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The contribution of additional Geological and Structural Studies on the Conceptual Model and Temperature Gradient Holes Sites for Kibiro Geothermal Field.

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ABSTRACT

Kibiro geothermal field is located in western Uganda in the administrative district of Hoima along shores of Lake Albert. The regional structure along which the field is located is the North Toro - Bunyoro fault (NTBF) of the Western branch of the East African rift system which is an extensional terrain. The field has three main hot springs; Mukabiga, Muntere and Mwibanda with measured temperature of 37 – 86.7˚C, maximum observed flow rate estimated at 4 litres per second discharging brines mainly sodium chloride with an average total dissolved solids of 4500 mg per kilogram.

EAGER carried out additional exploration activities under U38 assignment to support UNEP ArGeo models previously suggested (Alexander et al 2016). The additional work was mainly structural mapping to try and understand all the fault systems and their dips that contribute to permeability and upflow of Kibiro geothermal area. Surficial thermal features were also taken into consideration

This exercise revealed that Kibiro geothermal system occupies a series of step overs covering about 1.5 km section of the NTB fault resulting into a series of fault intersections. Within this area of fault intersections, there occurs the active thermal manifestations which include hydrogen sulphide – Sulphur fumaroles and hot springs, which thermal features occur at either end of the damaged zone. The entire zone is also covered by highly fractured basement rocks the have also been altered. From the temperature and soil gas flux surveys conducted by UNEP, the area is characterized with the highest carbon dioxide flux. Also anomalous soil temperature span for a distance of about 2km along the strike the strike of NTB fault (withn

The interplay of the NTBF together with other synthetic faults and oblique ones, resulted into formation of the Kibiro sub-graben (the damaged zone) that is characterised by a highly fractured zone. From recent structural studies, it has been observed that the mid synthetic fault (upper NTB fault) of the Kibiro sub-graben has an upper hand in terms surface manifestations within the sub-graben. The interplay of different fault systems caused a down throw of the sub-graben in the NE –SW manner. It has been noticed that the Northeast part of the sub-graben is more down thrown that the Southwestern end.

Recently, six (6) TGH were sited (UNEP – ARGeo report) based on transient electromagnetic surveys (TEM) from which a shallow secondary reservoir has been suggested at 300 metres depth within Kibiro delta. Recent structural analysis tried to map all possible fault systems within the survey area together with their angles of Dip. This will allow for TGH to be strategically positioned in order to, 1) try to hit the NTBF at optimum depth (from angle of dip), 2) try to hit the seconday predicted shallow reservoir from TEM surveys and 3) establish the most probable fault intersection zone of the NTBF based on dips and orientation of fault systems within Kibiro. This will give the first category of reservoir in highly damaged zones of the basement, (the second one being the predicted shallow 300m depth reservoir thought to be hosted within gravels, sands and conglomerates). Many of the measured faults are of the order N 40 - 48˚E strike and 45 - 46˚ dip with the main NTB fault having dip of the order 65^0. Details mapping and temperature measurement of the spring reveal that Muntere and Mwibanda springs are probably located on another linear structure buried within the sediments.

Structural mapping data sets will avail strain data, fault slip history which will be integrated with temperature gradient data, heat flow data, spring temperature, fluid geothermometry and Geophysical data to refine the conceptual model of Kibiro. From recent mapping soil temperatures above 45˚C have been measured 1Km away from the main hot spring and it has been noticed the damaged area coupled with surface manifestations that Kibiro is a wider reservoir than previously thought.

1. Introduction

1.1 Background

Like any other African developing country, Uganda has had a drastically growing population over the years. This population growth has been in line with growing energy demand which stands at over 8% per annum. The total access to electricity for the whole country stands at only 12% whereas that of rural areas is only at 6%. Climatic fluctuations have resulted into change in water levels in most of the rivers not only in Uganda but also in the whole East African region. This has affected on the quantities of electricity generated from hydro which has been the main source of power generation in Uganda.

Government of Uganda has selected the energy sector as a priority in national social and economic development. It is expected that energy availability will be an important contribution to the national goals of rapid poverty alleviation nationwide and increase the well-being of Ugandan population. The general energy policy of Uganda (2002) emphasize the development of renewable energy sources, geothermal being one of them, while the renewable energy policy(2007) ranks geothermal very highly due to its being multidisciplinary with vast direct uses that can boost social economic development. Uganda Geothermal Resources Development Project 1199 was initiated (fully funded by the Government of Uganda) to help Uganda develop her geothermal resources by taking upfront risks to attract potential investors to develop the resources. The project has been used to do further exploration work on most of the major geothermal prospects of Uganda (Buranga, Kibiro Katwe and Panyimur).

Part of the proceedings of the project has been used to make more detailed surface studies over Kibiro and it was discovered that all the surface manifestations were following the major North Bunyoro Toro fault -NTBF (Mawejje et al 2014) which means Kibiro is a fault controlled geothermal system. Later in 2016, UNEP ARGeo funded a project that did more work over Kibiro with involvement of multidisciplinary consultants to the level of citing temperature gradient holes (TGHs) basing on integrated geothermal model.

The East African Geothermal Facility (EAGER) funded a project to do further studies over the main Ugandan geothermal areas. Part of the proceedings have been used to review available data and geothermal models of Kibiro Geothermal area and also to refine the models. The previous Geothermal models did not take into considerations structural models to more detailed levels under the activity U38 for Kibiro structural mapping, but also under assignments U30 and U37 aimed at planning and managing a proposed TGH programme.

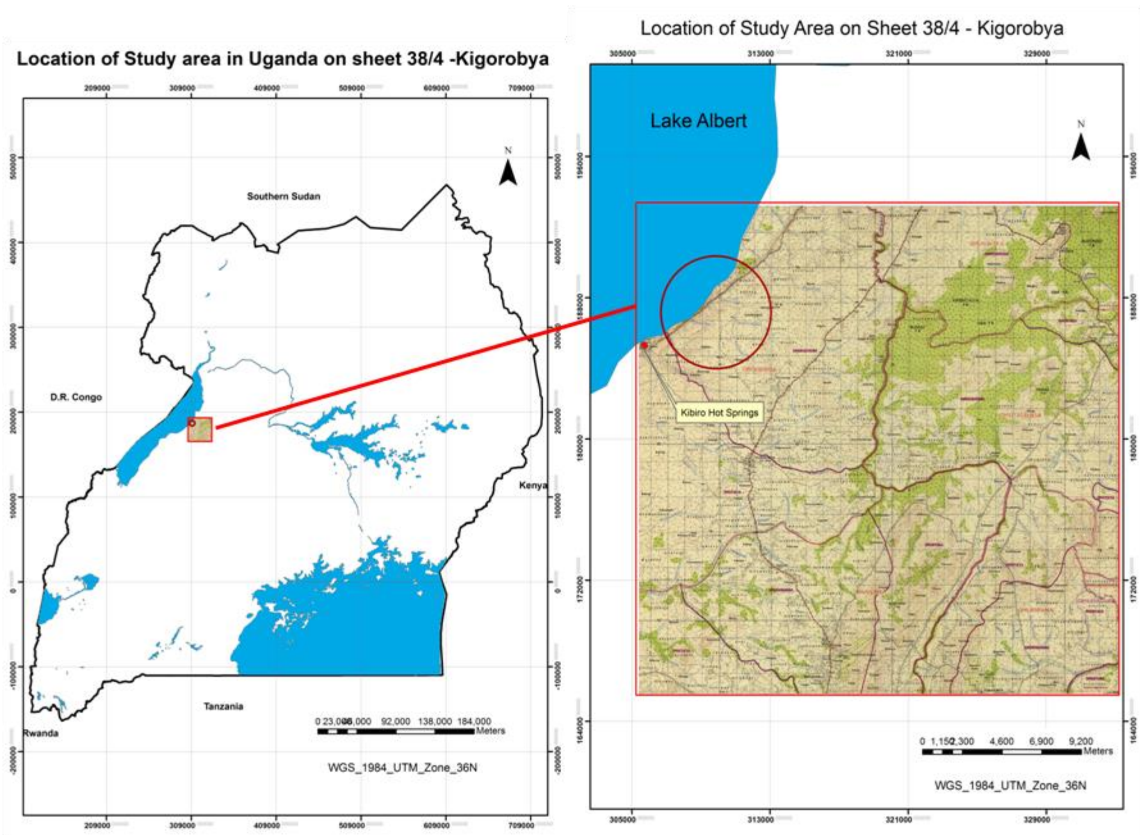


Figure 1: Showing location of Kibiro geothermal prospect

1.2 Location and Accessibility

Kibiro area is located in the Western side of Uganda on the shores of Lake Albert at the edge of the Western arm of the East African rift valley. It is situated on topographic sheet 38/4 – Kigorobya in the administrative district of Hoima (Fig.1)

Kibiro can be accessed by driving on good tarmac road Kampala – Kiboga – Hoima for a distance of about 202 Km. From Hoima you drive along good marram road to the North-west and make a left turn at Kigorobya trading center.

1.3Rationale of the study

The temperature gradient holes that were drilled by the ICEIDA and DGSM project during February – March 2006 were sited basing primarily on geophysics (the low resistivity anomaly within the footwall of the main NTB fault and gave results that never reflected the would be true thermal gradient of Kibiro. In a fault bound geothermal system, it was very wise to carry out detailed structural studies with benchmarks from analogous geothermal systems such as the great basin of USA. It was therefore prudent to carry out more detailed structural mapping to refine the geothermal model and TGH targets generated by UNDP ARGeo during 2016 with a more detailed structural model.

1.4 Objective of the study

At the end of UNEP ARGeo project it was resolved that the ascending branch of the Kibiro thermal circuit is controlled by intersection of NE-SW North Bunyoro Toro normal fault (dipping 60 – 65^0) and the oblique Kachuru fault. The model so produced did not map into details of the fault system regime of the area to be integrated into the overall model. Six temperature gradient wells were targeted using the model and assumptions so derived from the UNEP ARGeo project.

The main objective of the study was therefore to review the existing data and conceptual models for Kibiro project area, followed by fieldwork investigations and ground-truthing focused on evaluating the structural geology and surface manifestations.

The new field structural studies were to do a refinement on the Kibiro conceptual models and TGH targets generated by UNEP ARGeo studies by Alexander et al (2016)

2. Previous Work.

Geothermal investigations at Kibiro started way back in 1993 by the Department of Geological Survey and Mines (DGSM) in co-operation with UNDP under a project called Geothermal Exploration UGA/92/002 & UGA/92/E01, a project co-funded by the Government of Uganda, UNDP, the Government of Iceland and OPEC (Gislason, 1994). The project was primarily focused on geochemistry and geology in the areas of Katwe, Buranga and Kibiro, and the main conclusion was that although the surface manifestations were not extensive, the chemistry of the spring water indicated sub-surface temperatures in the range of 200°C (Ármannsson 1994). No clear indication was found on the nature of a heat source, but the main attention for a reservoir was directed towards the thick sediments of the tertiary rift system.

In 1999, a new DGSM project, Isotope Hydrology for Exploring Geothermal Resources, UGA/8/003, in co-operation with International Atomic Energy Agency (IAEA), was initiated in 1999 and completed in 2002 (IAEA, 2003). Under the project work was carried out in the same three areas as the earlier project and the findings regarding the Kibiro area showed that the sources of recharge was meteoric water, and originated from higher ground than in the immediate escarpment area, pointing inland away from the rift. The isotope geothermometers pointed towards lower reservoir temperature than conventional geothermometers (140°C), and the isotope research implies water-rock interaction, old age of the system, or low water/rock ratio. The study suggests that the reservoir rock in Kibiro is granitic gneiss.

In 2002 ICEIDA prepared a status report, where the current situation in geothermal survey was reviewed, and recommended further actions to be taken to complete a pre-feasibility study in the three above-mentioned geothermal areas (Gislason 2002). Since then the Africa Development Fund (ADF) funded a project to complete the study in two of the areas, Katwe – Kikorongo and Buranga, but ICEIDA agreed to assist DGSMD to complete the study in Kibiro. A project agreement was signed in 2003 and a work plan agreed upon, based on the recommendation set forward in the status report.

In 2004 and 2005 ICEIDA together with DGSM conducted surface exploration studies at Kibiro (Gislason et al 2004). The surveys included magnetics, gravity and Tem resisitivty surveys. A very low resistivity anomaly (<1 ohm m) in the Precambrian metamorphic rocks (footwall block of the NTB fault scarp). The low resistivity anomaly was misinterpreted to represent a geothermal reservoir in the basement rock and the Kibiro thermal springs to be its outflow.

Based on the conclusions of the 2004-05 surveys, six temperature gradient wells were drilled in the basement rock of the escarpment south of Kibiro. The results of the drilling showed low, generally conductive temperature gradients typical of other ancient continental shields (e.g., the Canadian and South African shields). The conductive gradients and different water levels in most wells indicated a general lack of permeability in the Precambrian, except in isolated fracture systems. The well cuttings demonstrated that the low-resistivity features in the basement rock were not caused by a currently active magmatic heat source but rather by relict conductive mineralization (Árnason & Gislason, 2009).

Mawejje et al (2012) carried out geological investigations over a low magnetic anomaly north east of Kibiro hot spring. Altered ground with silica, clayey grounds and calcite were discovered. In 2013 further investigations were made and gap between magnetic anomaly and Kibiro hot springs filled up. An area covered by geothermal surface manifestations was delineated and zonation based on Silica, sulphur and calcite was also done. Based on distribution of manifestations, it was concluded that Kibiro geothermal field is a fault controlled geothermal system, and that the upflow is through the main fault scarp.

A UNEP ARGeo project was conducted in 2015 and 2016 to carry out field geologic investigations, a review of the geochemistry data, a review of oil exploration data from nearby in the lake basin, a review of existing geophysics data and acquisition of new TEM and MT data, a soil gas and soil temperature survey, development of conceptual models, resource capacity estimates, and selection of TGH drill targets. Key findings from the UNEP study (Alexander et al., 2016) include:

• **Structural Framework and Fluid Flow Pathways** – The springs at Kibiro discharge through fractured rock due to the enhanced permeability of the intersection of the NTB fault and minor fault splays of the Kachuru fault. There is an increased fault density in the vicinity of Kibiro compared to other areas along the NTB fault along the SE margin of Lake Albert. The northern end of the Kachuru Fault bends toward the NE before terminating near Kibiro hot springs. Based on oil well data, the NTB fault dips 65° NW. Based on field observations, the Kachuru Fault appears to dip to the NW at an average of 60°. Oil seeps show fluid migration through nearby sediments and up the NTB Fault. Bitumen has been observed in association with bedrock alteration in the Kibiro area, and active oil seeps have been reported along the NTB fault about 4 km north of Kibiro.

• **Hot Springs** – There are three hot spring areas at Kibiro. The main area is located at the base of the main fault escarpment, where the temperature range is 57-86°C and the flow is estimated at 4 L/s. A second group of hot springs are found downstream in an area of salt gardens, where the temperature range is 33-72°C and the cumulative estimated flow rate is 2.5 L/s. A third group of springs is in the salt gardens further north, with the highest recorded temperature of 45°C.

• **Geohydrology** – The elevation of Kibiro hot springs is about 20 m higher than the level of Lake Albert (about 620 m asl) indicating that they are not hydrologically connected. However, the lake water elevation has decreased about 100 m over the past ~2000 years, affecting the regional water level as well as the location and flow of thermal water discharges at the surface. Based on available data, the discharge of Kibiro springs has declined over time from 13 L/s in 1967, to 6.7 L/s in 1969 and 4.0 L/s in 2015.

• **Geothermometry** – All of the hot springs have relatively similar chemistry due to limited mixing with brackish shallow groundwater. Their chemical composition is Na-Cl, with average TDS of 4500 mg/kg. Gas chemistry is dominated by methane (CH4). The geochemistry analyses conducted in conjunction with the geologic structure, stratigraphy, and reflection seismic information suggest that the Kibiro hot springs are most likely associated with a 115 to 150°C fault-hosted upflow with no direct magmatic heating.

• **Reservoir rocks** – Available geological data suggest that the deep geothermal reservoir is probably hosted in the sedimentary rocks above the pre-rift basement beneath Lake Albert. A review of the stratigraphy near shore (based on oil exploration well Waki-B1) shows that the base of the Kisegi unit is a thick (~15 m) conglomerate unit. Possible reservoir rocks are present in the Lower Kisegi at a depth of approximately 800 to 1000 m. The sandstone bed thickness encountered in the Waki-B1 well reaches a maximum of 30 m about 885 m beneath the surface. Both of these formations represent potential reservoir rocks for a geothermal system. The Waki-B1 is representative of the general lake stratigraphy whereas stratigraphy local to Kibiro is likely to include sands and gravels associated with the more deltaic environment at the drainages associated with the Kachuru Fault.

• Cap rocks – The deep cap rock probably consists of low permeability shale beds in the Lower Kisegi beneath Lake Albert. In Waki-B1 above a depth of about 800 m, sandstone beds become less prevalent in favour of moderately thick sequences composed of many stacked shale beds. A shallow, flat-lying clay zone with a base shallower than 300 m appears to extend from the lakeshore to the Kibiro hot springs, potentially capping a shallow thermal outflow aquifer hosted in young deltaic gravels and sands.

• **Fluid flow** – The ascending branch of the thermal circuit could be the zone of intersection between the NTB Fault and the Kachuru fault, whereas the descending branch of the thermal circuit, that is the descending pathways for the meteoric waters recharging the Kibiro geothermal system, could be fractures and faults dissecting the basement to the SE of Kibiro.

3. Work carried out.

3.1. Personnel, equipment and Logistics.

The structural mapping work was carried out by a team comprising the EAGER expert (Nicholas H. Hinz), plus three Geothermal Resources Department Staff (James Natukunda, Edward Isabirye, Peter Mawejje and Isa Lugayizi) plus drivers.

The team had two field vehicles (one for EAGER expert and the other for GRD Staff). We were also assigned consumables and field equipment which included global positioning systems (GPS), Brunton compasses, specialized Protractor for structural measurements geological hammers, digital cameras, Thermo-Couples for temperature measurements spikes and hydrochloric acid.

3.2. Desktop studies

These geological investigations started with literature review of the work that has been carried out in the area of study with more emphasis on the conceptual models, findings and recommendations resulting from the then very recent UNEP ARGeo Kibiro project. A thirty meter resolution SRTM image was used to interpret easy map fault system within the Kibiro area.

3.2. Methodology.

Images and maps so generated from the desktop studies were fed into a tablet with GIS so as to track back to the predicted fault systems and for ground truthing. Some coordinates for the target areas were generated and fed into Global Positioning System (GPS) so as to guide us within the field by tracking back to pre-determined points. Geological traverses were made in the area to map surface geothermal manifestations and fault systems that were not captured from the 30 meter resolution SRTM . Photographs of interesting sites were taken in the field and were inserted appropriately into the text during report compilations and also for illustrations.

At the fault planes, measurements have been made to understand dip directions and amounts as well as strike directions. The protractor ruler has been used to try and under the sense of direction of displacement and the stress regime and characterisation of the faults. Thermo-couples were used to measure temperatures where we felt it was deemed necessary such as thermal springs, hot grounds and suspected fumarole areas.

The spatial positions of observation points were fixed by the use of Global Position System (GPS) and recorded in the UTM Coordinates System (Datum of WGS 1984 and UTM Zone 36 projection). All the data that has been collected and compiled has been stored in geothermal geo-database and can readily be available for use in GIS environment. Such data has been overlain with other data sets such as gas flux and soil temperature survey data plus the targeted temperature gradient holes and visualised for interpretation.

4. Data presentation, analysis and interpretation

All the data that was captured in the structural mapping survey was downloaded from the Global positioning system on the computer and carefully processed with the help of field notebooks notes and sketches together with photographs taken during the study. The data was

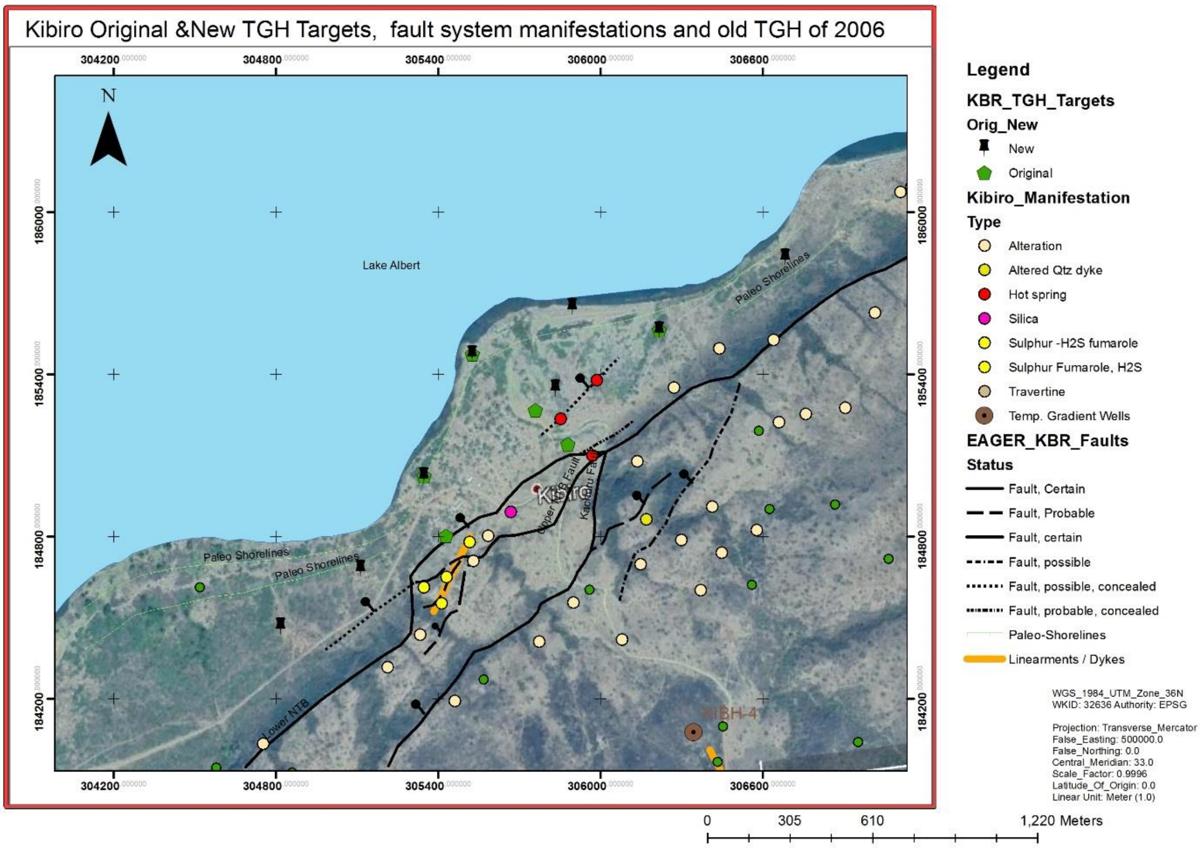


Figure 2: Showing the faults that form the damaged zone, thermal features as opposed to fig. 3 below which shows structural mode for UNEP ARGeo model

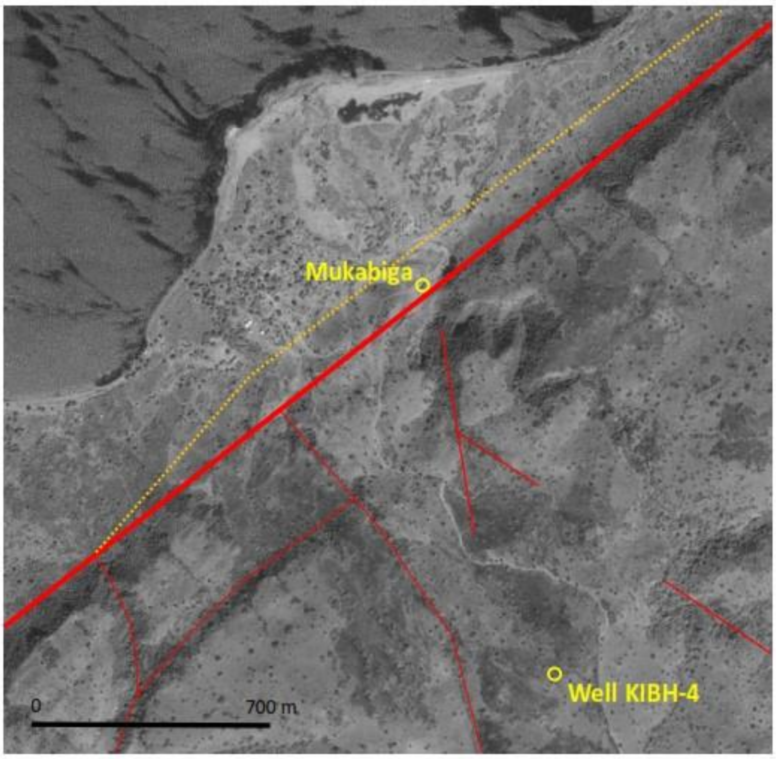


Figure 3: The UNEP ARGeo structural model

tabulated and further processed within the ArcGIS environment and visualised by overlays to have a synoptic view for proper interpretation and presentation.

The fault were observed to have a North-east south-west strike generally and they are all synthetic in nature or nearly so because they are all dipping to the North-west (Fig. 1). The structural model arising from the new work by EAGER team - Hinz et al. (2018) differs from that adopted by UNEP ARGeo – Alexender et al (2016). However, the dip angles of NTB fault is the same as that reported by UNEP project

The main discoveries and additions to the model after data analysis and interpretation are summarized in the following way:

There is higher confidence in achieving commercial production of geothermal fluids from NTB fault since it has been found to consist of several step overs with a much bigger damaged zone. The is also a great confidence in achieving commercial production from within stratigraphic hosted outflow as a result of fault hosted upflow with better permeability giving a much broader reservoir (fault-based and stratigraphy-based).

The production area is much wider than previously thought by Alexender et al (2016) where it was thought that the upflow was as a result of intersection of the oblique Kacuru fault with the NTB fault. A much bigger damaged zone has been discovered during the additional structural mapping. This will result into a much wider area of upflow as well as higher volume of fluid flow due to increase permeability. This is better than a simple fault intersection model previously presented. Step overs increase chances of production from the main fault boundary.

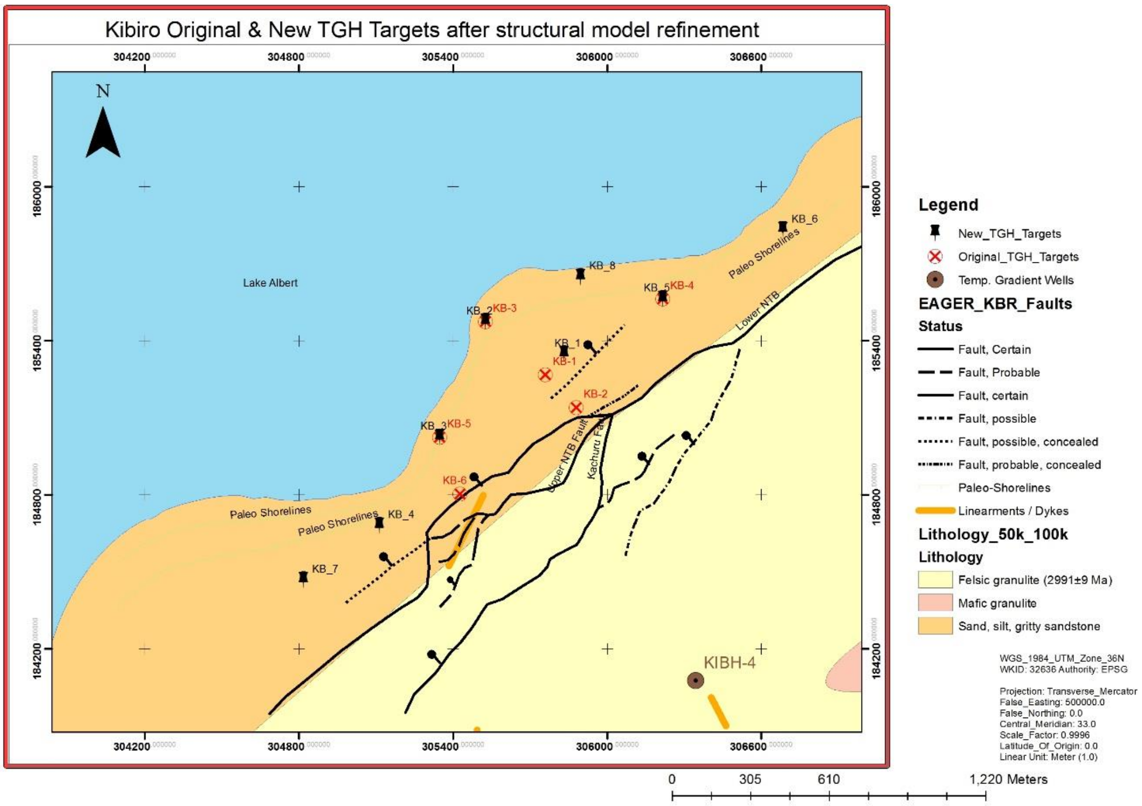
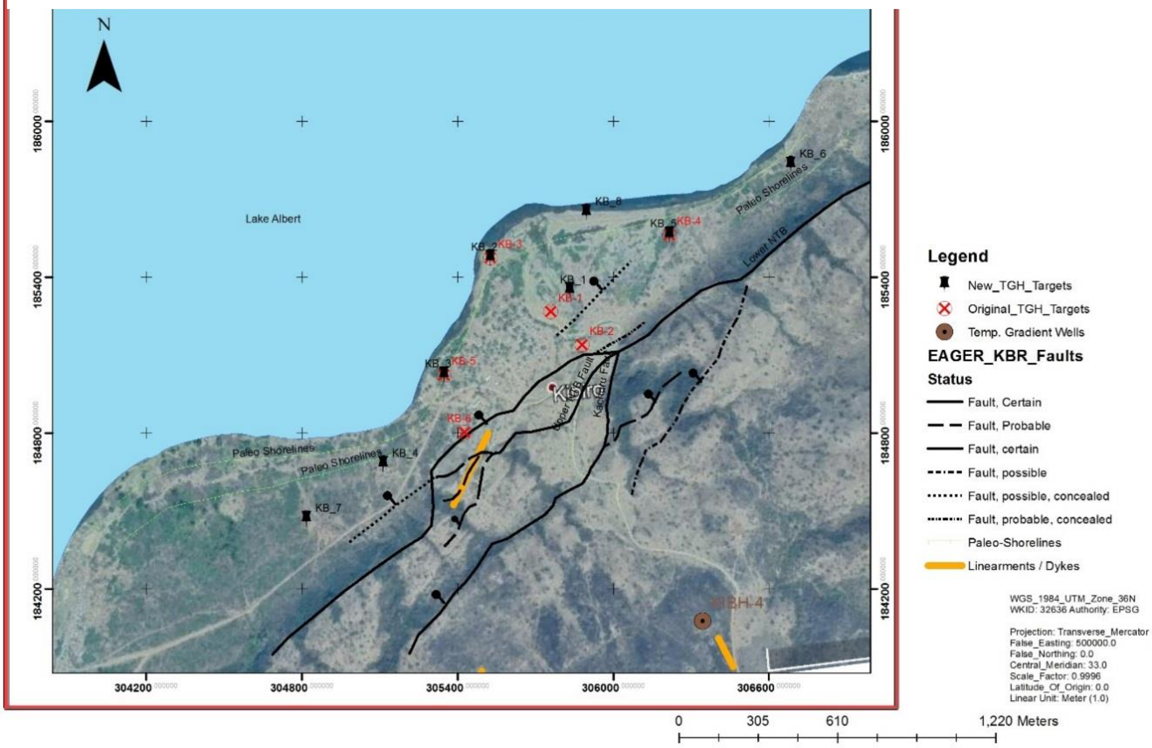


Figure 4: Showing original TGH targets and new TGH Targets Below is same features displayed over google image



This exercise revealed that Kibiro geothermal system occupies a series of step overs covering about 1.5 km section of the NTB fault resulting into a series of fault intersections. Within this area of fault intersections, there occurs the active thermal manifestations which include hydrogen sulphide – Sulphur fumaroles and hot springs, which thermal features occur at either end of the damaged zone. The entire zone is also covered by highly fractured basement rocks the have also been altered. From the temperature and soil gas flux surveys conducted by UNEP, the area is characterized with the highest carbon dioxide flux. Also anomalous soil temperature span for a distance of about 2km along the strike the strike of NTB fault (withn the damaged zone).

New findings follow the common patterns associated with many deep circulation fault systems. The basin and Range region of the USA have commercial power production in step overs analogous to Kibiro and Panyimur.

The UNEP ARGeo project on completion suggested six temperature gradient holes that were to be drilled on the Kibiro delta area. On concluding the EAGER project, the number of TGH target were increased to eight holes. This was as a result of finding that the length and width of the step overs (an hence the damaged zone) extend much longer and wider increasing the size of the area.

5. **Discussions, conclusions and recommendations**

Kibiro geothermal system is typically a fault-based system with a deep circulation that depends of fault system like any other fault bound geothermal system such as the Great Basin of the USA. No volcanic nature relics have so far been mapped within Kibiro.

The temperature gradient holes that were drilled during February to March of 2006 were targeted based mainly on Geophysical interpretation with a lot of volcanic model biasness. The result from such drilling program presented a very big lesson such that GRD and its counterparts had to do things differently with different models and approach altogether. All TGHs at that time were targeted onto the footwall of the main NTB fault without taking into consideration the dip directions of the fault system. From the maps above it can be noticed that the nearest gradient wall to the Kibiro delta and therefore closest to the thermal springs is KIBH-4 which is still in the footwall.

From geochemical and geophysical studies two reservoirs have been suggested, the deep seated higher temperature one whose cap rock is thought to be non-permiable shales below the lacustrine sediments. The upflow of this deep seated reservoir is mainly controlled by the main NTB fault. It forms a new shallower reservoir within the clastic delta deposits whose cap rock is interpreted to be a flat layer of smectite clay according to TM and TEM findings. The shallow reservoir may be productive enough and utilized, but it can also pause a risk during drilling in attempt to try to characterize and utilize the deeper reservoir. The new targeted TGH program will help throw some light on this model, but care must be taken to avoid blow outs since reservoir is shallow.

All surveys including Geophysics, geochemistry, geology (structural geology), gas flux and soil temperature surveys are all in agreement and they point at the same area to be the most favourable area thermal fluid extraction. The models will be refined after the first shallow TGH program.

From recent structural studies, it has been observed that the mid synthetic fault (upper NTB fault) of the Kibiro sub-graben (damaged zone) has an upper hand in terms surface manifestations within the sub-graben. The interplay of different fault systems caused a down throw of the sub-graben in the NE –SW manner. It has been noticed that the Northeast part of the sub-graben is more down thrown that the Southwestern end.

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