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GEOTHERMAL EXPLORATION IN UGANDA – STATUS REPORT

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ABSTRACT

A secure and sustainable energy mix is one of the key challenges facing the Government of Uganda (GoU) as the entire world responds to the issues of climate change, energy security, energy independence and economic competitiveness. Based on current projection, energy demand could double or even triple in the next twenty years. GoU faces the need to increase its power generating capacity to meet the increasing energy demand. As a strategic intervention, GoU decided to grow its energy sources including renewable generation to mitigate the increasing energy demand. Among the renewables is geothermal energy, distributed in several districts all over Uganda. Once developed, geothermal has a potential to provide large scale, base load power 24 hours a day, 365 days a year.

Geothermal exploration timeline has stretched too far dating way back to the 1950s when shallow wells were drilled in Buranga. Numerous donor support projects have been undertaken to support geothermal investigation surveys in Uganda. These have included UNDP, ICEIDA, BGR, IAEA, BGR, JICA, WB, ADB and UNEP. The situation warranted breakthrough techniques and technology to fast track geothermal development in Uganda. Experience has shown that successful geothermal development is related to four main elements: Policy, institutions, information, and finance. GoU initiated a four-pronged strategic intervention. GoU established a Geothermal Resources Department with a budget and logistics (survey equipment and tools). GoU is in final stages of putting in place a geothermal energy policy and bill. Since financial year 2011/12, GoU has committed funds to undertake government-led geothermal exploration in 4 high priority areas. Preliminary geothermal conceptual models have been developed for four areas and preliminary surveys have commenced at Ihimbo and Rubaare. There are key accomplishments and impacts. A skilled geothermal workforce is in place but with capability gaps. There is a need to reinforce the skills mix by recruiting engineers, managers and technicians. It is mostly a workforce of geoscientists.

It is now recognized that the western arm of the East African Rift System (EARS) is quite different structurally and tectonically from the eastern arm. The western arm is in initial stages of rift development as opposed to the eastern arm, which is in mature stage. Uganda's geothermal systems are extensional deep circulation amagmatic systems that are driven by deep circulation of meteoric waters. This is attested by low Helium signatures and deep reaching boundary faults. Rift border faults are principal exploration targets, and more so where there is fault interaction, due to increased permeability, critically stressed zones and high fracture density. Exploration workflow applied includes a combined MT/TDEM survey, soil gas and gas flux measurements, shallow temperature probe, micro-seismic survey, reflective seismic data from oil and gas companies. Integrated models will be developed to aid well targeting. Thermal Gradient Holes (TGH) are recommended to confirm the sub-surface temperature anomaly prior to committing risky and cost intensive deep full diameter exploration. A drilling supervisor and contractor have been procured to supervise and drill TGH holes in Kibiro, Panyimur and Buranga areas to commence by end of 2019. Deep exploration test wells thereafter will be planned and designed for Kibiro and Panyimur. Data gap closure is planned for Katwe to qualify the field for temperature gradient drilling.

1. INTRODUCTION

A secure and sustainable energy mix is one of the key challenges facing the Government of Uganda (GoU) as the entire world responds to the challenges of climate change, energy security, energy independence and economic competitiveness. Based on current projections, energy demand could double or even triple in the next twenty years. GoU faces the need to increase its power generating capacity to meet the increasing energy demand. As a strategic intervention, GoU decided to grow its energy sources including renewable generation to mitigate the increasing energy demand. Among the renewables is geothermal energy distributed in several districts all over Uganda. Once developed, geothermal has a potential to provide large scale, base load power 24 hours a day, 365 days a year.

Experience dictates that successful geothermal energy development is tied to four main elements: Policy, finance, information and institutions. GoU embarked on a four-pronged intervention to its geothermal development strategy. Geothermal investigation surveys timeline in Uganda has stretched too far dating back to 1954 when 4 shallow holes were drilled in Buranga. The situation invited breakthrough techniques and technology to fast track geothermal development. Several projects were implemented but with no key accomplishments.

Since financial year 2011/2012, GoU committed funds towards the development of geothermal resources. Government-led exploration in Kibiro, Panyimur, Katwe and Buranga has advanced to pre-production drilling investigations. Preliminary geothermal conceptual models have been developed for these sites presumed to be fault hosted extensional geothermal systems (non-magmatic). Models will be refined and constrained with new data which will lead to more informed and sound decisions regarding proceeding with deep exploration drilling, while also identifying drilling sites that are more favourable. Outlined below is the current status of geothermal exploration in Uganda.

2. UGANDA'S GEOTHERMAL POTENTIAL

Geothermal resources with moderate to high sub-surface temperatures can be found at several locations in Uganda (Figure 1). This is the result of the presence of deep reaching tectonically active fault zones in extensional terrains. Uganda is endowed with geothermal resources due to its geographic location in the western arm (Figure 1) of the east Africa Rift System (EARS). The western rift valley is a zone which experienced crustal extension and thinning of the crust which caused the mantle to become elevated. This elevated mantle results in a higher geothermal gradient within the crust. Meteoric water circulates through deep fault zones or permeable formations in the crust and becomes heated. This type of geothermal systems is called extensional domain type.

In an Extensional Domain Geothermal Play (CV3), like those occurring in Uganda, the mantle is elevated due to crustal extension and thinning. The elevated mantle provides the principal source of heat for geothermal systems associated with this Play Type. The resulting high thermal gradients facilitate the heating of meteoric water circulating through deep faults or permeable formations. During rifting, faults are formed and these are usually high angle rift faults. The faults normally extend to considerable depth forming deep geothermal resources. Permeability is usually restricted to fault zones bounding the rift (Glassley, 2010). Most of Uganda's geothermal systems are deep-circulation system and typifies other fault-controlled geothermal fields that are driven by deep circulation of ground waters. Fluid movement is by fault zones that bound the rift valley.

FIGURE 1: Map showing distribution of geothermal sites in Uganda

3. GEOTHERMAL ENERGY IN UGANDA'S ENERGY MIX

To date, geothermal energy has not played any role in Uganda's energy mix. It remains largely undeveloped with enormous potential. In the current climate change and energy security environment, it is an interesting power generation source. The geothermal sector in Uganda shows great promise as a near zero-emission base-load supplier of renewable energy. However, the industry is still relatively young, and much learning is yet to be achieved.

In addition to providing an energy source, geothermal energy can contribute to the Government's commitments to renewable energy and climate change, and energy security requirements. The resource is not intermittent like other renewable energy sources, and therefore does not require large amounts of offsetting excess capacity.

Economic activity and standards of living more generally are underpinned by access to reliable, competitively priced energy. The role played by the energy sector is of importance to the society and economy. Securing energy is a top priority for Uganda's energy policy.

4. EARLY STUDIES

Geothermal studies by Department of Geological Survey and Mines (DGSM) dates way back in 1950s when shallow wells were drilled in Buranga area (McConnell and Brown, 1954). In early 1970s, preliminary studies were initiated by DGSM. Subsequent projects conducted are briefly summarized below.

Geothermal Energy Exploration Programme, phase 1 (1993-1994): This was the first detailed exploration programme carried out on the three highly ranked prospects. The project was funded by the GoU, United Nations Development Programme (UNDP), Organization of Petroleum Exporting Countries (OPEC), and Government of Iceland. It was implemented by DGSM and executed by Department of Development Support and Management Services of United Nations (UNDDSMS). Work included geological, geochemical and isotopic surveys, in Kibiro, Katwe-Kikorongo and Buranga (Gíslason et al., 1994). The results justified further exploration efforts.

Isotope Hydrology for Exploring Geothermal Resources, phase 1 (1999-2003): This was funded by IAEA together with Ministry of Energy and Mineral Development (MEMD) with the aim of up-grading and refining the exploration models of Kibiro, Buranga and Katwe-Kikrongo prospects, using isotopes. This was a data gap closure and follow up of the UNDP-ICEIDA project of 1992-1994.

Katwe-Kikorongo preliminary exploration (2003): African Development Bank (ADB) funded geothermal investigation surveys in Katwe-Kikorongo in 2003, under the "Uganda Alternative Energy Resource Assessment and Utilization Study (UAERAUS). This was to upgrade the exploration model of Katwe-Kikorongo to pre-feasibility status.

Kibiro prospect investigations (2004): This exploration project was implemented by ICEIDA experts and GoU counter parts with the aim of refining the pre-drilling assessment initiated by MEMD. Activities included geophysical studies (Resistivity, gravity and magnetic survey) and geological mapping.

GEOTHERM Project: Germany Federal Institute for Geosciences and Natural Resources (BGR) together with MEMD conducted preliminary surveys in Buranga beginning 2003. This was under the GEOTHERM programme, which promoted the utilization of geothermal energy in developing countries. Exploration workflow included surface water sampling and analysis, isotopic studies, geophysical surveys (Gravity, TEM, and Schulmberger sounding). Micro-earthquake survey was conducted around Buranga to map seismically active structures (Ochmann et al., 2007). Results indicated active Rwenzori bounding faults presumed to control geothermal fluids flow. A magma body was inferred under Rwenzori Mountain. The 3He/4He ratios of geothermal fluids were measured to determine if a deep mantle signature was present. These elevated 3He/4He ratios were believed to be evidence of deep permeability and possibly deeper, higher-temperature fluid reservoirs.

ICEIDA-World Bank Power IV program: ICEIDA together with MEMD undertook studies in Kibiro and Katwe-Kikorongo. Project activities included drilling shallow Thermal Gradient Holes (TGH). TGH results were not encouraging. Under this project a national wide preliminary resource assessment was carried out to down-select prospective areas for future advanced studies.

UGA/8/005 – Isotope Hydrology for Exploration Geothermal Resources, phase 2: IAEA funded project "UGA/8/005 - Isotope Hydrology for Exploration Geothermal Resources- phase 2" was undertaken. This was a data gap closure intended to refine exploration models for Kibiro, Buranga and Katwe-Kikorongo prospects using isotopes.

Introducing Isotope Hydrology for exploration and management of geothermal resources, RAF/8/047: This project was funded by IAEA together with GoU to improve the exploration models of the geothermal systems in Uganda.

JICA-2014: Following the situation analysis, JICA and MEMD undertook a joint venture technical study of Uganda's geothermal resources. The preliminary survey was implemented by West Japan Engineering Consultants Inc. and Mitsubishi Materials Techno Corporation. 17 geothermal sites were sampled for geochemical surveys. These included Kagamba, Karungu, Bubaale, Kiruruma, Ihimbo, Kanyinabalongo, Rubaare, Kitagata, Minera, Rubabo, Kizizi, Biarara, Rwimi, Kibenge, Muhokya, Rwagimba and Bugoye-Ndugutu. On ground verification of interpreted satellite data was undertaken as well as preliminary geological mapping. Satellite images used included LANDSAT/ETM+ and SRTM/DEM, ASTER, and ASTER/GDEM. The main objective of this study was to down select prospective sites for possible further technical assistance from JICA.

UNEP-ARGeo Study-2016: UNEP-ARGeo under its programme, technical assistance for surface studies, funded pre-feasibility study of Kibiro prospect. Exploration efforts were complimented by GRD and GDC of Kenya. Preliminary conceptual models of Kibiro were developed for this fault hosted extension (non-magmatic) system. UNEP Donated micro-seismic equipment which were installed around Kibiro to delineate active faults presumed to control geothermal activity.

5. CURRENT STUDIES

5.1 Uganda geothermal energy resources development project (1199)

GoU has invested public funds in geothermal energy project over the last five years. This exploration project started in FY 2011/12 and is ending in December 2016. This Government-led exploration was aiming at developing exploration models of four geothermal prospects (Panyimur, Buranga, Kibiro and Katwe-Kikorongo) and locate test drilling sites. Exploration models of Kibiro and Panyimur have been developed. Data gap closure is going in Buranga and preparation for pre-drilling data acquisition at Katwe is in advanced stages. GoU has worked in collaboration with UNEP-ARGeo, Geothermal Development Company (GDC) of Kenya and EAGER.

5.2 Regional geology

Without a good understanding of the geology of a prospect area, exploration is merely guesswork. Approximately 100-km-long normal fault systems with 1- to 6-km throws bound the deeper side of asymmetric basins (border-fault segments), and the sense of basinal asymmetry commonly alternates along the length of the rift valley. The broad flanks of the Western rift have been uplifted 1-4 km above the surrounding topography of the East African Plateau, and metamorphic basement lies below sea level beneath many basins.

Lithologically, it has tertiary-quaternary sediments in the graben and Precambrian basement metamorphic rocks at the escarpment. The Western rift is seismically active both from felt and instrumental information. Frequent occurrences of earthquakes were reported at Kibiro by early explorers. Krenkel 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. This seismicity attest to seismically active basin bounding faults. The available geophysical and geological data in the Albertine Graben indicate that rifting was initiated from the western side during mid Miocene about 17 ma (Abeinomugisha, 2010). Main bounding fault permeability increases during and after an earthquake as evidenced in flow rate of geothermal fluids.

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. According to Corti (2009), 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). 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 whereby 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).

Studies of earthquake source parameter in the Western Rift show deep events down to 30-40 km (Nyblade and Langston, 1995) indicating deep faults. The western rift is bounded by high angle normal faults systems. Depth to detachment estimates of 20-30 km 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 indicates up to 67°C/km; Abeinomugisha, 2010) and numerous geothermal systems. In addition, persistent seismicity throughout the basin attests to active crustal extension tectonics and normal faulting. Extensional / strain rates are not so high as compared to Basin and Range in the USA. But 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 up lift 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 and the fumaroles at the surface, generally at favorable structural settings where faults intersect thus increasing fracture density.

5.3 Local geology

Located in the western rift valley on the main RIFT fault, most geothermal systems are deep-circulation system in a tectonically active zone. These systems are believed to be fault-bounded in an amagamatic setting (non-volcanic region, high regional heat flow, and high temperature gradient). Surface features include hot springs, fumaroles and gaseous emissions. Others include travertine, calcite veins, hydrothermal alteration and silica veins. Helium ratio indicate a value of 0.2 supporting amagmatic (not related to volcanic or magmatic activity) setting. One has to note that amagmatic systems are much more wide-spread, but cooler at shallow depth.

These systems are related to circulation of meteoric waters along deep (crustal scale) normal fault planes in an extensional setting. This is supported by unusually low Helium Isotope signature, low surface temperature, near neutral ph, low concentration of TDS. This is common with extensional driven (deep circulation type) as opposed to magmatic driven geothermal system. The location of these systems is related to high fracture density ascribed to intersection of several faults including the main bounding fault. Alignment of surface manifestation along the main fault (Figure 2) indicates structural permeability.

In many respects, these systems typify other fault-controlled Rift valley geothermal fields that are driven by deep circulation of ground meteoric waters (Figure 3) into high-heat-flow upper crust zone. For example, at Kibiro, fluid movement is presumed to be controlled by the main fault zone (Figure 4, Toro-Bunyoro fault) as evidenced by alignment of surface features.

Kibiro, gives a geothermometry temperature of 196°C, close to sodium/ potassium solute geothermometer of 205°C. Total gas content is dominated by methane due to thermal dissolution of organic rift sediments.

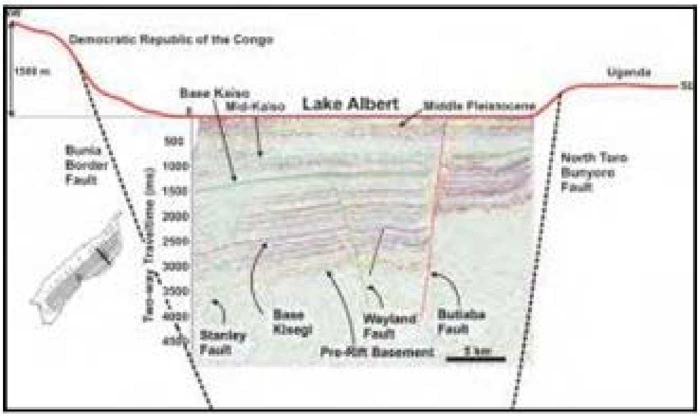

FIGURE 2: Section showing multichannel seismic line 57 from the northern part of Lake Albert (see track line inset for location). Red line at surface of profile indicates regional topography (Karp et al., 2012)

At Kibiro and Panyimur systems, we are looking at a deep circulation system within faulted crystalline basement rocks (Table 1; Figure 5). An exploration model can help guide decisions when designing an exploration plan and aid in interpreting the results of the collected data. A good exploration model is very important for selecting targets for test drilling. Faults have high permeability in crystalline basement rocks but fault intersection have increased permeability hence are key geothermal targets.

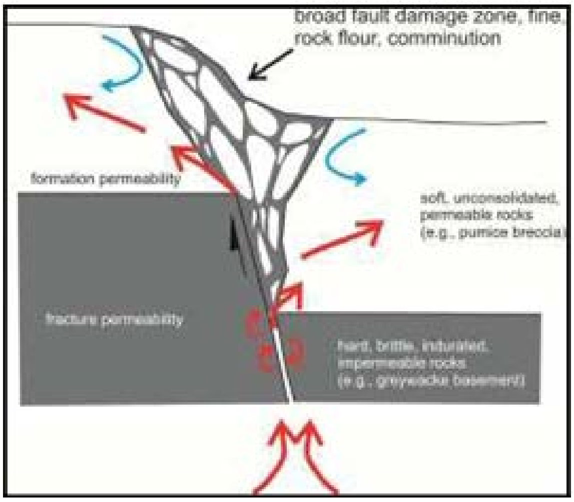

FIGURE 3: Idealized exploration model which fits Kibiro

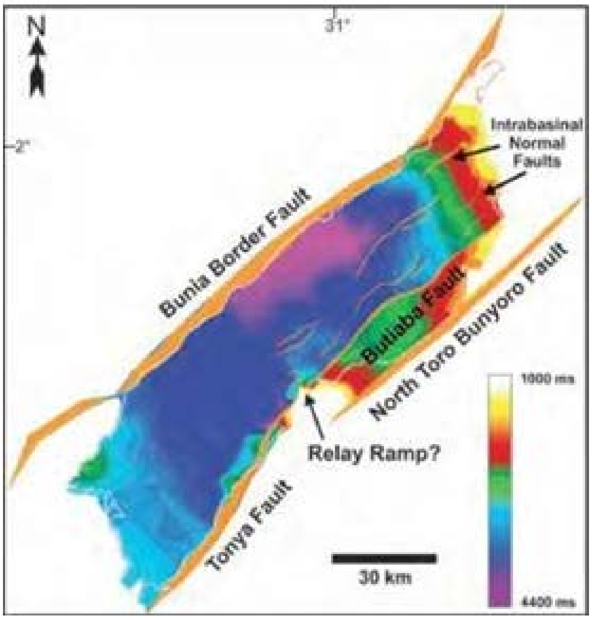

FIGURE 4: Main rift bounding fault (Karp et al., 2012)

TABLE 1: Summary of Kibiro and Panyimur geological settings

Tectonic setting	➢ Extensional tectonic regime
Controlling structures	➢ Main bounding fault ➢ Fault intersection
Controls of permeability	➢ Fracture permeability in basement – faults (secondary) ➢ Formation and fracture (primary in sediments)
Topographic feature	➢ Horst and graben
Brophy model	➢ Type E: Externsional, tectonic fault controlled geothermal resource
Moeck-Beardsman play type	➢ CV-3 extensional domain
Geological features	➢ Modern features (hot springs, fumaroles, gaseous emissions, salt precipitates) ➢ Relict features (travertine, gypsum, calcite veins, silica veins, hydrothermal alteration)
Volcanic age	➢ No volcanism (R/Ra: Kibiro 0.2 => nearly pure radiogenic He (crustal He, i.e. no volcanic heat source, no known magmatic activity, amagmatic origin)
Heat source	➢ High heat flow in areas of thinned and extending crust (extension geothermal systems). This is regionally dispersed amagmatic heat flux as opposed to focused and identifiable magmatic heat source
Horst rock age	➢ Precambrian basement metamorphic rocks, fracture dominated reservoir
Horst rock lithology	➢ Precambrian basement + sediments
Cap rock lithology	➢ Smectite rich clay

5.4 Geothermal plays

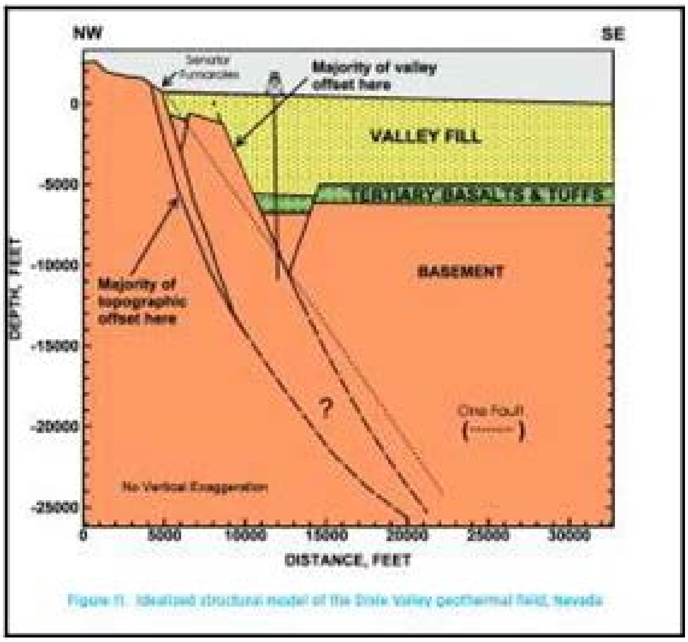

FIGURE 5: Idealized structural model of the Dixie Valley geothermal field, Nevada, which typifies Kibiro and Panyimur (DoE, 2006)

According to Corti (2012), during the initial rifting stage, 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). This makes major rift bounding faults exploration targets. According to Corti (2012) the western rift is in stage one of boundary fault (early continental rifting) evolving to intermediate stage where by incipient internal faults begin to develop (Corti, 2012). A case is major Bunyoro-Toro fault (Main-boundary fault) and Butiaba fault (incipient internal fault).

Kibiro and Panyimur geothermal system like many geothermal systems in the western rift valley are fault-bounded extensional (horst and Graben) complexes (Brophy Type E). They occur where extension and thinning of crust occurred. As the crust pulled apart it fractured forming steeply dipping normal faults (Main boundary faults) that are perpendicular to the general direction of extension (Glassley, 2010). These high-angle main bounding normal faults can extend to considerable depth and can be focus for magma ascent into the crust or can act as fluid pathways or conduits. This created zones of high geothermal gradient and high heat flow ideal for geothermal resources. A combination of high heat flow and active extensional tectonics are ideal for forming structurally complex zones and with concentrated stress to facilitate deep circulation.

Geophysical evidence for crustal thinning across the 1,300-km-wide East African Plateau is restricted to 40- to 75-km-wide zones beneath the Western rift valleys. On the basis of seismic refraction data, crustal thinning beneath the northern part of the Western rift system is less than 25% (Ebinger, 1989). Along the length of the Western rift system, numerous small magnitude earthquakes generally with tensional focal mechanisms occur throughout the depth range 0-30 km with no apparent vertical gap in seismicity (Ebinger, 1989).

Permeability seem to be restricted to fault-controlled zones in the vicinity of the main rift faults (Glassley, 2010). The main rift faults are exploration targets according to Glassley's description of the rifting stage and fault-bounded extensional horst and graben complexes. This exploration model is the one to be tested, supplemented, and refined by field work. The process continues until a reliable model is achieved. Active crustal extension appears to enhance fracturing / dilation in normal fault system and thus favour deep fluid circulation along fault zones. The heating of deeply circulating meteoric fluids along faults is facilitated by high temperature gradient ascribed to crustal extension and thinning.

According to Moeck: Classification of geothermal plays according to geological habitats, Kibiro and Panyimur Geothermal System can be classified as Extensional Domain play type - CV3. In an Extensional Domain play type - CV3 the mantle is elevated due to crustal extensional and thinning (Moeck, 2013). The elevated mantle provides the principal source of heat for geothermal systems associated with this Play Type (Moeck, 2013). The resulting high thermal gradients facilitate the heating of meteoric water circulating through deep faults or permeable formations. This explain the heat source for these systems ascribed to crustal extension and thinning. Moeck (2013) gives a generic model of a fault controlled extensional domain play with elevated mantle due to active crustal extension (Moeck, 2013).

Heat source is ascribed to thinned crust, elevated heat flow and recent extensional domain. The majority of geothermal systems in western rift are amagmatic, relying on high regional heat flow throughout the rift valley. These systems employ discrete fault intersection and interaction areas as conduits for geothermal circulation. In geothermal exploration we look for normal faults as they provide open pathways for large quantities of fluids to move through rocks.

5.5 Geothermal exploration targets

Amagmatic geothermal systems in the western rift valley are controlled by a variety of fault intersections and fault interaction areas (favourable structural setting). Here we have high heat flow and active faulting in extensional geothermal systems. These geothermal systems are believed to be deep convecting / circulation geothermal systems, occurring in the relatively permeable pathways along the main fault zones where they intersect multiple fault zones (high fracture density). In tectonically active regions like in Kibiro, fault zones are commonly the most important exploration targets as they can channel geothermal fluids from deep levels in the crust to relatively shallow reservoirs thus providing a more accessible and more economical resource. However, it is critical to determine which type of structures and which of the faults are most favourable for providing fluid conduits. Such structures must be fully characterized to guide exploration. Major rift fault exploration targets are shown in Figure 6.

During rifting, as the crust pulled apart, it fractured forming steeply dipping normal faults that are perpendicular to the general direction of extension (Glassley, 2010). These high-angle faults can extend to considerable depth and can be focus for magma ascent into the crust or can act as fluid pathways if active and permeable. This created zones of high geothermal gradient and high heat flow ideal for geothermal resources. Permeability tends to be restricted to fault-controlled zones in the vicinity of the main faults (Glassley, 2010). Escarpment ranges nearby allow meteoric waters to infiltrate to deep hot regions and these represent favourable exploration targets in fault-controlled non-magmatic systems.

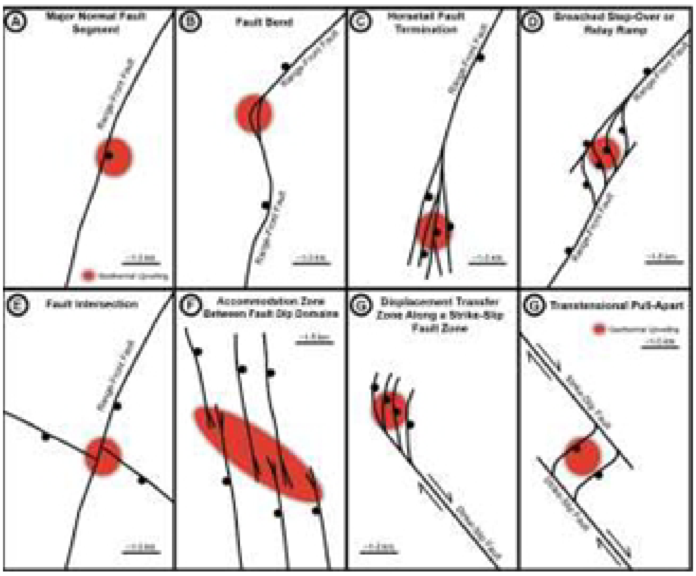

FIGURE 6: Favorable structural setting for geothermal systems in the Great Basin region (Faulds and Hinz, 2015)

5.6 Type of exploration method

According to Glassley, geothermal resources in fault-bounded extensional systems tend to be relatively deep. This calls for deep penetrating measurements to detect deep permeability. The MT survey is one of the recommended methods (Figure 7) in combination with TDEM. This would permit assessment of which fault segment or stratigraphic horizon can accommodate geothermal fluid. Seismic reflection data would indicate location of major faults and areas of structural complexity such as fault intersections, where fracture density would likely be greatest.

5.7 Kibiro exploration results

5.7.1 Geophysical results

MT/TDEM measurements were run across Kibiro geothermal field. Inversion of the data revealed a deep, sub-vertical conductor (structural controlled permeability) coinciding with main rift fault (Figure 8). The sub-vertical conduit is presumed to be a highly fractured rocks along main fault zone oriented perpendicular to the least principal stress direction.

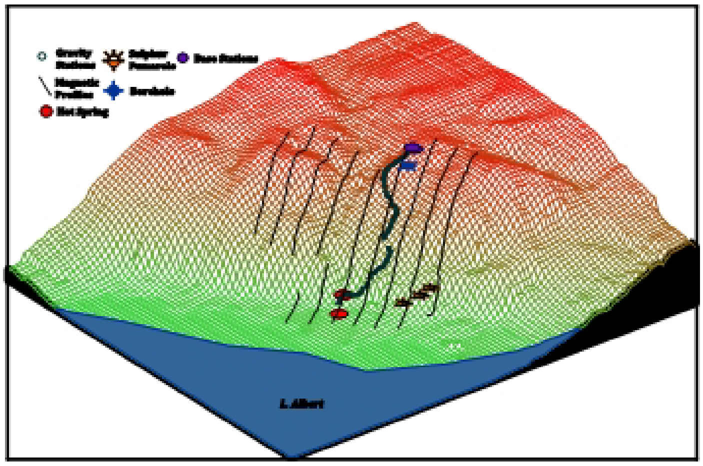

FIGURE 7: MT/TDEM planned profile lines targeting main rift fault at Kibiro

The interpretation of seismic surveys formed a highly detailed and reliable picture of the subsurface structure, with resolution unattainable by most other geophysical methods. Such a picture is highly desirable in geothermal exploration to guide drilling. The seismic section reveals active faults (deep seated structural discontinuity; Figure 9) that function as conduits for subsurface fluids. These faults allow deep crustal scale fluid circulation and represent prospective "Play" for geothermal exploration. Systems with connectivity to deep crustal heat supply are favorable for sustained geothermal production.

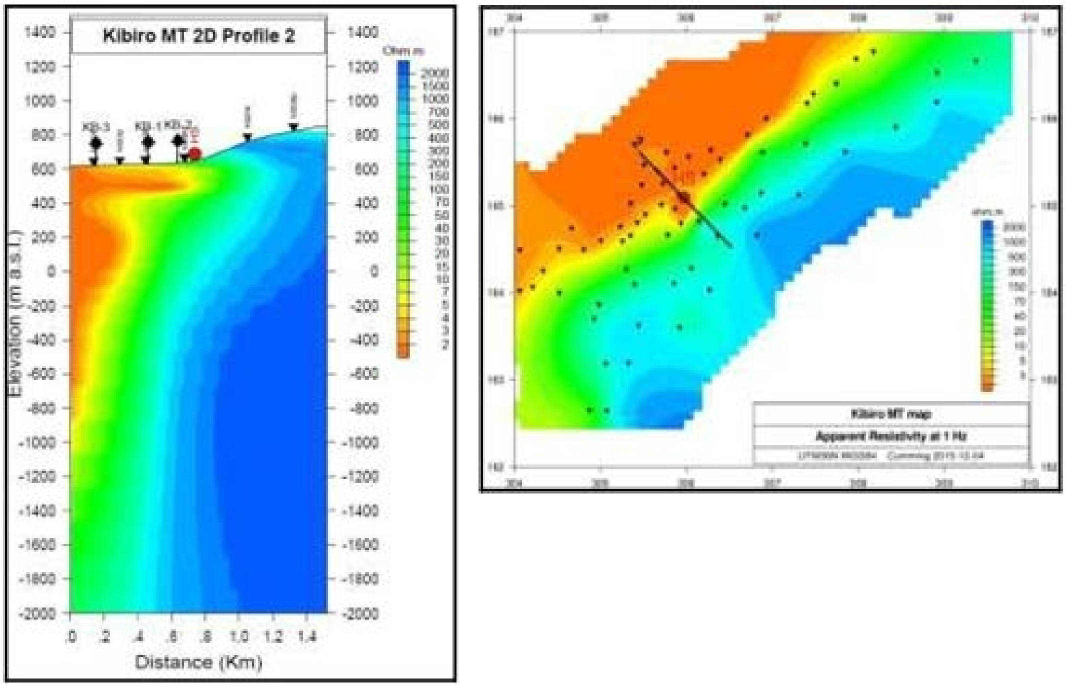

FIGURE 8: a) MT sounding revealed a sub-vertical conduit, which is interpreted as main rift bounding fault; b) Apparent resistivity map of Kibiro showing resistive basement rocks and conductive basin fill

TEM data has indicated a shallow reservoir at 300m and this has been recommended for TGH (Figure 9).

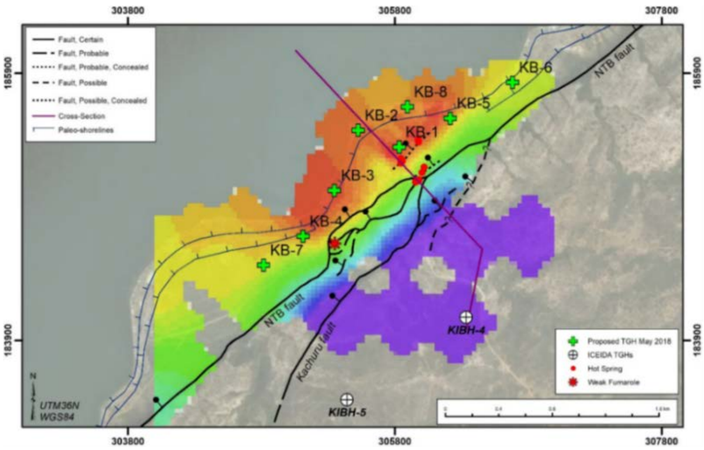

FIGURE 9: Map showing resistivity values around Kibiro. Note locations of recommended TGH

Preliminary conceptual model (Figure 9, 10 and 11) has been developed for Kibiro by integrating all data sets. This is going to be constrained by TGH data (see Figure 9 for TGH locations).

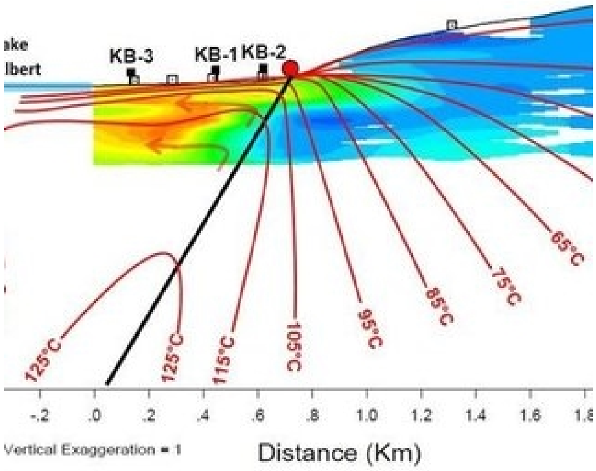

FIGURE 10: Section showing a preliminary conceptual model of Kibiro

TEM data acquired by ÍSOR has been re-interpreted using a geophysical software (*Geotools*) to refine and up-date the preliminary model of Kibiro. The project plans to drill TGH to reduce the geological uncertainity and risk prior to drill deep full diamter exploration wells. Siting of locations of TGH holes has been conducted and drilling is expected in December 2019. Prefeasibility studies of direct use application have been conducted by EAGER recommending salt drying, spa, heating oil pipeline, fish drying and aquaculture.

5.7.3 Geological mapping

Obvious magmatic heat sources are lacking. Younger structures were targets like recent faults (normal) and fractures. The main rift fault (deep penetrating) was targeted particularly in areas of fault intersection (increased fracture density). Permeability controls were found to be main rift bounding faults (fracture permeability) as evidenced by alignment of modern and relict surface features (Figure 11). Enhanced dilation here facilitates deep circulation of hydrothermal fluids. One cannot rule out formation permeability from Tertiary - Quaternary sediments. Faults intersections were targeted and Kibiro geothermal system is located at fault intersection an area of increased fracture density. EAGER Consultants produced a structural and thermal anomaly map which aided in siting TGH (Figure 12).

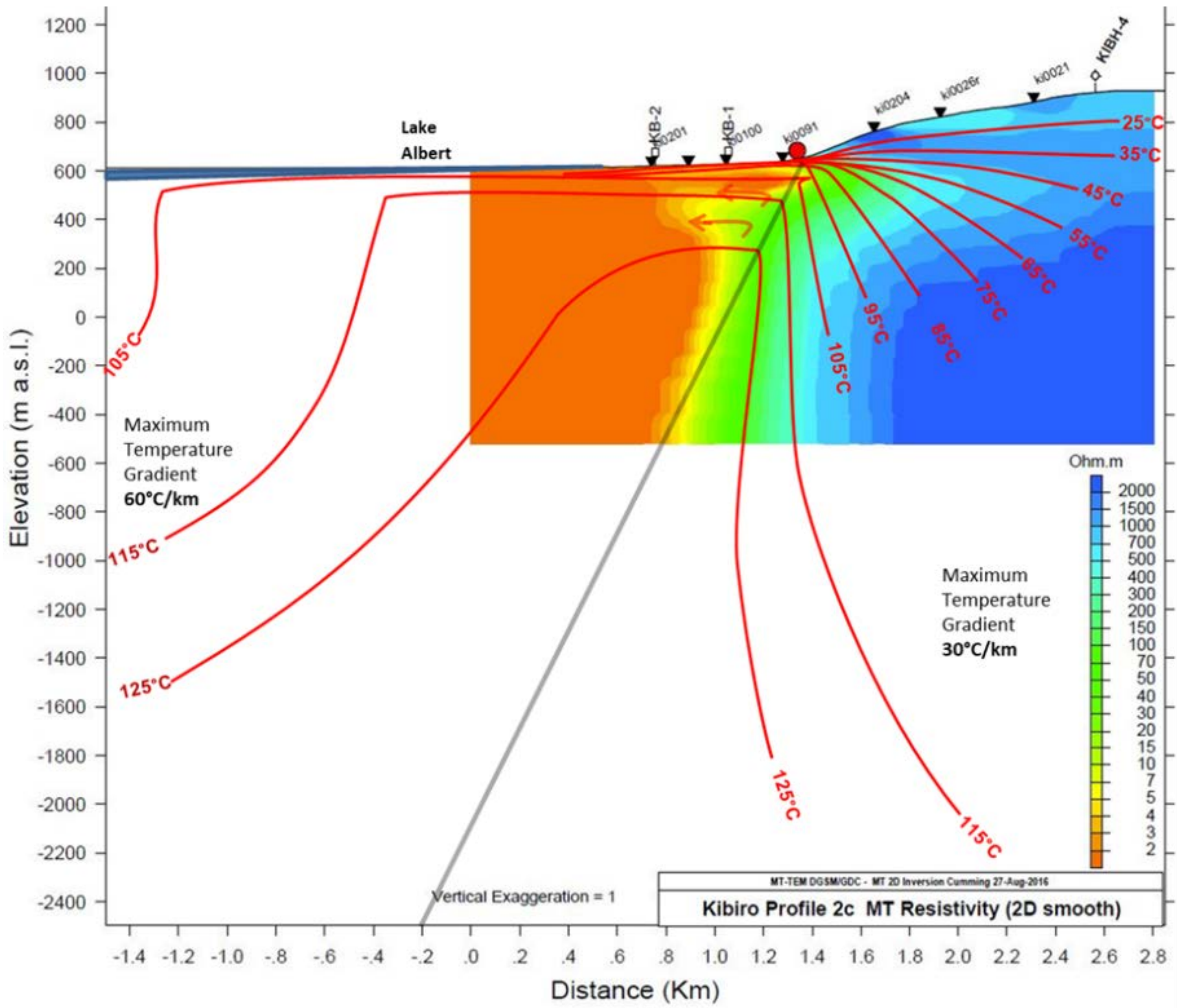

FIGURE 11: Section showing a preliminary conceptual model of Kibiro

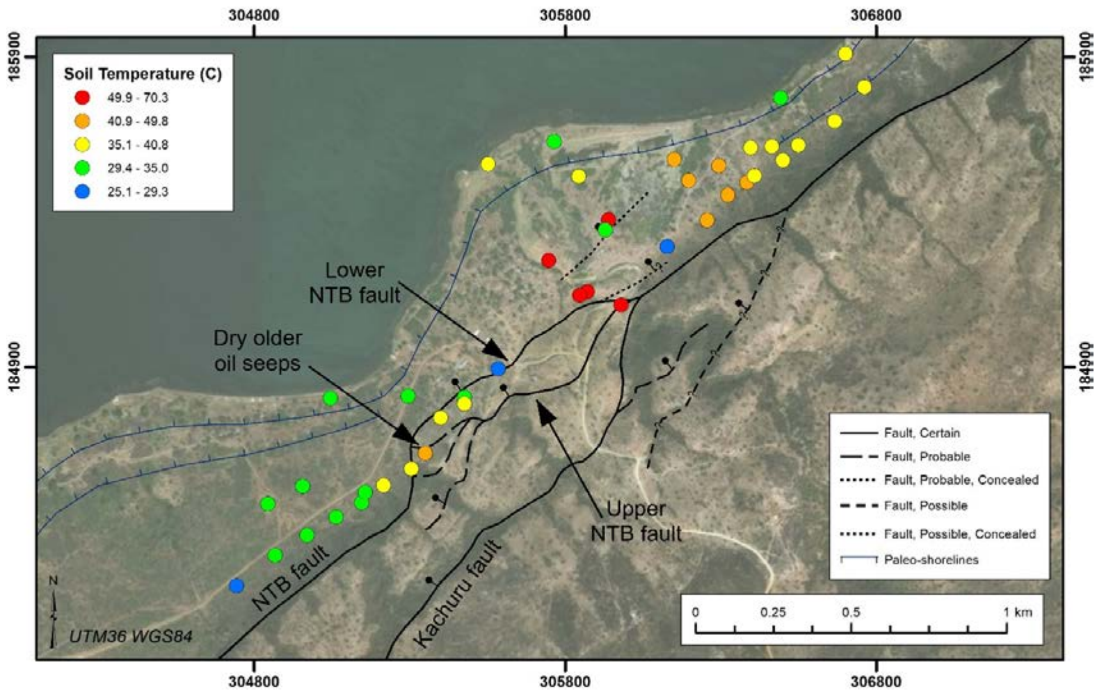

FIGURE 12: Map showing structures and surface temperatures around Kibiro (EAGER, 2017)

5.8 Panyimur exploration results

Government-led geothermal investigation surveys have been undertaken at Panyimur area by GRD, technically supported by EAGER hired experts. Preliminary geothermal conceptual models have been developed and these are being updated and refined as new data emerge. Work included detailed structural mapping (Figure 13) combined with an MT/TDEM survey (Figure 14, 15, 16 and 17), carried out together with EAGER hired structural geologist (EAGER, 2017).

Like, Kibiro, Panyimur prospect is a *deep-circulation amagmatic extension system* and in many respects, typifies other *fault-controlled geothermal systems* that are driven by deep circulation of ground waters. At Panyimur, fluid movement is controlled by the main rift bounding fault zone that bounds the west side of the rift valley. Data gap closure is planned at Panyimur to include TEM survey, shallow temperature probe surveys, soil gas and gas flux measurements.

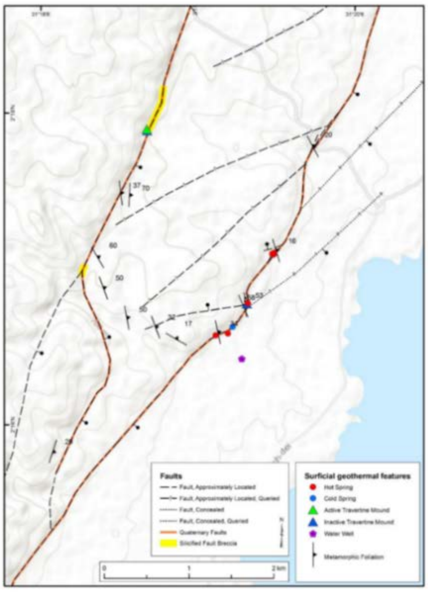

FIGURE 13: Map showing Structural mapping results of Panyimur (EAGER, 2017)

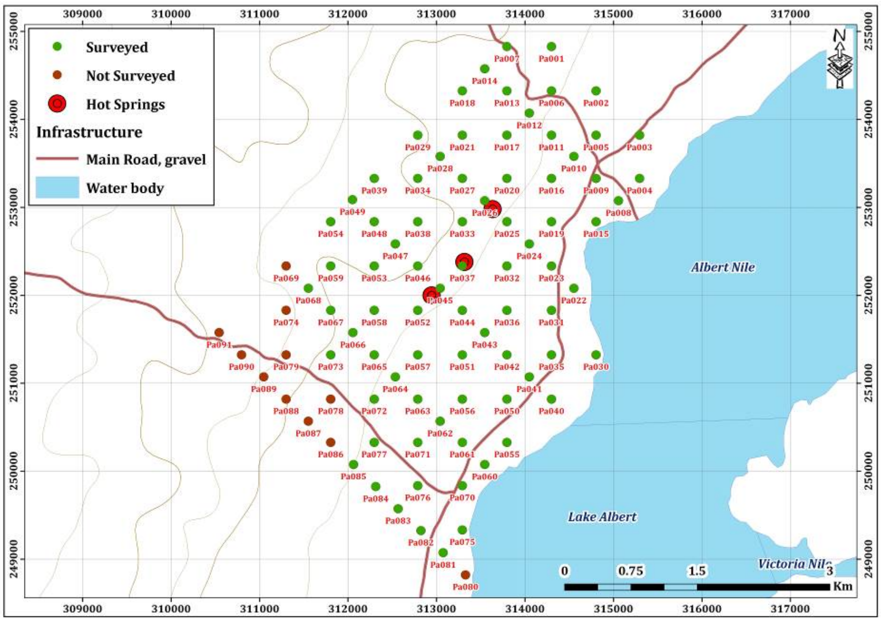

FIGURE 14: Map showing MT/TDEM Survey points in Panyimur area

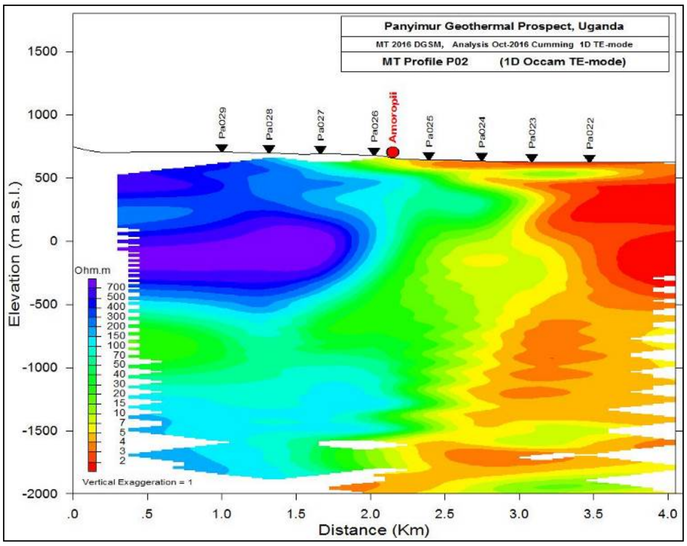

FIGURE 15: Section showing Panyimur profile P02-ID MT Resistivity (Cumming, 2016). Warm colors (red) indicate areas of low resistivity and cool colors (green and blue) indicate areas of high resistivity.

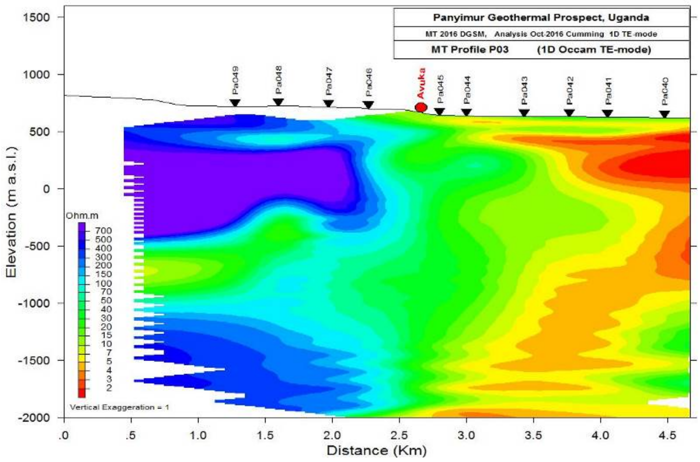

FIGURE 16: Section showing Panyimur profile P03-ID MT Resistivity (Cumming, 2016). Warm colors (red) indicate areas of low resistivity and cool colors (green and blue) indicate areas of high resistivity.

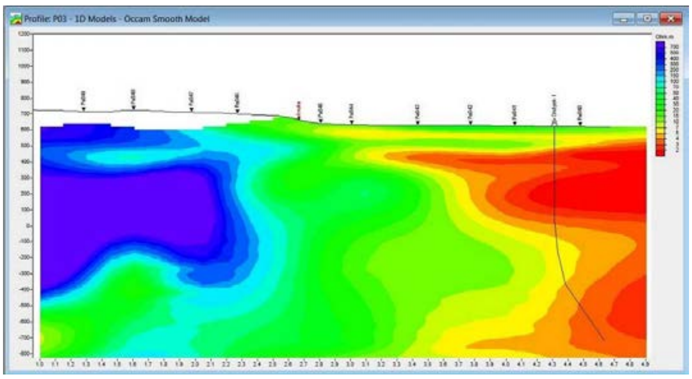

FIGURE 17: Section showing MT Profile along Panyimur. Warm colors (red) indicate areas of low resistivity and cool colors (green and blue) indicate areas of high resistivity.

A preliminary geothermal conceptual model (Figure 18) has been developed, which will be refined and up-dated with TGH data. TGH drilling is planned in January 2020.

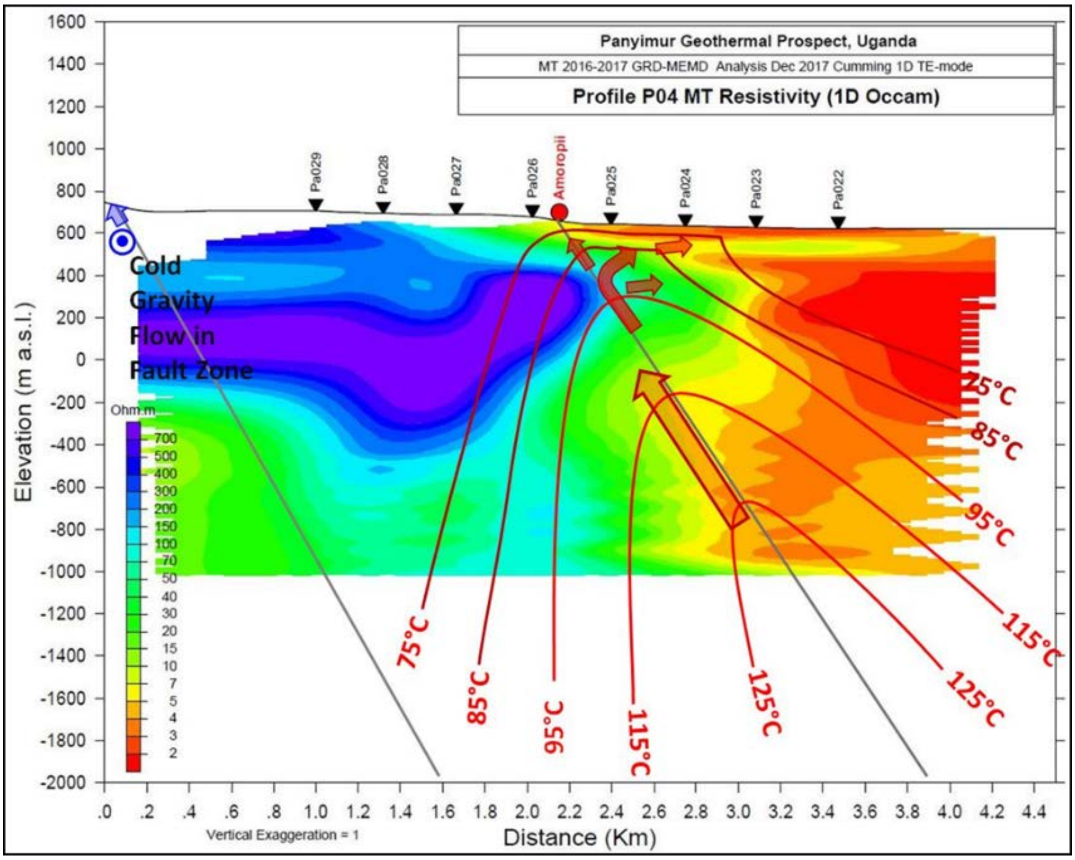

FIGURE 18: Section showing a preliminary conceptual model of Panyimur area (EAGER, 2017)

Direct use application pre-feasibility study was undertaken by EAGER experts who recommended crop drying, heating oil pipeline, aquaculture, spa, fish drying and greenhouses.

5.9 Katwe-Kikorongo exploration results

Kawe-Kikorongo geothermal prospect lies in a rift valley. It is also presumed to be a *deep circulation extension system*. This system is presumed to be *fault-bounded extensional (horst and graben) complex (Brophy Type E)*. The system is structurally controlled by the prominent NE-SW trending rift bounding fault (Figure 19). The deep penetrating crustal faults are indicated by reflective seismic section from oil and gas survey. The faults are seismically active and aligned with numerous geothermal surface manifestations including tufa towers.

Unlike other fault-bounded systems in Uganda, the *deep crustal fractures extended to a considerable depth* giving way to magma escaping culminating into Katwe-Kikorongo quaternary volcanic field. These volcanic materials are characterised by SIO_2 under saturation, low Al, moderately high K but extremely high Ca content. Pyroclastics dominate over lavas (Holmes and Harwood, 1932) due to the *extremely volatile rich explosive nature of the volcanism*. Magmatism was active in upper Pleistocene and continued intermittently until recent times (Holmes, 1950; Lloyd et al., 1985). These are *less viscous* and all the material is likely to have been ejected with minimal chances of forming *shallow magma chambers* (intrusion of young magmas). Silicic magma are viscous and in most cases get lodged in shallow high level magma storage chambers producing heat needed by geothermal systems unlike basaltic magmas which are less viscous and extremely volatile.

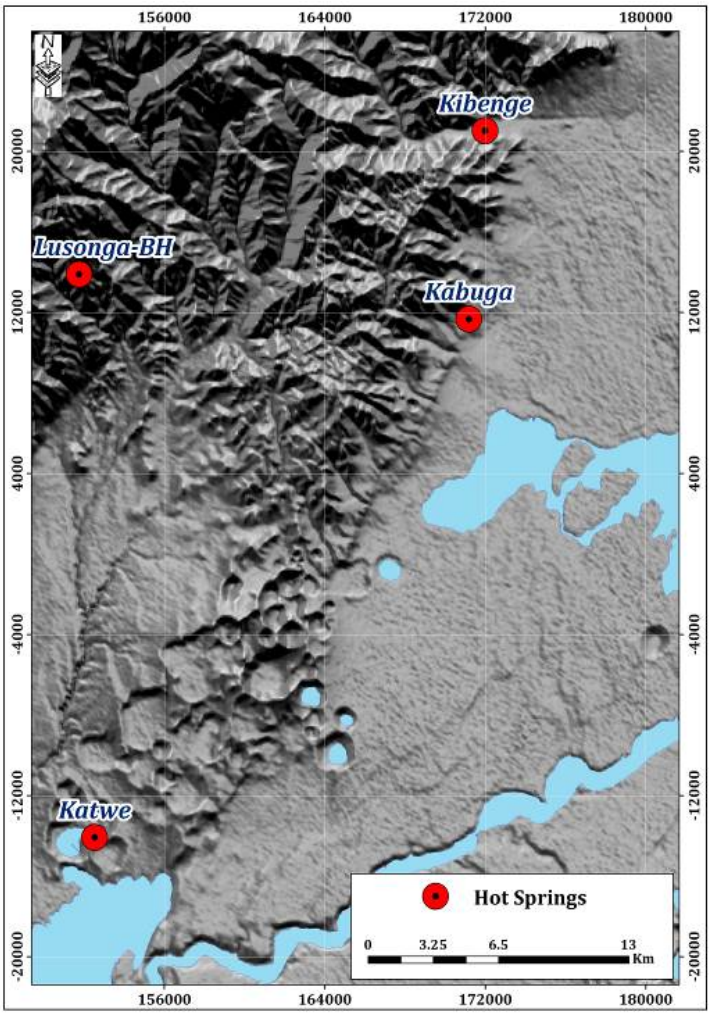

FIGURE 19: Map showing NE-SW principal rift bounding fault zone which is presumed to control geothermal activity

MT field survey was conducted to image the sub-surface structures presumed to control geothermal activity and results are presented in Figures 20, 21 and 22.

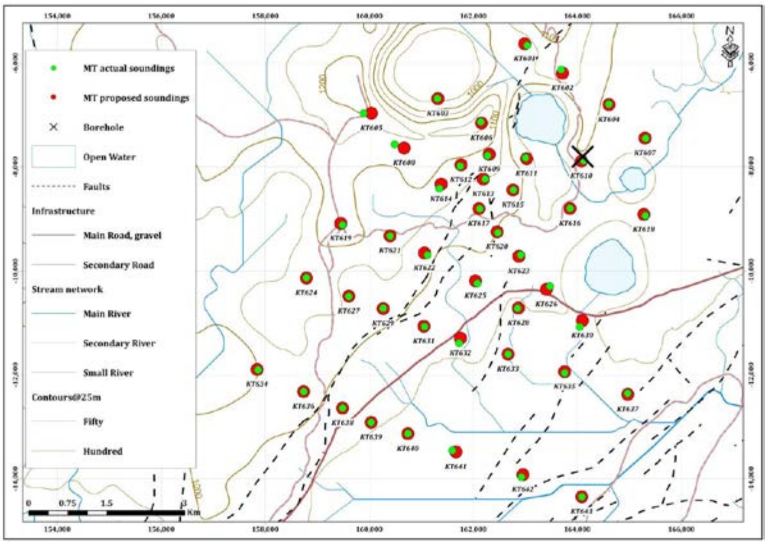

FIGURE 20: Map showing MT station locations

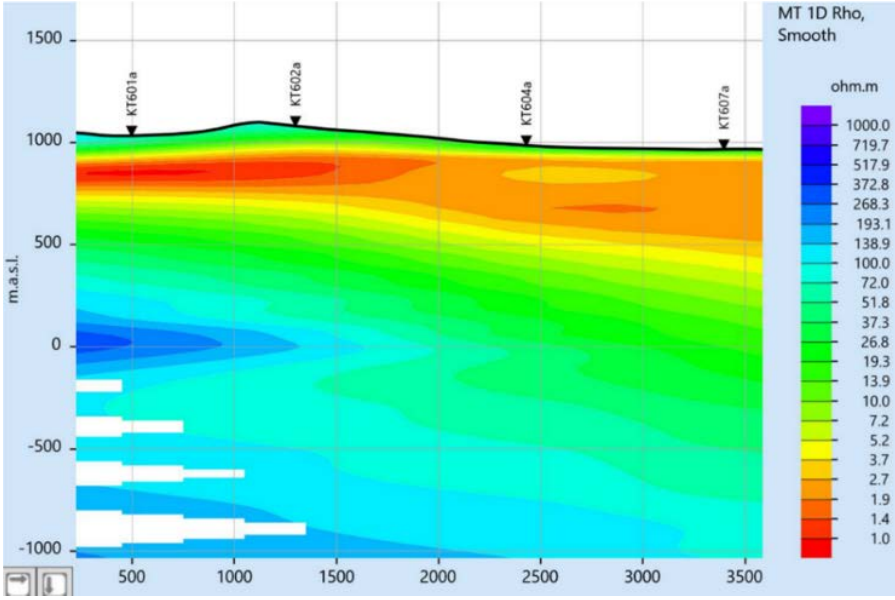

FIGURE 21: Katwe MT slice line resistivity cross-section - Profile 00a

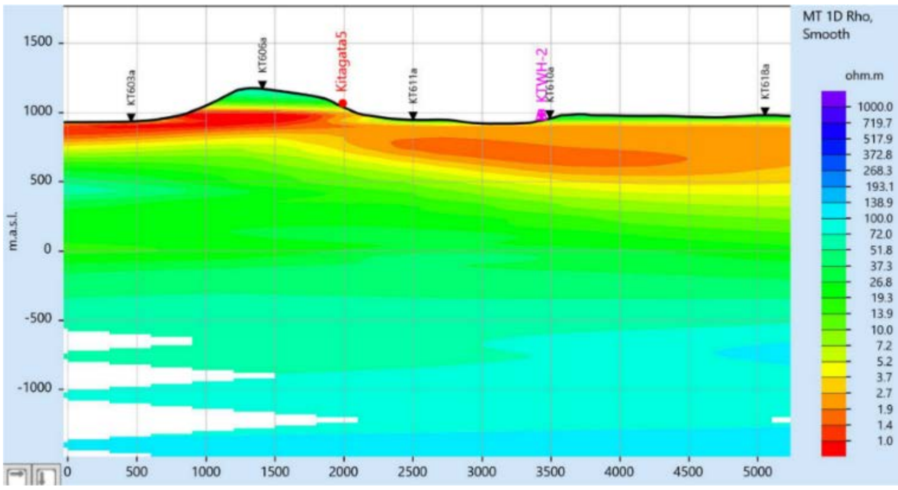

FIGURE 22: Katwe MT slice line resistivity cross-section - Profile 00

Results are still being interpreted and more processing is expected with EMpower geophysical data processing software to develop a 3D conceptual model. One has to note that this a volcano-tectonic regime which should be taken into account when interpreting data.

5.10 Buranga exploration results

Geothermal investigation surveys have been undertaken in Buranga by GRD technically assisted by EAGER hired expert. EAGER undertook structural analysis and thermal anomaly mapping (Figure 23).

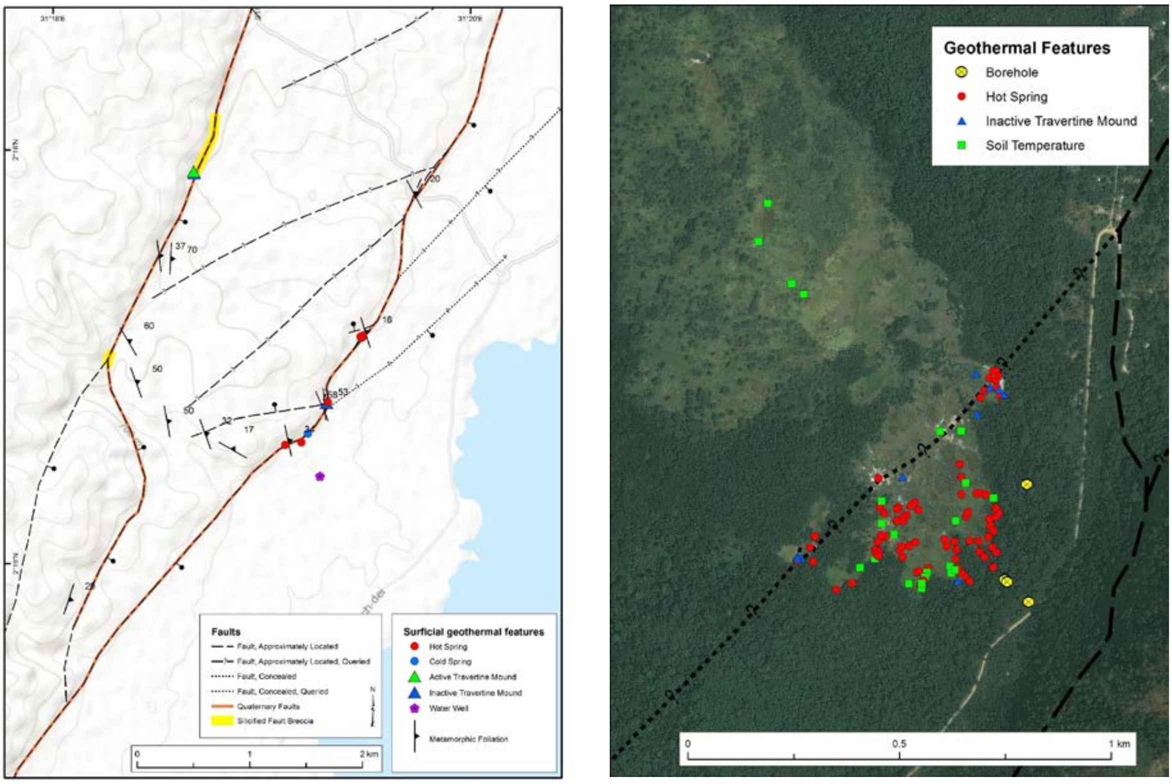

FIGURE 23: Structural map of Buranga on left and thermal anomaly map (EAGER, 2017)

EAGER hired experts conducted drone aided thermal anomaly mapping in inaccessible areas of Buranga. A thermal anomaly map was produced (Figure 24).

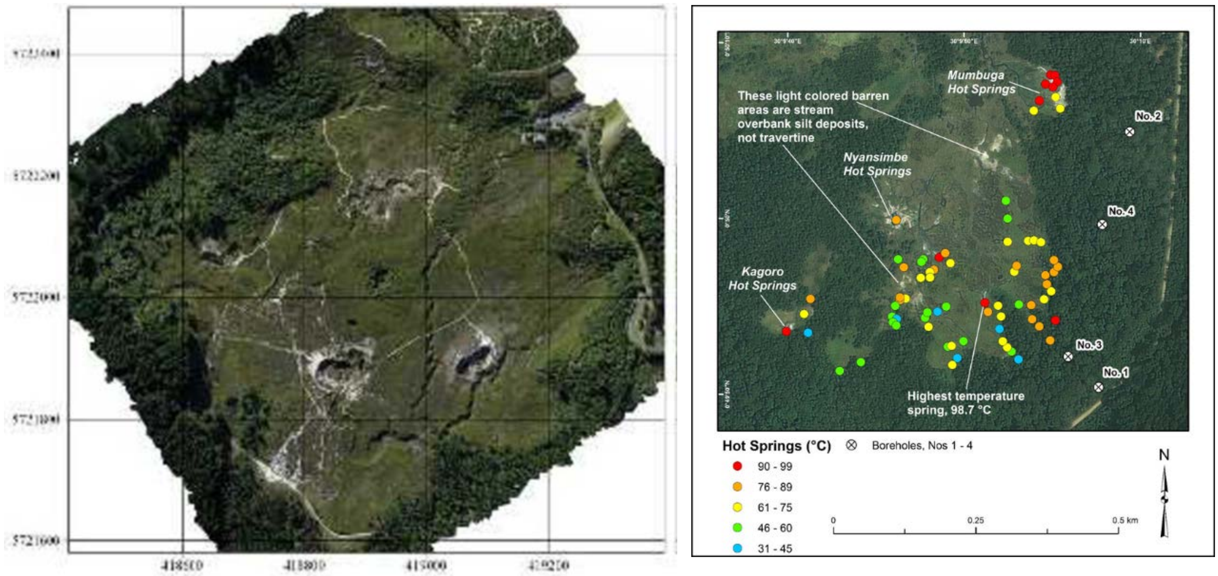

FIGURE 24: Map showing a thermal anomaly map of Buranga

Soil gas surveys have been conducted in Buranga and reveal a NE-SW trend presumed to indicate a structural control (Figure 25).

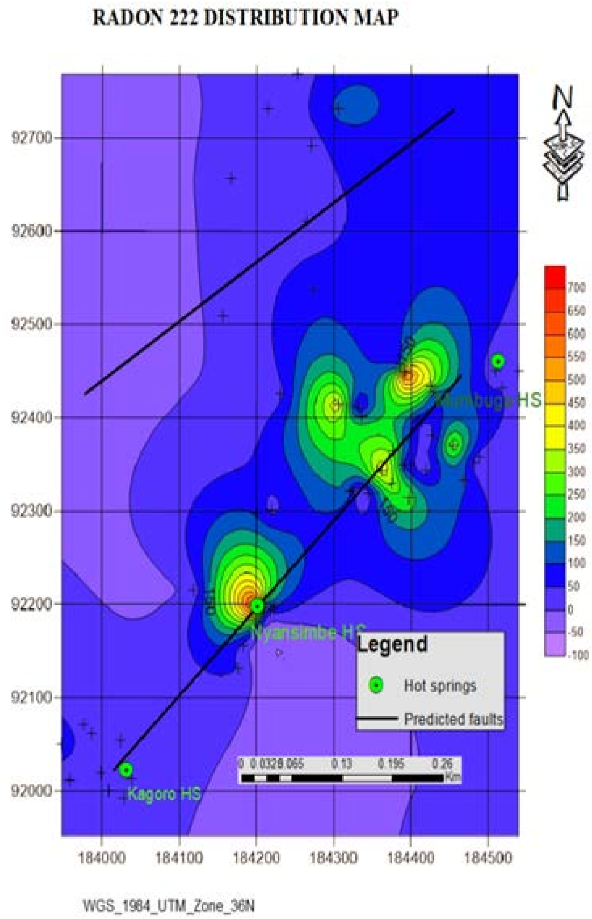

FIGURE 25: Map showing Radon distribution

A preliminary conceptual model (Figure 26) has been developed which will be refined and up-dated with TGH data.

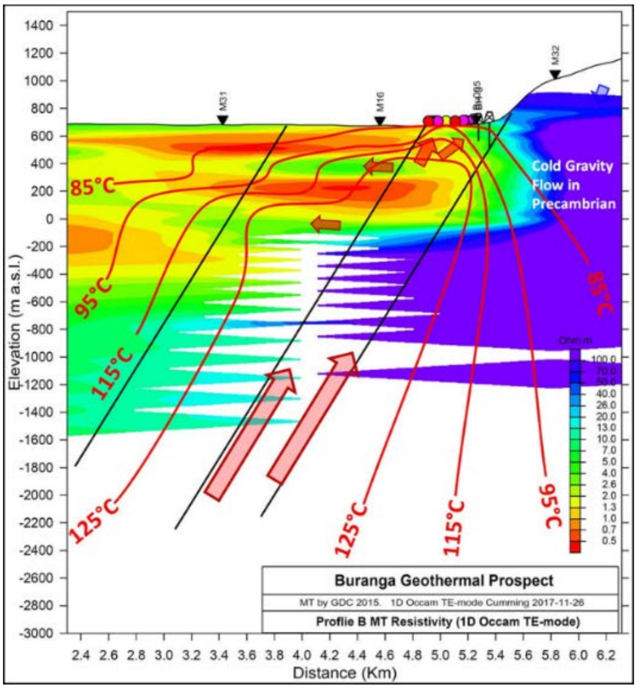

FIGURE 26: Section showing a preliminary geothermal conceptual model of Buranga (EAGER, 2017)

5.11 Ihimbo Geothermal Area

Geothermal studies have been conducted in Ihimbo (Figure 27) and surface manifestations include hot springs, travertine domes, vegetation kill areas, warms springs and gaseous emissions. Ihimbo prospect is an extensional deep-circulation non-magmatic system. In many respects, the Ihimbo geothermal system typifies other fault-controlled geothermal fields that are driven by deep circulation of ground meteoric waters. At Ihimbo, fluid movement is controlled by the Ihimbo fault zone (an internal fault) trending NE-SW. The main rift bounding fault is characterized by travertine dome and cones an indication of past geothermal activity.

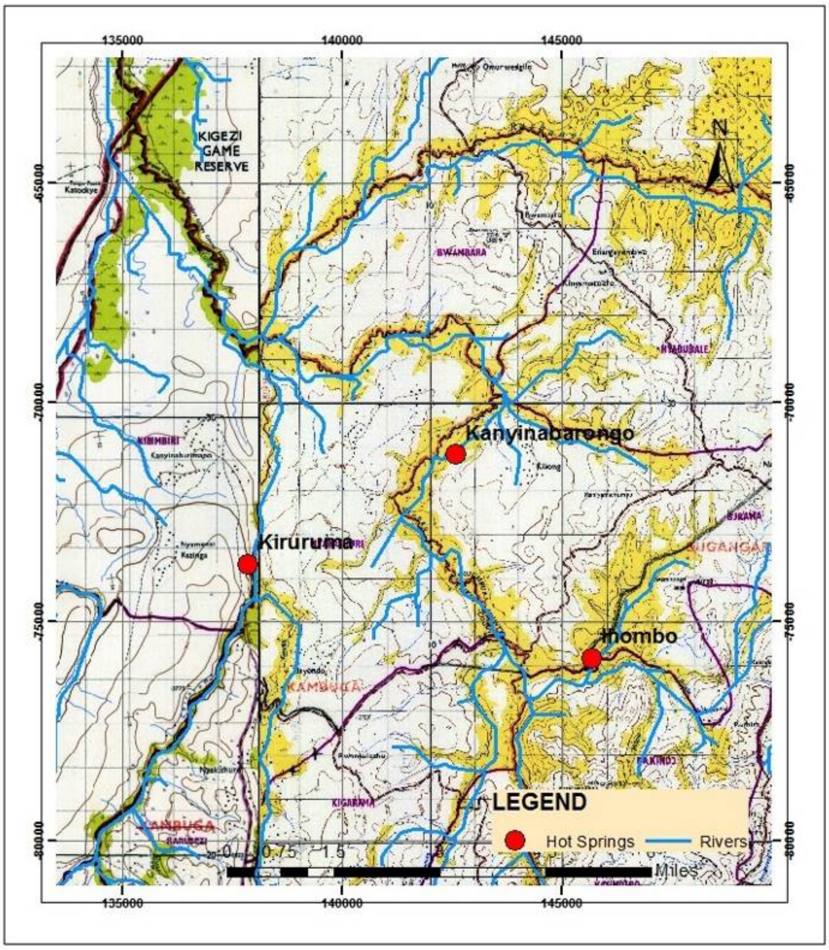

FIGURE 27: Topographic map of Ihimbo Area

Geochemical surveys have involved surface water sampling and analysis (JICA 2014; Ármannsson, 2010), soil gas (Rn) and gas flux measurements. Shallow temperature measurements were also undertaken during the soil gas and gas flux measurements. Gas flux data and soil gas data (Rn) were processed (Figure 28 and 29). Anomalous gas concentrations are presumed to locate active fault zones presumed to control geothermal activity. High flux is presumed to be indicative of anomalous flux associated with geothermal activity.

Magnetotelluric survey (40 MT soundings) were conducted (Figure 30 and 31) around the geothermal area. TDEM survey is planned in this area to correct for static shift in MT data. Focused structural mapping will aid in developing a geothermal resource model of this site. The field crew will leverage on the oil and gas data which was collected in this area more so reflective seismic data and gravity data.

Data processing, analysis and interpretation is still going on using geotools and geophysical data processing software.

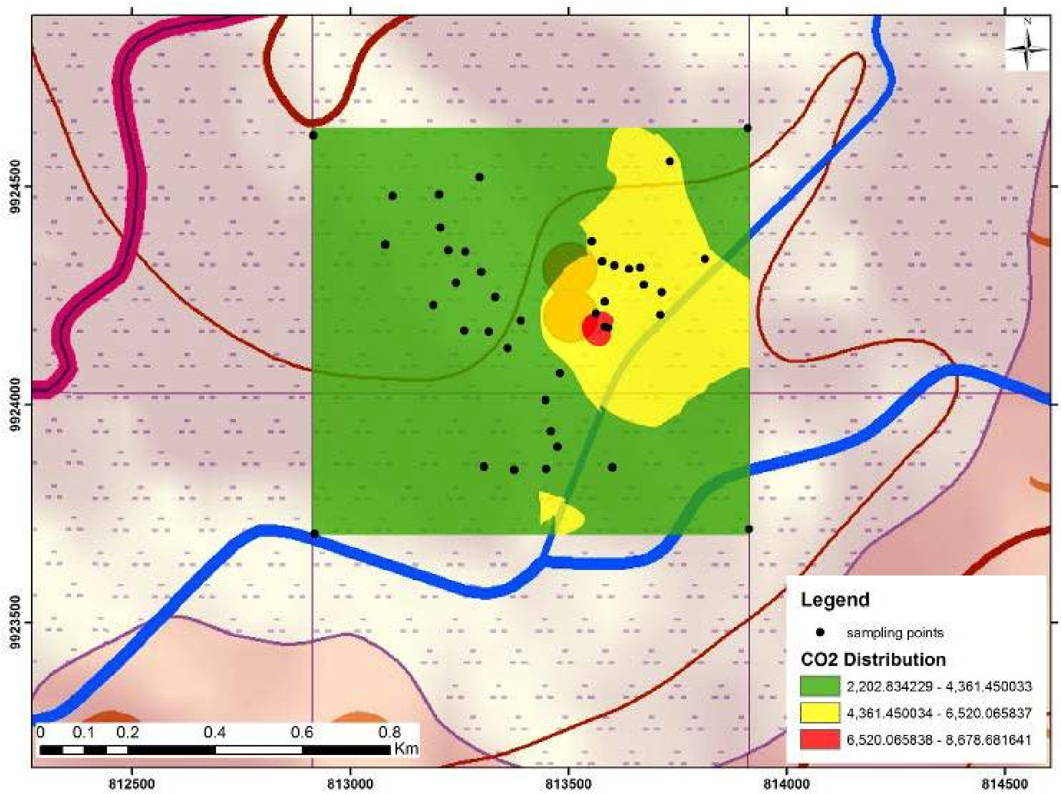

FIGURE 28: Spatial distribution of CO_2 flux measurements in Ihimbo area. Anomolous gas flux are presumed to indicate geothermal activity (permeable conduits).

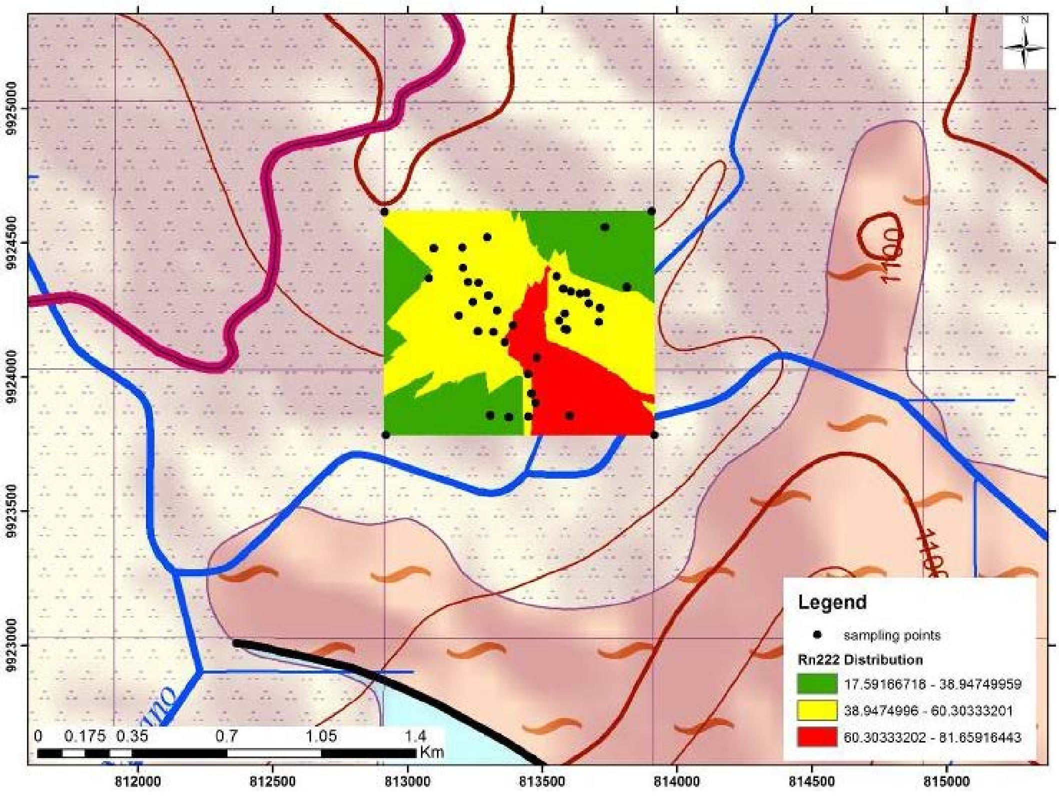

FIGURE 29: Distribution of activity of 222Rn diffusively degassed from the soil in Ihimbo geothermal prospect. Anomolous concentrations are presumed to indicate concelaed faults that act as conduits for geothermal fluids.

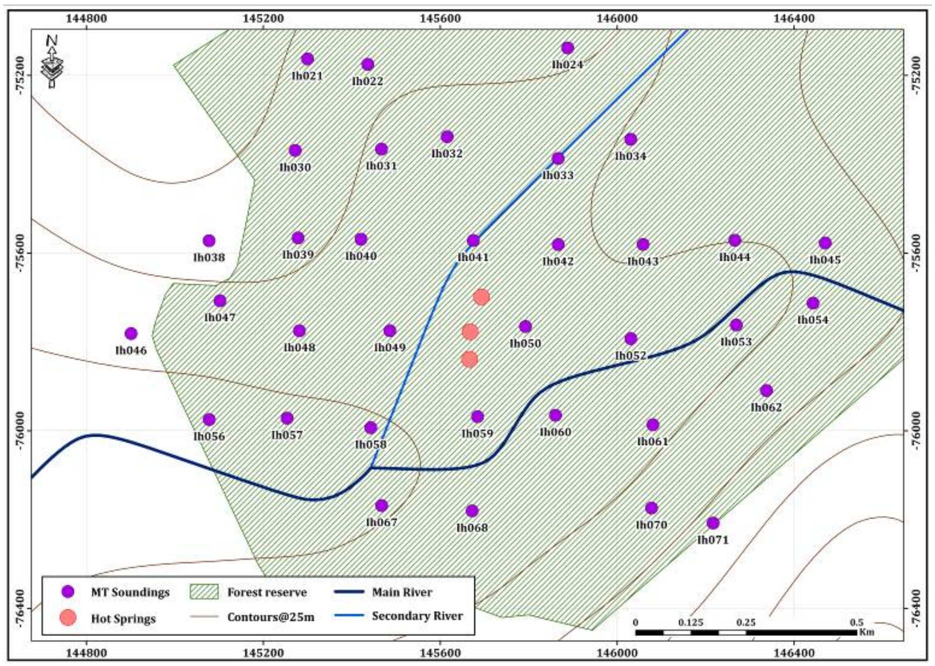

FIGURE 30: Map showing stations for MT Sounding at Ihimbo Geothermal Resource Area

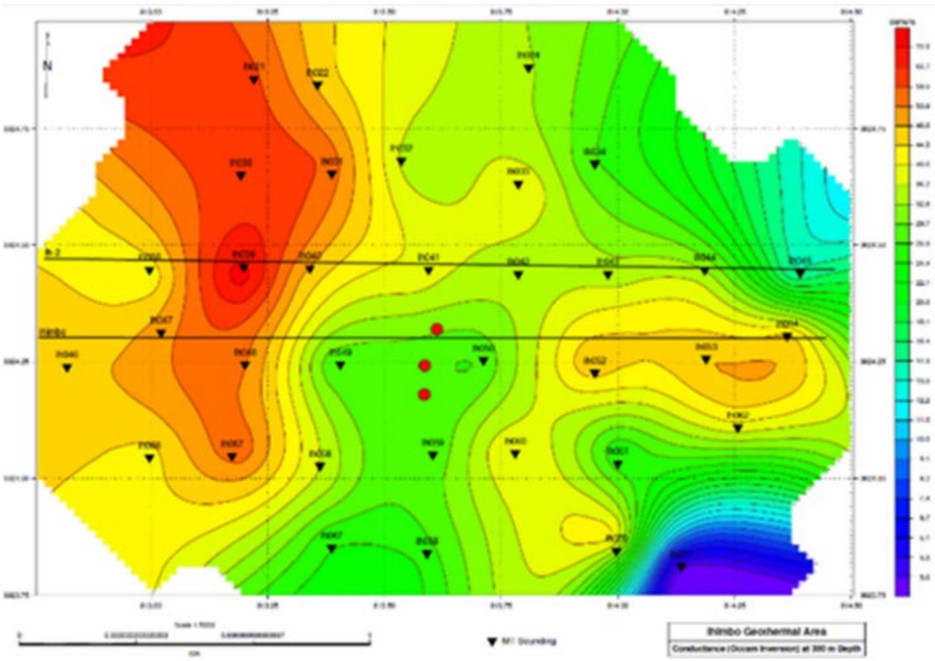

FIGURE 31: Map showing resistivity results around Ihimbo. Note the open anomaly in NW.

5.12 Other areas

Preliminary geothermal investigation surveys have been conducted around other areas after geothermal play fairway analysis as covered below.

Rubaare Geothermal Area: Geological mapping, shallow temperature survey, ground magnetic survey and MT survey (Figures 32 and 33) have been conducted in this area. Planned work includes soil gas survey, detailed structural mapping and MT data gap closure.

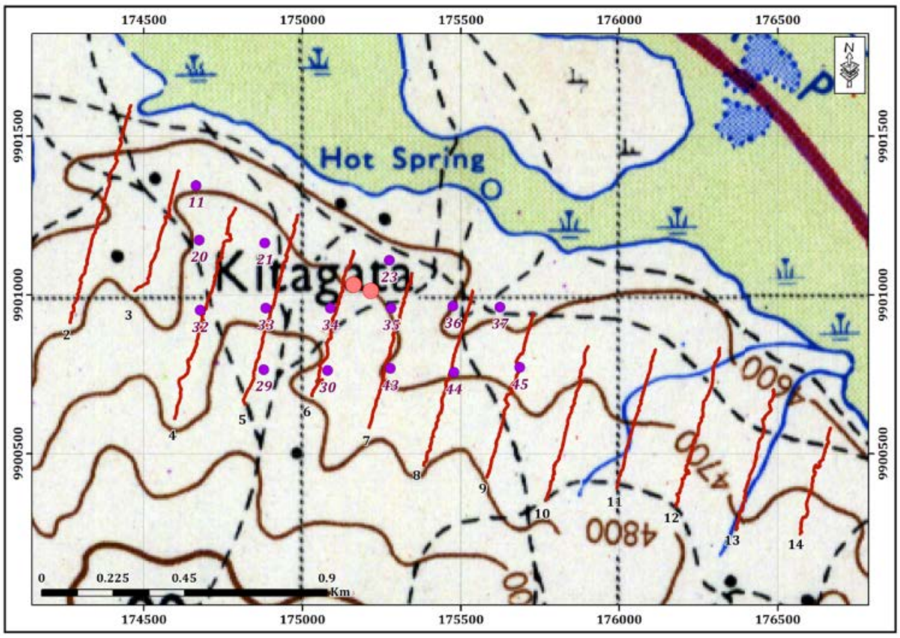

FIGURE 32: Map showing survey design overlain on topographic map

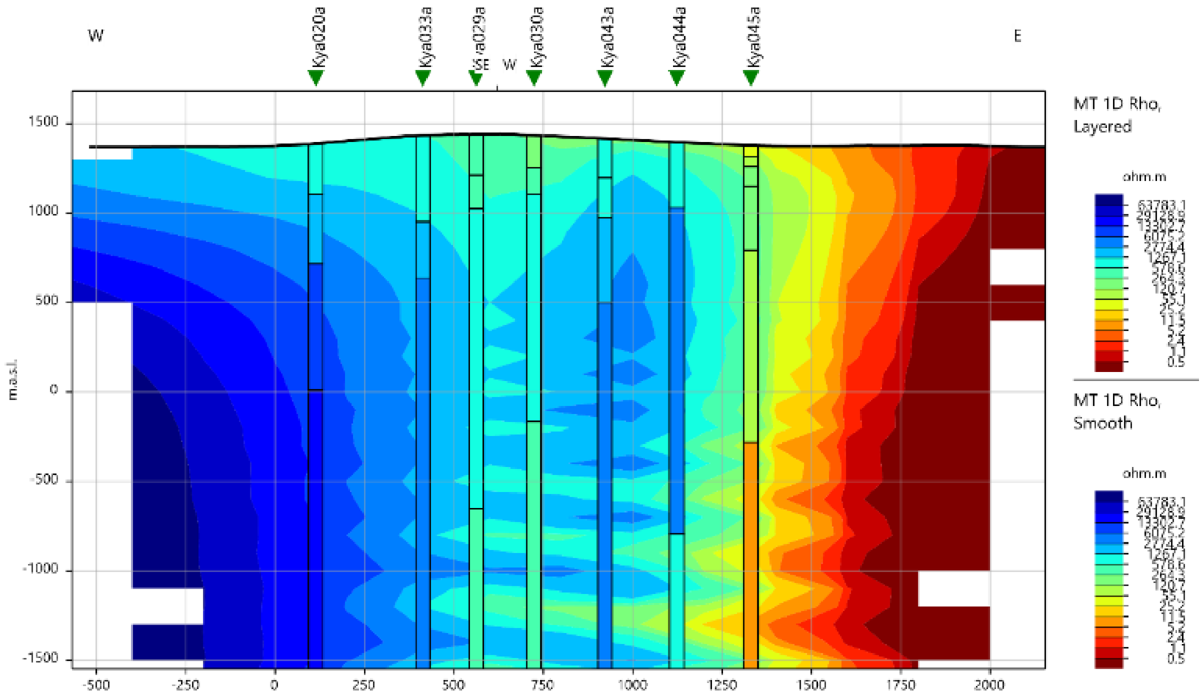

FIGURE 33: Cross sectional map showing 1D layered (model bars) apparent resistivity over laid on 1D smooth apparent resistivity

Nyamwamba Fault Site: This principal normal fault, NE-SW trending, fault dipping SE (Figure 34) is characterized by thermal manifestations. It is seismically active and deep seated according to seismic information. It is an ideal geothermal exploration target which is presumed to allow deep circulation of water to be heated by heated crust.

Geothermal exploration should focus basin ward where the faults are dipping starting with low cost methods. LiDAR imagery will be used to bring out details of topographic features that are previously unavailable revealing structural patterns.

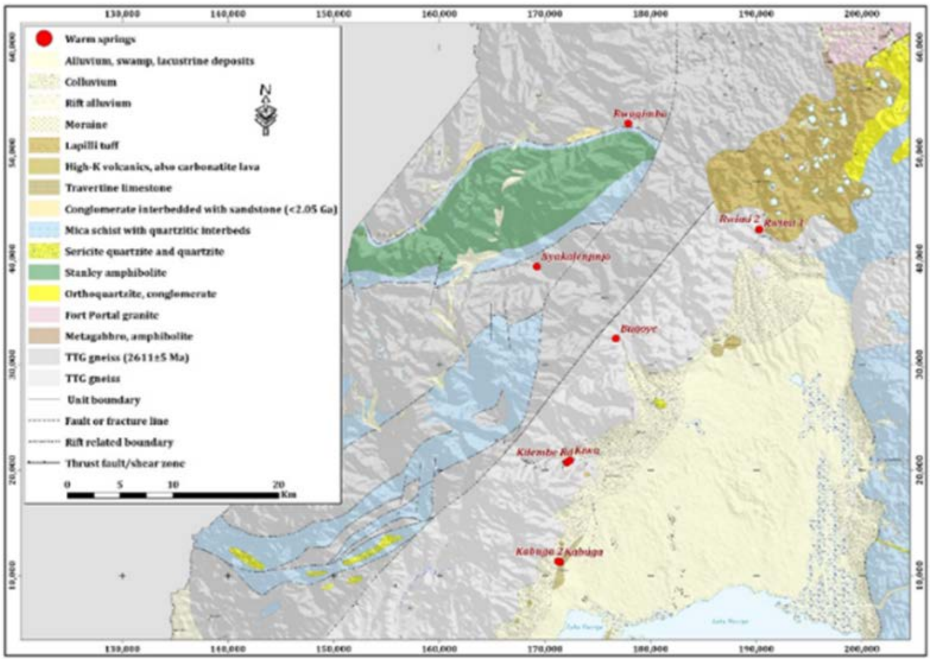

FIGURE 34: Map showing geology around Nyamwamba normal fault and thermal manifestations

George Fault Site: This site is located in rift extensional regime (Figure 35) and has surface manifestations which include travertines, gaseous emissions and warm springs (Dwenkorebe spring). It is seismically active (Figure 36). It is recommended to conduct soil gas surveys and shallow temperature measurements *basin ward* prior to deploying cost intensive MT/TDEM surveys.

LiDAR data is recommended to help map subtle linear faults in this area obscured by volcanic debris. LiDAR data will be acquired primarily to delineate the traces of faults.

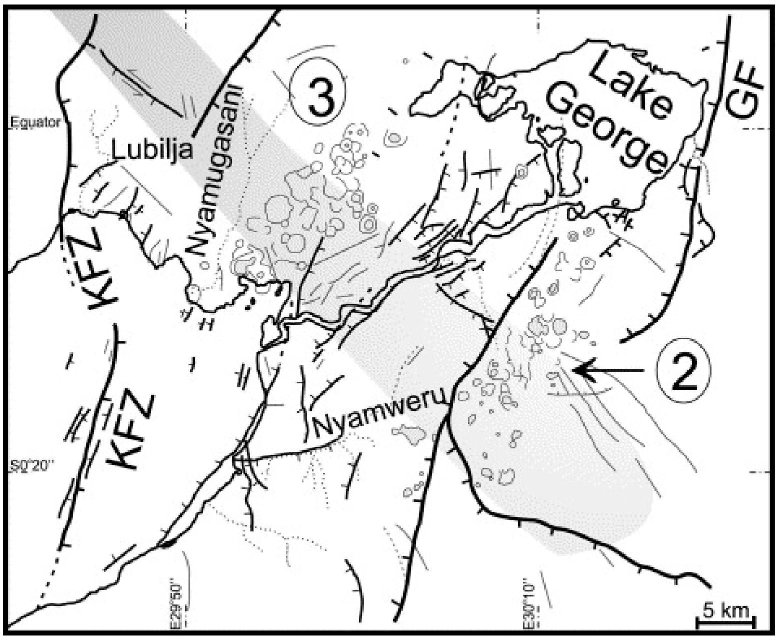

FIGURE 35: Map showing George normal Fault (GF) on eastern side of Lake George dipping westward

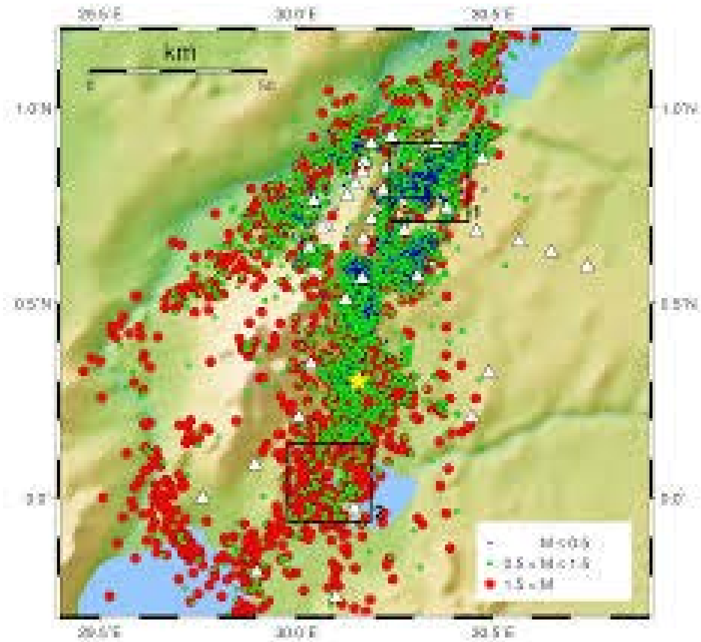

FIGURE 36: Map showing seismicity of the area.

Rwimi-WASA fault: This is on the eastern side of Rwenzori. It is steeply dipping and seismically active (Figure 37). It is almost similar in setting to Bwamba fault which hosts the Buranga hot springs.

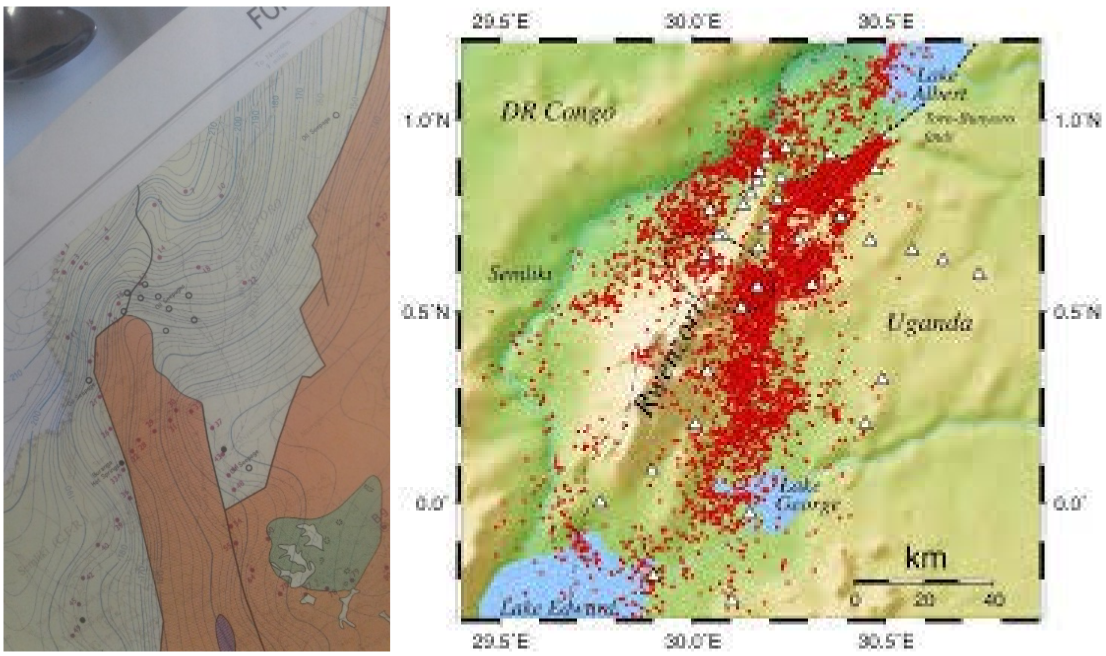

FIGURE 37: Map showing Rwimi-Wasa fault on eastern edge of Rwenzori almost parallel to Bwamba fault. On the right is a seismicity map of the area.

Kichwamba Fault: This is ideal in that it is STEP-OVER or relay ramp (Figure 38) and is a main bounding fault which is tectonically active. Mapping has revealed fossil surface indicators of geothermal activity.

It is recommended to conduct soil gas surveys and shallow temperature measurements basin ward prior to deploying cost intensive MT/TDEM surveys.

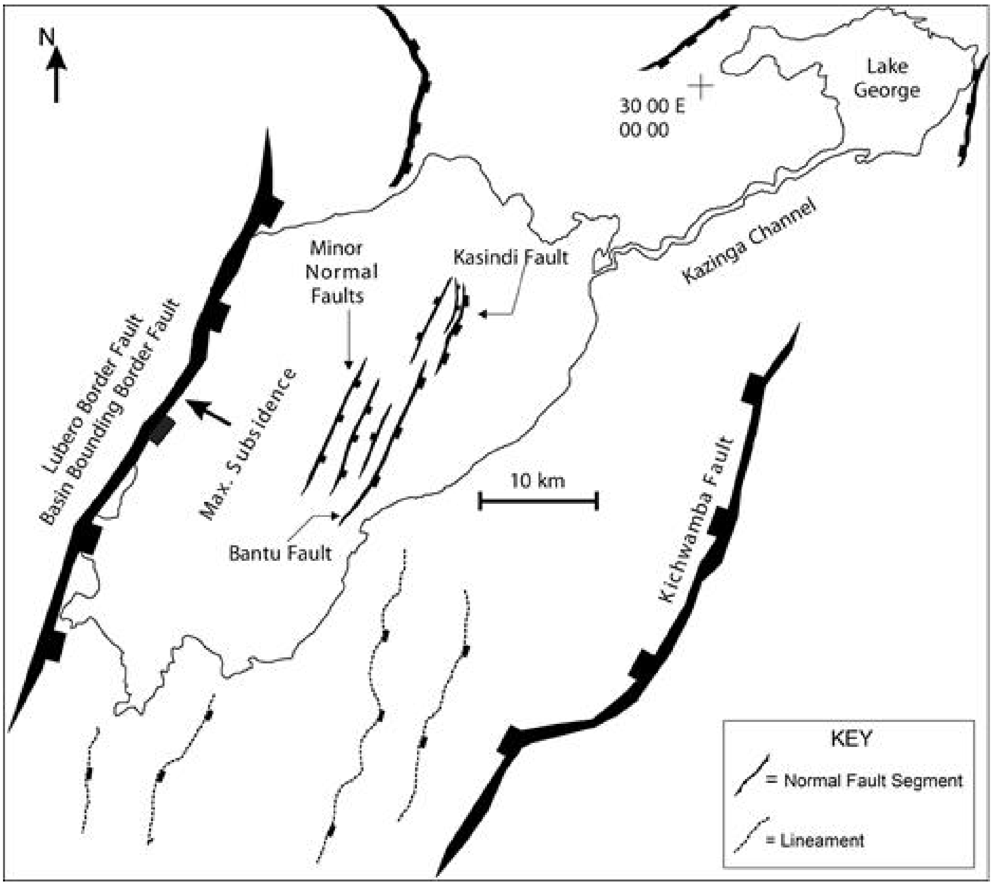

FIGURE 38: Map showing Kichwamba fault dipping NW

Kaiso-Tonya Site: A large relay of step over (Figure 39 and 40) was mapped by oil companies and surface indicators of geothermal activity were mapped. The area has favourable characteristics for geothermal activity.

It is recommended to conduct soil gas surveys and shallow temperature measurements basin ward prior to deploying cost and labor-intensive MT/TDEM surveys.

FIGURE 39: Map showing Kaiso-Tonya main normal faults and displacements

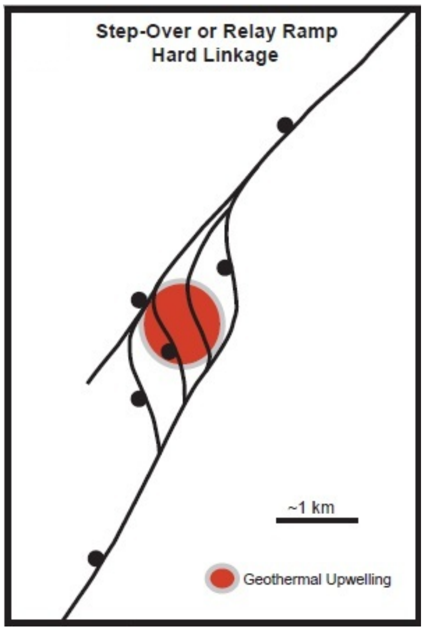

FIGURE 40: Diagrammatic representation of relay ramp (Faulds and Hinz, 2015)

5.12 Exploration strategy

The projects now follow an exploration strategy to reduce cost and maximize success in exploring for geothermal resources. It was important to learn from past failures and determine which of the techniques used for geothermal exploration did not identify a geothermal system. DGSM assessed both failed and successful techniques.

- **Seismic reflection analysis** to map deeply penetrating fault zones. The interpretation of seismic surveys form a highly detailed and reliable picture of the subsurface structure, with resolution unattainable by most other geophysical methods. Such a picture is highly desirable in geothermal exploration to guide drilling.
- **MT/TDEM survey** to delineate and detect the geometry and depth of the clay cap, and also in determining the boundary between the alteration zone and the geothermal reservoir. Static shifting techniques have been applied utilizing TDEM surveys.
- **Soil gas and gas flux measurements** to delineate permeable deep penetrating faults.
- **Shallow temperature surveys** to map shallow thermal anomalies associated with geothermal activity
- **Geological mapping:** Detailed surface and structural analysis of faults to involve LiDAR mapping.
- **Thermal Gradient Holes** drilling to map and delineate the shallow thermal anomaly.
- **Data integration:** All data sets will be integrated to build conceptual model.

No geophysical "silver bullet" currently exists for the geothermal industry. Rather, we will employ various studies from a suite of geophysical exploration methods to better understand a geothermal reservoir prior to drilling.

6. INSTITUTIONAL FRAMEWORK

MEMD was restructured and a Directorate of Geological Survey and Mines (DGSM) was established. Under DGSM is a Geothermal Resources Department (GRD) which oversees, promote and manages geothermal exploration and development in Uganda. Core geothermal survey equipment have been procured. Much as the institution has been established there are still some capability gaps (technical, management, engineering and scientific). More effort is needed to put in place a skilled geothermal workforce to spearhead geothermal development.

Currently, geothermal resources are regulated by the *Mining Act 2003* and its regulation 2004. The *Mining Act 2003*, gives potential geothermal investors inadequate legal security. There is legal and regulatory gaps and the Mining Act 2003 is being reviewed. Geothermal energy has a peculiar nature (it has an element of mineral and water) that it needed a specific law taking into consideration its uniqueness. GoU was technically assisted by Climate Technology Center and Network (CTCN) to draft geothermal policy and regulation. The Draft documents have been reviewed by EAGER experts and internally by an inter-Ministerial committee. Drafts are yet to be submitted to Cabinet and Parliament for further management.

7. ON-GOING GEOTHERMAL PROJECTS

- **Uganda Geothermal Energy Resources Development project** (1199) is a government funded project ending in June 2020 with a promise of funding another successor project.
- **World Bank ERT-3:** Within this programme, Energy for Rural Transformation (ERT-3) there is a geothermal component which is being implemented.

8. CONCLUSION

Uganda has made a substantial progress towards exploring its geothermal resources as well as putting in place the necessary institutions and policies. Human capital development has been addressed as well. An exploration strategy has been developed.

Uganda geothermal systems are *fault-hosted extensional (non-magmatic) systems* which rely on deep circulation of meteoric waters. They are presumed not to be derived from active or recently active magmatic activity. They are a result of thinned crust, elevated heat flow in recent extensional domains. Preliminary conceptual models of Kibiro, Panyimur and Buranga have been developed, and plans are in advanced stages to drill TGH beginning December 2019.

MT survey was conducted in Katwe following structural mapping by EAGER experts and local staff. Preliminary conceptual model is being developed. Data processing, analysis and interpretation will be carried out using *Empower* software being procured.

Further analysis in Ihimbo will include resistivity surveys (TEM), structural mapping, LiDAR mapping, leveraging oil and gas data and finally developing a geothermal conceptual model. TGH exploration is recommended prior to deep drilling.

Work has commenced in other selected areas with favourable characteristics (structural and tectonic controls) of geothermal prospectivity. Two (2) sites, that are found to be most promising, will be selected for detailed study.

9. RECOMMENDATIONS

- Data closure should be undertaken in Katwe to complete pre-drilling studies.
- The 3He/4He ratios of geothermal fluids from fault-bounded geothermal systems should be measured to determine if a deep mantle signature is present.

- Most of these geothermal systems are deep circulation systems and typifies other fault-controlled geothermal fields that are driven by deep circulation of ground waters. Here, fluid movement is controlled by the main fault zone (structure controlled permeability) that bounds the rift and hence should be key exploration target.
- LiDAR data should be acquired to map subtle fractures and faults in the areas investigated due to their high resolution and enhanced elevation data (70 cm).
- Completely independent subject matter experts should review the geologic conceptual models prior to drilling.

REFERENCES

Abeinomugisha, D., 2010: *Development of a petroleum system in a young rift basin prior to continental break up: The albertine graben, of the East African Eift System*. AAPG, Search and Discovery Article #10284. *Website: http://www.searchanddiscovery.com/documents/2010/10284abeinomugisha/*

Ármannsson, 2010: Investigations of geothermal areas in Uganda other than Katwe-Kikorongo, Buranga and Kibiro. ÍSOR / Iceland GeoSurvey, Reykjavík, Iceland, report ÍSOR-2010/003, 11 pp.

Corti, G., 2009: Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. *Earth-Science Reviews, 96,* 1-53.

Corti, G., 2012: Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System. *Tectonophysics, 522-523,* 1-33.

Cumming, W., 2016: *Kibiro geophysics*. Presentation.

DoE, 2006: *A history of geothermal energy research and development in the United States*. United States Department of Energy, Energy Efficiency and Renewable Energy – Geothermal Technologies Program, 212 pp.

EAGER, 2017: *Structural geology at Panyimur and Buranga*. East Africa Geothermal Energy Facility, report U-23-D02.

Ebinger, C.J., 1989: Tectonic development of the western branch of the East African rift system. *Geological Society of America Bulletin, 101-7,* 885-903.

Faulds, J.E. and Hinz, N.H., 2015: Favorable tectonic and structural settings of geothermal systems in the Great Basin Region, Western USA: Proxies for discovering blind geothermal systems. *Proceedings of the World Geothermal Congress 2015,* Melbourne, Australia, 6 pp.

Gíslason, G., Ngobi, G., Isabirye, E., and Tumwebaze, S., 1994: *An inventory of three geothermal areas in West and Southwest Uganda*. A report prepared for a UNDP project, Geothermal Exploration UGA/92/002, UNDEST/GSMD, 41 pp.

Glassley, W.E., 2010: *Geothermal energy. Renewable energy and the environment*. CRC Press, Boca Raton, Florida, United States, 320 pp.

Holmes, A., 1950: Petrogenesis of Katungite and its associates. *Amer. Miner., 35,* 772-792.

Holmes, A. and Harwood, H.F., 1932: Petrology of the volcanic fields east and south-east of Rwenzori, Uganda. *Quart. J. Geol. Soc. Lond., 88,* 370-439.

JICA, 2014: *Data collection survey on geothermal energy development in East Africa. Final report*

(Uganda). Japan International Cooperation Agency, West Japan Engineering Consultants Inc., and Mitsubishi Materials Techno Corporation, 148 pp.

Karp, T., Scholz, C.A., and McGlue, M.M., 2012: Structure and stratigraphy of the Lake Albert Rift, East Africa: Observations from seismic reflection and gravity data. AAPG Special Volumes.

Lloyd, F.E., Arima, M., and Edgar, A.D., 1985: Partial melting of phologpite-clinopyroxenite nodule from south-west Uganda: An experimental study bearing on the origin of highly potassic continental rift volcanics. *Contributions to Mineralogy and Petrology, 91*, 321-329.

McConnell, R.B. and Brown, J.M., 1954: *Drilling for geothermal power at Buranga hot springs, Toro*. Geological Survey of Uganda, unpublished report R.B.M/16.

Moeck, I, 2013: Classification of geothermal plays according to geological habitats. In: Bracke, R., Harvey, C., and Rueter, H. (eds.), *Geothermal exploration best practices*. IGA Services GmbH, Bochum, Germany, 156 pp.

Nyblade A.A. and Langston C.A. 1995**:** East African earthquakes below 20 km and their interpretation for crustal structure. *Geophysical J International, 121*, 49-62.

Ochmann, N., Lindenfeld, M., Barbirye, P., and Stadtler, C. 2007: Microearthquake survey at the Buranga geothermal prospect, Western Uganda. *Proceedings of the Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, United States, 8 pp.