

Pre-Drilling Geothermal Investigation Surveys in Uganda

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Uganda needs sufficient and secure energy supply to mitigate the ever increasing energy demand due to its growing economy and population. There are also pressing issues of climate change, energy security and economic competitiveness. As a long-term strategy, Uganda decided to develop all its renewable alternative energy sources in order to grow its energy supply. Among the renewables was geothermal energy resources.

Uganda is endowed with geothermal resources which are widely distributed in several districts across the country. These are ascribed to areas of thinned crust and high heat flow which are tectonically active. Deep circulation of water along fracture and fault zones allows water to be heated by heated crust to form geothermal systems. These are amagmatic extension deep circulation geothermal systems. Geothermal investigation surveys in Uganda begun way back in 1954 when four swallow wells were drilled in Buranga. Exploration results were not so encouraging and the project was abandoned. Several preliminary surveys were undertaken supported by ICEIDA, JICA, World Bank, IAEA, ADB and BGR. These surveys culminated in drilling swallow wells in Kibiro and Katwe. Results were not encouraging which affected the morale of the geothermal industry in Uganda.

Since FY 2011/12, Government of Uganda (GoU) committed public funds and implemented government-led exploration to develop its geothermal resources. Uganda has been implementing the “Uganda Geothermal Resources Development Project” since. Under this project core survey equipment were procured, human capital has been developed, legal and regulatory framework is being put in place, an institution Geothermal Resources Department (GRD) was established. Pre-drilling Exploration in five priority areas have been advanced with technical support from UNEP-ARGeo, GDC and East African Geothermal Facility (EAGER). Geothermal investigation surveys (pre-drilling exploration) are at Pre-Feasibility stage at five sites; namely Kibiro, Katwe, Panyimur, Ihimbo and Buranga.

Deployed exploration techniques included routine Magnetotelluric (MT) surveys, Time Domain Electromagnetics (TDEM), Soil gas and gas flux measurements, swallow temperature measurements, micro seismic survey, baseline determinations, entailed geological mapping and structural analysis. This information has been supplemented by data from oil and gas industry particularly 3D seismic survey and well logs data. Preliminary structural conceptual models have been developed for Kibiro, Panyimur and Buranga by geothermal consultants. Conceptual models are being developed which will be followed by well targeting. Buranga geothermal area has a problem of inaccessibility. Here surveys are dangerous and time

consuming. Drone aided thermal anomaly mapping was designed and conducted. The coverage was extensive and made the survey faster. Thermal imagery maps have been produced with high spatial resolution. The main rift bounding faults are key exploration targets more in critically stressed zone like fault intersection or interaction.

Other prospects were focused geothermal investigations have commenced include Ihimbo, George, Kichwamba, Nyamwamba and Rwimi-Wasa areas. Like the four prospects above, these other geothermal sites are extensional deep circulation systems where heat sources are derived from heated crust resulting from extension and thinning of the crust. Most of Uganda's geothermal systems are extensional driven as opposed to magmatically driven systems. They typify other deep circulation (amagmatic) geothermal systems in Great Basin and Range (Western USA) and in Western Turkey. These are called *fault-bounded extensional (Horst and Graben) complexes* (Brophy Type E). They comprises of horsts (ridges) and grabens (flat-bottomed valleys). LiDAR mapping techniques has been recommended to obtain highly detailed topographic maps of resource areas. High resolution digital elevation models (DEM) from LiDAR will help locate subtle fault and fracture systems (fault and structural maps) which are presumed to control geothermal activity. Fault zones play an important role in the circulation of geothermal fluids in the crust. Since Uganda's geothermal systems are fault-hosted geothermal systems, structural characterization of the resource areas is crucial in assessing these resources.

1. Introduction

Uganda needs sufficient and secure energy supply to mitigate the ever increasing energy demand due to its growing economy and population. There are also pressing issues of climate change, energy security and economic competitiveness. As a long-term strategy, Uganda decided to develop all its renewable alternative energy sources in order to grow its energy supply. Among the renewables was geothermal energy resources. Like other developing countries, Uganda is faced with a problem of increasing power demand and energy security which has to be mitigated by growing its energy sources.

Hydro remains the mainstay of Uganda's energy production. The Government decided as a strategy to develop its renewable alternative sources including wind, solar, geothermal and hydros for energy security, reliability and economic development. Uganda is endowed with abundant geothermal resources ascribed to the tectonic setting. The geothermal activity is genetically related to the intra-continental rift extensional active tectonism. Exploration for geothermal resources dates back in 1954 when the first shallow wells were drilled at Buranga Geothermal Site. Several geothermal investigation surveys followed technically supported by several international organization. Since Financial Year 2011/2012 to date, Government-Led exploration has been undertaken with significant accomplishments. Outlined below are key accomplishments registered from the pre-drilling geothermal investigation surveys undertaken in Uganda to-date

2. Previous Studies

Geothermal studies by Department of Geological Survey and Mines (DGSM) dates way back in 1950's when 4 shallow wells were drilled in Buranga area (McConnel et al, 1954). In early 1970,s, 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 3 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, G, et al 1994). The results warranted advanced exploration to up-grade and refine the exploration model.

Isotope Hydrology for Exploring Geothermal Resources phase-1 (1999-2003):

IAEA together with Ministry of Energy and Mineral Development (MEMD) funded this project with the aim of up-grading and refining the exploration models of Kibiro, Buranga and Katwe-Kikorongo prospects, using isotopes. This was 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 investigations were carried out 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.

GEO THERM Project: Germany Federal Institute for Geosciences and Natural Resources (BGR) together with MEMD conducted intermediate exploration in Buranga beginning 2003. This was under the GEO THERM programme, which promoted the utilization of geothermal energy in developing countries. Project activities 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 $3\text{He}/4\text{He}$ ratios of geothermal fluids were measured to determine if a deep mantle signature was present. These elevated $3\text{He}/4\text{He}$ ratios were believed to be evidence of deep permeability and possibly deeper, higher-temperature fluid reservoirs.

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

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. Initial exploration models were tested, supplemented, and refined by further field work. The process will continue until a hopefully reliable exploration model is achieved.

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: Data collection survey on geothermal energy development in East Africa, Final Report (Uganda): Following the situation analysis, Japan International Cooperation Agency (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 resource 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 locate a prospective site 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. A conceptual model of Kibiro was developed. UNEP Donated micro-seismic equipment which were installed around Kibiro to detect active tectonic fractures presumed to control geothermal activity.

3. Evolution of Western Rift Valley

Without clear understanding of the geology of a prospect area, exploration is merely guesswork. Unsuccessful attempts to explore for geothermal resources in Uganda invited a decision to first clearly understand Uganda's geothermal systems, their structural and geological setting. A working hypothesis was vital prior to undertaking any further geothermal investigation surveys.

The western rift valley is approximately 100-km-long normal fault systems with 1- to 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 et al, 1984). The flanks of the rift have been uplifted 1-4 km above the surrounding Plateau, and basement lies below sea level beneath many basins.

Lithologically, it has tertiary-quaternary sediments in the graben and Precambrian basement rocks at the escarpment. The rift is seismically active both from felt and instrumental information. It is 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 active basin bounding young faults. Geophysical and geological data in the Albertine Graben indicate that rifting was initiated 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 hosting most of Uganda's geothermal prospects is at different stage of rift evolution (initial to intermediate stage / bounding fault to internal fault) compared to the Eastern Arm of the EARS. According to Corti et al (2011), 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. Major bounding 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* (figure 3) in the early stages of extension (Uganda) toward *magma assisted-rifting during the final stages of continental break-up* (Kenya, Ethiopia, Afar, Corti et al 2011, figure 4).

Studies of earthquake source parameter in the Western Rift show deep events down to 30-40 km (Nyblade and Langston, 1995) indicating *deep faults*. Depth to detachment estimates of 20-30km and seismicity throughout the depth range 0-30km suggesting that planar *border faults penetrate the crust* (C.J Ebinger, 2015).

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, Abeinomuhsa, 2010 personal comm) and numerous geothermal systems. 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. Modern geothermal systems are ascribed to focused and identifiable magmatic heat sources, but extension type systems are related to regionally dispersed amagmatic heat flux

These are *fault-bounded extensional (horst and graben) systems* in non-volcanic environments which rely on deep circulation of meteoric water into the heated crust (see figure 1). Complexes of horsts and grabens occur in regions where there has been crustal extension and thinning. As the crust is pulled apart, it tends to fracture, forming steeply dipping faults that are perpendicular to the general direction of extension (Glassley, 2010).

Blocks of crust subside between faults forming grabens, whereas surrounding ground on opposite side of the bounding fault remain elevated forming horsts. The *high angle faults* that bound the horst and grabens can extend to considerable depth (see figure 1). Such setting are places where magma often rises in the crust, (Glassley, 2010) in response to decreased lithostatic pressure caused by crustal thinning during extension. As a result of presence of these heat, geothermal reservoir may occur. Permeability is commonly restricted to *fault-controlled zones* in the vicinity of horsts and grabens boundaries. In this case, rift bounding faults are geothermal exploration targets.

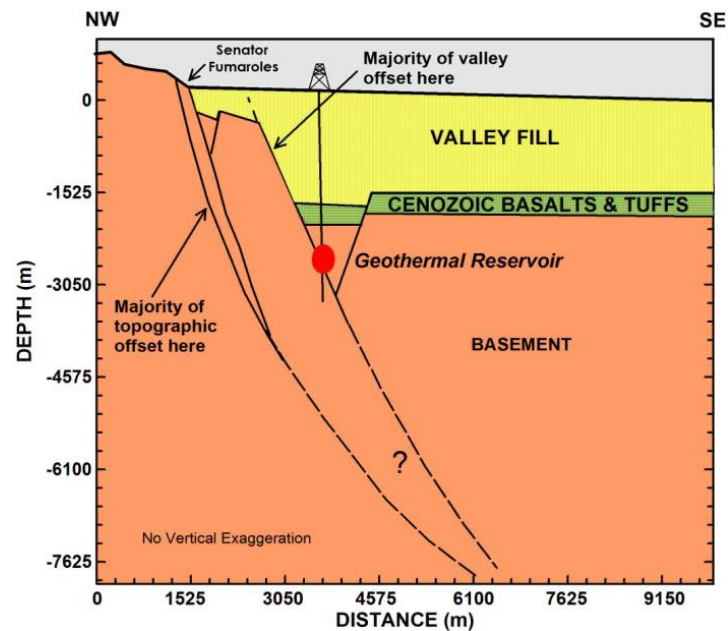


Figure 1: Idealized structural model of the Dixie valley (Desert Peak) geothermal system which typifies Uganda geothermal systems (Blackwell et al 2000).

According to Inga Moeck, classification system of geothermal systems, most Uganda geothermal systems are Extensional Domain play Type CV3. In an extensional Domain Geothermal Play (CV3), the mantle is elevated due to crustal extension and thinning. The elevated mantle provide the principal source of heat for the geothermal system associated with this play type. According to Moeck, these are fault controlled geothermal plays in domains with extensional deformation. These non-magmatic conventional dominated geothermal plays systems are either *fault controlled* or *fault leakage controlled*.

Main rift bounding faults are key exploration targets but fault intersections / interactions are main targets due to enhanced permeability and fracture density. Faults have high permeability but fault intersections have increased permeability and fracture density (figure 2).

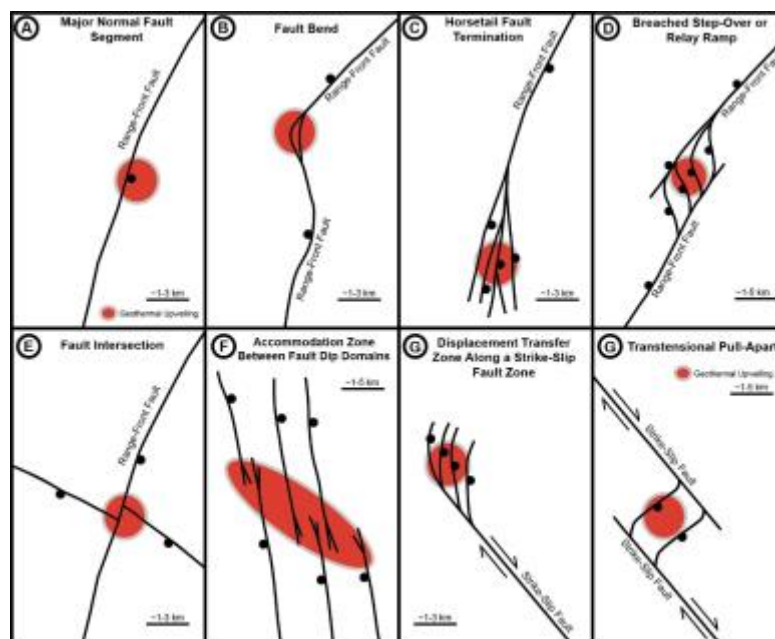


Figure 2: Structural setting idea for geothermal occurrence (Moeck, 2011)

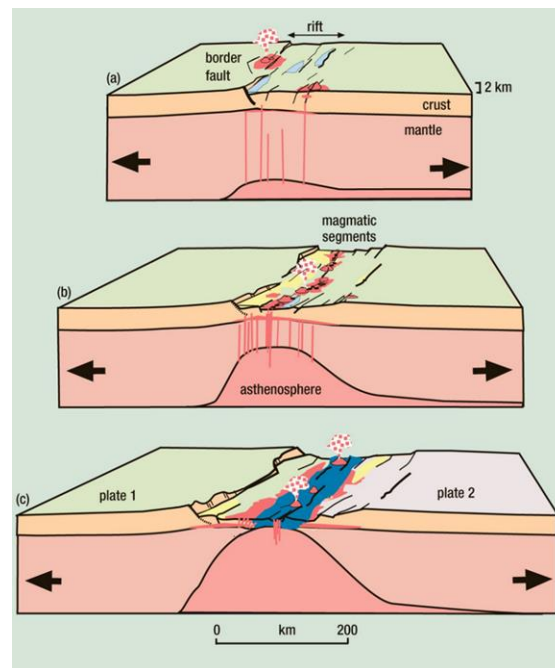


Figure 3: Stages of rift evolution. Western rift is presumed to be in stage (a) evolving to stage b (Corti et al 2011).

4. Current Geothermal Investigation surveys on Uganda's geothermal sites

Uganda geothermal investigation surveys are on Pre-feasibility stage aimed at justifying continued exploration and moving to a full feasibility study. Western rift valley is between Stage 1 (Boundary fault) and stage 2 (Internal Fault) of rift development. Boundary faults control most geothermal activity in Uganda. Most of Uganda's geothermal systems are extensional driven as opposed to magmatically driven systems. They typify other deep circulation (amagmatic) geothermal systems in Great Basin and Range (Western USA) and in Western Turkey. These are called *fault-bounded extensional (Horst and Graben) complexes* (Brophy Type E). They comprises of horsts (ridges) and grabens (flat-bottomed valleys). There is regionally dispersed amagmatic heat flux (high crustal heat flow) as evidenced by crustal helium at Kibiro. Once you identify these field characteristics, you can strategically plan for the exploration.

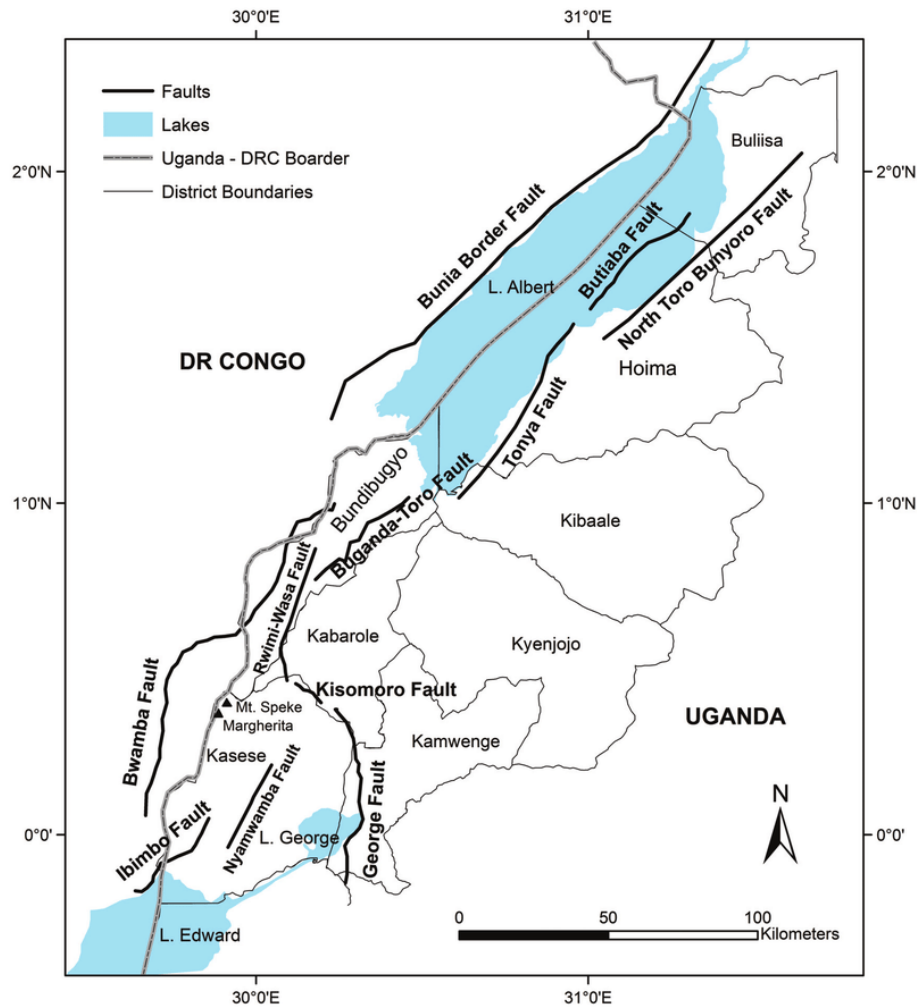


Figure 4: Master Rift normal bounding (deep reaching border faults) faults controlling geothermal activity in Western Rift. Note active broad scale normal faults associated with anomalous thermal gradients.

These faults act as vertical permeability pathways that enable groundwater to effectively convect through or around heat source. Active faults provide conduits for deep circulation and most prospects are driven by deep circulation of meteoric waters. Normal fault systems are primary control on geothermal activity

Due to active rift extension, the continental crust thinned (extended crust) calling for mantle upwelling and high regional heat-flow. Beneath the continental crust is a thermal zone of elevated heat flow and high geothermal gradient. During extension the crust tend to fracture forming deep reaching fractures and faults. These fractures can reach several kilometers as attested by seismic studies (focal depth >50km events, Young and Chen 2010). The structures favor deep circulation of surface water which is heated in the thermal zone and rise by buoyancy forces. Permeability is restricted in border fault controlled zones in the vicinity of horst and graben boundaries. These normal faults are key exploration targets and are characterized by geothermal surface manifestations.

Geothermal systems in Uganda are amagmatic and thus lack a mid to upper crustal magmatic heat sources, instead regional tectonism has significantly thinned the crust and lithosphere and induced a high geothermal gradient through rift valleys.

4.1 Kibiro Geothermal Resource Area

Surface water sampling and analysis was undertaken by Halldor Aramannsson (1993) and this data was reviewed in detail by Luigi Marini (2016). In collaboration with UNEP-ARGeo, GDC and GRD, a geothermal resource conceptual model was developed for Kibiro site (see figure 5,6 7, 8 & 9). Kibiro prospect is a *deep circulation (amagmatic) extensional geothermal system*. This is attested by low helium signature (BGR, 2006). The geophysical survey effectively constrained the geological setting of the Kibiro prospect, with reflection seismic, gravity and magnetics, all providing detailed constraints on the geometry, of the large scale structures affecting Kibiro area. Permeability is presumed to be structurally controlled by steeply dipping main rift bounding fault more so where it is intersected / interacted with cross-cutting faults (Kachuru, critically stressed zones). The main rift bounding fault provides high permeability flow-path that allows for deep circulation of meteoric waters into the thermal zone beneath the crust. TEM data has indicated a shallow reservoir at 300m and this has been recommended for TGH.

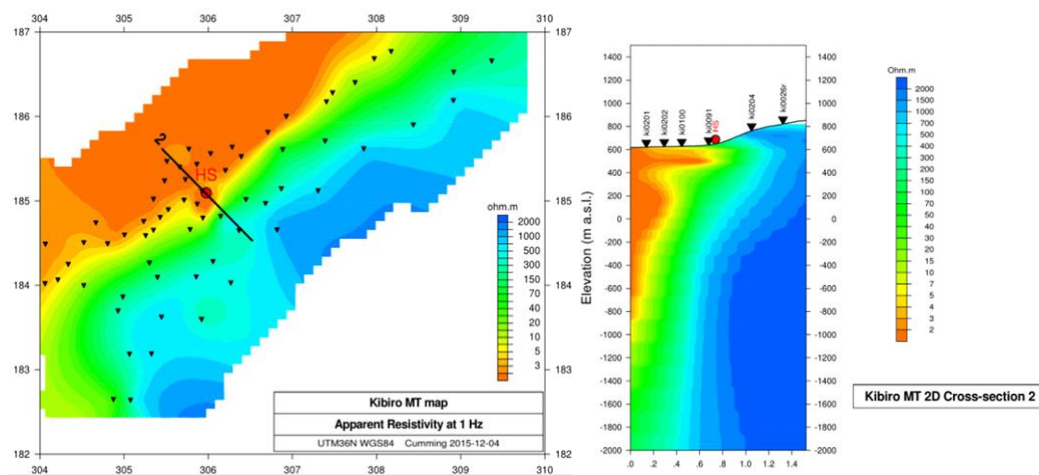


Figure 5: Magneto telluric section (MT upwellings) across Kibiro Prospect (Cumming, 2016). Warm colors (red) indicate areas of low resistivity (conductive zones) and cool colors (green and blue) indicate areas of high resistivity.

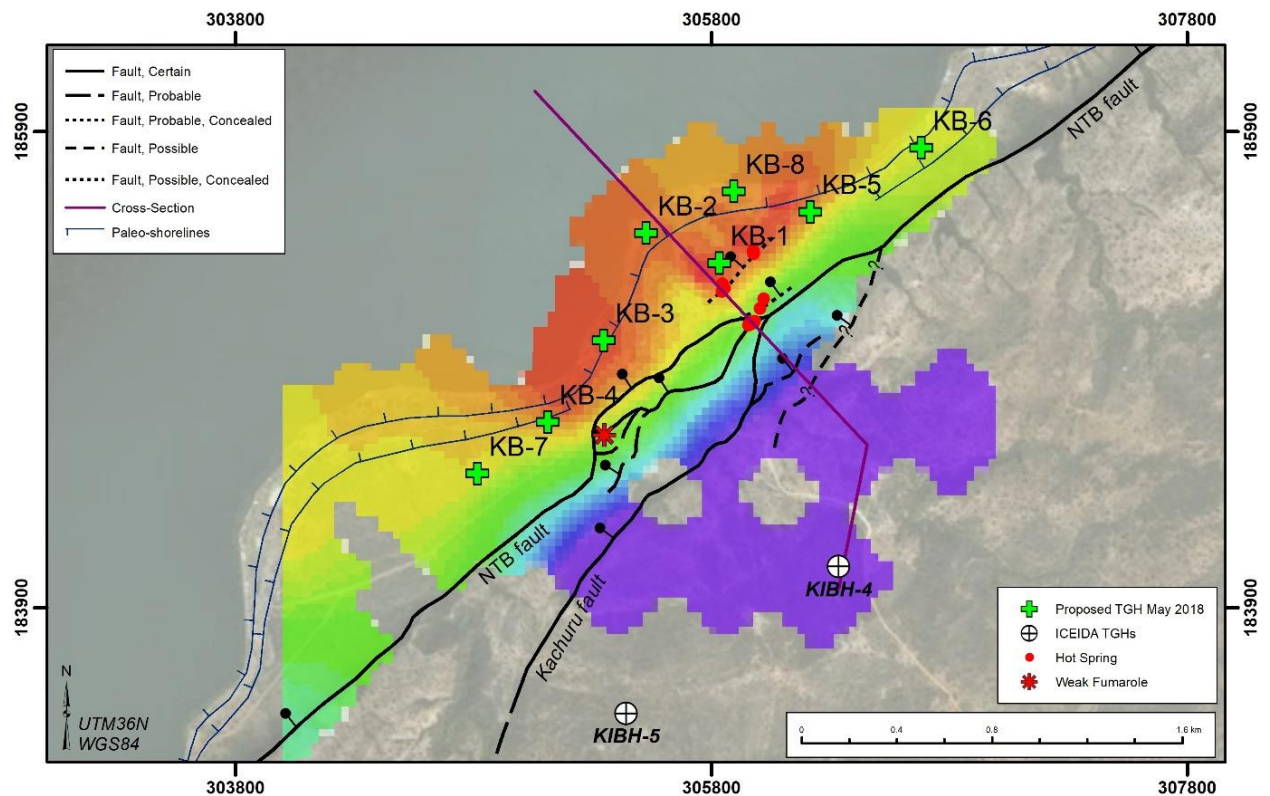


Figure 6. Updated TGH targets for Kibiro (EAGER, 2018)

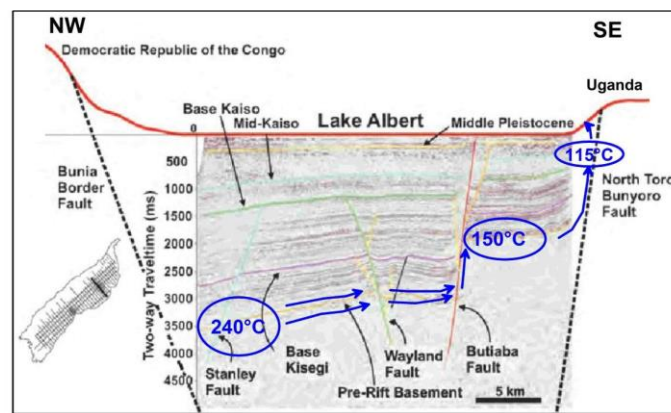


Figure 7: Multiple conceptual models were developed using geochemical data (Luigi Marini, 2016) targeting fault related permeability

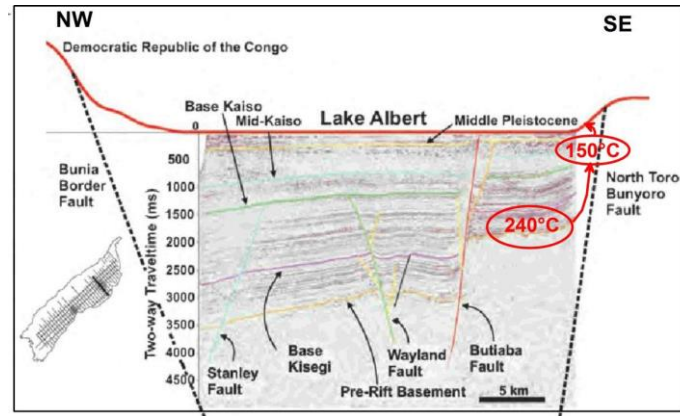


Figure 8: Multiple conceptual models were developed using geochemical data (Luigi Marini, 2016)

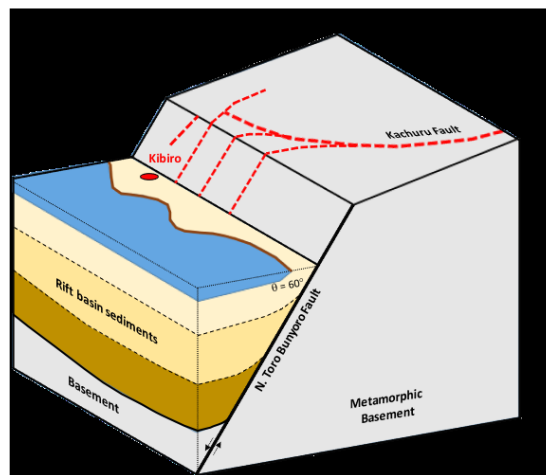


Figure 9: Schematic block diagram for Kibiro (Kenneth, K 2016) indicating fault related permeability

Gas flux measurements indicate high anomalies along main rift bounding fault complimenting soil gas data and shallow temperature probe survey data. The main rift bounding fault (North Toro Bunyoro Fault) is seismically active according to preliminary micro-earthquake survey being undertaken in Kibiro (Figure 10).



Figure 10: Installing micro-seismic (temporally micro-earthquake network) equipment donated by UNEP-ARGeo around Kibiro area. This will aid in mapping active faults.

Stress is not relieved by major earthquakes, abundant micro-earthquakes characterise fault interaction areas which precludes pervasive healing of fractures and thus facilitate fluids flow. Critically stressed regions are characterised by numerous small to moderate earthquakes in contrast to large Earthquakes.

4.2 Panyimur Geothermal Resource Area

Government-led geothermal investigation surveys were conducted at Panyimur area by GRD, technically supported by EAGER hired experts (Figure 11). Geothermal conceptual models were developed (figure 13) and these are being updated and refined as new data emerge. Work included a combined MT/TDEM survey, swallow temperature survey, soil gas survey supplemented by detailed structural mapping (structural model development) together with EAGER hired structural geologist (EAGER Report, 2017) figure 12.

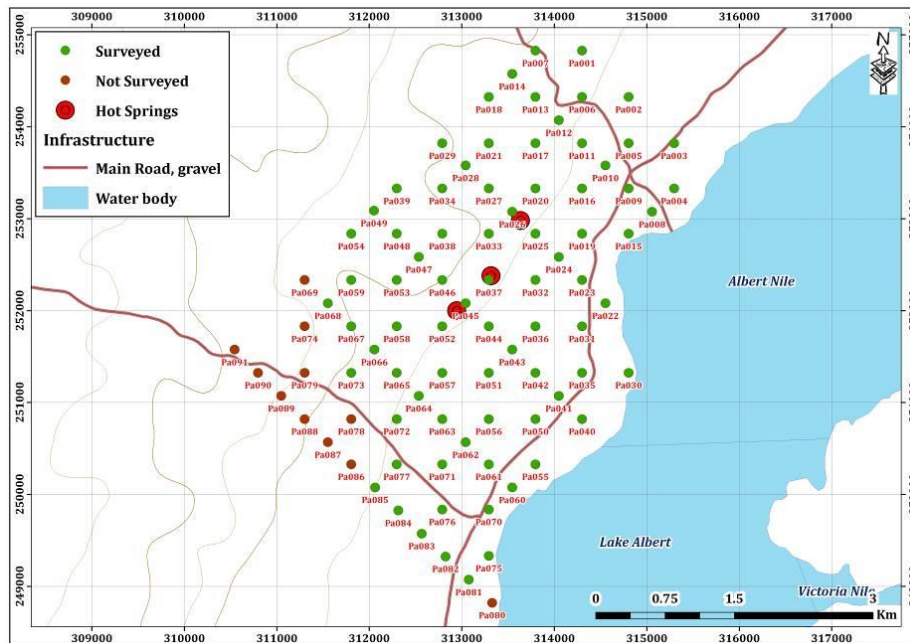


Figure 11: MT/TDEM Survey points in Panyimur area.

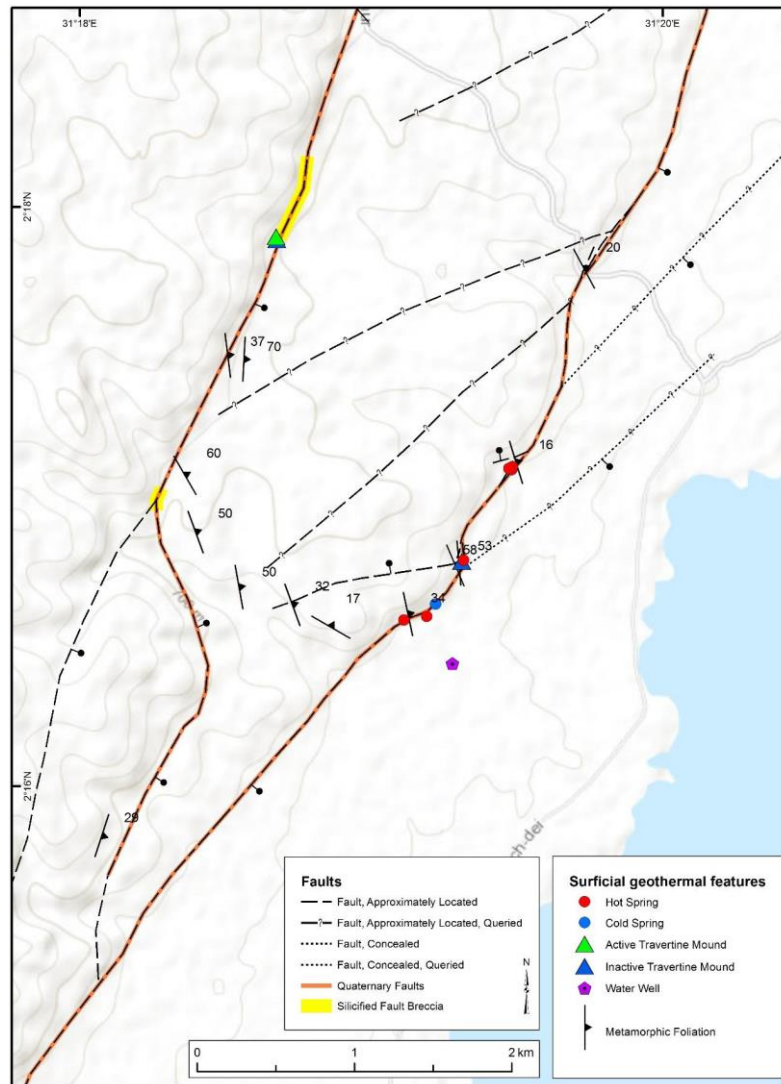


Figure 12: Structural mapping of Panyimur, (EAGER 2017) showing surface geothermal signatures aligned on main border faults

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. The heat that drives the Panyimur amagmatic system is believed to result from active extensional tectonics that permits the deep circulation of meteoric fluids and elevated heat flow that rises the temperature of the fluids to 150°C or more. At Panyimur, fluid movement is controlled by the main NE-SW rift bounding fault zone that bounds the west side of the rift valley. This system also relies on regionally dispersed amagmatic heat flux.

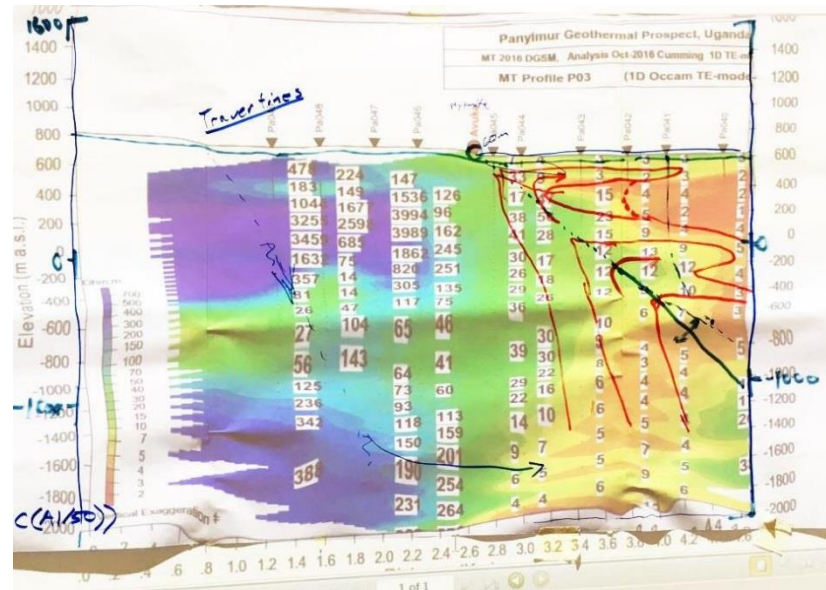


Figure 13: Developed conceptual model of Panyimur (Cumming 2018)

Geothermal investigation surveys in this area is leveraging on oil and gas data accumulated by oil companies.

4.3 Buranga Geothermal Resource Area

Geothermal investigation surveys have been undertaken in Buranga by M/s Gids Consult Ltd supported by Geothermal Development Company (GDC) of Kenya. Further work has been undertaken by GRD technically assisted by EAGER hired expert. EAGER hired expert are involved in geothermal and structural model development (Figure 14 & 15). The area has been structurally mapped by GRD supported by EAGER experts. Review of MT data acquired by GDC revealed key data gaps which warranted data gap closure. In October 2017, GRD undertook focused MT in-fill surveys around the hot spring areas. A conceptual model has been developed by EAGER experts revealing a conductive anomaly.

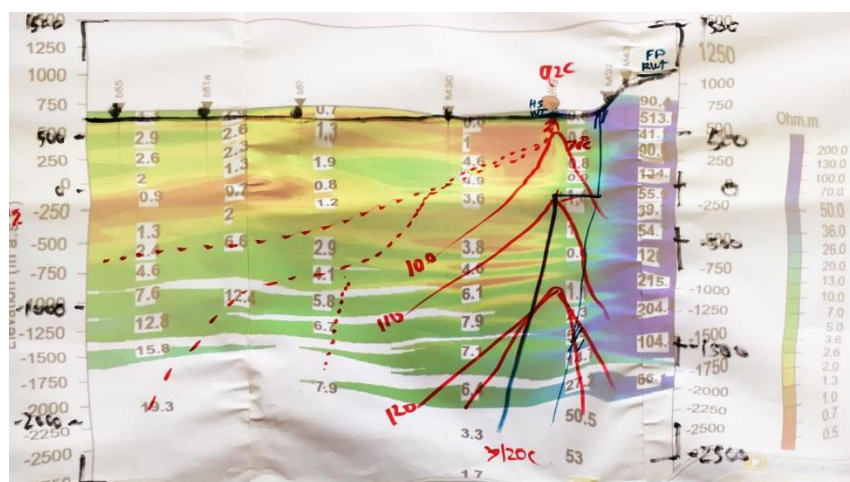


Figure 14: Buranga model (Cumming, 2018)

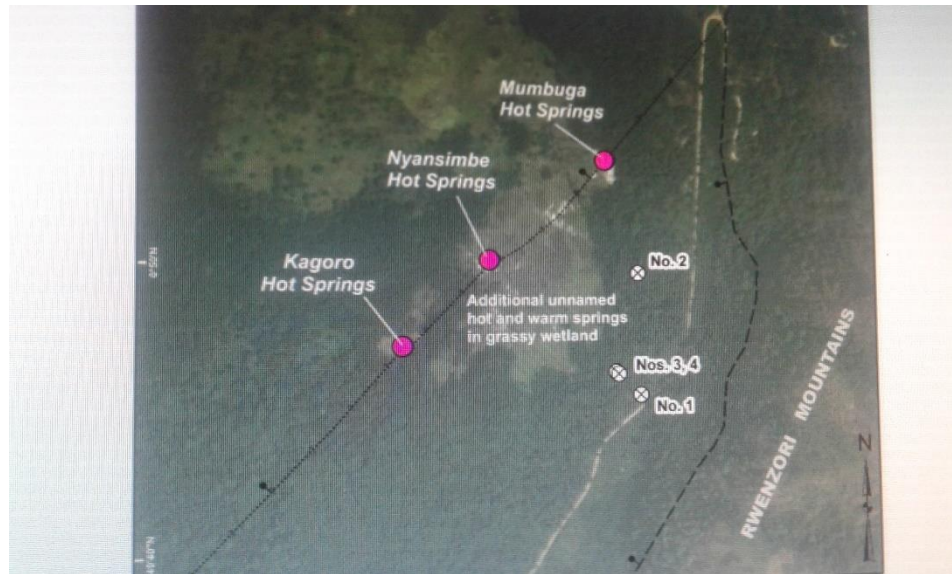


Figure 15: Structural map of Buranga (EAGER, 2017) showing alignment of hot spring along an internal fault.

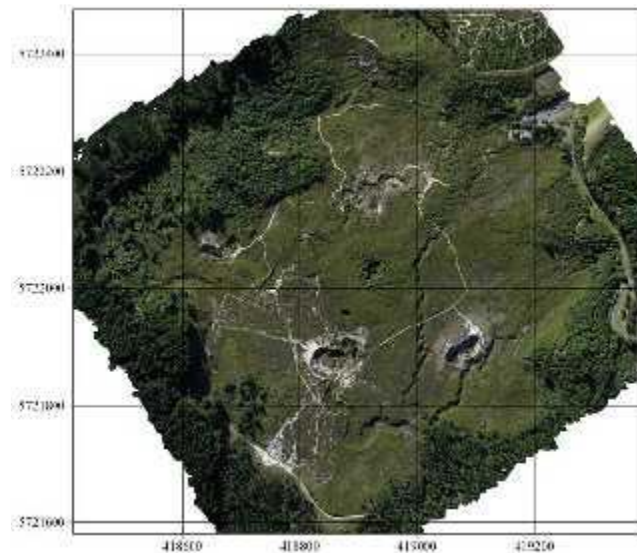


Figure 16: Thermal anomaly map of Buranga (EAGER, 2018)

EAGER hired experts conducted a drone aided thermal anomaly mapping in inaccessible areas of Buranga. Thermal anomaly maps (figure 16) were produced to aid in building a model.

4.4 Katwe Geothermal Resource Area

Kawe-Kikorongo geothermal prospect lies in a rift valley (extensional domain). 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 ([see figure 17](#)). 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. All previous relevant data was assessed revealing where key data gaps and critical geological uncertainties remain. A SE dipping sub-vertical fluid flow conduit (fault

zone) is targeted and is targeted in the rift basin. It is a fault-controlled permeable zone allowing geothermal fluids to up-well.

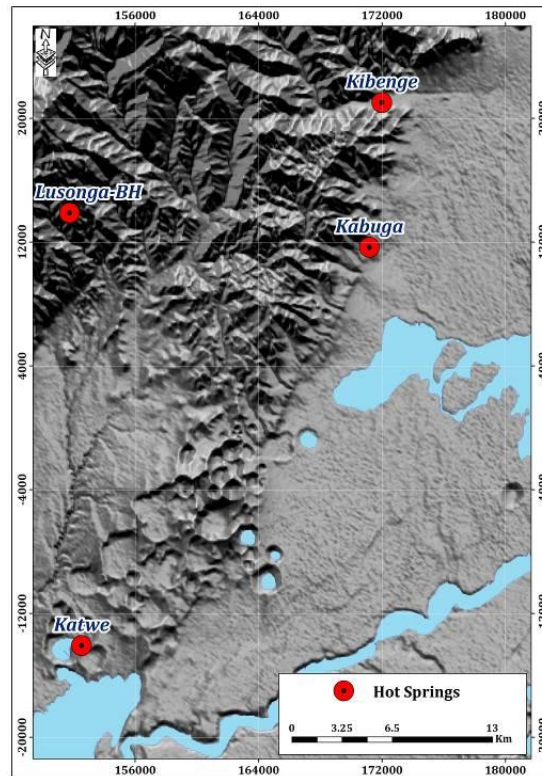


Figure 17: Note NE-SW principal rift bounding fault (Nyamwamba Fault, favourable structural setting)

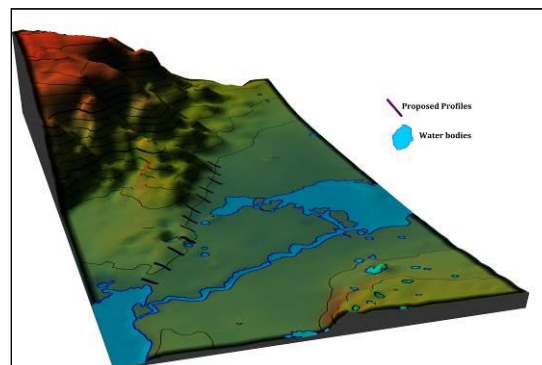


Figure 18: Planned MT profiles perpendicular to principal strike of the main NE-SW rift bounding fault

Unlike other fault-bounded systems in Uganda, the NE-SW *deep crustal fractures extended to a considerable depth* giving way to magma escaping (off-axis volcanism) 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 (Sebastaian, et al 2003). 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 1191). 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 swallow high level magma storage chambers producing heat needed by geothermal systems unlike basaltic magmas which are less viscous and extremely volatile.

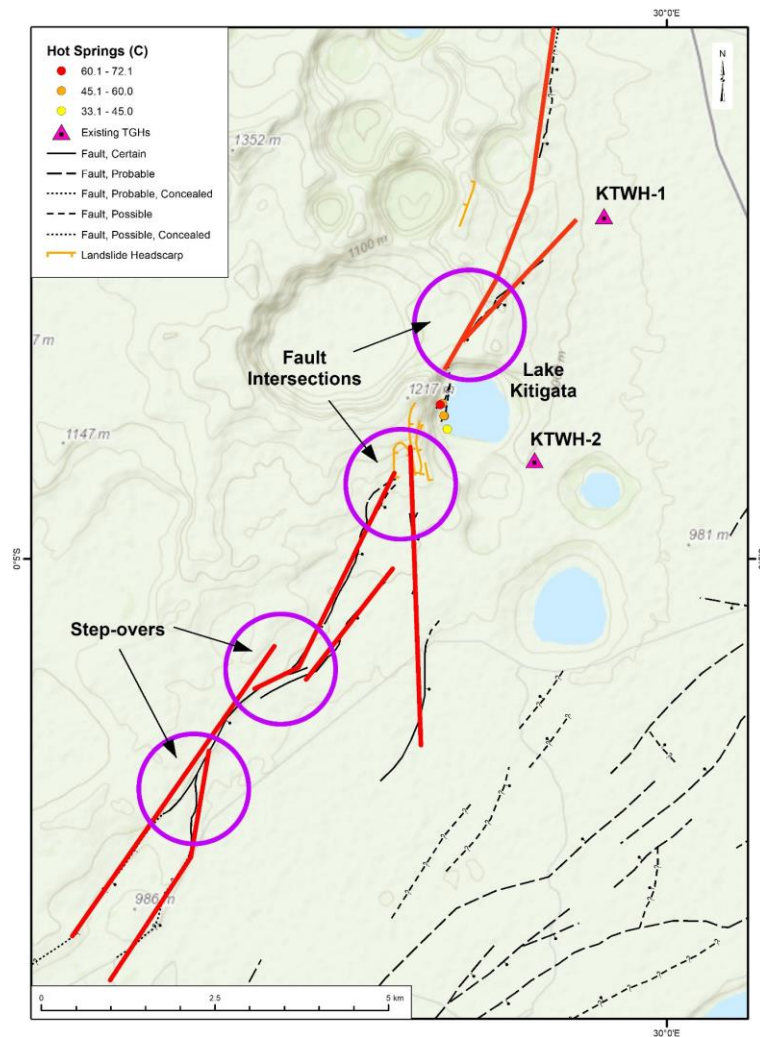


Figure: Map showing structures and critically stressed zones along Nyamwamba border fault.

Geothermal investigation surveys involved reviewing oil and gas data more so gravity, and reflective seismic. This was followed by focused structural mapping. MT Field survey (figure 18) is planned (to find MT upwellings) and soil gas and gas flux measurements were undertaken. Data will be integrated a geothermal conceptual model developed. LiDAR mapping is recommended to delineate faults, create high resolution DEMs, quantify fault kinematics and develop linear maps.

4.5 Ihimbo Geothermal Site

This geothermal site is located in Rukungiri District, South Western Uganda. It is predicted to be a fault-hosted extensional driven system. The rift extension and thinning of the crust resulted in elevated heat flow and high geothermal gradient. Deep water circulation along Ihimbo fault favors formation of geothermal waters due to heated crust. Surface manifestations include hot springs, warm springs, gaseous emissions, stressed vegetation and travertine. The area is seismically and tectonically active favoring geothermal activity.

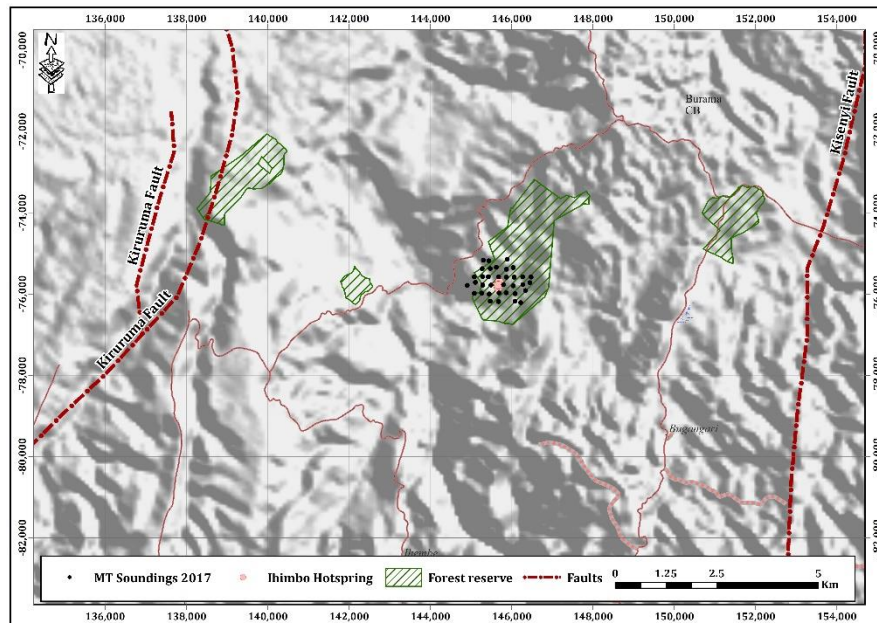


Figure 19: Showing main rift bounding faults and Ihimbo prospect in Bwambare trough. Ihimbo geothermal activity is presumed to be controlled by an internal fault.

According to Katumwehe et al (2015), Lakes George-Edward basin has shallow curie point depth, cpd ($19-22 \pm 1$ km); high heat flow $\sim 67-79 \pm 0.2$ mWm²; thin crust $26-33 \pm 2$ Km; high temperature gradients $27-31^\circ\text{C/Km}$. Ihimbo fault zones (controlling structure) allows deep circulation of meteoric waters to be heated by elevated rock temperature ascribed to extension and thinning of continental crust (thinned extended crust). Extensional tectonic activity favours deep (2-6km) circulation rapidly ascending a fault controlled conduit.

Geothermal investigation surveys so far undertaken include; geological mapping, soil gas surveys, swallow temperature measurements and MT surveys. Reflection seismic by oil companies revealed deep penetrating faults which are presumed to control geothermal activity. Resistivity surveys revealed an open anomaly which calls for data gap closure. Data will be integrated and evaluated to build a conceptual model.

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, figure 19) trending NE-SW. The main rift bounding fault is characterized by travertine dome and cones an indication of past geothermal activity.

Geochemical surveys have involved surface water sampling and analysis (JICA 2014, ISOR, 2004), soil gas (Rn) and gas flux measurements. Swallow temperature measurements were also undertaken during the soil gas and gas flux measurements. Gas flux data and soil gas data (Rn) were processed (see figure 20 & 21). Anomalous gas concentrations are presumed to locate active fault zones presumed to control geothermal activity. High flux are presumed to be indicative of anomalous flux associated with geothermal activity.

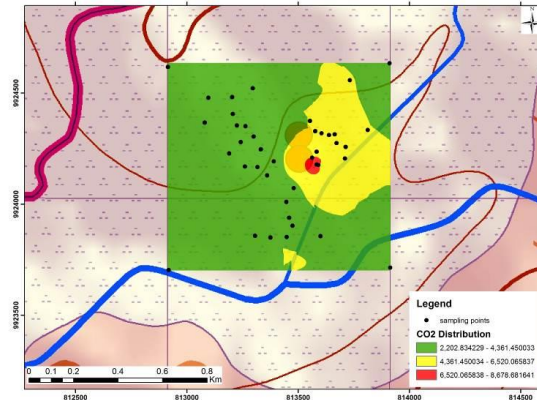


Figure 20: Spatial distribution of CO₂ flux measurements in Ihimbo area. Anomalous gas flux are presumed to indicate geothermal activity (permeable conduits).

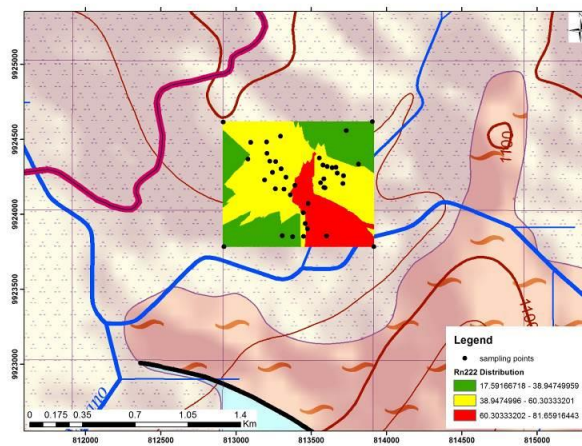


Figure 21: Distribution of activity of ²²²Rn diffusively degassed from the soil in Ihimbo geothermal prospect. Anomalous concentrations are presumed to indicate concealed faults that act as conduits for geothermal fluids.

Magnetotelluric measurements (40 MT soundings) have been conducted (see figure 22) around the geothermal area. Key gaps in data were identified and subsequent data gap closure is planned. 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.

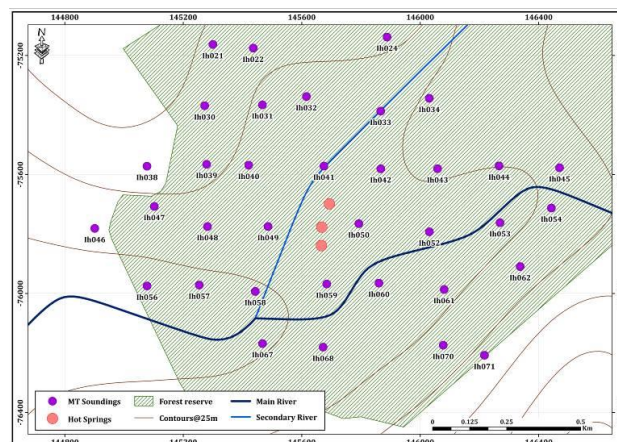


Figure 22: Stations for MT Sounding at Ihimbo Geothermal Resource Area.

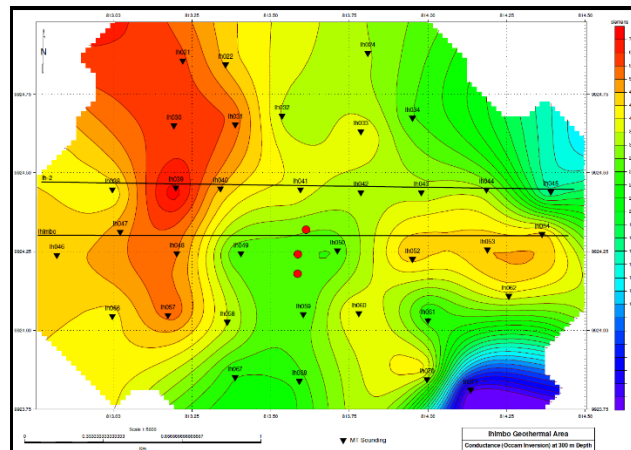


Figure 22b: Ihimbo Magnetotelluric results showing an open conducting zone

Table: 1 summarizing geological setting of Ihimbo

Exploration setting	Type E, Extensional tectonic fault controlled resource, rift zone
Structural Geologic setting	Extensional zones (rift valley)
Topography	Rugged on upthrow (Bwambara escarpment), low on downthrown side (Rift basin).
Climate	Dry with low precipitation
Depth to resource	Presumed to be deep.
Surface Manifestations	Travertine deposits, thermal springs, gaseous emissions
Permeability	Presumed to be fault controlled (Ihimbo Internal Fault zone)

4.6 Nyamwamba Fault Geothermal site

Five other sites have been down-selected for detailed studies due to presence of favorable structural setting. Favorable structural setting for geothermal systems correspond to fault interactions areas which are critically stressed regions. This is NE-SW Rwenzori bounding master fault (figure 23) and is seismically active. It is characterized by geothermal activity with surface manifestations at Kibenge (warm water, gaseous emissions), Bugoye (travertine deposits, geothermal grass), Nyakalenjijo (warm water), Rwagimba (gaseous emissions, hot springs), Rwimi (travertine deposits, gaseous emissions) and Kihyo (travertines). The heat source of these geothermal sites is ascribed to elevated heat flow, high geothermal gradient and thinned crust. This steep normal fault allow deeps circulation (several kilometers) of meteoric surface waters which get heated by elevated rock temperature. These are *amagmatic (non-magmatic) extensional systems* which rely on high permeability fault zones. Geothermal activity is more pronounced in areas of fault intersections or termination which offer high fracture density. The geothermal site are classified as fault-bounded extensional systems. Planned work here will include soil gas surveys, swallow temperature measurements, combined MT/TDEM survey on the down throw side.

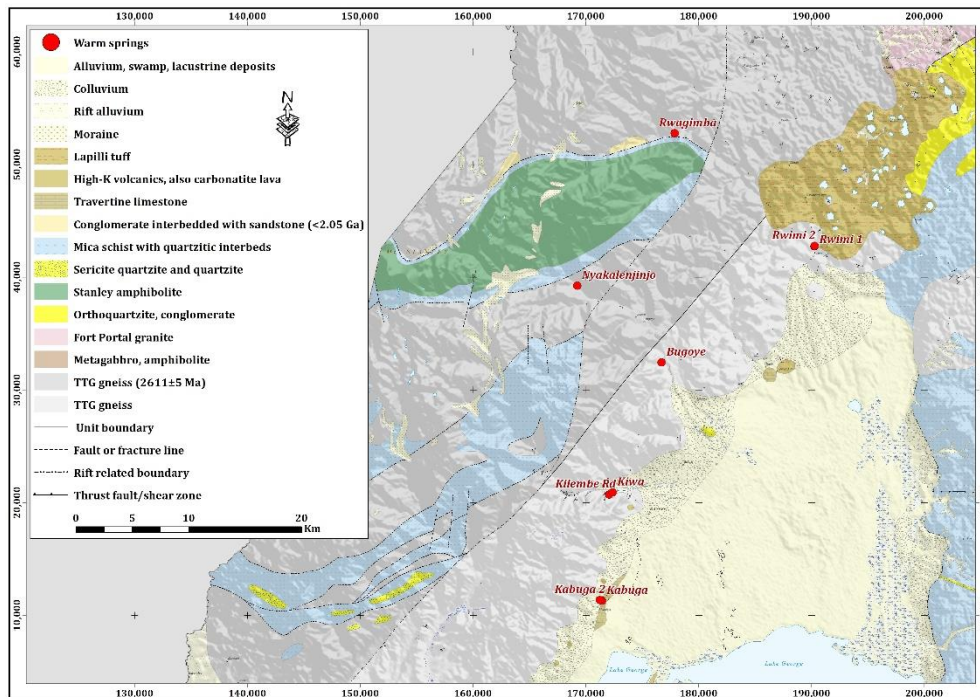


Figure 23: Showing Nyamwamba master fault.

Table 2: Summarizing Geological Setting of Nyamwamba thermal area

Exploration setting	Type E, Extensional tectonic fault controlled resource
Topography	Rugged on upthrow (Rwenzori Mountain), low on downthrown side.
Climate	Dry with low precipitation
Depth to resource	Likely to be deep
Surface Manifestations	Hot springs, warm springs, geothermal grass, travertine deposits, gaseous emissions
Permeability	Presumed to be fault controlled

4.7 George Fault Geothermal Site

This is located on the N-S rift bounding extensional normal master fault. It is characterized by geothermal activity with surface manifestations at Dwemukorebe (thermal springs and travertine). One has to note the spatial association of geothermal features and main rift bounding faults. The fault is steeply dipping west and is seismically active. The heat source is presumed to be from elevated rock temperature due to extension and thinning of the continental crust. According to Katumwehe et al (2015), Lakes George-Edward basin has shallow curie point depth, cpd ($19-22 \pm 1$ km); high heat flow $\sim 67-79 \pm 0.2$ mWm²; thin crust $26-33 \pm 2$ Km; high temperature gradients $27-31^\circ\text{C/Km}$. Lake George fault zones (controlling structure) allows deep circulation of meteoric waters to be heated by elevated rock temperature ascribed to extension and thinning of continental crust (thinned extended crust). Elevated mantle due to crustal extension and thinning provides the principal heat source for the geothermal system. This geothermal site is classified as deep circulation extensional driven (non-magmatic) geothermal system similar to those in western Turkey and Great Basin and Range in USA.

Deep circulation of meteoric waters is favored by zones of high permeability such as fault intersection.

Table 3: Summarizing Geological setting of George Fault

Exploration setting	Type E, Extensional tectonic fault controlled resource, intra-continental rift zone
Topography	Rugged on upthrow (Rift escarpment), low on downthrown side (George Basin).
Climate	Dry with low precipitation
Depth to resource	Likely to be deep
Surface Manifestations	Thermal springs, travertine deposits.
Permeability	Presumed to be fault controlled

4.8 Rwimi-Wasa Fault Geothermal Site.

This is NE-SW Rwenzori bounding fault and is tectonically and seismically active (BGR, 2004, see figure 24). It deeps in SW direction. It has the potential for geothermal activity. Base maps including structures and lithology have been prepared. Soil gas surveys, swallow temperature measurements and geological mapping is planned prior to deploying a combined MT/TDEM survey. Work will focus on downthrown side of the fault zone. This is presumed to be a convectional deep circulation extensional driven geothermal (non-magmatic) system. It is not a magmatically driven geothermal system associated with young plutonic rocks. Elevated mantle due to crustal extension and thinning provides the principal heat source for the geothermal system. It is fault-controlled extensional geothermal system with the master Rwimi-Wasa boundary fault as a controlling structure favoring fluid permeability. This fault zone typifies Bwamba master fault on the western side of Rwenzori which is hosting Buranga geothermal site. LiDAR mapping is recommended to reveal subtle structural features (young faults) presumed to control geothermal activity. LiDAR images will help identify small faults and detailed topography to provide better models and constrain on the geophysical data.

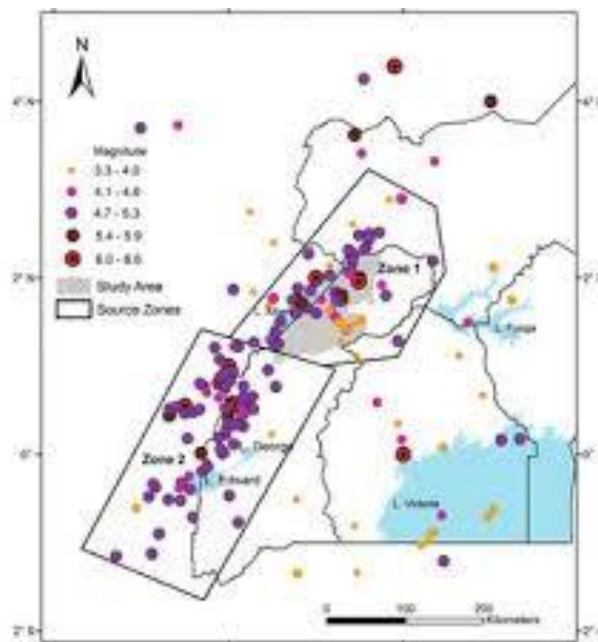


Figure 24: Showing a seismically active region in western rift valley.

Most of the epicenters are on faults which border the rift and a few on faults which crosscut it. The presence of epicenters suggest that the graben bounding faults are still active which is a condition favorable for maintaining open pathways for circulation of geothermal waters in the fault zones

Table 4: Summary of Classification of geological setting of Rwimi-Wasa.

Exploration setting	Type E, Extensional tectonic fault controlled resource
Topography	Rugged on upthrow (Rwimi-Wasa fault boundary fault), low on downthrown side.
Climate	Dry with low precipitation
Depth to resource	Presumed to be deep
Surface Manifestations	Travertine deposits, thermal springs.
Permeability	Presumed to be fault controlled (Rwimi-Wasa fault boundary fault)

4.9 Kichwamba Fault Geothermal site

Kichwamba geothermal site is characterized by explosion craters (off-axis volcanism). It is presumed that the rift bounding fault was deep enough to allow escape of volcanic materials forming craters. The rift faults acted as preferential paths ways for magma ascent. There was minor lava flows. Chances of forming swallow magma chambers is minimal as these basaltic materials are less viscous and must have escaped all. Geothermal activity here is presumed to be related to the master Kichwamba fault (rift bounding fault) which strikes NE and lies just West of the Bunyaruguru craters (off axis volcanism on rift shoulders). The heat source is ascribed to extended thinned crust which resulted into high heat flow and high geothermal gradient. Elevated mantle due to crustal extension and thinning provides the principal heat source for the geothermal system Much as the site has volcanic craters, the author prefers extensional deep circulation geothermal system to magma driven system (see table for summary of geologic setting). According to Katumwehe et al (2015), Lakes George-Edward basin has shallow curie point depth, cpd ($19-22 \pm 1$ km); high heat flow values $\sim 67-79 \pm 0.2$ mWm²; thin crust $26-33 \pm 2$ Km; high temperature gradients $27-31^\circ\text{C/Km}$. LiDAR mapping is recommended as a structural mapping technique to reveal subtle structural features (young faults) in this area.

Table 5: Summary of Geologic setting of Kichwamba / Bunyaruguru prospect.

Exploration setting	Type E, Extensional tectonic fault controlled resource, extension basins or rift zones
Topography	Rugged on upthrow (Bunyaruguru Escarpment), low on downthrown side (Rift basin).
Climate	Dry with low precipitation
Depth to resource	Presumed to be deep.
Surface Manifestations	Travertine deposits, thermal springs.
Permeability	Presumed to be fault controlled (NE-SW Kichwamba normal fault)

Table 6: Summary of geological setting and features.

Geologic setting	Kibiro	Panyimur	Buranga	Katwe	Kichwamba
Tectonic setting	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics
Controlling structure	NE-SW North Toro-Bunyoro Normal Fault	NE-SW Master Panyimur normal fault	NE-SW Bwamba	NE-SW Nyamwamba fault	NE-SW Kichwamba rift bounding fault
Topographic features	Horst and graben	Horst and Graben	Horst and Graben	Horst and Graben	Horst and Graben
Brophy Model	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource
Moeck Beardson Play type	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain
Modern geologic features	Hot springs, gaseous emissions, mineral precipitates, geothermal grass, elemental sulphur	Thermal springs, gaseous emissions	Hot springs, warm springs, thermal pools, gaseous emissions, mineral precipitates, steaming pools	Hot springs warm springs, gaseous emissions,	-
Relict geologic features	Travertine deposits, gypsum flakes, altered ground	Travertine deposits	Travertine deposits	Travertine deposits, fumarole orifices	Travertine deposits
Volcanic age	No volcanism	No Volcanism	No volcanism	Middle Pleistocene to Quaternary	Middle Pleistocene to Quaternary
Geothermal System	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation
Principal heat source	Elevated mantle due to active crustal extension and thinning; non-magmatic heat source	Elevated mantle due to active crustal extension and thinning, non-	Elevated mantle due to active crustal extension and thinning non-	Elevated mantle due to active crustal extension and thinning; non-magmatic heat source	Elevated mantle due to active crustal extension and thinning non-magmatic heat source

		magmatic heat source	magmatic heat source		
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Elevated mantle due to crustal extension and thinning provides the principal heat source for these geothermal system.

Table 7: Summarizing geological and tectonic setting of prospects.

Geologic setting	Nyamwamba	George	Rwimi-Wasa	Ihimbo	Kichwamba
Tectonic setting	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics	Extensional Tectonics
Controlling structure	NE-SW Nyamwamba Normal Fault	N-S Master George normal fault	NE-SW Rwimi-Wasa fault	NE-SW Internal fault	NE-SW Kichwamba rift bounding fault
Topographic features	Horst and graben	Horst and Graben	Horst and Graben	Horst and Graben	Horst and Graben
Brophy Model	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource	Type E: Extensional Tectonics, Fault controlled resource
Moeck Beardson Play type	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain	CV-3 Extensional Domain
Modern geologic features	Hot springs, gaseous emissions	Thermal springs	-	Hot springs (67°C), gaseous emissions, heated ground	-
Relict geologic features	Travertine deposits	Travertine deposits	Travertine deposits	Travertine deposits	Travertine deposits
Volcanic age	No volcanism	No Volcanism	No volcanism	No volcanism	Middle Pleistocene to Quaternary
Geothermal System	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation	Extensional driven deep circulation
Principal heat source	Elevated mantle due to active crustal extension and thinning, non-magmatic heat source	Elevated mantle due to active crustal extension and thinning,	Elevated mantle due to active crustal extension and thinning non-	Elevated mantle due to active crustal extension and thinning,	Elevated mantle due to active crustal extension and thinning, non-

		non-magmatic heat source	magmatic heat source ng,	non-magmatic heat source	magmatic heat source
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1. Future Planned activity

- a) **Katwe-Kikorongo:** MT Field survey, shallow temperature measurements, processing TDEM data (ISOR, 2004) using Empower software and integrating data to build a conceptual model. LiDAR mapping is recommended to map subtle structural features during structural mapping. TGH exploration is planned prior to committing funds on full diameter exploration drilling.
- b) **Kibiro:** Locating TGH drill site on ground and drilling TGH/ Slim wells to confirm reservoir prior to selecting of targets for deep well drilling. This will improve well targeting failures.
- c) **Panyimur:** Locating TGH drill site on ground and drilling TGH to confirm reservoir prior to selection of targets and deep well drilling.
- d) **Ihimbo:** Field crew plan to conduct additional MT infill, TDEM survey, detailed structural mapping along an internal fault, review oil and gas data (down-hole temperature data, reflective seismic data), integrate data and develop multiple conceptual models. LiDAR mapping is recommended to map subtle structural features. GRD plans to drill TGH prior to committing deep exploration wells. Noble gas isotope geochemistry is recommended to ascertain whether there is geological or geochemical evidence of mid or upper crustal magmatic activity.
- e) **Buranga:** Locating TGH drill site on ground and drilling TGH to confirm reservoir prior to drilling deep full diameter wells.

6. Funding opportunities

The World Bank (WB) Energy for Rural Transformation (ERT-3) has committed funds USD 700,000 towards geothermal development. The project is under implementation. Uganda has submitted request for GRMF to undertake slim-hole exploration in two prospects.

7. Conclusions

- Uganda has made a substantial progress towards exploring its geothermal resources though at Pre-Feasibility stage. An exploration strategy has been developed.
- Western rift valley development is between Stage 1 (Boundary fault) and stage 2 (Internal Fault) of rift development. Hence boundary faults control most geothermal activity in Uganda. Elevated mantle due to crustal extension and thinning (shallow crust) provides the principal heat source for the geothermal system. Majority of geothermal prospects are aligned along bordering normal faults.
- Due to its high geothermal gradient (Katumwehe et al, 2015) and relatively high extensional strain rates, Western rift valley is geothermally prospective.
- Uganda geothermal systems are *fault-hosted extensional amagmatic 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.

- The conceptual models of Kibiro was developed, and plans are in advanced stages to drill TGH. GRD is technically assisted by EAGER hired experts.
- Data gap closure is going in Panyimur technically assisted by EAGER hired experts which include TDEM survey, soil gas and gas flux measurements, shallow temperature surveys and detailed structural mapping. Data has been integrated and conceptual model developed. TGH exploration is planned.
- After integrating and evaluating data, a conceptual model was developed for Buranga and Drilling TGH is planned.
- MT field survey is planned for Katwe following structural mapping by EAGER experts and local staff. LiDAR mapping is recommended in Katwe to reveal concealed structural features. TDEM data collected by ISOR (2004) will be processed using Empower software. TGH drilling will follow.
- Further studies in Ihimbo will include resistivity surveys (TEM), structural mapping, leveraging oil and gas data and finally developing a geothermal conceptual model. Shallow temperature measurements are planned for this area. Finally TGH drilling will be undertaken.
- Other areas identified where focused investigations have commenced include Kichwamba, Rwimi-Wasa, George Fault, and Nyamwamba geothermal prospects. Preliminary investigations and exploration workflow have begun on these areas by synthesising all previous geological data. These are presumed to be extensional domain play type CV3 where the mantle is elevated due to active crustal extensions and thinning. The elevated mantle provides the principal heat sources for these geothermal systems. High thermal gradient facilitates the heating of meteoric water circulating through deep faults and fractures. The generic model is a fault controlled extensional domain play with elevated mantle.
- LiDAR mapping and structural analysis (stress field determinations, fault kinematics, slip dilation tendency analysis) is recommended in all investigation to map concealed *young* faults which are presumed to control geothermal activity. In all the investigated prospects TGH drilling is planned prior to committing cost intensive and risky deep exploration. It is better to drill a cheap dry well than an expensive dry well.

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