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EXPLORATION FOR GEOTHERMAL RESOURCES USING GEOLOGICAL STRUCTURES WITH EMPHASIS ON FAULTS - A CASE STUDY OF NORTHERN MALAWI

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ABSTRACT

Malawi has a number of geothermal occurrences that are manifested on the surface as warm and hot springs. The northern part of the country has the greatest potential in terms of geothermal occurrences and temperature hence the choice for this study. Structurally, the study area (northern Malawi) lies in the apparent meeting point of three major mobile belts that were formed during the three main Orogenic episodes. These episodes were associated with rifting and faulting of the crust. The movements resulted into formation of geological structures such as faults which are believed to have a direct bearing on the geothermal occurrences in the area. As such, a study was done to assess whether there is any relationship between faults and the occurrence of geothermal springs in the area and whether the faults can be used for geothermal exploration. The study showed that there are two main sets of faults with a general orientation of NE-SW and NW-SE and less pronounced N-S orientation in the area. It was further shown that there is a relationship between faults and the geothermal spring occurrences in the study area. It was established that, apart from being associated with the occurrence of geothermal springs, different types of faults also influence the temperature of geothermal springs in the study area. For instance, geothermal springs associated with border faults registered high temperature readings as compared to those that occur on ordinary faults. In addition to that, fault density analysis showed that areas with a high number of faults were also associated with high number of geothermal occurrences and fewer faults were also associated with less geothermal occurrences. Therefore, fault density analysis can be used to predict areas of geothermal occurrence which means that geological structures such as faults can be used for geothermal exploration in areas of similar geological setting especially in areas where geothermal occurrences are fault controlled.

1. INTRODUCTION

Geothermal Systems are defined as all parts of the hydrological system involved, including the recharge zone, all subsurface parts and the outflow of the system (Loksha, 2002). When these geothermal systems are contained in the earth's crust and become usable by man, they are referred to as geothermal resources (Dickson et al., 1965). The geothermal systems of the northern part of Malawi have been known since 1890s (Dulanya, 2006). They are mostly manifested in form of warm and hot springs. Recently, geochemical exploration activities have been conducted country wide to determine the geothermal potential of Malawi. For instance, Dulanya et al., (2010) conducted a study on comparison between silica (quartz and chalcedony) and cation geothermometers (Na-K-Ca and K-Mg) of some selected geothermal spring areas. In addition to that, Geothermal Development Company (2010) carried out a geochemical study to assess the geothermal potential using geochemical characteristics of geothermal spring waters. The results indicated a subsurface temperature of 169 to 245 degrees Celsius for most springs and the temperature range of 245 to 249 degree Celsius for northern Malawi springs. The studies were mainly done on already known geothermal sites.

The previous studies have indicated that the geothermal springs in Malawi are structural controlled as such this study was aimed at using faults to delineate potential areas of geothermal springs in order to use it as a tool for geothermal exploration.

2. STUDY AREA

The study area is located in the northern part of Malawi and covers the districts of Karonga, Rumphi, Nkhatabay as well as the northern part of Nkhotakota districts (Figure1). Malawi lies within latitudes 9^0S and 18^0S and longitudes 32^0E and 36^0E (Dulanya et al., 2010).The area has over 12 known geothermal springs (Figure 2) with different surface temperature ranges. Previous studies on geothermal indicated that this area has a lot of potential as compared to the rest of the country. For instance geothermal springs with highest temperatures were recorded in this area. However, few studies have been done on these geothermal springs due to lack of technical capacity and financial resources. The study area also falls within the western branch of the East African Rift System (EARS). As such, the tectonics associated with it are much reflected in its geography and geology most notably in the deep graben or trough manifested in the Lake Malawi (Gondwe et al., 2012).

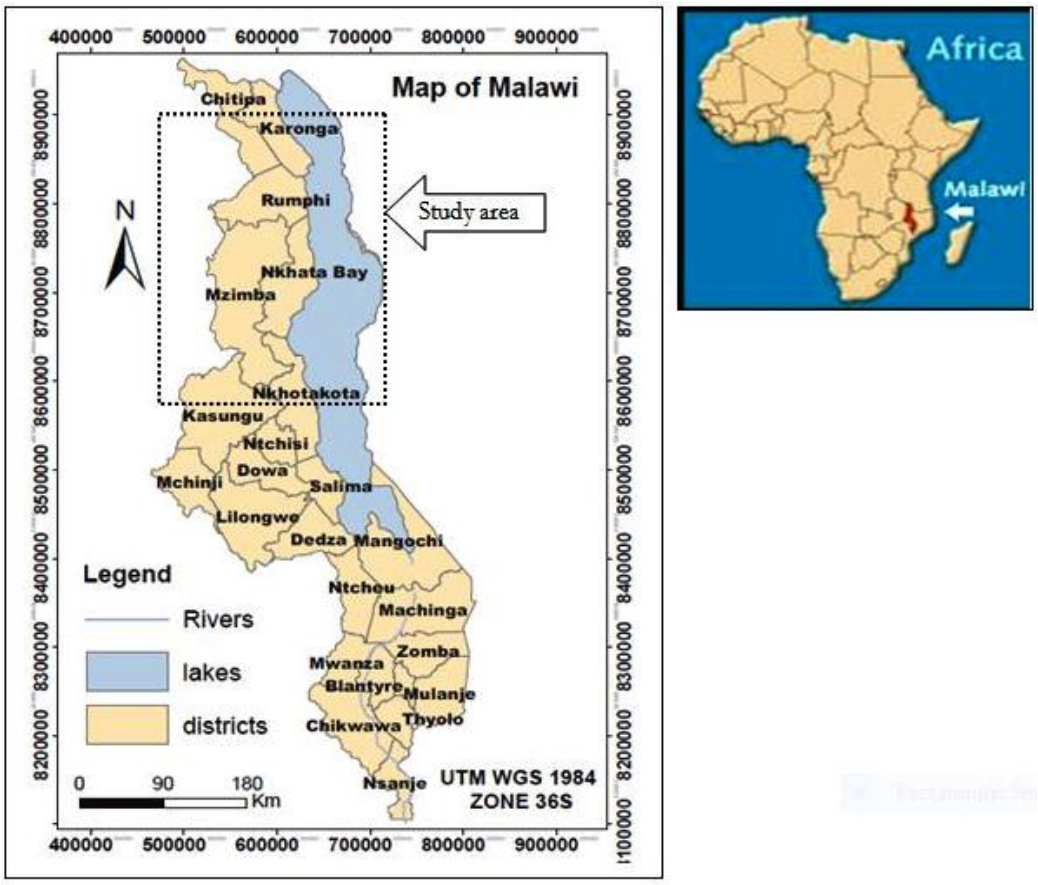

Figure 1: Map of Malawi showing the study area in dotted lines and Africa (insert) showing location of Malawi.

2.1. Geothermal surface manifestations in the study area

Like other countries within the EARS, Malawi has also a number of geothermal systems that are undeveloped. Previous geothermal exploration activities, unveiled a number of geothermal resources that are manifested on the surface in form of warm and hot springs. The surface water temperatures range from 30-80^{0}C and estimated subsurface temperatures (from geochemistry) of more than 200^{0}C (Dulanya et al., 2010). Geothermal surface manifestations entail how geothermal system indicators are expressed on the surface. In the study area, geothermal surface manifestations mainly occur in form of geothermal springs.

3. GEOLOGICAL SETTING OF THE STUDY AREA

The northern part of the study area where Mwankenja (1 and 2), Mpata and Ngara are located, is geologically underlain by gneisses, schist and granites of the Malawi Basement Complex of Precambrian to Lower Palaeozoic age. In the western and central portions, there are scattered Karoo sediments. Tertiary sediments occur on the lake shore plains and a general superficial cover of residual soils, particularly on the western plains (Ray, 1975). The Rumphi-Nkhatabay area where Chiwondo, Chiweta, Kanunkha, Chiyawa, Movya, Chilunguza and Chiwi springs are located is underlain by gneisses, schist and granites of the Malawi Basement Complex of Precambrian to Lower Palaeozoic age. The gneiss rocks found in the area are mainly biotite and biotite garnet gneiss, biotite sillimanite gneiss, and calc-silicategneiss(Carter et al,.1973) (Figure 2)

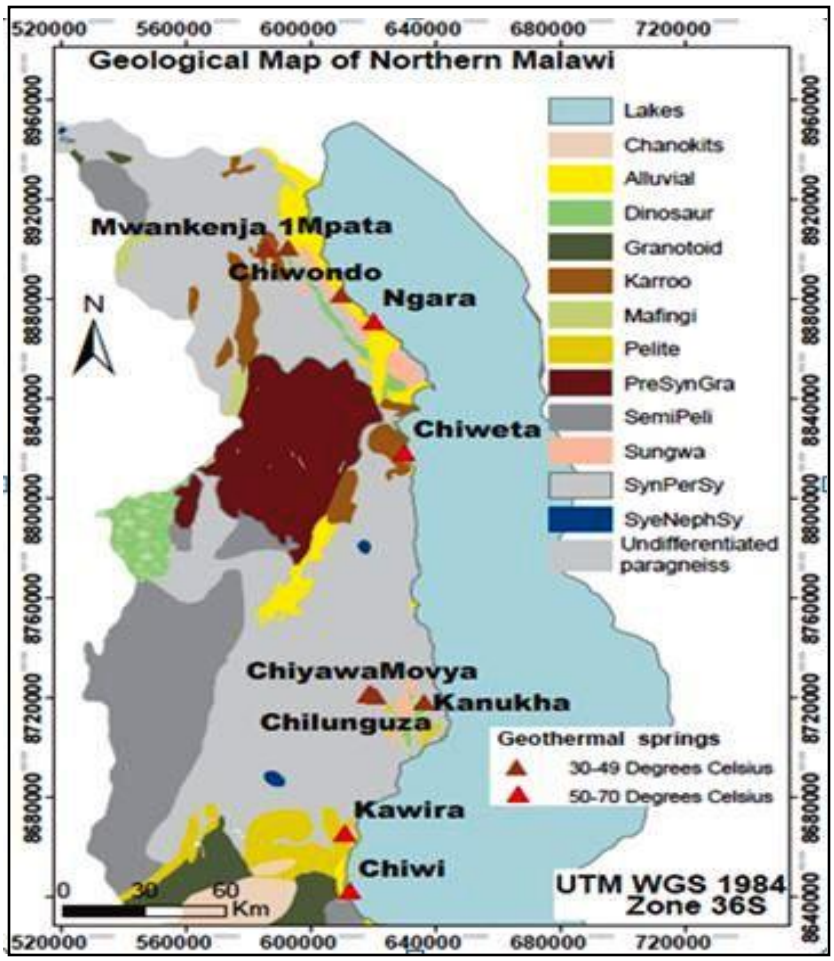

Figure 2: Geological map of northern Malawi showing geothermal springs and their locations

4. STRUCTURAL SETTING OF THE STUDY AREA

Structurally, the study area is located at the apparent meeting point of three major mobile belts that were formed during the orogenic episodes. The orogenic episode was followed by rifting and faulting within the Malawi rift. The first mobile belt is known as the Ubendian Belt of Tanzania (Figure 3A). The Ubendian Mobile belt originates from the south-western Tanzania (Ray, 1975) and it extends into Malawi in a south-easterly trending pattern. This was characterized in Malawi by a NW – SE trending pattern. It is well pronounced in the Northern Malawi and resulted into the formation of geological structures with trending pattern of NW –SE.

The second mobile belt is known as the Irumide Belt of Zambia (Figure 3B). The Irumide Mobile belt is made up of reworked Ubendian Basement (Ring, 1993). It is well pronounced in the Northern and Southern province of the Malawi Rift and is characterized by geological structures which have a general trending pattern of NE – SW direction (Carter et al., 1973). Finally, the third one is known as the Mozambique belt of East and Central Africa (Hopkins, 1973) (Figure 3C).

The Mozambique is the last mobile belt that affected the country and northern Malawi. This mobile belt caused deformation of the Basement Complex rocks which resulted into folding and movement along shear zones which are oriented parallel to the structures of the Ubendian belt (Ray, 1975). It approximately run in a N - S trending pattern (Ring, 1993).

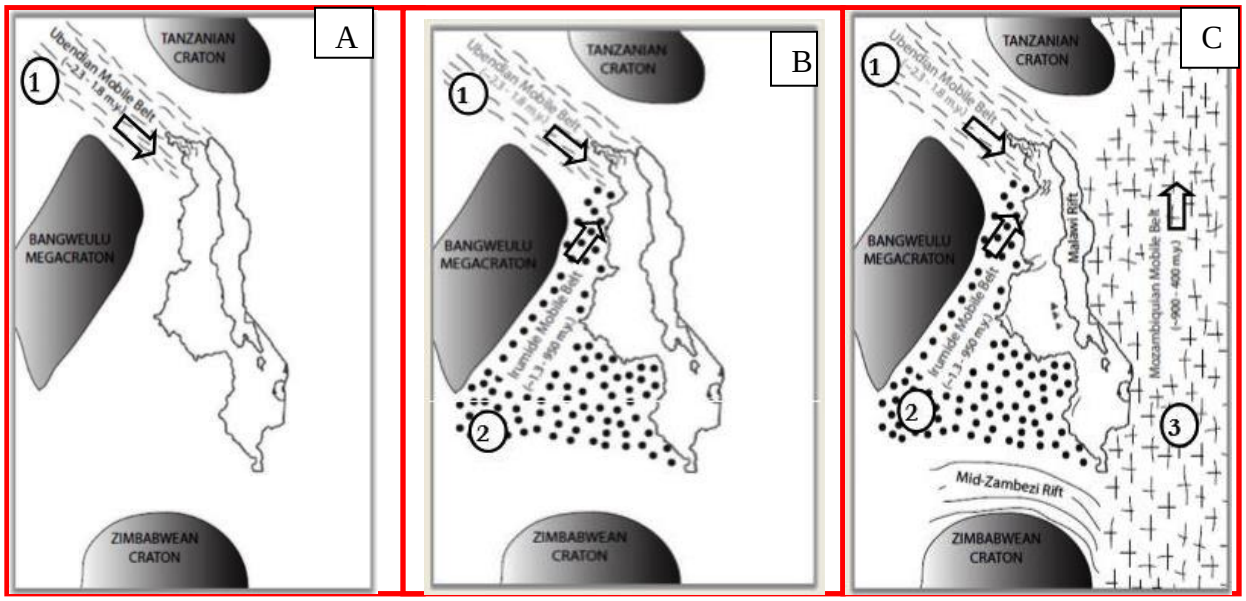

Figure 3 (A): Schematic diagram of the Ubendian Mobile Belt dated ~2300 – 1800 m.y. It is depicted as the first and oldest mobile belt within the Malawi Rift. Black circle with number indicate sequential order of the belt and black arrow indicate direction of the belt. (Source: Carter & Bennet, 1973; Roberts et al., 2012).

Figure 3 (B): Schematic diagram of the Irumide Mobile Belt dated ~1350 – 950 m.y. It is the second mobile belt that followed the Ubendian. Black circles with numbers indicate sequential order of the belts and black arrows indicate direction of the belts. (Source: Carter & Bennet, 1973; Roberts et al., 2012).

Figure 3 (C): Schematic diagram of Mozambiquian Mobile Belt dated ~900 – 400 m.y. Black circles with numbers indicate sequential order of the belts and black arrows indicate direction of the belts. (Source: Carter & Bennet, 1973; Chapola, 1997; Roberts et al., 2012).

After the orogenic episode, the rifting episode followed and initiated the formation of Malawi rifting which caused normal faulting which is a characteristic of Lake Malawi and also other rifting structures associated with rifting (Chapola, et al., 1992). The geothermal systems in Malawi seem to be influenced by these tectonic activities within the Malawi rift. The study area is highly faulted because of the rift faulting process that affected it as evident from its active seismicity. Some of the known faults in the area include the Livingstonia border fault to the eastern side of Karonga, the Karonga faults and the Karroo faults which define the Karroo basins. Many faults in the study area are associated with a general NW-SE and NE-SW as well as N-S trending pattern (Figure 8-1). Faults play a major role in the geothermal system because they provide major conduits for meteoric water to circulate to depth and get heated by the elevated geothermal gradient and return to the surface(Carranza et al., 2008).

In addition to that, the study area is also seismically active. The movements that occur along the rift faults are responsible for the seismicity in the area. Majority of earthquakes occur along the faults that are situated on the margins of the rift (Chapola et al., 1992). The recent earthquake in the study area occurred on 19th December 2009 with a magnitude of 6.2 (Macheyeki et al., 2015). This could have a direct bearing on the geothermal springs because active seismicity maintain an open conduit of flow through continuous fault slip by preventing healing of the fault through mineral deposition(Anderson et al., 2013).

5. RELATIONSHIP BETWEEN FAULTS AND GEOTHERMAL SPRINGS

The relationship between faults and geothermal springs in the study area was evaluated by using rose diagrams, field based faults as well as fault density analysis.
The faults are believed to have a bearing on the geothermal occurrences in the study area(Ray, 1975). As such, it was necessary to establish their relationship with the geothermal springs. Rose diagrams were used to assess the general orientation of faults and also confirm what other authors indicated in their studies, while faults density analysis was used to assess the density of faults in the area.

5.1. Methodology

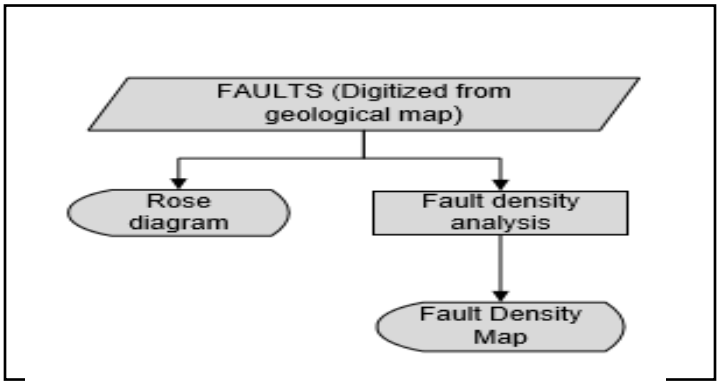

Figure 4: Methodology flow chart

5.2. Faults

The faults were digitized from the geological map of Malawi using Arc GIS software 10.2 and a shapefile was created. It was displayed on SRTM data to see how it correlates spatially with the structural features (Figure 5A). The shapefile containing faults was exported from Arc GIS to PCI Geomatica software and saved as AutoCAD vectors in a data interchange file (DXF) format in order to be compatible with Rockworks software where the rose diagrams were plotted. The rose diagram (Figure 5B) was plotted in rockworks using the linear algorithm under the utilities function.

5.3. Rose diagrams

A rose diagram is a circular histogram plot which displays directional data and frequency of each class (Prabu et al., 1964). These diagrams have been used in many studies to define structural trend. For instance Chenrai, (2012) used rose diagrams to interpret geological structures in Koh Samui area in gulf of Thailand. Further, Prabu et al., (2013) used rose diagrams to analyse orientation of lineaments in the mapping of Lineaments for groundwater study in India.

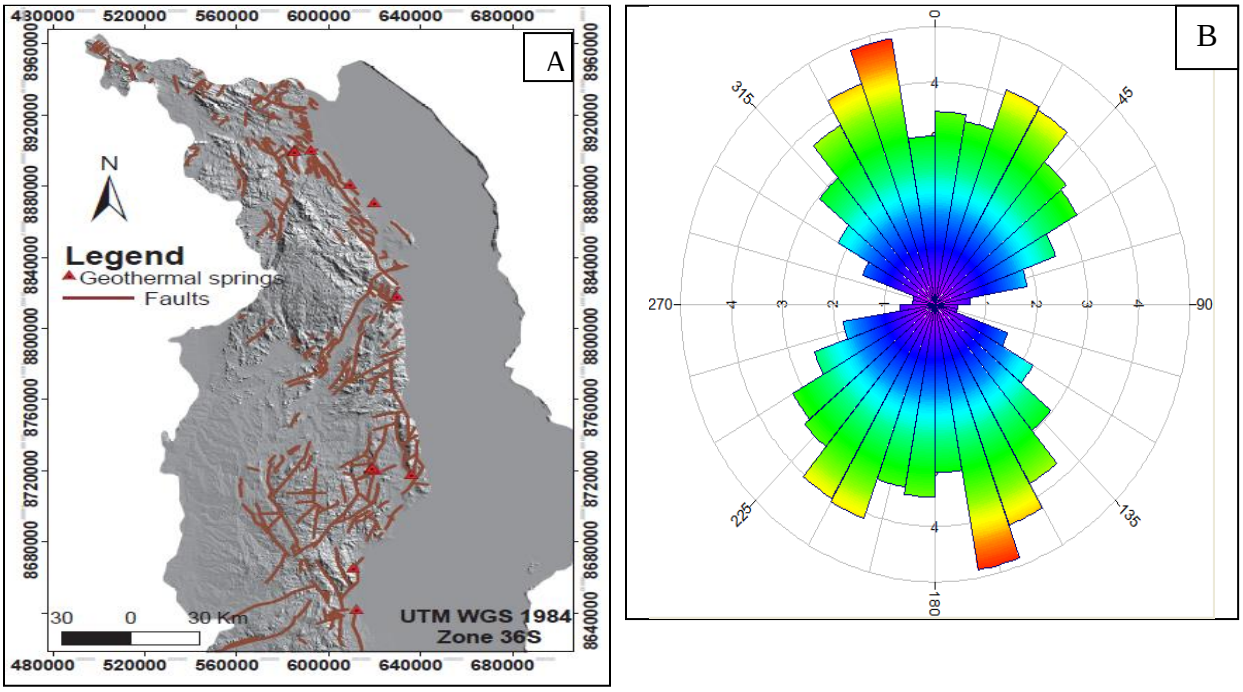

Figure 5 A & B: (A)Field based faults overlain on SRTM DEM,(B) Rose diagram, showing two main prominent NE-SW, NW-SE trending pattern and less prominent NS trending pattern

5.3.1. Results

The results from the rose diagram have shown that there are two main NW-SE and NE-SW general orientation of the faults in the study area and less pronounced N-S orientation (Figure 5B). This means that most of the faults in the study area are oriented in the NW-SW and NE-SW direction. However, the results also indicated that there are also some faults that have a N-S orientation hence the less pronounced N-S orientation was also observed. As discussed earlier, these trending patterns were influenced by the three major Orogenic processes that affected the area. Therefore the general trending patterns of faults that are associated with geothermal springs in the study area can be described as NE-SW, NW-SE as well as N-S.

Furthermore, it was also observed in the field that almost all the geothermal springs are either bordered by faults or located along faults which justifies that they might be highly controlled by these faults.
The results correlate well with the field observations as well as literature(Ray, 1975, Carter. et al., 1973).

5.4. Fault sets associated with geothermal springs

The study also tried to establish the actual sets of faults that are associated with geothermal springs in the study area. As such, known geothermal springs, border faults and major faults were overlain on SRTM

DEM in ArcGIS. The results showed that the geothermal springs are mainly located within the major faults especially the northern part and partly central areas while in the central and southern part are located within border fault zones(Figure 6). Therefore, it can be deduced that the geothermal springs in the area are controlled by two sets of faults which are the border and major faults. Both of the two fault sets belong to rifting tectonic events (Carter and Bennet, 1973). Furthermore, it was also observed that according to previous studies (Dulanya et al., 2010) highest temperatures were recorded on geothermal springs located on border faults (Figure 6)

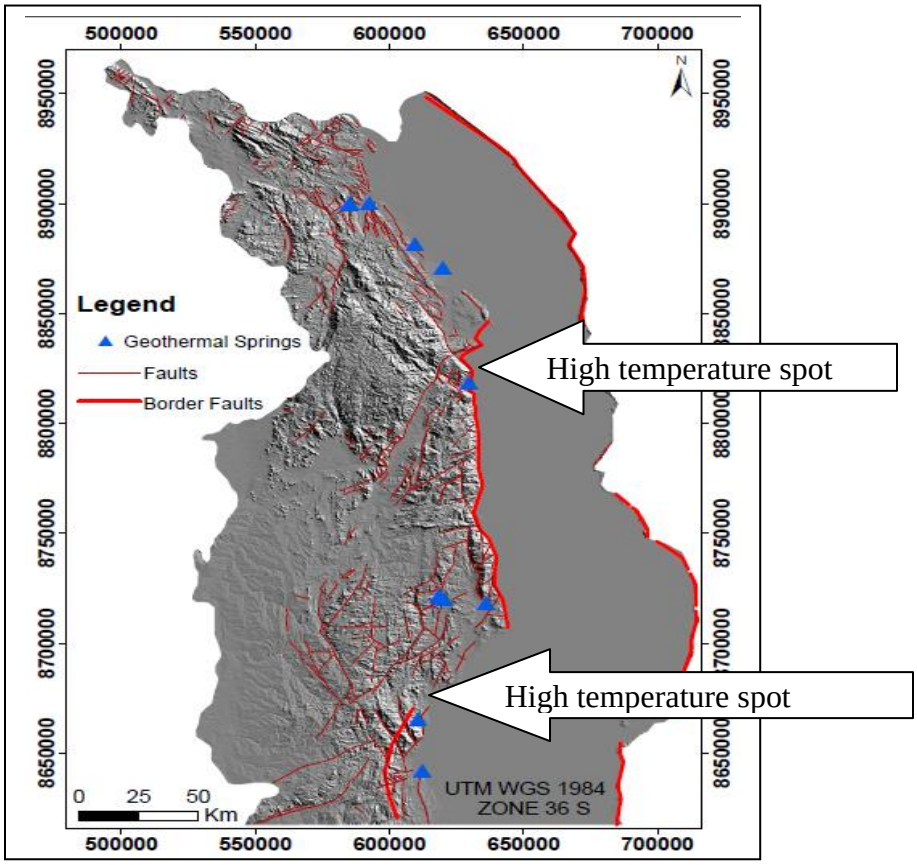

Figure 6: Known geothermal springs, border faults and major faults overlain on SRTM DEM (arrows show areas where higher temperatures were recorded, Figure 2)

5.5. Fault density analysis

Fault density refers to the total number of faults per unit area, thus areas with more faults per unit area are considered as high fault density areas hence high density zone while those with few or less faults per unit area are considered as low fault density areas hence low density zones. Fault density analysis is a method that is used to calculate the number of faults per unit area(Wibowo, 2010). Faults are important in geothermal studies because they are considered as potential permeable zones where thermal fluids flow from the reservoir at depth to the upper levels. As such, areas with more faults and cracks are considered as high fault density areas. These areas are considered as having more potential and they are target for geothermal drilling(Prabu et al., 2013). Fault density is used in geothermal exploration to locate highly fractured areas that are assumed to be associated with geothermal reservoirs at depth (Anderson et al., 2013). A study conducted by Wibowo (2010) showed a good correlation between fault density and geothermal manifestations. Since the study area is located within Malawi rift which is believed to be

tectonically active with many faults (Ray, 1975), fault density analysis was done in order to find out the relationship between the presence of faults in an area and the occurrence of geothermal springs. Fault density analysis was calculated using the line density option under spatial analyst tool in arc GIS. The software simply counts the number of faults per unit area. Areas with a high number of faults per unit area were identified as high density areas followed by medium and low density zones. Different colours and contouring were used to highlight boundaries between areas of different densities (Figures 7).

5.5.1. Results

The results from the fault density analyses showed that the study area has high, medium and low fault density zones (Figure 7). When geothermal spring points of known locations were plotted on the map it was shown that, 6 geothermal springs occur in high density areas, 5 in medium density areas and 1 in low density zone (Table 1). In terms of percentage, it means that out of 12 geothermal springs in the study area 50% of them occur in high density areas, 42% in medium density areas and 8% in low density areas (Table 1).

Table 1: Geothermal spring areas and their location in relation to fault densities

Number	Geothermal spring	Fault density area
1	Chiwi	Medium
2	Kawira	Medium
3	Kanunkha	High
4	Movya	High
5	Chiyawa	High
6	Chilunguza	High
7	Chiweta	Medium
8	Ngara	Low
9	Chiwondo	Medium
10	Mpata	Medium
11	Mwankenja I	High
12	Mwankenja II	High

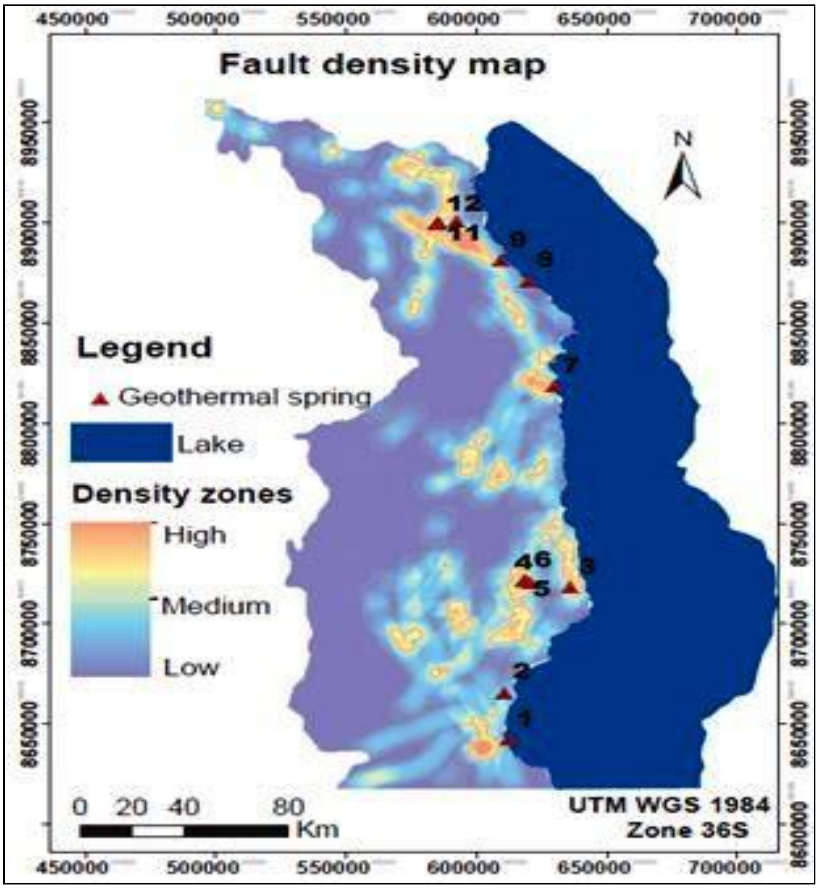

Figure 7: Fault density map showing high, medium and low density zones. (Numbers on the map represent known geothermal spring locations and correspond to those shown in table 1).

6. DISCUSSION

The study has shown that, faults in the study area have two main NW-SE and NE-SW general orientation and less pronounced N-S orientation. However, it was also noted that the general occurrence of geothermal springs mainly follows a similar trend.

It was also observed that the geothermal occurrences in the study area are controlled by two sets of faults namely major and border faults. After comparing the results with those from previous studies, it was noted that high temperature geothermal springs were also recorded on geothermal springs located within border faults zones as compared to ordinary or major faults. This could be attributed to the fact that border faults tend to extend deeper into the earth's crust hence closer to magma chamber as compared to the ordinary or major faults. Such being the case, those prospecting for high temperature geothermal springs in the study area can target areas located within border fault zones.

Furthermore, fault density analysis showed that geothermal springs mainly occur in medium and high fault density areas (Figure 7). These areas are also found within the rift system of Malawi which is an

indication that, the geothermal springs are fault controlled. Medium and high fault densities areas have high concentration of geothermal springs because they provide a conducive environment for their occurrence. Faulds et al., (2008) indicated that faults and fractures are permeable zones where meteoric water and thermal fluids circulate. This also means that prospecting for geothermal resources in the study area should be mostly done in areas where faults are concentrated.

7. CONCLUSION

In conclusion, the study has shown that it is possible to use geological structures such as faults to delineate potential areas for geothermal exploration especially in areas where the geothermal resources are structurally controlled. This technique can also be applied to other areas of similar geological setting.

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