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GEOLOGICAL LIMITATIONS OF A GEOTHERMAL SYSTEM IN A CONTINENTAL RIFT ZONE: EXAMPLE THE ETHIOPIAN RIFT VALLEY

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ABSTRACT

In an active rift like that of Ethiopia, rifting is preceded by volcanism and doming. These are effects of the deep-rooted mantle up welling or "plume". The process is continuous even in the developed rift, particularly in its axial part.

This situation has a strong effect on the stratification of the rocks, situated on both sides of the rift axis. That is, due to the up doming at the axial part, the rocks are remarkably inclined outwards of the axis in both directions. The rift margins being the highest picks, the general slope of the whole dome is outwards of the rift, hence it controls the regional drainage and the ground water flow. The strong inclinations of rock beds can be easily observed on global scale topographic maps, images and is clearly indicated by the regional distribution of the basement and volcanic rocks of Ethiopia. This is again reflected on the drainage pattern i.e., the most important rivers in the Northwestern Plateau flow to the northwest and those on the Southeastern Plateau flow towards southeast, in both directions away from the rift. Therefore, water circulation both on the surface and in subsurface at the axial parts of the rift is minimal. The axial part of a rift is hotter than the marginal and external parts. To have a geothermal system, there needs to be a heat source and a good recharge together with an aquifer and a cap rock. These conditions could be fulfilled, except for the recharge, in the axial part of a rift.

A second limitation for a geothermal system in a Continental Rift Zone is the block forming nature of the fractures or faults that allows fluid circulation only along the weak zones. Deep geothermal exploration wells in the Main Ethiopian rift (Aluto-Langano) and Afar (Tendaho) geothermal fields have proven the existence of high temperature (sometimes more than 350°C), but relatively small amounts of steam production.

1. INTRODUCTION

1.1. Generalities

The necessary conditions for the existence of a geothermal system are heat source, a permeable reservoir rock, recharge of the ground water and a cap rock. If one of these parameters fails, then it should either be compensated by an artificial means or other alternatives areas should be explored.

In a Continental Rift Zone (CRZ), such as the Ethiopian rift, there can be many areas that have big heat sources, but usually one of the above mentioned parameters are lacking, hence the natural geothermal system remains infeasible. The most common factors for the low success or failures of the geothermal exploration in the Ethiopian rift are the absence of a permeable aquifer and lack of ground water recharge.

1.2. Scope of the work

The main aim of this work is to create an awareness and understanding among the geoscientific community who are engaged in the research and development of a geothermal and ground water potential in CRZs, such as the Ethiopian rift. Once the regional set-up of the rift system and the associated dome is well understood, then the effects on the surface and sub-surface water circulation can be seen and areas of maximum potential for geothermal and ground water resources can be delineated.

2. THE ETHIOPIAN DOME AND ITS RIFTS

The East African Rift System (EARS) separates the Horn of Africa (Somalian Plate) from the rest of Africa (Nubian Plate). The EARS splits in to two at about N35° to the Western and Eastern branches. The Eastern branch comprises the Kenyan and Ethiopian Rifts, (Fig. 1).

The Ethiopian Dome (Afro-Arabian Dome) extends from the southern border of Ethiopia to the Yemen in the north. It is elongated in the NE direction (Fig. 2) and dissected by the Red Sea, Gulf of Aden and the Ethiopian Rifts forming a triple junction at the Afar triangle. The Ethiopian Rift is further sub divided in to the Afar Rift and the Main Ethiopian Rift (MER) at about N8°20' (Fig. 1 and 5).

The Ethiopian Rift forms a funnel shape decreasing in width to the south from more than 100 to about 40 km.

The axial part of the Rift is indicated by the alignment of recent and acid central volcanoes. Alignment of the central volcanoes generally strikes NNE with a dextral en-echelon displacement (Fig.6).

2.1. Physiography

Ethiopia can be divided in to 3 major physiographic regions, these are, 1) the Northwestern Plateau and low lands, 2) the Southeastern Plateau and lowlands and 3) the Rift Valley (Fig.2). Maximum elevation difference is registered between the highest peak of Ras Dashin (4550 m above sea level) on the north-western Plateau and the Lake Asal in the Dallol Depression (120 m below sea level).

Generally the Rift margins are the most elevated areas in the Ethiopian dome. These suddenly drop to the Rift from more than 2500m a.s.l. to less than 1600 m a.s.l. Elevation also decreases gradually from the Rift margins out wards both to the Northwest and Southeast away from the Rift (Fig.2).

On both flanks of the Dome there are deep canyons excavated by the major rivers. In addition there are many scud volcanoes (attaining a height of 3000 – 4550 m a.s.l) on the Plateau that

have pronounced the elevation difference formed by the river canyons. Due to these factors a spiked topography can be observed in the central parts of Ethiopia.

2.2. Drainage pattern

Ethiopia has many important rivers among which 13 are the most important. Almost all these rivers start from the Rift margin and drain away from the Rift to the Southeast and Northwest. The major rivers that flow to the Southeast are Fanfan, Wabi Shebele, Genale, and Dawa. Those that flow to the Northwest are Akobo, Baro, Abay, Tekeze and Mereb (Fig.3).

There are two important rivers that do not follow the above-described general pattern. These are Awash and Omo rivers, which flow in to the Rift Valley flowing to the Northeast and south respectively. The reason that Awash and Omo flow in to the Rift unlike all the other major rivers is due to some anomalous structures which cross-cut the Rift margin. In the case of Awash, it is the east-west running transtensional structure known as Yerer-Tullu Wellel Volcano Tectonic Lineament (YTVL) (Abebe et al., 1995), which cuts the western margin of the MER at the latitude of Addis Ababa and flows into the rift. The western margin of MER between 8° 20' and 9° (latitude of Addis Ababa) is not in fact well defined (Morton et al., 1979, WoldeGabriel et al., 1990) for the above reason. Tributaries of Awash either start from the Rift floor or the internal side of the Rift margin. The Omo River on the other hand drains from the southwestern part of the Western Plateau and to the northern part of the Kenyan Rift. The interruption at the limit between the Ethiopian and Kenyan Rifts together with the limited amount of up-lift of the Dome and the thinner volcanic pile have allowed Omo River to flow into the Rift.

Chernet (1993) estimated the total annual amount of runoff from the major rivers to be about 104 billion m^3. Most of the water drains away from the rift. This is mainly due to the significant inclination of the surface formed by the Ethiopian Dome. High relief areas have higher ground water table and the gradient towards the low lands is also high.

The drainage pattern in Ethiopia is controlled by the three important fracture systems. These are related to the Red Sea, Gulf of Aden, and Ethiopian Rift systems, following NW - SE, E - W and NE - SW respectively. The central volcanoes and other circular collapse structures form local radial drainage patterns.

2.3. Lithological set up and general beddings

The major rock units within the Ethiopia Dome can be most simplified to: 1) the Precambrian metamorphic basement, 2) the Mesozoic sediments and 3) the Tertiary – Quaternary volcanics and associated sediments (Fig.4).

Since in the process of an active rift formation, up doming precedes volcanism and rifting, all the oldest rocks, including the Precambrian basement and the Mesozoic sediments are thought to be up-lifted to at least 1500 m (Fig. 5). Nevertheless, progressive doming, volcanism and rifting took place at the axial zone of the Rift until present, hence including the young volcanic and associated sedimentary rocks are inclined outwards of the Rift axis. The regional inclination of the rocks related to the up doming, might not be easily measured in the field. This is due to the global scale of the Dome and local structures like foliation in the metamorphic rocks, sedimentary stratification, and local volcanic flow bedding in the sedimentary and volcanic rocks respectively will mask the inhomogeneous and gently inclined surface of the Dome.

3. GEOTHERMAL RESEARCH IN ETHIOPIA

Geothermal studies in Ethiopia started back in 1969 by the Ethiopian government in collaboration with the United Nations Development Program (UNDP). A regional reconnaissance work was conducted in the whole Rift, including geology, geochemistry, hydrogeology, and remote sensing (infrared imagery) (UNDP, 1973). This work led to the selection of the most promising areas such as the Dallol, Tendaho, Aluto-Langano, Corbetti, and Abaya (Fig.6).

Geothermal exploration did not continue in the Dallol area for various reasons, like the very high brine content of the hydrothermal fluid, security problems during the exploration period and the long distance from the major towns of northern Ethiopia to utilise the energy.

3.1. The Main Ethiopian Rift

The Main Ethiopian Rift is bounded between about N5° and N8°20' within the Ethiopian Rift. Areas with Quaternary central acid volcanoes and manifestations were first selected for geothermal exploration. These were Aluto, Shalla, Corbetti, and Abaya area.

Detailed geological geochemical and geophysical studies were carried out in Aluto and Corbetti. Shallow Temperature Gradient (TG) wells drilling were also conducted to asses the subsurface temperature, fluid chemistry, permeability and other geophysical parameters. At last Aluto-langano geothermal field was further developed and deep geothermal wells were drilled.

Aluto-Langano Geothermal field

Aluto-Langano was the first Ethiopian geothermal field that was studied in detail and promoted for deep exploration drilling 1981. The site is located at about 200 km southeast of Addis Ababa on the way to Kenya. 8 deep wells (LA1 – LA8) were drilled between 1981 and 1986.

LA1 and LA2 were drilled at the southern and western edges of Aluto volcanic complex respectively. Then exploration shifted to the top of the volcano and the remaining 6 wells were sited on top of Aluto, since the first two wells were found to have low temperature and permeability. LA3 and LA6 were drilled following the most active fault system (Wonji Fault Belt (WFB), Mohr, 1967a) and these were found to have a maximum temperature of 315 and 335°C respectively. In addition high enthalpy was registered in these wells (about 1650 kj/kg, ELC 1985 and 1986).

LA4 and LA5 were drilled to the east, and LA7 and LA8 to the west of the WFB zone. All the wells were productive except LA5, but with lower heat and enthalpy as compared to LA3 and LA6, (ELC, 1986, and Endeshaw, 1988).

3.2. Southern Afar

Southern Afar is bounded between N8°20' and about N12°, within the Ethiopian Rift. Areas with central acid volcanoes in the axial part of the Rift and where there are hydrothermal manifestations were sites of the preliminary geothermal exploration. In these areas regional geology and geochemistry were carried-out. Among the selected areas were Tendaho, Ayelu, Dofan, Fantale, Nazret, Gedemsa and Tullu Moye (Fig.6).

Among these areas, Tendaho, Fantale, Gedemsa and Tullu Moye were chosen for second phase detailed studies of geology, geochemistry and geophysics. Based on the data obtained shallow TG wells are drilled in Tendaho and Gedemsa geothermal prospecting areas. Further more Tendaho was promoted to deep geothermal exploration drilling.

Tendaho Geothermal field

Tendaho is located at about 600km Northeast of Addis Ababa on the way to Assab and Djibouti, in the centre of the Afar triangle. Between 1979 and 1980 detailed exploration was conducted in Tendaho and 6 deep exploratory wells (TD1 – TD6) were drilled between 1993 and 1998. TD2 and TD4 are drilled from one platform and TD4 was drilled inclined to meet a young fault zone. TD1 is also drilled at about 1 km to the north of these wells. The highest temperature recorded was 270 °C in TD1 at a depth of about 1000m. Nevertheless, permeability was very low as compared to the other two wells that were drilled only to about 400m. (Aquater, 1996). Therefore, Tendaho geothermal exploratory wells indicate us that permeability away from the active fault zones is poor and fluid circulation in a young rift like Tendaho is limited.

4. DISCUSSION

All fields for geothermal energy exploration in Ethiopia are located within the Rift and are along the axis in almost all cases. As mentioned in section 2.3, the axial part of the Rift is uplifted as compared to the marginal parts. Recharges of the geothermal systems from the marginal parts of the Rift are therefore very difficult. More over, precipitation in the axial parts of the Rift is scarce.

Recharge from the Plateau is localised to some anomalous areas, such as:

1) when the Rift margin is crosscut by transversal structures such as the Axum-Adwa, YTVL and Goba-Bonga lines, (Fig.1),
2) the southern end of MER, where the Rift gets diffused and the margins are not strongly uplifted.

Therefore, in general the central (axial) part of the Ethiopian Rift and probably all CRZs are hot enough but relatively dry.

Primary permeability of volcanic rocks is generally low except for some coarse grained and unconsolidated pyroclastic rocks. Secondary permeability in hard lava flows is generally good but the Rift fracturing is usually in blocks form, hence fluid circulation is only limited to these joints.

Unlike the poor permeability and inadequate recharge of the Rift, the heat generated under the recent acid central volcanoes, by their differentiating and crystallising magma chambers is proved to be sufficient, (see sec. 3.1). It is therefore important to note that geothermal exploration in the Ethiopian Rift or the CRZs in general, is limited to some anomalous areas not only for the temperature but also for the recharge and permeability.

5. RECCOMMENDATION

In a CRZ like that of Ethiopian Rift, heat is readily available. It is the recharge and permeability that are scarce as compared to geothermal systems of other plate boundaries. Therefore, anomalous areas like the Awash and Omo river basins are recommendable for geothermal and ground water exploration in the Ethiopian Rift.

The NW and SE flanks of the Ethiopian Dome are expected to have high ground water potentials, since the general surface and subsurface water flow is towards these directions. Filling of Lake Tana in a small graben at the NW foot of the Ethiopian Dome and position of the source of the Abay (Blue Nile) river can be explained by the same reason. Therefore, it is worth noting that the area around the Tana Rift is rich in ground water and low enthalpy geothermal energy can also be expected, since recent volcanic activities are reported (Kazmin , 1973, and Merla et al., 1973).

To realise better the effects of the Ethiopian Dome on ground water circulation, reconstruction of a 3 dimensional panel diagram of the whole Dome is needed. Logging all the major river canyons, Rift escarpments and the deep drilled wells can easily do this. This 3D model will not only show the possible routes of ground water circulation, but also indicates the depth and structures of the major rock units of Ethiopia, that can be utilised to estimate the volume of minerals and other raw material deposits.

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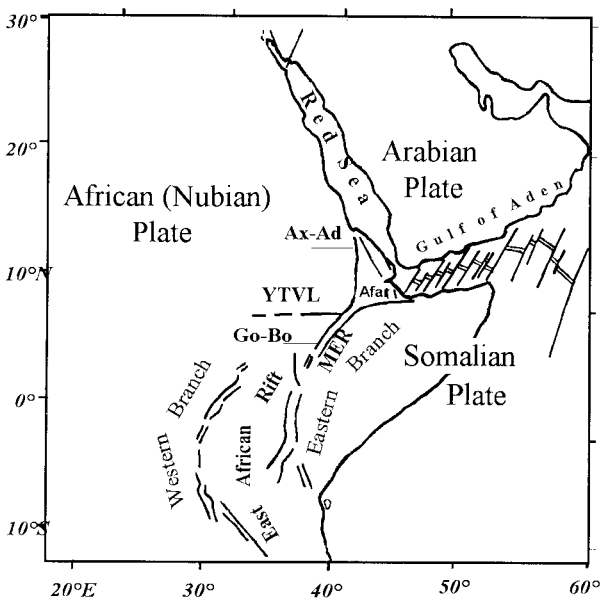

Figure 1. The East African Rift System (EARS) and other major structures in the Afro-Arabian Dome. Ax-Ad = Axum - Adwa lineament, YTVL = Yerer - Tullu Wellel VolcanoTectonic Lineament, Go-Bo = Goba - Bonga lineament. Note that all the lineaments are transversal to the MER.

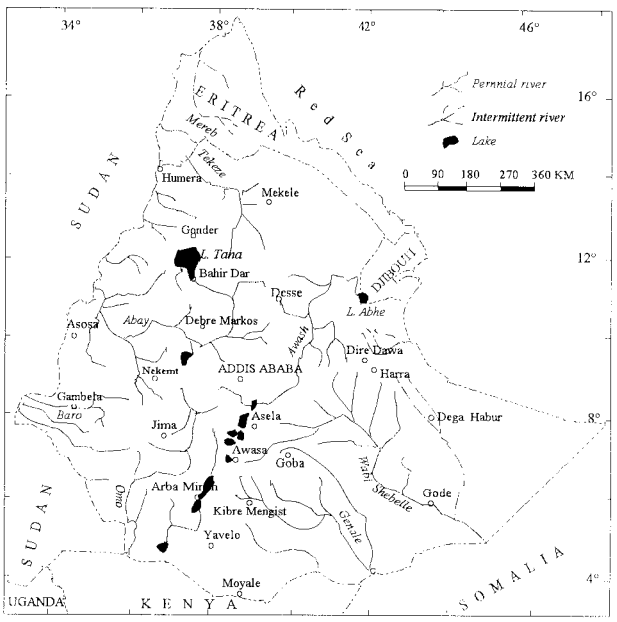

Figure3. Drainage pattern of the major rivers of Ethiopia.

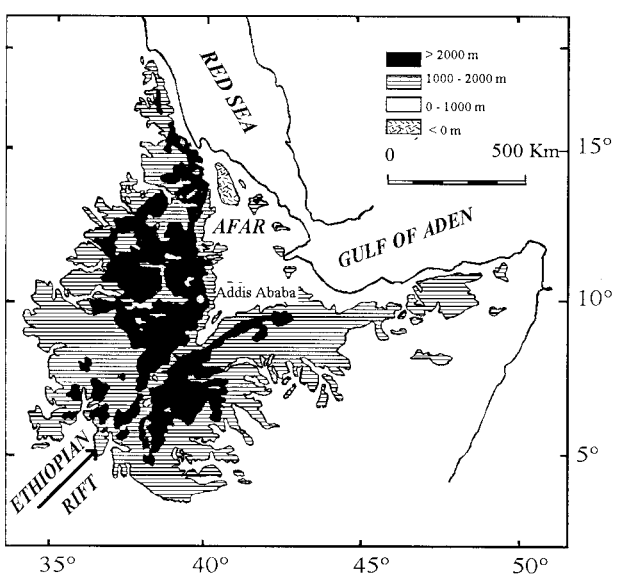

Figure 2. Topographic configuration of the Ethiopian Dome at intervals of 1000 meters.

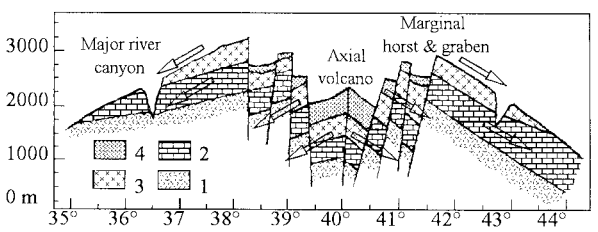

Figure 4. Hypothetical cross-section of the Ethiopian Dome at about N8^0. 1) Precambrian metamorphic basement, 2) Mesozoic Sediments, 3) Tertiary Volcanics, 4) Quaternary Volcanics and associated Sediments.

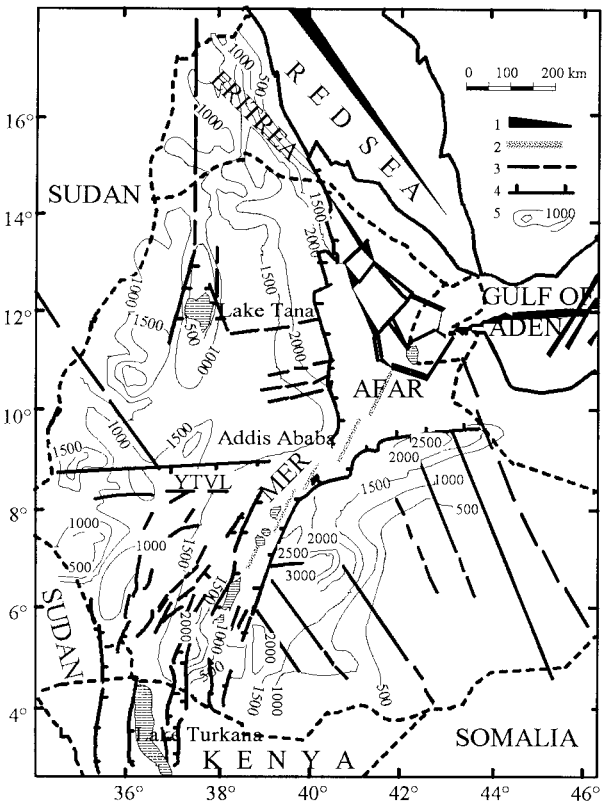

Figure 5. Structural map of Ethiopia (modified after Berhe et al., 1987). 1) Major oceanic crust expansion axis, 2) Axis of continental rift, 3) Rift transversal structure, 4) Major fault, 5) Elevation contour of the out cropping Precambrian basement rocks.

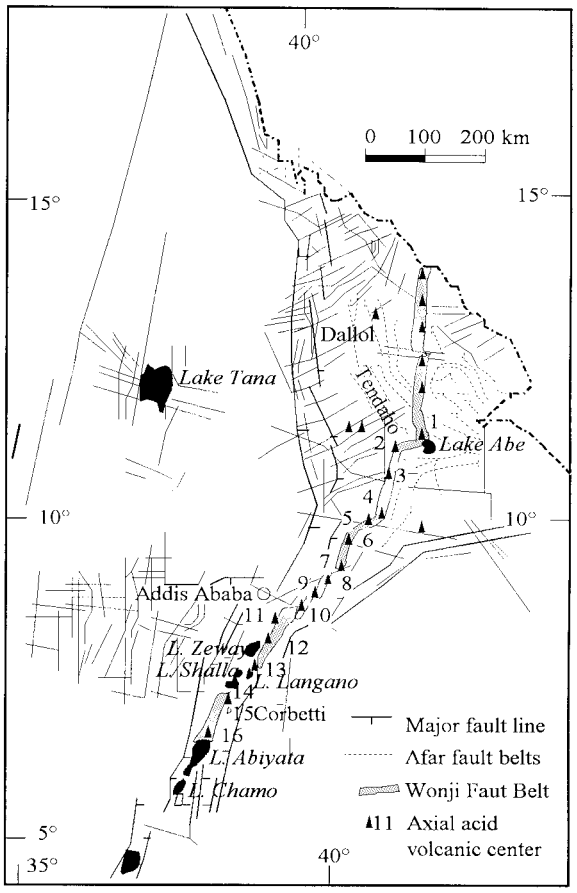

Figure 6. Tectonic outline of the Ethiopian Rift and the major central volcanoes of the axial zone. 1) Dama Ale, 2) Yangudi, 3) Gabilema, 4) Amo Issa, 5) Ayelu, 6) Dofan, 7) Fantale, 8) Kone, 9) Bosti, 10) Boku, 11) Gedemsa, 12) Tullu Moye 13) Aluto, 14) Shalla, 15) Chbi, 16) Hobicha (modified after Mohr, 1971).