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GEOTHERMAL EXPLORATION STRATEGIES, UGANDA’S CASE STUDY

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ABSTRACT

Uganda is endowed with geothermal energy resources related to extensional tectonics and high heat flow areas. It lies in area on stretched and fault-broken rocks (rift valley). The intra-continental rift is favourable target for geothermal resources. Timeline for geothermal exploration has stretched far dating back as far as 1954 when first swallow wells were drilled in Buranga. It appears without a good understanding of the geology of an area, exploration is merely guesswork. You have recognize the importance of having and following a strategy to minimize cost and maximize success in exploring for and evaluating geothermal resources. It is important to determine which of the techniques used for geothermal exploration did not succeed and which was successful. We have reviewed the geology of geothermal resources in Uganda and come out with an exploration strategy. The Western rift, the western branch of the East African rift system (EARS), is bordered by high angle normal fault systems bounding one side of spoon-shaped basins (Ebinger, C.J. 2015). Depth-to-detachment estimates of 20-30 km, the rollover geometry of asymmetric basins, and seismicity throughout the depth range 0-30 km suggest that planar border faults along one side of rift basins penetrate the crust (Ebinger C.J, 2015). 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 (Rykounov and others, 1972; Bram and Schmeling, 1975; Maguire and Long, 1976; Hebert and Langston, 1985; KRISP, 1987). On the basis of seismic refraction data, crustal thinning beneath the northern part of the Western rift system is less than 25% (Ebinger, C.J. 2015). The western rift arm of the EARS is in initial stages of continental rifting (early continental rifting). According to Corti G (1022), in these initial phases of continental rifting, 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 boundary faults are ideal exploration targets. Moeck I (2013) classifies the rift valley geothermal system as Extension Domain play type CV3. In an Extensional Domain Geothermal Play (CV3) the mantle is elevated due to crustal extension 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. According to Moeck (2013), these are fault controlled extensional domain play with elevated mantle due to active crustal extension. Glassley W (2014) classifies the rift system as Fault-bounded Extensional (Horst and Graben) complexes Brophy Type E. Extension and thinning of crust give rise to fracturing and faulting resulting in formation of steeply dipping faults. These high angle faults bound the graben (Glassely, 2014) and can extend to considerable depth. Such setting are places were magma often rises into the crust. According to Glassley (2014), as a result of the presences of the heat sources, numerous geothermal reservoirs can be present. Permeability and controlling structure is restricted to fault-controlled zones in the vicinity of horst and graben boundaries as evidenced by alignment of geothermal features. Uganda main geothermal prospects (Kibiro, Panyimur, Katwe-Kikorongo and Buranga) are deep-circulation geothermal systems. In many respects, they typifies other fault-controlled geothermal fields that are driven by deep circulation of ground waters into the thermal zone beneath the crust. Here fluid movement is controlled by the main fault zone that bounds rift valley. Joint Magnetotelluric (MT) and TEM profiling across these geothermal field is expected to reveal a deep, sub-vertical conductor (Kibiro case). Gravity and magnetic data may be useful and cost effective in defining the reservoir’s structural setting and fault locations. The utility of the gravity data is due to the large displacement between the escarpment and the rift valley. Reflection seismic is good in defining deep basement involved faults. One has to note that individual geothermal prospects, even in the same geological setting may differ hence no single technique can be recommended. Nevertheless you must have a strategy. “There are no bad wells”. Plan for failure, i.e have a plan for what to do next if a well in not successful and have an exit strategy.

Key words: Extension tectonics, crustal thinning, horst and graben, high-angle border faults, Extensional Domain Geothermal Play, Fault-bounded Extensional (Horst and Graben), Magnetotelluric (MT) and TEM

1. INTRODUCTION

In geothermal exploration programmes, it is very important to have and follow a strategy to minimize cost, save time and maximize success. It is crucial to explore in the right place with the right method, right technique and equipment. There are failed and successful techniques that we need to learn from them. Without a good understanding of the geology of a prospect area, exploration is merely guesswork. Understanding the geology of the area (regional setting, structure and stratigraphy) is crucial in geothermal exploration. In Uganda, geothermal exploration dates way back in 1950's when the first swallow wells were drilled in Buranga. There was no exploration strategy. This spurred the need for breakthrough techniques and technology with an exploration strategy. In this paper the author tries to understand well the tectonic setting and geothermal play to inform the exploration strategy. The heat source and working model are very important. A good understanding of geology is a prerequisite for developing geothermal resources and the knowledge required is scale dependent. Conceptual models are developed from the earliest stage (preliminary conceptual model), exploration to production. Conceptual models are living / working models. This working model is the one to be tested, supplemented and refined by subsequent field work. Generalization can be made about geothermal systems but remember each system is unique.

2. REGIONAL GEOLOGIC SETTING

The western rift, the western branch of the East African Rift System, is bounded by high angle normal faults systems. 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).

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 (Ebinger and others, 1984; Rosendahl and others, 1986; Peirce and Lipkov, 1988; Burgess and others, 1989). 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 (1921, 1922) reported that the Western rift is the most seismically active zone in Africa with a frequency of more than 100 felt earthquakes per year on average. This seismicity attests 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 (Abeinomugihsa, 2010). Main bounding fault permeability increases during and after an earthquake as evidenced in flow rate of geothermal fluids.

The entire western rift valley, which includes Kibiro, is an area of extended and thinned crust, anomalously warm upper mantle rocks, high crustal heat flow (the geothermal gradient interpreted from well data indicate up to $67^{o}C$ /km, Abeinomugihsa,, 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.

Kibiro geothermal system is controlled by the main boundary fault structure (sub-vertical conduits) with a down throw to NW. Understanding of regional tectonics allows for structural understanding and therefore better exploration at the local scale. The tectonic setting of Kibiro geothermal Prospect in Uganda is *extensional tectonics* situated in the Western Rift valley. The controlling structures are normal fault zones (main rift bounding faults). Topographic features are Horst and graben of rifting system. According to Brophy Model, this is type E, Extensional tectonic fault (See Table 1) controlled geothermal resource and according to Moeck Beardsmore play type, Kibiro is CV-3 Extensional Domain type. Modern geothermal features include hot springs, fumaroles, salt precipitates and gaseous emissions. Relict features include hydrothermal alteration.

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 Kibiro hot springs and the fumaroles at the surface, generally at favorable structural settings where faults intersect thus increasing fracture density.

3. LOCAL GEOLOGY

Located western rift valley on the main boundary fault Kibiro geothermal system is a deep-circulation extension system in a tectonically active area. Kibiro is believed to be fault-bounded geothermal system in an amagamatic setting (non-volcanic region, high regional heat flow, and high temperature gradient). Modern geothermal features include hot springs, fumaroles and gaseous emissions. Relict geothermal features include travertine, calcite veins, hydrothermal alteration and silica veins. Helium ration indicate a value of 0.2 supporting amagmatic (not related to volcanic or magmatic activity) setting (BGR, 2006). One has to note that amagmatic systems are much more wide spread but cooler at swallow depth.

Geothermal system is related to robust 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 Kibiro is related to high fracture density ascribed to intersection of several faults including the main bounding fault. Alignment of modern and relict geothermal surface manifestation features along the main bounding normal high angle fault (see figure 1) indicates structural permeability in this case.

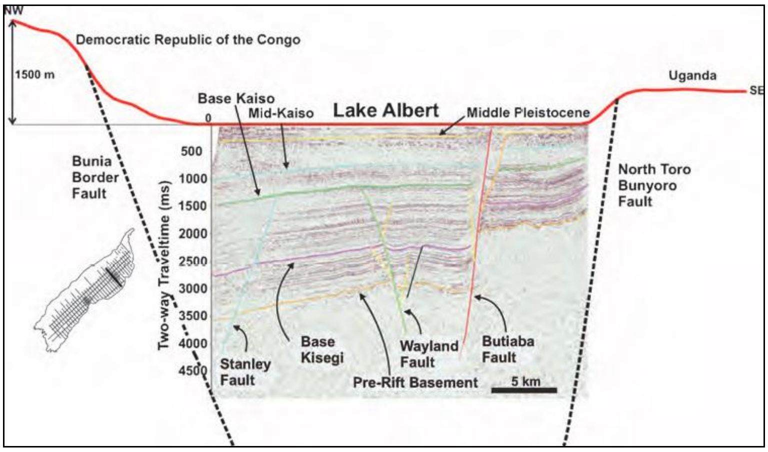

Figure 1: Multichannel seismic line 57 from the northern part of Lake Albert (see track line inset for location). Red line at surface of profile indicates regional topography (Karp1 et al, 2012). Black dotted lines indicate deep penetrating faults (Boundary faults).

In many respects, the Kibiro geothermal system typifies other fault-controlled Rift valley geothermal fields that are driven by deep circulation of ground meteoric waters (see figure 3)into high-heat-flow upper crust zone which is tectonically active. At Kibiro system, fluid movement is presumed to be controlled by the main boundary normal fault zone (see figure 2, Toro-Bunyoro fault) that bounds the east side of the rift valley as evidenced by alignment of active and relict geothermal surface features.

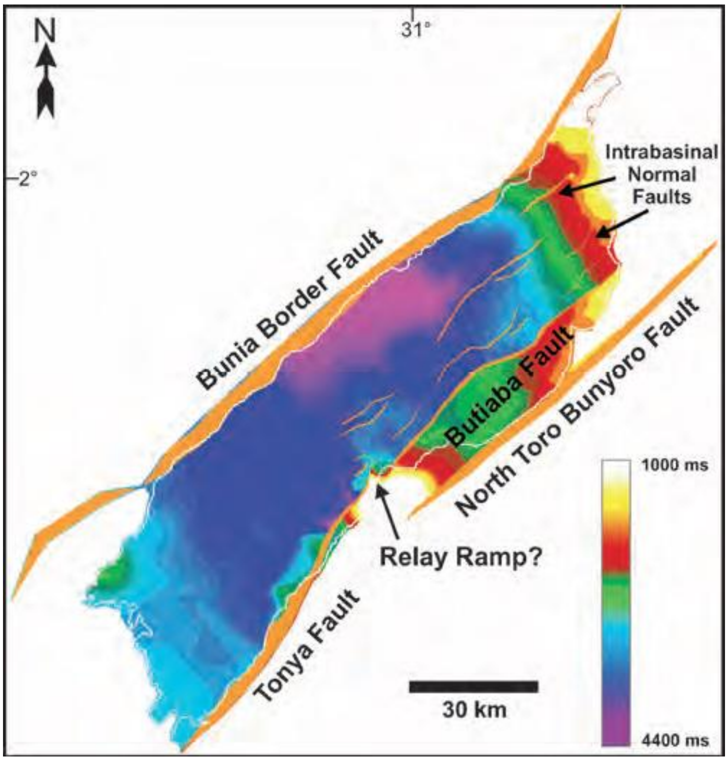

Figure 2: Showing main rift bounding fault presumed to control permeability and fluid flow (Karp1 et al, 2012)

Kibiro, gives a C_1/C_2 temperature of 196 degrees centigrade, close to Sodium/ Potassium solute geothermometer of 205 degrees centigrade. Total gas content is dominated by methane due to thermal dissolution of organic sediments.

Table 1: Summary of geological Setting

Tectonic setting	• Extensional Tectonics
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: Extensional, 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 system). This is regionally dispersed amagmatic heat flux as opposed 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

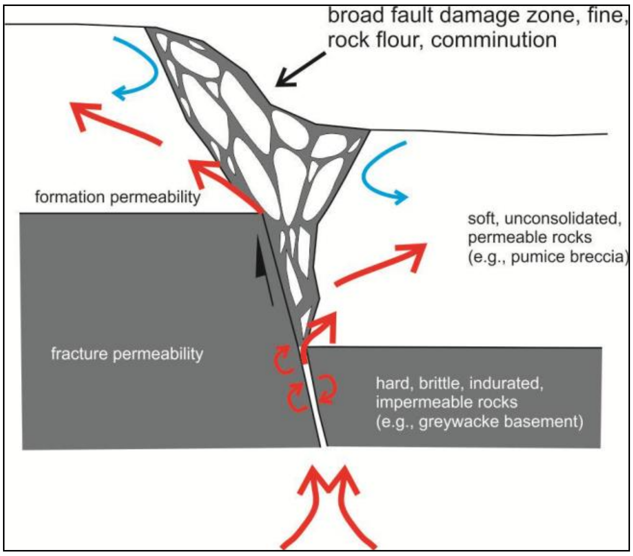

Figure 3: (Andrew Rae): Showing idealized model which fits the Kibiro system.

At Kibiro system we are looking at a deep groundwater circulation system within fractured / faulted crystalline basement metamorphic rocks (see figure 4). A well-constrained conceptual model can help guide decisions when designing an exploration plan and aid in interpreting the results of the collected data. A good conceptual model is very important for selecting locations and drill targets. Faults have high permeability in crystalline basement rocks but fault intersection have increased permeability hence are geothermal targets. Geothermal activity at Kibiro owes its existence to high crustal heat flow and active extensional Tectonism.

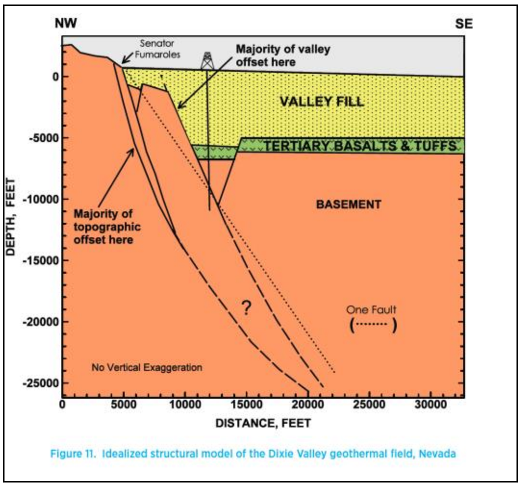

Figure 4: Dixie valley Idealised model, Kibiro system typfies this model

4. GEOTHERMAL PLAYS

According to Giacomo Corti (2011), 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 Giacomo Corti (2011) the western rift is in stage one of boundary fault (early continental rifting) evolving to intermediate stage where by incipient internal faults (G. Corti / Tectonophysics 522–523 (2012) 1–33) begin to develop. A case is major Bunyoro-Toro fault (Main-boundary fault) and Butiaba fault (incipient internal fault).

Kibiro 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 (William E. 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 and Kenya rift valleys (Rykounov and others, 1972; Bram and Schmeling, 1975; Maguire and Long, 1976; Hebert and Langston, 1985; KRISP, 1987). On the basis of seismic refraction data, crustal thinning beneath the northern part of the Western rift system is less than 25% (C.J Ebinger, 2015). Along the length of the Western rift system, numerous smallmagnitude earthquakes generally with tensional focal mechanisms occur throughout the depth range 0-30 km with no apparent vertical gap in seismicity (C.J. Ebinger, 2015).

Permeability is restricted to fault-controlled zones in the vicinity of the main bounding faults (William E. Glassley, 2010). The main bounding faults are exploration targets according to William E. Glassley description of the rifting stage and fault-bounded extensional horst and graben complexes. This Initial working 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 and 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 an anomalously high temperature gradient in the rift valley ascribed to crustal extension and thinning. Without a good understanding of the geology of a prospect area, exploration is merely guesswork.

According to Moeck: Classification of geothermal plays according to geological habitats, Kibiro 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, I, 2013). The elevated mantle provides the principal source of heat for geothermal systems associated with this Play Type (Moeck, I, 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 ((Ebinger and others, 1984). Moeck, I (2013) gives a generic model of a fault controlled extensional domain play with elevated mantle due to active crustal extension (from Moeck, in press).

Dominant heat transport mechanism fault-controlled hydrothermal circulation and heat source is ascribed to thinned crust, elevated heat flow and recent extensional domain. The majority of the known geothermal systems in western rift are amagmatic, relying on high regional heat flow throughout the rift valley to heat fluids. 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. GEOTHERMAL EXPLORATION TARGETS

Most young amagmatic geothermal systems in the western rift valley are controlled by a variety of fault intersection and fault interaction areas (favorable structural setting). Here we have high heat flow and active faulting in extensional geothermal systems. Kibiro geothermal system believed to be a deep convecting / circulation geothermal system, occurs in the relatively permeable pathways along the main bounding active fault zones where it intersects multiple fault zones (high fracture density). In tectonically active regions like in Kibiro, fault zones are commonly the most important targets as they can channel geothermal fluids from deep levels in the crust to relatively swallow reservoirs thus providing more accessible and more economical resource.

However, it is critical to determine which type of structures and which of the faults are most favorable for providing fluid pathways. Such structures must be fully characterized to guide exploration. According to Giacomo Corti (2011), 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 (see figure 5).

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

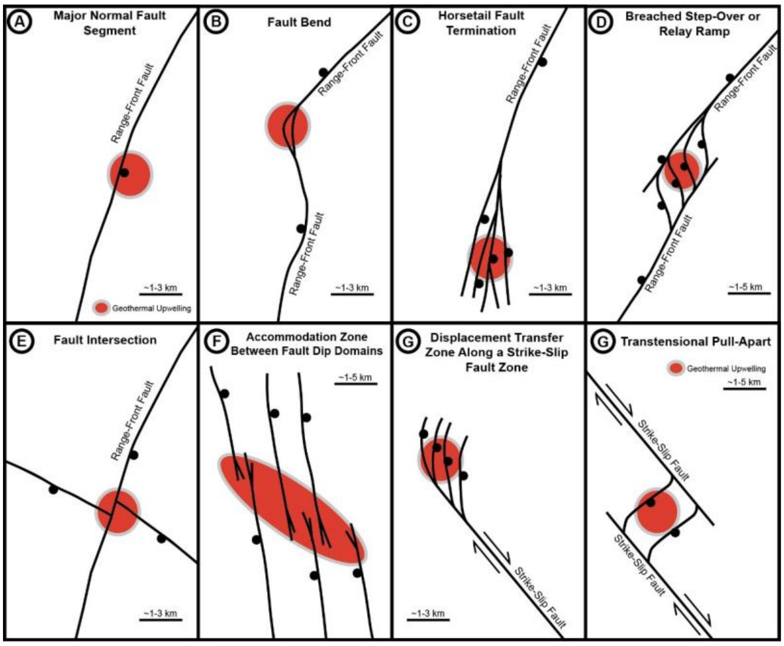

Figure 5: Favorable structural setting for geothermal systems in the Great Basin region (James E. Faulds and Nicholas H. Hinz)

6. TYPE OF EXPLORATION METHOD

According to William E. Glassley (2013), geothermal resources in fault-bounded extensional systems tend to be relatively deep. This calls for deep penetrating measurements to detect deep permeability. The MT (Magnetotelluric) survey is one of the effective method to be used (see figure 6) in combination with resistivity data (TDEM) would permit assessment of which fault segment or stratigraphic horizon accommodated significant fluid flow. Seismic reflection data would collectively indicate location of major faults and areas of structural complexity such as fault intersections, where fracture density and permeability would likely be greatest.

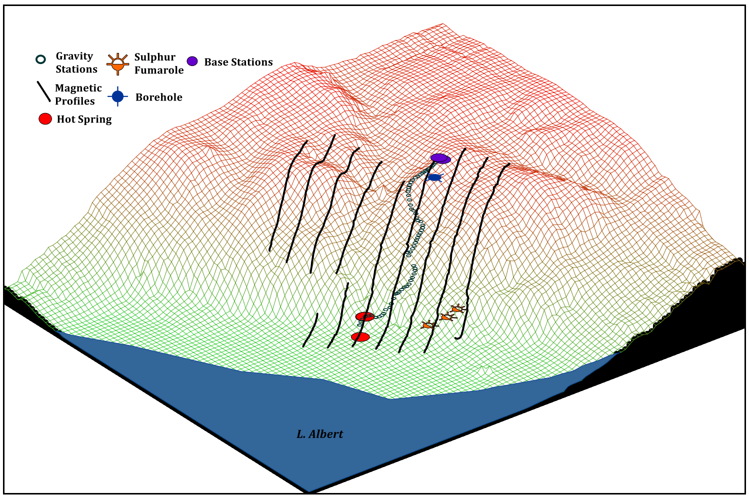

Figure 6: MT Profile lines in black targeting main rift bounding fault.

7. KIBIRO EXPLORATION RESULTS

Geophysical results

Magnetotelluric measurements were run across Kibiro geothermal field. Inversion of the data revealed a deep, sub-vertical conductor / conduit (vertical permeability) coinciding with main boundary rift fault (see figure 7). The Sub-vertical conduit is presumed to be highly fractured rocks along main active normal fault zone oriented perpendicular to the least principal stress direction.

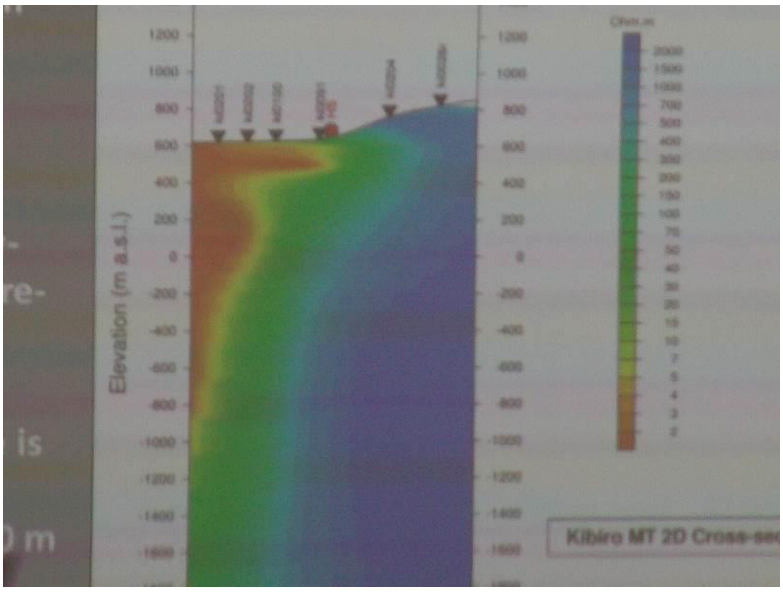

Figure7: MT sounding, red color is interpreted to represent a sub-vertical conduit which is interpreted as main rift bounding fault

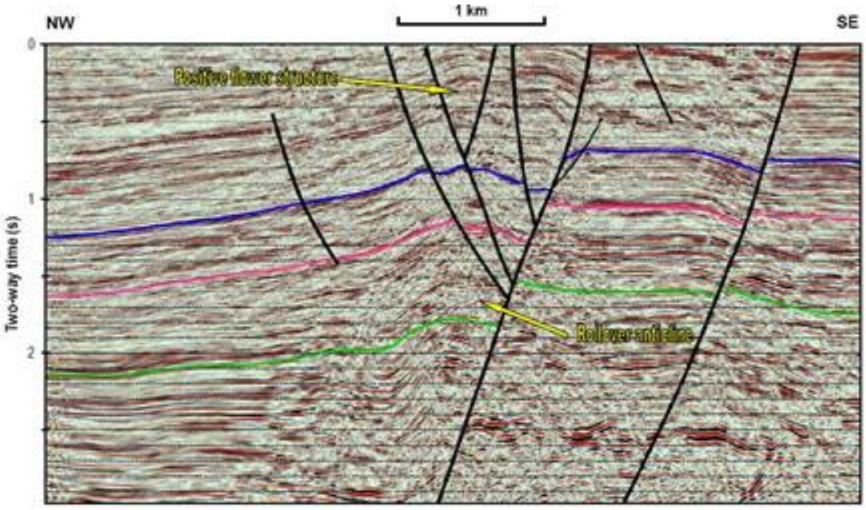

Figure 8: Seismic section, black lines and interpreted to represent high angle deep penetrating boundary normal faults near Kibiro (Karp1 et al, 2012)

The seismic section reveal high angle active faults (deep seated structural discontinuity, see figure 8) that function as conduits for sub-surface fluids. These faults allow deep crustal scale fluid circulation and represent prospective “Play” for geothermal exploration. Geothermal systems with connectivity to deep crustal heat supply are favorable for sustained geothermal production.

Geochemical survey

Carbon dioxide (CO2) and radon (Rn) were also measured at Kibiro active geothermal system during the study. Elevated gas concentrations coincide with the main active rift bounding normal fault. The 3He/4He Isotope ratios of geothermal fluids from fault-bounded Kibiro geothermal system were measured to determine if a deep mantle signature was present through fault conduits. These 3He/4He ratios were not elevated and are believed to be crustal helium sources. Kibiro geothermal system is non-magmatic based on Helium Isotope ratios.

Geological mapping

Obvious magmatic heat sources are lacking. Younger structures were targets like recent faults (normal) and fractures. The main rift bounding normal 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 geothermal features (see figure 9). 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 and permeability.

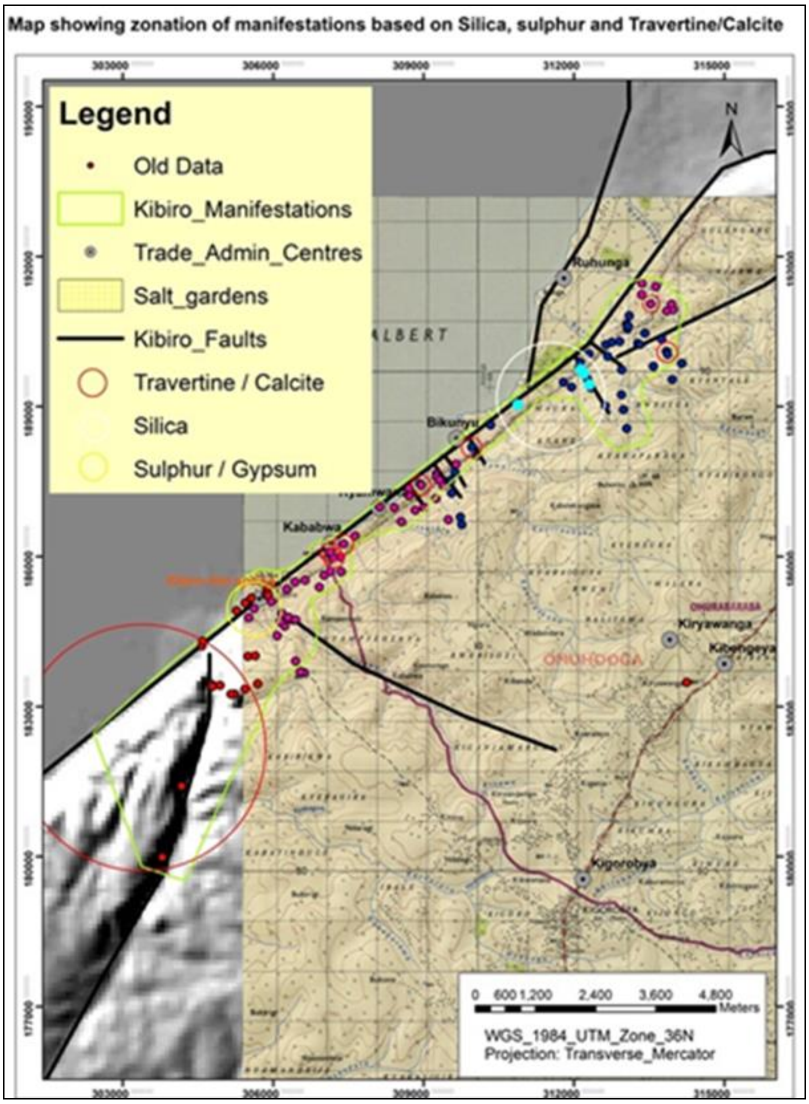

Figure 9: Showing alignment of geothermal surface manifestation's along main bounding fault.

The major accomplishments of the geological mapping are in reducing the cost and risk of geothermal exploration.

8. EXPLORATION STRATEGY

- **Gravity survey** will be useful in delineating rift bounding faults due to the large displacement between the escarpment and the low-density rift valley fill. In principle, density contrasts among rock units permit the method to map intrusive rocks, faulting, deep valley fill, and geologic structures in general.
- **Magnetic survey** will help to map lithological contact between crystalline basement metamorphic rocks and rift basins fill as well as demagnetised zones.
- **Reflection-seismic survey** to map deep penetrating faults (fault-bounded geothermal systems). Utilizing seismic reflection data, it is possible to constrain the structure in the vicinity of a geothermal reservoir, such as faulting, fracture zones, and impermeable cap rocks.
- **Magnetotelluric measurements** to delineate presumed deep, sub-vertical fault conduits and develop 3D images of sub-surface. Magnetotelluric (MT) method is preferred to be used to map resistivity at depths greater than 500 meters which is the case in Kibiro. The resistivity profile with depth as given in an MT sounding can assist in detecting 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. TDEM has no static distortion unlike MT.
- **Soil Gas and Gas flux Measurements** to delineate permeable deep penetrating faults and circulation (fault-bounded geothermal systems). The results could be used to identify extensional faults with deep permeability.

- **Geological mapping**: Detailed surface and subsurface mapping, structural analysis of faults, and interpretation of satellite images, analysis and evaluation of mineral distributions.
- **Data integration**: All data sets will be integrated to build a conceptual model. A well-constrained conceptual model shall help guide decisions when designing an exploration plan and aid in interpreting the results of the collected data. A good conceptual model is very important for selecting locations and targets for drilling.

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.

9. CONCLUSIONS

The western rift, the western branch of the East African Rift System, is bounded by high angle normal faults systems. Depth to detachment estimates of 20-30km and seismicity throughout the depth range 0-30km (C.J Ebinger, 2015).

Kibiro geothermal prospect is fault-bounded geothermal system genetically related to high crustal heat flow, high temperature gradients and active extensional tectonics. Recent faulting as a result of crustal extension and thinning resulted in forming deep penetrating faults which permit deep circulation and heating of meteoric waters in regions of high heat flow.

Kibiro system is in an area of high fracture density due to fault intersection between main bounding fault and cross cutting faults. Any exploration effort should be focused on mapping high angle rift bounding faults, presumed to be deep at crustal scale to allow deep circulation. A combination of geophysical, geochemical and geological methods will map fractures presumed to control fluid migration. One has to integrate and evaluate all these data sets and develop a conceptual model to aid locating drilling targets. Once a well has been drilled data from wells will aid in refining a conceptual model.

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