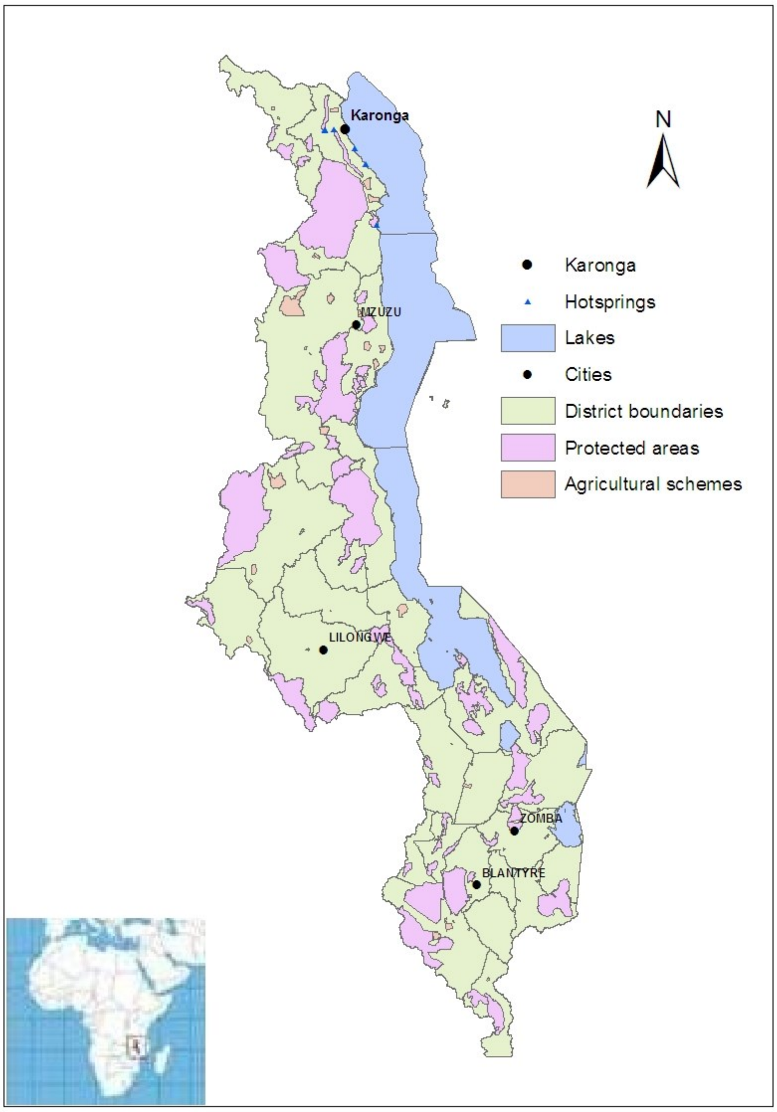

Figure 2: Schematic map of Malawi showing hotsprings, agricultural and protecting areas, and the studied area.

3. METHODOLOGY

The information and data presented in this paper is a compilation of published geological, geochemical and geophysical maps and scientific papers. The location of the hotsprings was documented by the Geological Survey of Malawi using Global Positioning System (GPS), published by Ray (1995) and Dulanya (2006).

Physico-chemical analyses were compiled from Bloomfield and Garson (1965); Ray (1975); Harrison and Chapusa (1975) and Dulanya (2006). Geothermometry analysis has been done by Dulanya et al (2010).

4. GEOLOGIC, TECTONIC AND SEISMIC SETTING

The general geology of Malawi is summarised in a report by Carter and Bennet (1973). The northern region of Malawi is mostly underlain by crystalline metamorphic and igneous rocks commonly referred to as the Basement Complex (Carter and Bennet, 1973) (Figure 3). The Basement Complex rocks were subjected to different periods of deformation namely the pre-1800 Ma Ubendian; the Irumide (ca. 1100 Ma) and the Mozambican Orogenies (700-400 Ma) (Ray, 1974; Schluter, 2006). During the Permo-Triassic times, the continental extension that eventually led to the split of the supercontinent Gondwana led to extensive faulting and development of long narrow troughs where various sediments were deposited. Examples of the Karoo formations include sandstones, limestones and mudstones with coal formations. The interval spanning from Jurassic to the present was associated with repeated periods of uplift, erosion and faulting. Several manifestations of these activities (Figure 2) are present within the rift scarp zone such as the following:

Dinosaur Beds consist of sandstones, shales and marls within narrow elongate basins oriented parallel to the Malawi Rift (Carter and Bennet, 1973), and rest unconformably on the Basement Complex rocks.

Sungwa Beds overlie the Dinosaur Beds and are separated by successive unconformities of Tertiary conglomerates and sandstones. They are thought to be of Miocene age.

Timbiri Beds consist of clays, grits, and conglomerates overlying the weathered Basement Complex rocks with a disconformity. These sediments were deposited in the localised grabens morphology which was produced during the Mesozoic and Tertiary due to rifting.

Chiwondo Beds overlie unconformably the Sungwa Beds comprising limestones, marls, sands and conglomerates, pebble beds and poorly consolidated sands and muddy sands of middle Pleistocene age.

Chitimwe Beds are of Pleistocene age and uncomfortably overlie the Chiwondo Beds. They consist of conglomerates at the base overlain by sands and gravels

Songwe Volcanics are of Pleistocene age and are considered to be the southern-most extension of the Rungwe volcanic province of southern Tanzania, They are found in the northern part of the country and were emplaced at a triple-junction where the eastern and western branches of the EARS converge.

Quaternary lacustrine sediments are well developed along the major drainage systems including Lake Malawi. These include alluvial sediments, pebble beds such as the Dwangwa Gravels, and the lacustrine sands and gravels of the lakeshore Plain which mark the retreat of Lake Malawi to its present position.

4.1 **Regional tectonics**

The western branch rift topography is characterized by long assymetric half-graben basins associated with steeply-dipping border faults (Ebinger et al., 1987; Specht and Rosendahl, 1989) concentrated within rocks of Precambrian age. The longest (~100 km) and tectonically active structure with evidence of surface rupturing events in 2002 is the Livingstone fault zone, a predominantly NW–SE striking normal fault which forms a high escarpment of about 2000 m. in the eastern edge of Karonga basin, where the deeper part of the basin is found (Scholz et. al., 1989; Specht and Rosendahl, 1989). Synthetic tilted fault blocks to the Livingstone fault show also evidence of surface rupturing events, for example the tectonic activity developed in the Karonga basin during 2009. Tilting in the Karonga basin extends 50 km, consistent with the Livingstone Fault extending to the base of the crust at 40 km (Biggs et al.. 2010). The western margin of the basin is bounded by the antithetic east-dipping Karonga fault which is surrounded by Precambrian rocks. The Livingstone fault influences greatly the regional tectonics, geomorphology and hydrology in northern Malawi. Although, the opening of the Tanganyika-Malawi rift was initiated some 12-8my BP, geological and structural evidence seems to suggest that the rifting followed some pre-existing structures from the older rocks. For example, the Cretaceous was a transition period between the Karoo rifting and the formation of the recent East African Rift system (Castaing, 1991). It seems that tectonics in the area have acted at different times, the oldest being at 2000 – 1400 m y; the youngest still active today. These are considered to be mainly due to the reactivation of NW–SE structures (Tiercelin et al., 1988), which resulted in the creation of NE–SW troughs (Castaing, 1991).

Different models of the tectonic evolution of rifting have been proposed for northern Malawi. Ebinger et al., (1984); Tiercelin et al., (1988) and Wheeler and Karson (1989) proposed extension occurring along a W/WSW-E/ENE, or a WNW/NW-ESE/SE direction, while Delvaux et al., (1992, 1998) and Ring (1992) proposed two successive phases of rift formation, a WSW-WNW extension and strike-slip motion, along a WNW/NW-ESE/SE direction where half-grabens and the basin morphology were formed, and a second phase where NW-SE oriented sub-basins were formed due to transtension while transpression led to localized uplifts.

The rift system in its present form is a Tertiary feature and individual grabens and tilted fault blocks are filled by terrestrial and lacustrine sediments.

Most of the hotsprings in the Karonga basin lie within or along the major NW – SE regional trending of the rift (Figure 3). It seems that the geothermal activity in the area is mainly controlled by faulting due to lack of volcanic activity in the area. Accordingly, a geothermal model based on Manzella (unpublished) in comparison to the regional stratigraphy is shown (Figure 4). Despite the lack of detailed data on the geology, geophysical measurement and heat flow data, some similarities in terms of tectonic and stratigraphic configuration, heat flow characteristics (hotspring temperatures e.g. Dulanya et al., 2010) between the northern Malawi and non-magmatic geothermal systems exist. However, detailed mapping is necessary in order to locate those surficial features that may indicate hidden or blind geothermal activity in the area.

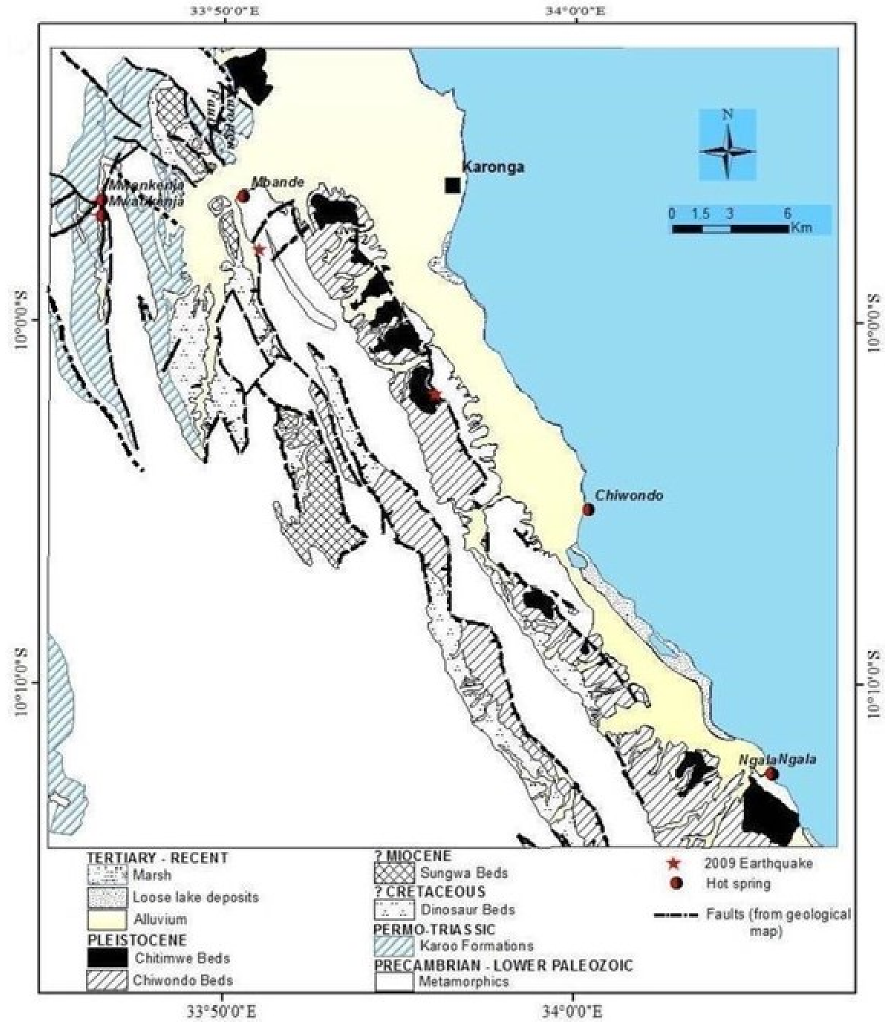

Figure 3: Generalized tectonic map of Karonga, Northern Malawi showing geology (after Ray, 1970, Thatcher, 1968); the 2009 earthquakes (after Biggs et al., 2010) and locations of some hotsprings (after Ray, 1975 and Dulanya, 2006).

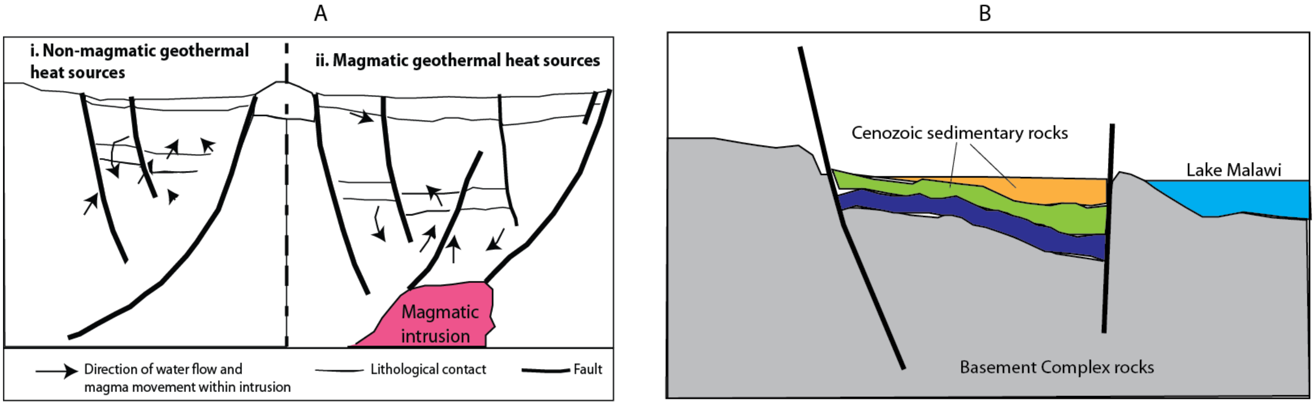

Figure 4: Proposed schematic section across the Karonga area of the Malawi Rift, Northern Malawi (after Manzella, 2009).

4.2 Seismology

The Karonga area is seismically active particularly in the extreme north and centre of Lake Malawi, where the seismic activity is characterized by moderate magnitude earthquakes. In 2002, an earthquake was reported by the Global CMT catalog in the Karonga basin and it corresponded to a normal faulting mechanism with a depth of about 20 km (Ekström et al., 2012). Biggs et al (2010) found that the orientation and location of this earthquake is consistent with rupture of a small path of the Livingstone fault.

In 2009, a sequence of earthquakes with magnitudes of about Mw ≤ 5.9 were recorded 50 km west of the rift-bounding fault within the hanging wall at a depth around 6 km. This area is characterized by a seismogenic layer of around 35 km (Ebinger et al. 1999). According to Biggs et al. (2010) the 2009 earthquakes showed a different style of faulting in comparison to the seismic events recorded in the Rukwa-Malawi rift zone were much deeper or unusual for active extensional regions. This seismic sequence demonstrates that the hanging-wall block is actively breaking up, reflecting temporal and spatial migration of activity or the release of stresses within it. Seismic reflection data interpreted by Mortiner et al. (2007) show that the hanging wall faults are synthetic to the border fault and dip steeper than 45º. Coulomb stress transfer in this sequence calculated by Fagereng (2013) found to be consistent with segmented slip on a fault system synthetic to a nearby border fault and restricted depths <12 km.

The strike directions of the 2009 events coincide with the strike of the hotsprings located in Table 1, suggesting that at least some faults or segment of faults accommodate Quaternary displacement in the area and this may contribute to development of permeability and provide pathways for upward circulation of hydrothermal fluids.

5. GEOTHERMAL ACTIVITY

Geothermal activity is manifested in several hotsprings (Table 1) in the studied area by the occurrence of cold/warm springs, steaming/gas bubbles and altered rock/grounds. These hotprings are mainly aligned along the major NW-SE faults which correspond with the major NW-SE rift trend that control the long-term development of northern Malawi rift basin (Delvaux et al., 2010) Sulphur deposits have been observed at Ngala and Mbande (Dulanya, 2006) which may be indicative of the presence of degassing magma bodies. Other manifestations in the form of gas bubbles have been found in several parts of the Karonga basin that may suggest geothermal activity.

Table 1: Chitipa-Karonga hotsprings.

Thermal springs	Manifestations	Location	Other	Source
Chinuka	Strong sulphurous smell	Breccias and quartz veins Minor fault parallel to Kaseye fault Paralell to the Mwanbuchilo river	Polluted	Ray, 1975
Mwankenja	Sulphurous smell Gas bubbles	Major N-S trending fault Banded biotite gneisses	Use for local purposes	Ray, 1975 Dulanya, 2006
Mwankenja	Sulphurous smell	Banks of Vungu stream N-S trending fault	Use for local purposes	Ray, 1975
Mbande	Strong sulphurous smell and sulphur compounds	Tributary of Rukuru river		Dulanya, 2006
Chiwondo	Sulphur smell Luke warm	Swamps western shore of Lake Malawi	Polluted	Dulanya, 2006
Ngala	Sulphur smell Yellowish sulphur compounds	Karonga		Dulanya, 2006
Mpata	Gas bubbles Strong sulphurous smell with steaming waters	N-S trending fault Tributary of the North Rukuru river.		Dulanya, 2006

The presence of surface manifestations in the area such as thermal springs, seismicity, fault features is evidence of a regional active tectonism in the region which may contribute to fluid flow. However, local mapping of the faults and superficial structures are necessary in order to understand better the relationship between faulting and geothermal activity.

Table 2 shows the results of the physico-chemical analysis of some hotsprings in the studied area. The results show that the fluids have high Na and HCO_3 contents which could be influenced due to the geological setting of the hotsprings. Other studies of the ionic strengths and saturation indices indicate that most of the hotsprings in northern Malawi are supersaturated (SI>0) with respect to chalcedony and quartz, and undersaturated with respect to calcite, dolomite, anhydrite and gypsum. Although most of the hotsprings in the Malawi Rift are within areas covered by recent superficial cover, the SI values may indicate that some of the hotsprings emanate from deeper lithological units and are suggestive of the geological formations through which these waters pass. For example, Mwankenja and Mpata hotsprings have SI>0 for calcium and magnesium. The alluvial cover in the areas where these springs are found is underlain by Karoo to Miocene and Pleistocene sedimentary sequences of high permeability comprising sandstones, marls and limestones (Carter and Bennet, 1973). In addition, these rock units are extensively jointed and faulted and contain constituents which are highly soluble in meteoric water.

A comparison between silica (quartz and chalcedony) and cation geothermometers (Na-K, Na-K-Ca and K-Mg) is shown by Dulanya et al. (2010), where the Na-K geothermometer shows that the hottest hotspring is Chinuka with a subsurface temperature of about 214^o C and a discharge temperature of about 29^o C. This may suggest a deep reservoir. According to the hydrochemical data, these springs are calcium-sodium-magnesium bicarbonate groundwaters just like those from the basement and alluvial aquifers as reported by Carter and Bennet (1973). However, these results indicate that some hotsprings have potential to generate adequate heat, which could be harnessed for energy generation upon further work to prove their viability.

Table 2: Selected physico-chemical analysis of some hotsprings (after Dulanya, 2006).

SPRING	T (°C)	pH	TDS (mg/l)	Ca	Mg	Na	K	Li	Cl	SiO_2	SO_4	HCO_3
Chinuka1	29	7.5	410	16	1.9	132	6.6	-	57	-	13.4	199
Chinuka2	-	8.1	360	18	3.5	134	10.5	-	57	-	27	171
Mwankenja1	-	8.2	440	5	12	108	3.1	.	32	-	37	226
Mwankenja2	53.4	7.8	482	6.8	6.2	324	4	-	22	70	10	-
Mwankenja3	50.1	8.5	-	<1	7	150	3.1	<0.2	22	42	75	271

Note: Chemical values in parts per million (ppm)

6. CONCLUSIONS

Low-temperature geothermal activity (< 60° C) occurs inside the active rift zone in Karonga basin, a 60 km wide basin bounded by long west-dipping faults (> 100 km). A segment of the border fault in the western part of the basin ruptured in an (Mw = 5) earthquake in 2002, while in 2009 several earthquakes Mw ≤ 5.9 were reported along synthetic faults to the border fault in the hanging wall. Both normal earthquakes in 2002 and 2009 and other structural features e.g. block tilting have been reported on land by e.g. Branchu et al. (2005); Biggs et al. (2010); Fagereng (2013) suggesting Quaternary vertical movements in the sedimentary basin. This corresponds to the Neotectonic period which is characterized by dextral strike-slip reactivation of NW trending rift faults (Delvaux and Hanson, 1993). NW – SE normal faulting seems to be the primary factor for geothermal activity in the basin, which corresponds to major rift trend that control the long-term development of the Rukwa and North Malawi rift basins. In addition to the NW – SE, widely spaced transversely oriented N - NNE striking faults dissect the NW – SE dominant strike in the area. The NNE faults breaks sometimes in several splays where the hotsprings appears (Figure 3). This may lead to a network of conjugated faults that may favour the conduction of geothermal fluids. In general, the results in this paper are similar to those observed in geothermal fields within the Basin and Range province in USA and western Turkey (Faulds et al., 2010) where quaternary faults control the geothermal activity.

Previous studies of the Na-K geothermometer shows that the hottest hotspring in the area is Chinuka with a subsurface temperature of about 214° C (Dulanya et al. 2010). This value is within the range proposed by Manzella (Figure 4). This spring is situated on a minor fault and rocks nearby contain breccias and quartz veins. Based on hydrochemical data, geothermal fluids in the studied area are classified as calcium-sodium-magnesium bicarbonate groundwater.

Although more local structural, stratigraphic, geochemical, geophysical and heat flow studies are necessary in order to develop, understand and enhance geothermal exploration in the Karonga basin, according to our results it seems that there is a strong correlation between the strike of the hotsprings, rock type, regional faulting and the seismic rupture in 2009, these will help to constrain the sources, reservoir rocks and fluid dynamics. The similarities of the geological setting with other geothermal fields (USA and Turkey) in active continental divergent zones suggest that the Karonga basin may have a great potential for geothermal energy but more studies are necessary in order to find the most suitable areas for geothermal exploration/exploitation.

ACKNOWLEDGEMENTS

The authors thank two anonymous reviewers for their helpful comments.

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