GEOLOGY OF EXTENSIONAL –TYPE GEOTHERMAL SYSTEMS IN UGANDA.

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ABSTRACT

Geothermal systems in East Africa are either magmatic or amagmatic/extensional-type systems. Magmatic driven systems rely on shallow magma chambers as their heat source for example in Ethiopia and Kenya while the extensional-type systems are associated with deep seated magma chambers. This clear distinction is highlighted in the subsurface temperature differences seen in the western and eastern branches of the East African Rift System. Most of Uganda's geothermal systems are non-magmatic deep-circulation/extensional-type systems similar to the Great Basin in the USA and Western Turkey. In many respects, they typify other fault-controlled geothermal systems that are driven by deep circulation of ground waters. At these rift fault-bounded geothermal systems, fluid movement is controlled by the permeable rift fault zone that bounds the rift valley. During the rift formation in Uganda; there was extension, fracturing and thinning of the crust causing the mantle to become elevated which results in areas of elevated heat fluxes that are exploration targets for geothermal resources.

The heat that drives these amagmatic systems is believed to result from active/extensional tectonics that permit the deep circulation of meteoric fluids through high angle faults and elevated heat flow that raises the temperature of fluids to 150˚C and above. The $^3He/^4He$ ratios of geothermal fluids from fault-bounded Kibiro Geothermal systems were measured to determine if a mantle signature was present, a value of 0.2 R_A was obtained (Kato ,2018) therefore no signature was indicated. The fact that the Kibiro prospect area is not proximal to young volcanic/magmatic rocks and the absence of the mantle signature, supports the presence of extensional-type system. Soil gas and gas flux measurements have indicated high permeability concealed fault-bounded geothermal systems at Kibiro, Buranga and Panyimur areas. During exploration studies in Uganda, the exploration targets are at the points where the escarpment and the basin intersect, this is believed to be the location of the rift bounding faults controlling the up flow of geothermal fluids.

1. INTRODUCTION

Geothermal Energy has gained more awareness and recognition in Uganda in the recent years with growing interest in the sector expressed by private companies getting involved in geothermal exploration. The use and potential of geothermal energy came to light when Kenya exploited her resources through companies such as KenGen and GDC which sparked interest of other African nations located along the East African Rift System. A good understanding of geology is the key to successful exploration of resources, therefore without extensive preliminary studies exploration can lead to loss of funds and premature closure of projects. Previous unsuccessful exploration studies prompted some development partners to conclude Uganda had no geothermal potential but a new school of thought brought about by understanding structural differences between the Eastern and Western arms of the East African Rift System (EARS) has brought hope to countries in the Western Branch. The East African Rift System is divided into the Eastern and Western Branch, which are characterized by Magmatic and Amagmatic/Extensional type systems. respectively. Amagmatic type systems typify the geothermal systems of the western branch and they are either characterized by medium-high temperature or low-medium temperature geothermal systems depending on the predicted subsurface temperatures. The major geothermal systems in Uganda (Buranga, Kibiro and Katwe) are located along the western arm of the rift valley within the Albertine graben, displaying a distinct alignment of hot springs showing structural control (Figure 1a and 1b).

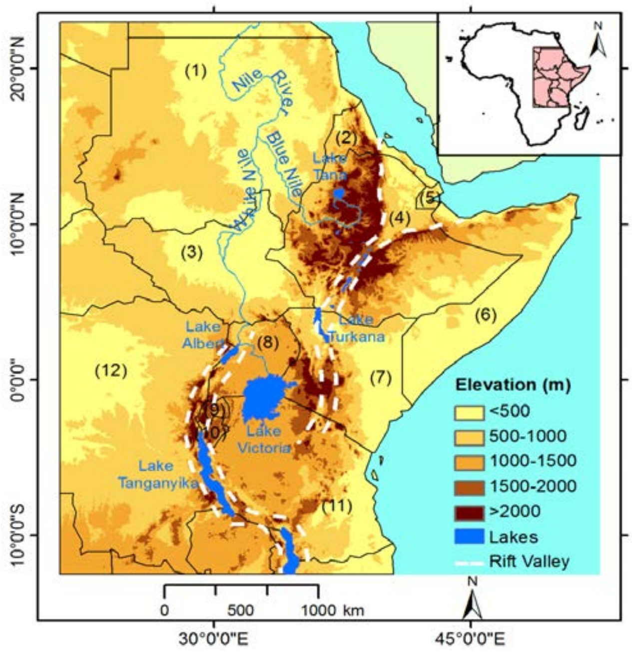

Figure 1: The location of the East African Rift Valley in Uganda. After Fenta, Ayela et al.,2017.

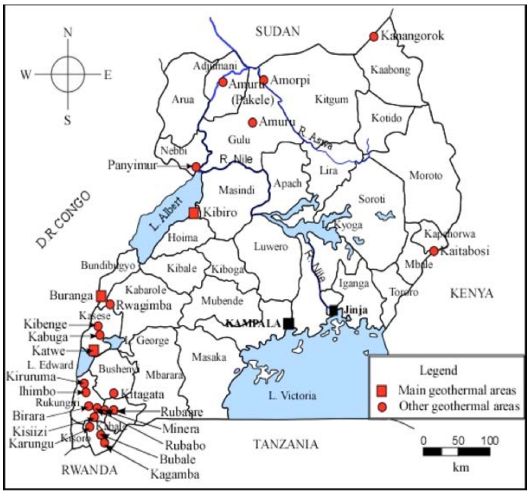

Figure 1: The geothermal areas of Uganda. After Bahati et al., 2005.

This paper will focus on the geology of extensional-type geothermal systems such as Uganda's with case studies from Kibiro, western Uganda.

2. EVOLUTION OF THE GEOLOGY OF THE WESTERN RIFT SYSTEM

The western rift valley is approximately 100 km long normal fault systems with 1-6 km throws bounded by deeper side of asymmetric basins (border-fault segments), and the sense of basinal asymmetry commonly alternates along the length of the rift valley (Ebinger, 1989). The flanks of the rift have been uplifted 1-4 km above the surrounding Plateau, and basement lies below sea level beneath many basins.

The lithology is comprised of Tertiary to Quaternary sediments in the graben and Precambrian basement metamorphic rocks at the escarpment (Krenkel 1921, 1922). reported that the Western rift is the most seismically active zone in Africa with a frequency of more than 100 felt earthquake per year on average. The seismicity attest to seismically active basin bounding faults (weak zones in the rift). It is reported that the Western rift is one of the most seismically active areas in Africa with Earthquake magnitudes up to 5.8 on the Richter scale (Manyele, 2016). Abeinomugisha (2010) reported that from geophysical and geological data, rifting in the Albertine Graben was initiated the during mid Miocene about 17 Ma. The fault permeability of the main bounding increases in permeability during and after an earthquake as evidenced in flow rate of geothermal fluids. (Kato,2018)

The Western Rift System hosting most of Uganda's geothermal prospects is at different stage of rift evolution (initial to intermediate stage) compared to the Eastern Arm of the EARS. In the initial rifting phases, widespread magmatism may encompass the rift, with volcanic activity localized along major boundary faults, transfer zones and limited portions of the rift shoulders (off-axis volcanism) (Corti, 2011). Major bounding Cenozoic normal faults are key players during early stages of rifting. Western rift is between boundary faults stages 1 to intermediate stage of evolution where by incipient internal faults begin to develop. The rift evolution is indicative of a progressive transition from fault-dominated rift morphology in the early stages of extension (Uganda) toward magma assisted-rifting during the final stages of continental break-up (Kenya, Ethiopia, Afar; Corti, 2012) (Figure 2). Studies of earthquake source parameter in the Western Rift show deep events down to 30-40 km (Maasha, 1975; Shudofsky, 1985; Wagner and Langston, 1988; Nyblade and Langston, 1995) indicating deep faults.

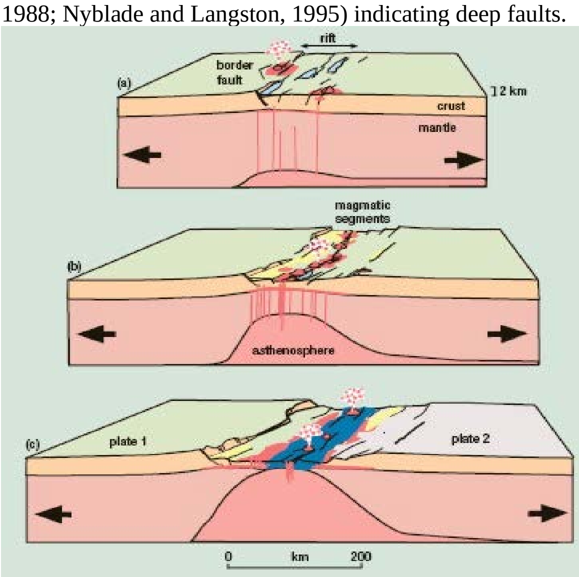

Figure 2: Stages in rift development of the East African Rift with Uganda believed to be at stage a. After Ebinger,2005.

The western rift is bounded by high angle normal faults systems. Depth to detachment estimates of 20-30km and seismicity throughout the depth range 0-30 km suggesting that planar border faults penetrate the crust (Ebinger, 1989). The entire western rift valley is an area of thin crust, anomalously warm upper mantle rocks, high crustal heat flow (the geothermal gradient interpreted from well data indicate up to 67°C/km (Abeinomugihsa, 2010) and numerous geothermal systems.

In addition, persistent seismicity throughout the basin affirms the active crustal extension tectonics and normal faulting. The crustal extension promoted deep fracturing / faulting which aided deep circulation of meteoric water and subsequent heating to form geothermal fluids. Most of the geothermal systems in western rift valley are amagmatic geothermal systems ascribed to high geothermal gradient caused by crustal uplift or extension which promoted deep fracturing and the circulation and heating of meteoric fluids to form hydrothermal system. These amagmatic geothermal systems occur in extensional setting, where meteoric water circulates along main boundary faults deep into the crust where it is heated. Ascending thermal water may result in hot springs at favorable structural settings where faults intersect and fumaroles in areas on high ground above the water table where vents and fissures allow the steam and hot gasses to escape to the surface.

As the crust is pulled apart in the initial stages of rifting, it undergoes extension and thinning consequently forming high angle normal faults that extend to a great depth. The direction of faulting is perpendicular to the direction of extension. Magma rises into the crust in response to reduced lithostatic pressure, due to crustal thinning caused by extension of the crust. The presence of heat may create a geothermal reservoir (Glassley, 2010) (Figure 3).

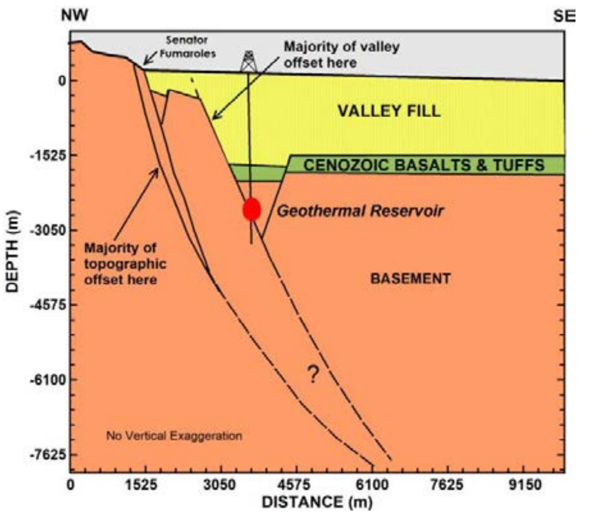

Figure 3: A fault bound extensional geothermal system which is typical of Uganda's Geothermal system. After DoE, 2006.

The intersection between the basin and escarpment is believed to be the location of the rift bounding faulting and permeability is commonly restricted along these zones which control the up flow of geothermal fluids. According to Moeck (2013) classification system of geothermal systems, most Uganda geothermal systems are Extensional Domain play Type CV3. In an extensional Domain Geothermal Play Type (CV3), the mantle is elevated due to crustal extension and thinning. The elevated mantle provides the principal source of heat for the geothermal system associated with this play type. According to Moeck (2013), these are fault controlled geothermal plays in domains with extensional deformation. These non-magmatic conventional dominated geothermal play systems are either fault controlled or fault leakage controlled.

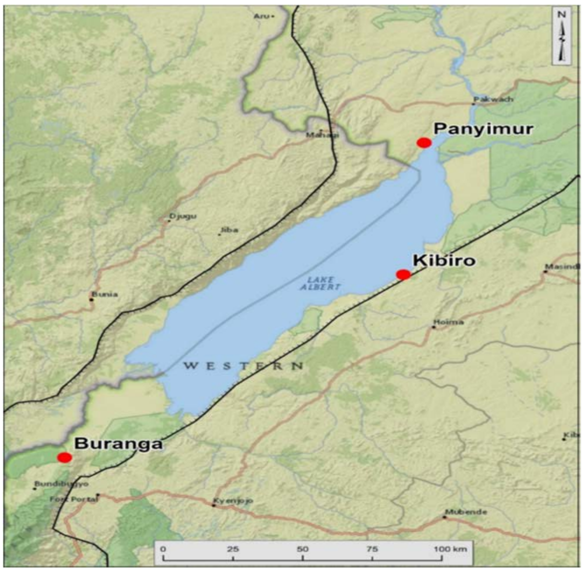

Figure 4: Location of Kibiro. After GRD-EAGER, 2018.

3. LOCAL GEOLOGY: A CASE STUDY OF KIBIRO

Kibiro is one of Uganda's exciting geothermal prospects. It is located in western Uganda on the shores of Lake Albert at the edge of the Western arm of the East African rift valley (Figure 4). It is situated on topographic sheet 38/4 – Kigorobya in the administrative district of Hoima.

Kibiro can be accessed by driving on good tarmac road Kampala – Kiboga – Hoima for a distance of about 202 km. From Hoima you drive along good marram road to the north-west via Kigorobya and branch off to the left either at Kibengeya trading centre or at Kapapi trading center. The area of study is about 35 km from Hoima town. Kibiro hot springs are best accessed by taking a left turn at Kigorobya trading center.

3.1 Geothermal Surface Manifestations.

The Kibiro geothermal prospect, has the second hottest measured hot springs in Uganda after the Buranga prospect (Figure 5). The prospect has a number of surface manifestations that include:

- Hot Springs

  Three groups of hot springs have been mapped in this area namely Mukabiga, Mwibanda and Muntere with surface temperatures of 86°C, 60-70°C and 39°C respectively. The areas around the hot springs, has a strong hydrogen sulphide smell, gas emissions are observed to bubble out of the water especially at Mukabiga. The water flow from Mukabiga through Mwibanda is characterized by algae downstream as a result of cooling of the geothermal fluid.

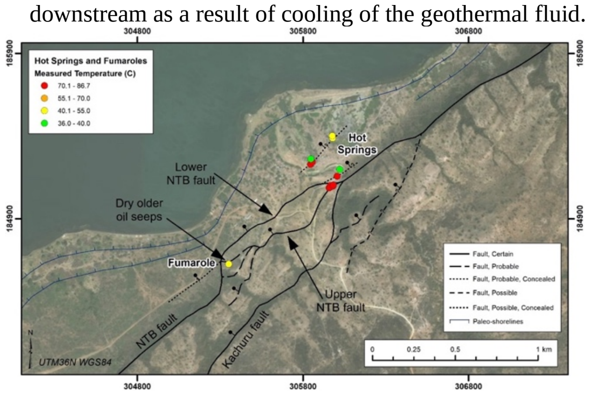

Figure 5: Surface temperatures of hot springs and fumaroles and major structural elements in the study area. After MEMD-EAGER, 2019.

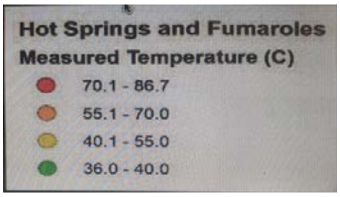

Figure 5(b) Expanded legend from Figure 5.

- Gas Emissions.

  The area around the hot springs has strong and distinct hydrogen sulphide gas smell. Hydrogen sulphide is typically generated through bacterial sulfate reduction coupled with oxidation of organic matter, which is abundant at Kibiro. The dissolved sulfate is converted to sulfide through bacterial sulfate reduction coupled with oxidation of organic substances to carbonate species. Based on these considerations, dissolved sulfate is unlikely to be of magmatic origin as suggested in previous studies (Alexander et al., 2016).

- Fumaroles.

  These fumaroles were observed at the south west of

Kibiro main spring and are located along the escarpment approximately 1 km SE of Kibiro hot springs. This zone is characterised with baked mylonite that has been stained by hydrocarbons giving the mylonite a black tone of colour. Gas emissions are detected by the pungent hydrogen sulphide smell and petroleum. The ground itself is hot in some places, and elemental sulphur was seen to occur close to rims of small fumaroles.

- Oil seeps.

  Oil discoveries have been made in the Albertine graben. In the process of geothermal mapping, oil seeps and old shallow exploration were encountered. Two old oil wells, one of dormant, while the other discharges black hydrocarbons especially during dry season. A small part of the discharging well can be viewed because most of the pipe in now submerged in water. The natural oil seepage has stained the surrounding sediments black. Locals reported that the seepage is more active during dry seasons. The stained sediments and rocks have a characteristic kerogeneous smell.

3.2 Structure of Kibiro.

Geological mapping together with other exploration methods have been carried out in Kibiro for many years by various teams of scientists to understand the structures responsible for the geothermal activity. In recent years a breakthrough was made to develop a conceptual model for the area. During mapping, it was noted that the area did not have any volcanics and the nearest volcanics were >150km to the southwest near the Rwenzori mountains (Ring, 2008) (Figure 6).

Figure 6: Simplified geologic map of the Albertine Rift showing rift sediments and basement. The nearest volcanic deposits of Kibiro are located >150km to the SW near the Rwenzori Mountains. After Ring, 2008

From the review of previous geological data, the Kibiro area was found to be a complex system of step over faults where each step intersects one or more faults in the footwall or hanging wall side. The main fault is a normal fault named the NTB (North Toro Bunyoro fault) with a NE-SW trend and a dip of 60-65°NW towards the rift (Alexander et al. 2016). The other faults such as the Kachuru fault with minor faults splays which intersect the major fault causing an area of high fault density in Kibiro compared to other areas along the NTB fault (Figure 7). The ascending branch of the Kibiro thermal circuit is likely to be controlled by the intersection between these two faults that are expected to determine conditions of high vertical permeability favoring up flow of thermal waters towards the surface (Alexander et al., 2016).

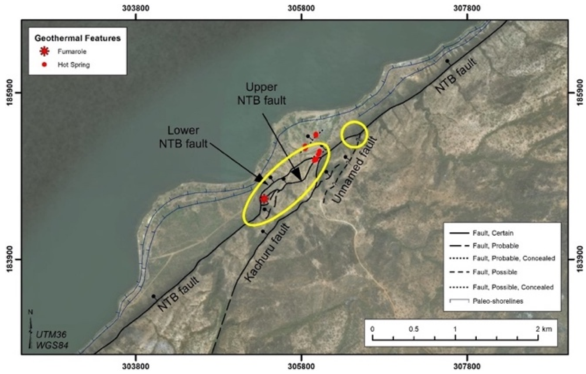

Figure 7: Structural map of the Kibiro Geothermal prospect area. Yellow eclipses correspond to step-overs at fault intersections along the NTB fault. After MEME-EAGER,2018.

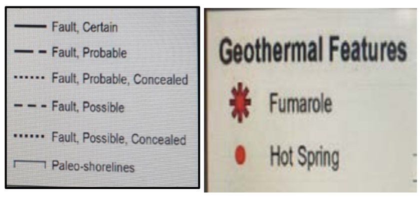

Figure 7(b). Legends for Figure 7.

The hottest clusters of hot springs at Mukabiga discharge at the north east end of the upper NTB fault next to where it intersects with the outer main NTB fault in the double ended fault splay. The second cluster of two hot springs at Mwibanda ranging from 40 to 75°C are located 60 to 90 m NE of Mukabiga. These are inferred to align along a possible concealed splay of the outer NTB fault. A weakly flowing 45.4°C fumarole was discovered by EAGER and GRD/MEMD in January of 2018 at the SW end of the step-over in a local area of intense argillic alteration of the bedrock with actively depositing fresh native sulphur and older bitumen (MEMD-EAGER, 2018). This weak fumarole extends the distance of surface thermal features about 1 km SW of the previously identified hot springs.

Alexander et al. (2016) noted from previous UNEP studies, soil gas and soil temperature measurements are consistent with the distribution of active thermal manifestations at both ends of the double-sided fault splay along the NTB fault. The highest soil gas flux (CO_2) were next to the hottest hot spring in the north east end and the fumarole in the south west of the step over. This is therefore indicative of enhanced permeability along the fault intersections allowing for movement of both thermal fluids and gas. In addition, at the SW end of the step over there is evidence of oil seeps (bitumen) in areas of high intensity alteration of bedrock which could be indicative of activity of the fumarole above the water table or of tectonic exhumation in the footwall of the NTB fault.

The precise history of the relict alteration cannot be fully worked out with the information available; however, it is likely that the relict alteration above the lake level and in the footwall of the NTB fault imply that the Kibiro geothermal system is relatively long-lived, perhaps several hundred thousand years, and is analogous to similar long-lived deep circulation systems in the Basin and Range system that persist along key structural settings such as fault step-overs, terminations of major faults, or intersections of major faults (e.g., Faulds et al., 2010).

4. CONCLUSION.

The Ugandan geothermal systems are fault controlled deep circulation system where fluids travel along high angle normal faults such as the NTB fault, get heated and ascend to the surface where they appear in the form of hot springs while in areas where favorable structures such as vents, small fissures occur on higher ground above the water table, thermal fluids and gases may ascend through these structures forming fumaroles. It should be noted that the fumaroles in Kibiro are considered weak with very low steam discharge and faint hydrogen sulphide smell. The hot springs are aligned along the faults indicating a structural control, furthermore in areas where faults intersect there is enhanced permeability which makes surface manifestations more pronounced. i.e. hot springs. It should be noted that these systems don’t have any evidence of volcanic activity around the prospect which dismisses the hypothesis of a volcanic system/magmatic system. Lastly from geothermometry and mixing models the temperatures in Kibiro are predicted to be between 150-250°C (Bahati,2018) which according to Axelsson and Gunnlaugsson (2000), would be classified as a medium-high temperature system. If these predictions turn out right during deep exploration drilling, Uganda could become part of the geothermal energy producers of the world. This would boost the countries economic development through provision of alternative energy sources that could lead to cheaper tariffs for users on the grid.

In addition, Uganda can also explore direct use application which would be best to utilize such resources before its potential for electricity generation is realized. Since Agriculture is the backbone of the economy, geothermal energy would boost certain agricultural activities such as aquaculture, fruit drying, floriculture and milk pasteurization among others, making Uganda’s produce more competitive on the international market. For example, using geothermal energy to heat pools in aquaculture would increase the yield of fish thus creating more income for the farmer, in addition geothermal energy could be used to dry fish and other fresh foods which would make them easier to export to foreign markets.

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