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Ihimbo Geothermal Exploration Approach

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ABSTRACT

Ihimbo is a geothermal resource area located in Rukungiri, South West Uganda. Geothermal surface manifestations include hot springs (70ºC), warm springs, travertine domes and gaseous emissions. The resource area is located in a sedimentary basin. Early studies in this generally involved surface water sampling and analysis. This was undertaken by ISOR, JICA and Directorate of Geological Survey and Mines. Ihimbo is presumed to be a deep circulation extensional amagmatic system. In many respects, it typifies other fault-controlled geothermal systems in Uganda like Panyimur, Kibiro, Buranga and Katwe that are driven by deep circulation of ground meteoric water. Fluid movement is controlled by an internal fault parallel to the main rift bounding fault. According to Moeck classification of geothermal system, Ihimbo is Extensional Domain play type CV3, where mantle is elevated due to crustal thinning and extension. The elevated mantle is presumed to be the principal source of heat at Ihimbo. The resulting high thermal gradient facilitate the heating of meteoric waters circulating through deep rift faults. According to Glassley, W. E’’s description of geothermal systems, Ihimbo is a typical fault-bounded extensional (horst and graben) geothermal system.

The western rift is still in intermediate phase of evolution of continental rift development, where by rift bounding faults are major players and are characterized by volcanism and high thermal gradients (Corti et al, 2011). This is called boundary fault stage of rift development. In the initial phases of rift development widespread magmatism may encompass the rift with volcanic activity localized along major boundary faults and transfer zones (Corti et al, 2011). Recent exploration approach included literature survey, geological survey, geochemical survey (gas sampling and analysis, gas flux measurements), geophysical survey (swallow temperature

measurements and Magnetotelluric MT surveys). This data is being supplemented by oil and gas exploration data. MT measurements have revealed a sub-vertical conductor (low resistivity signature) presumed to be a sub-surface geothermal reservoir. Soil gas and gas flux measurements have revealed anomalous gas concentration (near surface environment) ascribed to concealed fault that act as conduit for geothermal fluids. Identification of high concentration of gases is presumed to be related to enhanced permeability (critically stressed faults). Reflection seismic data from oil and gas exploration revealed deep penetrating faults presumed to control geothermal activity. The area is seismically active which keeps the fracture permeable. Chemical analysis indicate mixing of meteoric and geothermal waters as expected since recharging water and geothermal water use the same pathway.

Planned work include Time Domain Electromagnetic (TDEM) survey to correct for static shifting in the acquired Magnetotelluric Data. Static shifting is inherent issue due to near surface inhomegenities and distorts the magneto telluric response. Detailed structural mapping to characterize the structural stetting of Ihimbo is also planned. Geological conceptual models will be developed through data integration. Initial models will be tested, supplemented and refined by further field work. The process will continue until hopefully a reliable model is achieved. Thermal gradient drilling is recommended prior to committing deep expensive exploration wells. LiDAR mapping is recommended to delineate faults, create high resolution DEMs, quantify fault kinematics and develop linear maps. Shallow temperature measurements should be conducted more so where conductive anomalies have been revealed.

1. Introduction

Uganda like other developing countries is faced with a problem balancing the equation of energy demand against energy supply. By 2030, the demand for energy could double, as the population rises and the country expands its economy. The country has to grow its electricity supply and reduce greenhouse emissions. A secure and sustainable energy mix in one challenge which Uganda faces as the world responds to the challenges of climate change, energy security and economic competitiveness. As a strategy the Government took a decision to diversify and grow its energy sources by developing all its alternative renewable energy sources including geothermal resources.

Geothermal resources are widely distributed in several districts in Uganda and have the potential to provide base-load power. There are key elements for successful geothermal energy development which include policies, institutions, information and finance. Uganda has taken a multi-pronged approach to development of its geothermal resources. The Government is putting in place legal and regulatory framework, it has established a Geothermal Resources Department and has spearheaded Government-led geothermal investigation surveys. Core survey equipment has been procured and human capital development undertaken. Outlined below in a geothermal exploration approach which has been undertaken in Ihimbo Geothermal Resource area.

The geo-scientific approach involved; geothermal literature survey (desktop analysis), surface water sampling, developing a geological concept (working hypothesis / geologic play), focused geological survey, targeted soil gas and gas flux measurements combined with swallow temperature survey, combined MT/TDEM survey, detailed structural analysis, data integration and evaluation, developing a conceptual model and well targeting. The model is refined as more data is acquired. Oil and gas data mainly reflective seismic data has been incorporated in areas where is available

2. **Objective of the study**

The objective was undertake preliminary geothermal investigation surveys of Ihimbo geothermal resource area leading to a Pre-Feasibility Assessment.

3. **Location and accessibility**

Ihimbo is located in South Western Uganda in the District of Rukungiri (UTM 813593E, 9924179N). The hot springs with a maximum surface temperature of 69°C are located in Ihimbo Central Forest Reserve (see Figure 1 and 2). The study area is located on topographic map sheet 84/2 (Ruhinda), Bwambara subcounty, Rujumbura county, Rukungiri District. Rukungiri is located approximately 364km from Kampala and the survey area is roughly 15km northwest of Rukungiri town and can be accessed via Bugangari, Bwambara and Nyamirama. The hot springs are just 1.5 km from Rukungiri- Kihihi road

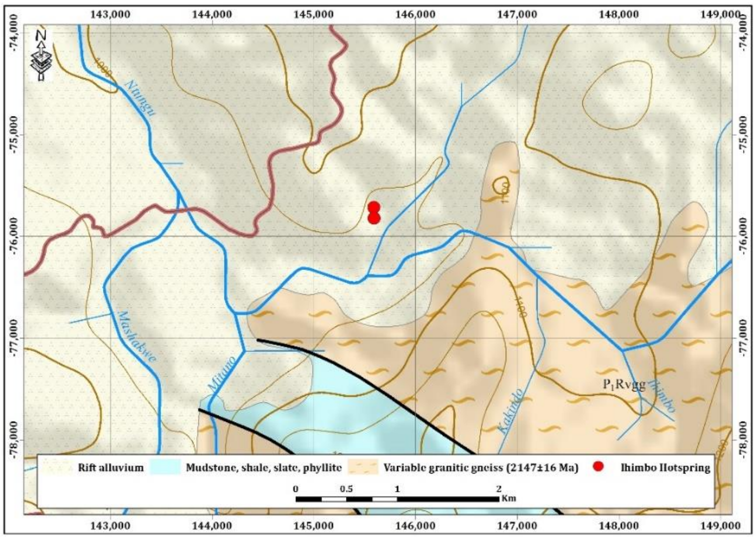


Figure 1: Map showing Ihimbo hot springs in red.

Figure 2: Google Map showing hot springs in Forest Reserve.

4. **Previous studies**.

Previous studies were carried by Geological Survey of Uganda (Wayland, 1935; Sharma, 1971, Bahati, 1996). This generally involved surface water sampling and analysis (see Table 1). Preliminary survey were carried out by ISOR and DGSM (Armannsson et al, 2004). Mainza (2006) undertook interpretation of surface water sampling results using ternary plots, stable isotope composition, geothermometry, mixing models and saturation index plots to characterize these geothermal waters. Ihimbo water are low to medium temperature waters according to geothermometry (Mainza, 2006).

Kato (2000) undertook characterization of Ihimbo hot waters using SOLVEQ software and found out that the Na-K-Ca source temperature is $122^{o}C$. JICA (2014) undertook preliminary survey of this area which involved surface water sampling and analysis, interpretation of remote sensing data (Landsat, SRTM, ASTER). JICA reported geothermometry temperatures between $83\text{-}96^{o}C$).

Table 1: Geochemical results for Ihimbo, Kanyinabarongo and Kiruruma geothermal field (JICA, 2012)

Geothermal Resource Area	**AIR TEMP ^{O}C**	**WATER TEMP ^{O}C**	**PH**	**EC**
Ihimbo	22	69	8.7	98

Generally investigation surveys involved geochemical analyses of geothermal fluids to characterize the chemical, thermal and hydrological properties of the geothermal system. The Geology was described in detail by Christopher et al (2013). Mineralogical and chemical analysis were carried out on the travertine samples at SEAMIC Tanzania. The samples were found to be dolomite-Ankerite-Carbonatite. CaO ranged from 26.73% to 35.36% while MgO ranged from 8.14% to 15.35%.

5. **Current studies**.

The exploration approach involved; geothermal literature review (desktop analysis), surface water sampling and analysis, developing a geological concept (working hypothesis / geologic play see figure 3), field-verification, geological mapping, soil gas and gas flux measurements combined with swallow temperature survey, MT field survey (see table 2). This approach speeds exploration area selection and reduces costs. According to exploration schema, exploration in Ihimbo is at intermediate stage up-grading to advanced exploration.

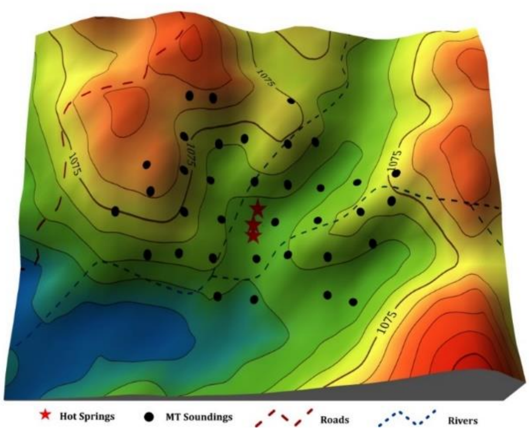


Figure 3: 3D cartoon of the Prospect

Table 2: Showing expectation from exploration techniques.

Geothermal Exploration technique	Lithology information provided	Structural / Stratigraphic Information	Hydrological Information	Thermal information
Swallow temperature survey				Identify and delineate swallow thermal anomalies.
Geological mapping	Lithology mapped	Locate active faults, map fault and fracture patterns, kinematic information	Can reveal whether faults are circulating fluids, map geothermal surface indicators, fracture pattern	Identify and delineate swallow thermal anomalies, map surface temperatures
Fault mapping		Locate active normal faults	Can reveal whether faults are permeable	
Gas flux sampling		High flux can be indicative of conduits for geothermal fluids		Anomalous flux is associated with active geothermal activity.
Gas sampling		High gas flux can be indicative of conduits for geothermal fluid flow.	Gas composition and source of fluids	Anomalous flux is associated with active geothermal activity
TDEM	Rock composition, mineral and clay content	Detection of permeable pathways, fracture zones, faults	Resistivity influenced by porosity, grain size, permeability, fluid saturation	Resistivity influenced by temperature
MT	Rock composition, mineral and clay content	Detection of permeable pathways, fracture zones, faults	Resistivity influenced by porosity, grain size, permeability, fluid saturation	Resistivity influenced by temperature

Source: USGS OpenEI

5.1 Tectonic Setting.

Without a good understanding of the geology of a prospect, exploration is merely a guesswork. Ihimbo geothermal resource area is located in an intra-continental rift extensional setting. Western rift is in early stages of continental rift evolution (fault border stage). The western branch in general has not yet progressed to an advanced rifting stage and rift basin architecture retains a pristine geometry (Ring, 2004). Western Branch, initiated during Mid Miocene (17Ma) while eastern branch initiated Early Miocene (20Ma).

According to Corti et al (2012), in the initial phase, 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 boundary faults key exploration targets. According to Glassley (2010), horsts and grabens occur in regions where there has been extension and thinning of the continental crust.

As the crust is pulled apart (subjected to tension), it releases stress by fracturing (rifting), forming steeply dipping faults perpendicular to the general direction of extension (Glassley, 2010). In case of western rift extensional direction is W-E to WNW-ESE (Rosendall, 1987; Ebinger, 1989a; . Blocks of crust subside (down-dropping) between faults forming grabens (valley or basin), whereas the surrounding areas on the opposite side of main bounding fault remains elevated forming horsts. The high angle (steep) faults that bound the horsts and grabens can extend to considerable depth. All these responses to tension lead to anomalous geothermal regions that may be conducive to exploitation. Steep faults associated with rift boundaries are targets of geothermal exploration. Such settings are places where magma often rise into the crust, in response to the decrease in lithostatic pressure caused by crustal thinning during extension (Glassley, 2010). In the crust is a thermal zone, in which thermal energy has been added by upwelling mantle below the rifting continental crust.

As a result of the presence of these heat sources, geothermal resources are likely to occur. Heat rises into faulted zones from the heated base of continental crust. High geothermal gradient is reported in western rift (28-67^{o}C/km (Abeinomugish, 2003). Permeability is restricted fault-controlled zones in the vicinity of horst-graben boundary. Once again main bounding faults are key exploration targets. Fluid flows in geothermal systems are often controlled by permeable faults and fractures.

Ihimbo geothermal system is a deep circulation amagmatic system. In many respects, Ihimbo geothermal system typifies other fault-controlled geothermal systems that are driven by deep circulation of meteoric waters. Fluid movement is controlled by an internal fault parallel to main bounding fault.

According to Moeck and Beardsmore (2014) geothermal play type, I would classify Ihimbo geothermal area as convection dominated, CV-3 Extensional Domain, in an intra-continental rift. The heat source is ascribed to thinned crust and elevated heat flow in recent extensional domain. This is similar to amagamtic geothermal systems in western USA, Western Turkey and Soultz-sous-foret (France). In an extensional domain geothermal play type CV3, the mantle is elevated due to crustal extension and thinning. The elevated mantle is the principal source source of heat for the geothermal system associated with this play type (Moeck, 2013).

According to Bwambale et al (2015), Albertine region is located is characterized by high levels of seismic activity (earthquake zone) and by many active normal faults. The western rift is bordered by high angle (steep) normal faults bounding on one side of spoon shaped basins (Ebinger, 1989). Depth to detachment estimates of 20-30km, the roll over geometry of asymmetry basins, seismicity throughout the depth range of 0-30km suggest that plannar border faults along one side of rift basins penetrate the crust. The loci of earthquakes corresponds very closely with main bounding rift faults and this area is geologically active.

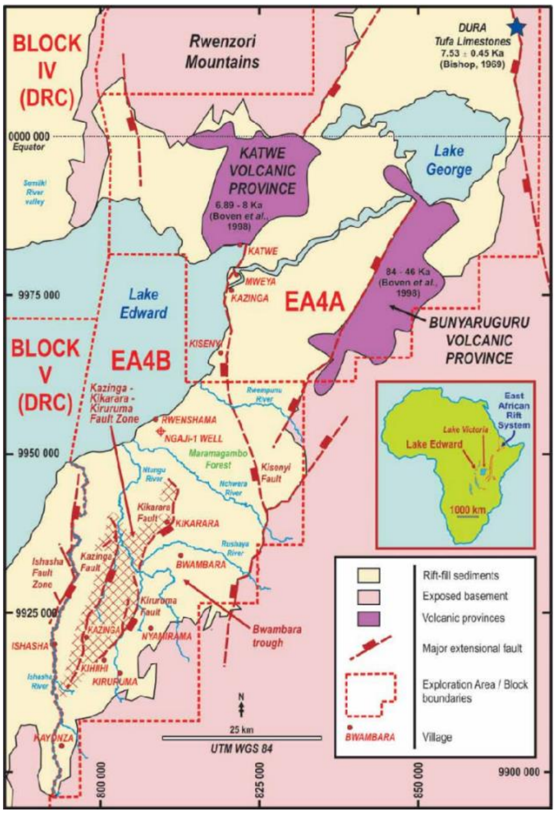


Figure 4: Regional map showing main NE-SW rift bounding faults and Bwambara Trough.

Border faults (see figure 4 and 5) in this rift zone are thought to have undergone extension perpendicular to their trend in a generally W-E to WNW-ESE direction (Rosendahl, 1987; Ebinger, 1989a,b; Tiercelin and Mondeguer, 1991; Rosendahl *et al.*, 1992; Foster and Jackson, 1998; Calais *et al.*, 2006), although extension directions may have altered over time. Extension is also thought to have occurred over a relatively narrow zone of continental crust and is estimated to have been less than 15% (Ebinger, 1989a; Rogers and Rosendahl, 1989) Morley, 1995) also note that individual half-graben basins within the rift zone are separated by accommodation zones, along which there may be a significant strike-slip component and that these accommodation zones are often orientated parallel to Precambrian discontinuities.

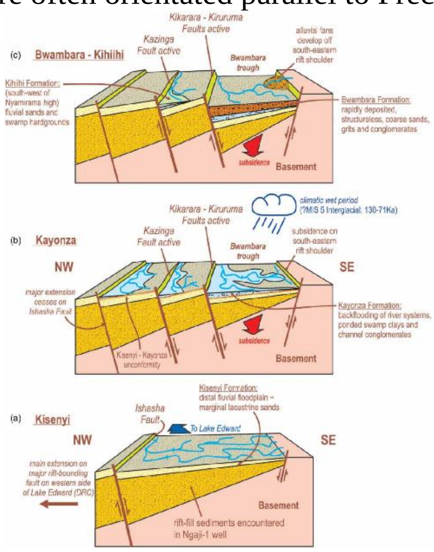


Figure 5: Showing Bwambara trough (C) where hot springs are located

5.2 Geological Survey.

This was mainly GPS based digital mapping. Ihimbo is located in an intra-continental rift setting and is underlain by rift fill sediments which include inter-bedded clays (impervious and good for cap rock), silts, sandstones, conglomerates, grits and gravels. Five rift sediments formation were identified and mapped accros the area to produce a geological map of EA4B (Christopher et al, 2015). Palynological analysis suggest that all exposed rift sediments are late to middle Pleistocene-Holocene.

This geological region was created by extensional forces that have given rise to horsts and grabens. Surface geothermal indicators include hot springs, warm springs, gas discharge zones, vegetation anomalies, swallow temperature anomalies and travertine domes. The hot springs with maximum surface temperature of 69^{o}C issues from sediments. The water is clear with vigorous gas emissions.

Geothermal indicators are located along linear trends that is believed to mark the fault system along which the fluids ascend. Fossil travertine dome could have formed in the bottom of Lake Environment for such a huge deposit to form because of rapid cooling as they mix with lake waters. These are aligned in NE-SW trend pointing to a possibility of structural control. The study area is dominated by a north-east to south-west trending fault zone which underwent significant extension within the last 130,000 years (Christopher et al 2015) to produce a graben. This trough subsequently filled, initially with ponded swampy clays, followed by coarse fluvial and alluvial clastics. Lithofacies changes within a short distance being alluvial and fluvial deposits (see figure 6).

It appears geothermal activity shifted from where travertine appear to where hot springs are located. While the main bounding fault is aligned with fossil travertine at Rugando (082127E, 9924677N) and Ihindiro-Kigati (0822546E, 9927098N), the hot springs are aligned on internal fault parallel to main rift fault (see figure 7). The area has several bentonite prospects but it is not clear whether they are genetically related to geothermal activity. Main boundary faults were mapped and areas of intersection and transfer zones were critically mapped.

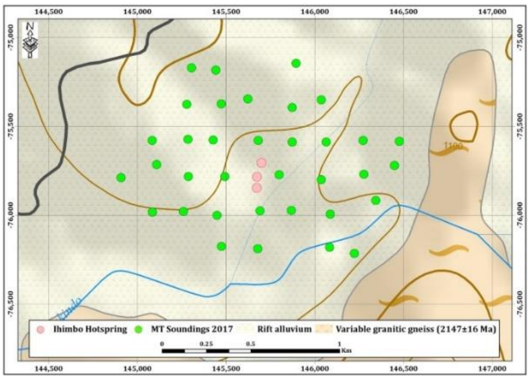


Figure 6 Map showing showing the geology of Ihimbo area.

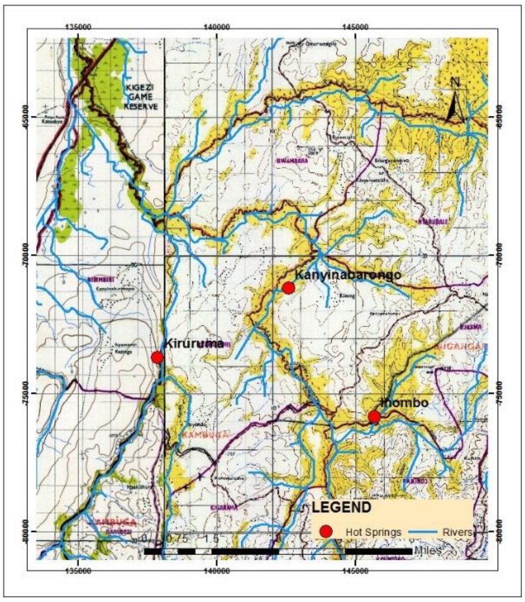


Figure 7: Map showing a NE-SW trend followed by a river on Ihimbo

Ihimbo geothermal system is fault-hosted (horst and graben) geothermal system driven by deep circulation of meteoric water into the heated continental crust. There are no young or old volcanic rocks in the area. Ihimbo is an extensional, fault-controlled resource summarized in table 3 below; The presence of epicenters suggest that the graben bounding faults are still active which is a condition favourable for maintaining open path ways for circulation of geothermal waters in the Ihimbo fault zone.

Table 3: Geological setting summary of Ihimbo (Using Brophy Classification Scheme / occurrence models**)**

Sn.		
1	Topography	Rugged on upthrow, low on valley floor (basin) hosting Ihimbo Central Forest reserve (1019m).
2	Climate	Dry (High temperatures) with low precipitation (low rainfall) but can be rainy sometimes, densely forested (Musisi, 1991). The rainfall is bimodal between Jan-Feb and June-July.
3	Depth to resource (m)	Not known yet
4	Surface manifestations	Hot springs, warm springs, vegetation anomaly, warm ground, gaseous emissions, travertine precipitates.
	Lithology	Rift fill sediments in Basin and basement on escarpment wall.
5	Permeability	Dominantly fault controlled by an incipient internal fault parallel to main rift bounding fault.
6	Seismicity	Seismically active (earthquake zone) according to recorded and felt earthquakes.
7	Heat source	High heat flow due to thermal zone beneath the continental crust ascribed to mantle upwelling into crust as a result of crustal extension and thinning.
8	Environmental Issues	Located in central forest reserve, hence environmentally sensitive. Local have spiritual and cultural attachment. It is a cultural resource
9	Geothermal Resource Classification	Extensional fault-controlled resource.

Paul Brophy classified geothermal areas based on a variety of properties such as tectonic setting, controlling structures and fluid properties. According to Brophy occurrence model, the exploration setting of Ihimbo Geothermal Resource area is extensional tectonics, fault-controlled resource (Brophy, 2006). It is too early to rule out sediment hosted geothermal system.

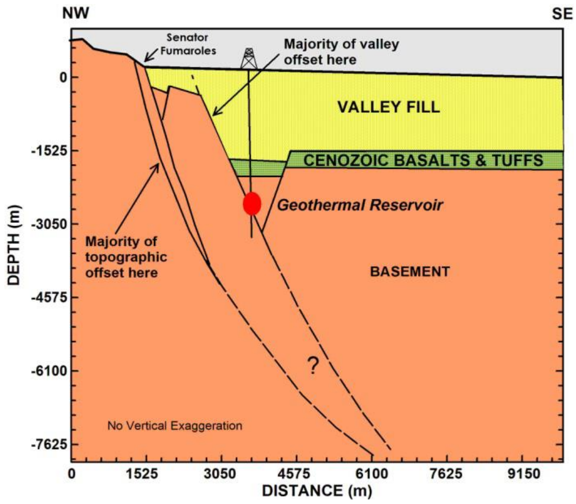


Figure 8: Showing idealized structural model of Dixie Valley geothermal field, Nevada which typifies Ihimbo.

The above (figure 8) serves as the first imaginative draft of a conceptual model of Ihimbo. We are looking deep reaching fracture, where rain water percolates deep to heated crust rock and returns to discharge as hot springs. It is a working hypothesis which depicts graphically the major sub-surface features of the system, including location of rock units, faults and fluids flow paths.

5.3 Hydrologic Survey.

One of the vital prerequisite for a commercial geothermal field is the presence of water in the formation in ample quantities. Hence hydrologic survey is an important part of the exploration program. According to Arrannsson (2004) this system is recharged by meteoric recent water. There are many big rivers in the area and one of them is Ntungwa River. The area also has a dense forest which is in many occasions wet. These are likely to ensure reliable and ample recharge water to the system. It is likely that cold recharge water (coming in as rain and river water) percolates through major faults and fractures deep into the formation where it comes into contact with heated crustal rocks.

5.4 Geochemical Survey

5.4.1 Soil gas and gas flux measurements

Targeted soil gas sampling and analysis was conducted using a RAD7 Durridge alpha spectroscopy instrument. Soil-gas surveying (Radon concentration measurements) consists of the collection and analysis of gas samples from the unsaturated, possibly dry zones. Samples were collected using a stainless steel probe driven in the ground to a depth 0.5m. The area is densely forested (thick vegetation) and it rainy. However an open anomaly was indicated which warrants data gap closure in dry weather conditions (see figure 9). High concentration are presumed to indicate geothermal activity and presence of enhanced permeability most probably along a fault zone.

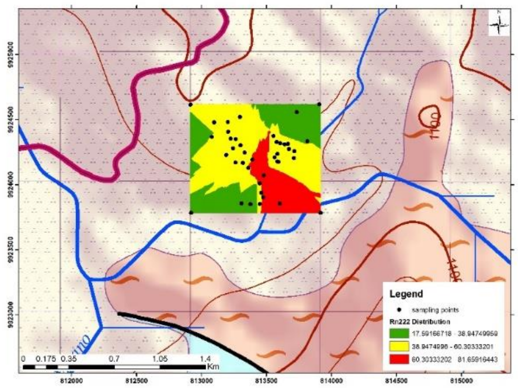


Figure 9: Map showing distribution of activity of 222Rn diffusively degassed from the soil in Ihimbo geothermal prospect.

Note that wet climates and thick vegetation can conceal gas discharges. Focused flux measurements were performed using a speed-portable closed dynamic accumulation chamber LIcor (West System Instruments).

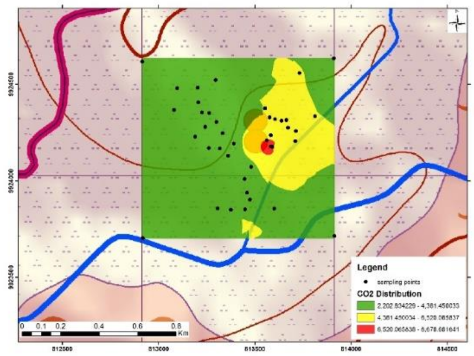


Figure 10: Map showing spatial distribution of CO_2 flux measurements in Ihimbo area

High gas flux anomalies (see figure 10) coincide with location of hot springs pointing to a possibility of structural control of gas flux. High concentration are presumed to indicate permeable structure most probably fault zone. Although geothermally derived CO_2 was detected in soil gas and soil-gas fluxes, interpretation of the data was complicated by soil respiration and biological processes, especially during rainy season.

5.5 Geophysical Survey

5.5.1 Magnetotelluric (MT) Field survey.

MT field surveys have become an effective means to image deeper structures. A total of 41 MT soundings were collected during the survey period (see figure 11).

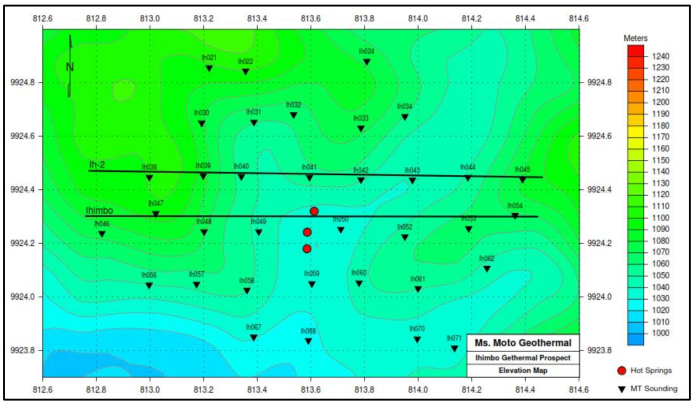


Figure 11: Map showing MT sounding stations

Data processing and Interpretation

Time Series Processing

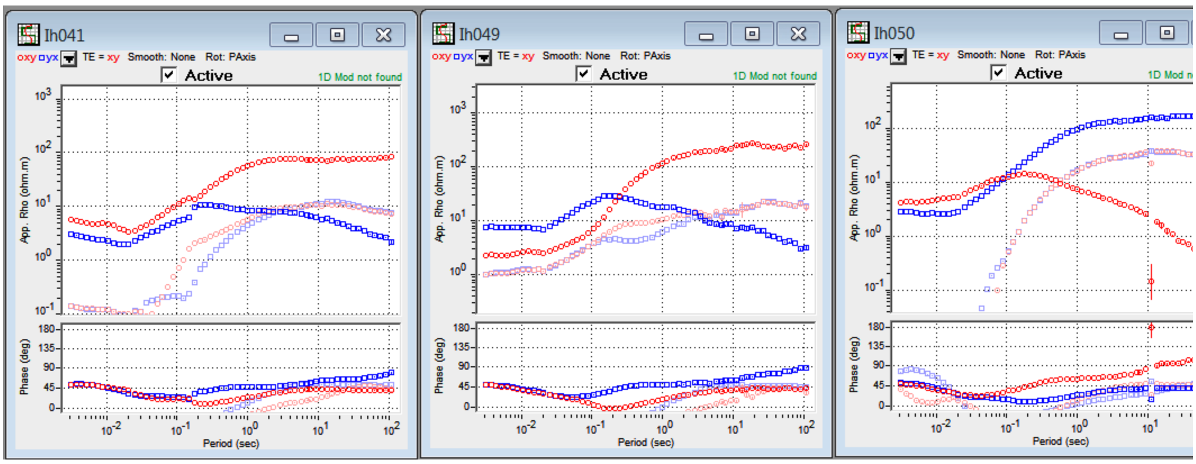
The collected time series data downloaded from the MT equipment are quality scrutinized using the time series viewer option in the SSMT2000 software (Phoenix Geophysics, 2005). This gives a first indication of the data quality that influences decision making on whether to repeat the sounding or not. Then parameter files (tbl) are edited to reflect the setup for the collected data. The resulting time series are fourier transformed to the frequency domain, before calculating the different auto- and cross-powers using the robust processing method (RPM).

The data are graphically edited using MTeditor a Phoenix geophysics software by masking the outliers to achieve apparent resistivity and phase curves and other relevant parameters. The resulting MT parameters are all saved as EDI files ready for export to Winglink - the interpretation software

Results of the MT Survey

Given that on average the stations were 200m apart, adjacent MT stations are expected to be similar - this was observed for most of the soundings. However, most of the stations become 2D or 3D at relatively high frequency, 10 to 50 Hz, implying a rapid lateral change in resistivity.

(a)



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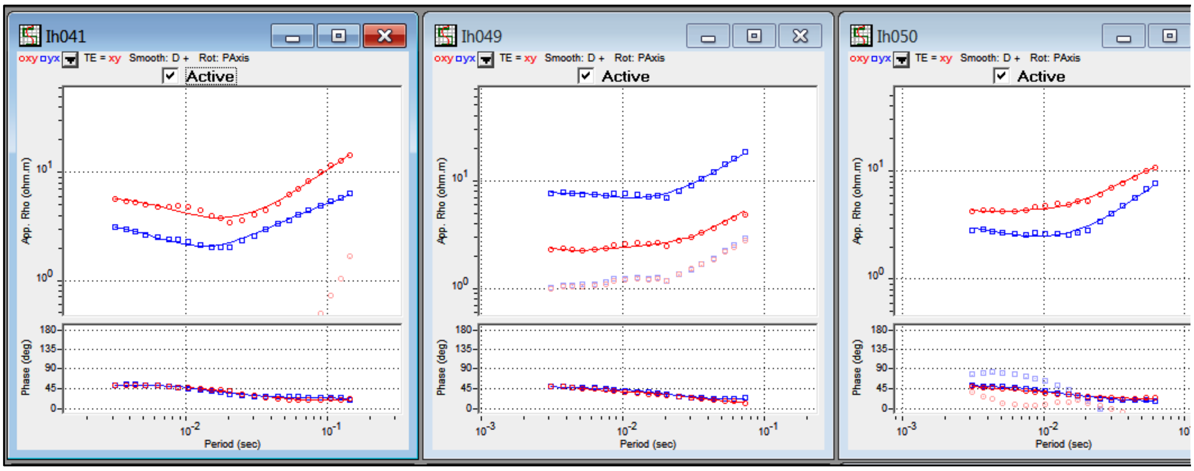

Figure 11: Examples of the data collected within the survey area (a) 2D / 3D data sections at relatively high frequencies and (b) 1D portion of the MT data used during the inversion.

The frequency ranges where the 1D and 2D inversions are more likely to become invalid are suggested by the rapid increases in amplitude in *xx* and *yy* components of the apparent resistivity. The conductance map, polarization diagrams and induction data all support a 2D approach along E-W cross sections, albeit still probably not deeper than a few 100m. Based on the induction data, some of the 2D and 3D distortion appears to be due to resistivity variations that are not covered by this MT data set.

The 2D and 3D data are mostly ok, but cannot just be interpreted using 1D tools without taking precautions such as identifying TE-mode in 2D cases or limiting the depth of the inversion in 3D cases. Although a 1D inversion of the TE-mode might work best over the conductor, a 1D inversion of the invariant mode was used over the more resistive rocks, using data over about 3 to 10 Hz.

The overall pattern of 1D resistivity to about 300m depth shown in the conductance map highlights the N-S conductor extending through the west part of the MT data set. The most conductive stations (outlined red in the map, see figure 13) have a shallow 2 to 4 ohm-m conductor to a depth of 100 to 200m below that is a resistor.

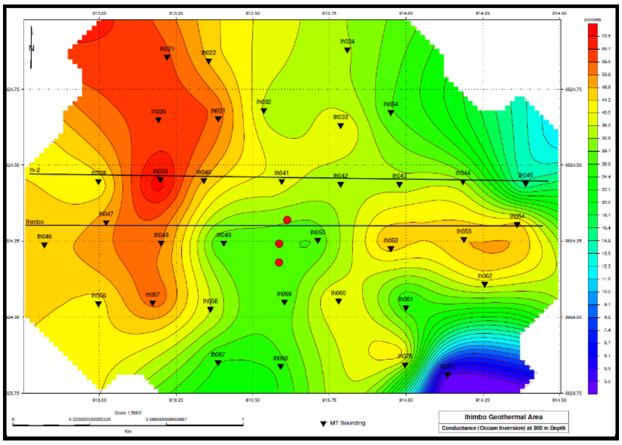

Figure 13: Map showing conductance at 300m depth - Red high conductance (Low average resistivity).

The 1D model of individual soundings were used to compile 1D models of the resistivity structure of the Ihimbo geothermal prospect. These models are presented here as vertical cross-sections and iso-depth resistivity maps. Resistivity cross-sections and iso-depth resistivity maps were plotted by use of Winglink interpretation software. The program calculates the best line between the selected sites on a profile and plots resistivity iso-lines based on the 1D model generated for each sounding. It's actually the logarithm of resistivity that is contoured so that the color scale is exponential, but the numbers at the contour lines are resistivity values.

Resistivity cross-sections

Two cross sections running in the east - west direction were made (see figure 14 & 15) within the study area. The sections are based on smoothed Occam's models that have consistent defined resistivity values (from the inversion) at many depth values and an automatic contouring and colouring of the resistivity has been applied.

Both *ihimbo* and *ih-2* cross sections shown in figures 13 and 14 show similar conductive patterns with a conductive resistivity structure observed in the western side of the study area between 900 - 1050 meters. This structure fades out towards the eastern side. Both profiles are 1.7km long.

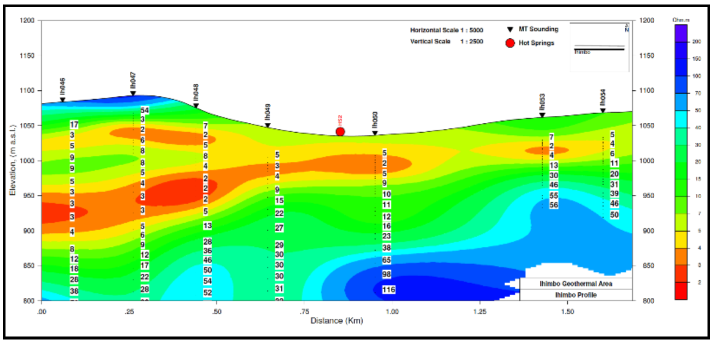

Figure 14: MT Resistivity cross - section for Ihimbo Profile down to 800 m.a.s.l

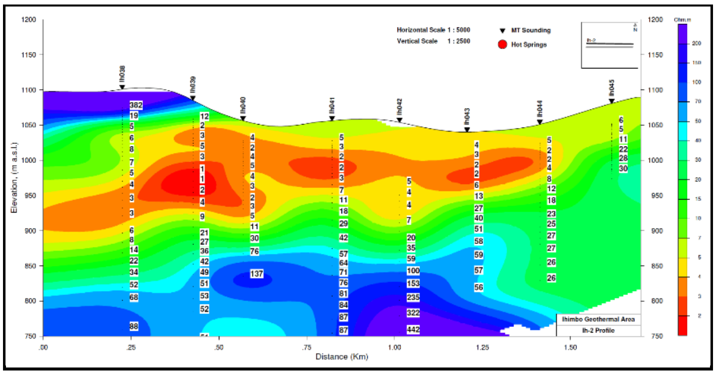

Figure 15: MT Resistivity cross - section for Ih-2 Profile down to 750 m.a.s.l

Iso resistivity maps

Iso-resistivity maps using winglink software were made to display the resistivity at different depths in the Ihimbo geothermal area (see figures 16-19). Of the several maps made, only four

(4) have been displayed in this report. It should be kept in mind that the maps are based on few soundings with relatively uniform distribution.

Resistivity map at 1000 m.a.s.l

Uniform conductive layers appear at this depth. It's more conductive around the hot springs and the northwestern part of the survey area, with resistivities less than 6Ωm. Elsewhere, in the south eastern part; it ranges between 8 to 40Ωm.

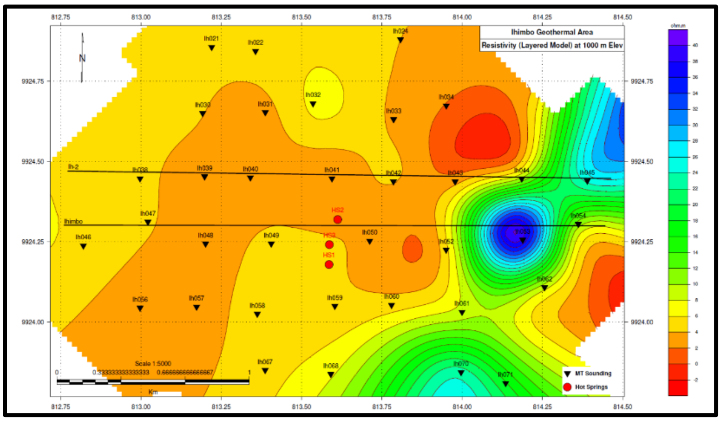

Figure 16: Iso-resistivity map at 1000 m.a.s.l

Resistivity map at 500 m.a.s.l

At this level, the rocks in the central part of the survey area surrounding the hot springs are less conductive with resistivities between 80 -300Ωm, but outside, they are less than 80 Ωm.

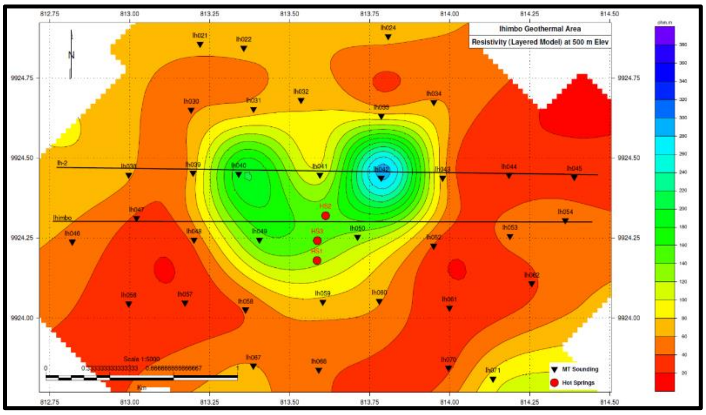

Figure 17: Iso-resistivity map at 500 m.a.s.l

Resistivity map at sea level

The map shows fairly uniform resistivity in the central part of the map ranging between 60 - 200 Ωm representing relatively unaltered rocks, except on the outside where the resistivity is relatively low at about 30 Ωm.

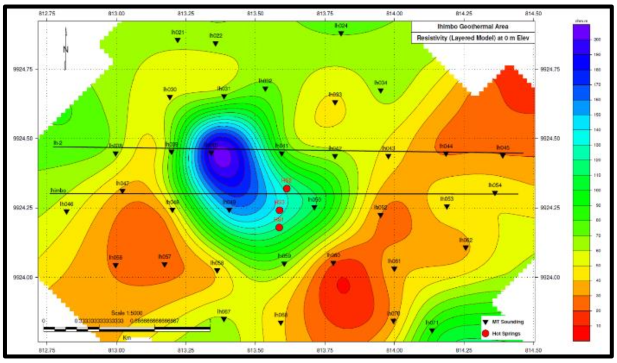

Figure 18: Iso-resistivity map at sea level.

Resistivity map at 1000m.b.s.l

The resistivity pattern in this map doesn't differ much from the one at sea level where the resistivity in the central part of the map and around the hot springs is relatively high in comparison to the surrounding.

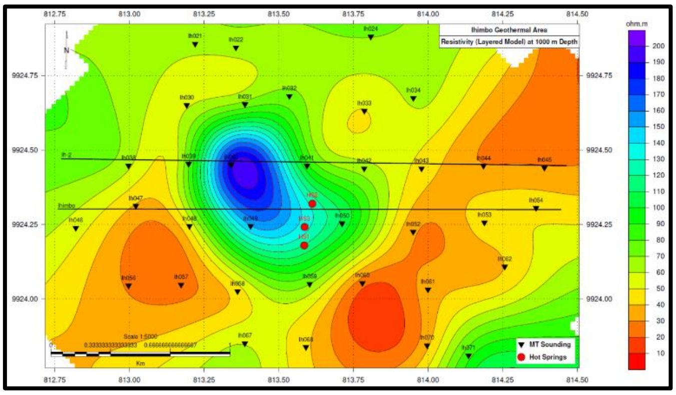

Figure 19: Iso-resistivity map at 1000 m.b.s.l

6.0 Conclusion

Western Rift: The western rift is still in early phases of rift evolution where by geothermal activity is mainly controlled by main rift bounding faults and few internal faults.

Working Hypothesis: It is important to have in mind a working hypothesis which should be constantly reviewed and refined as mode data is gathered.

Exploration schema: Ihimbo exploration schema involved desktop analysis, geological play analysis, geological mapping, soil gas and gas flux measurements, shallow temperature measurements and MT survey. Judging the level of exploration in this area, it saved time and money.

Geothermal activity: The presence of surface geothermal indicators (hot springs, gaseous emissions) suggest that Ihimbo is geothermally prospective.

Structural Control: The alignment of active geothermal indicators is indicative of structural control of geothermal activity and fluid flow along an internal normal fault dipping NNW-SSE. This is similar to structural controls (fault related geothermal systems) of geothermal activity in western USA and Turkey.

Amagmatic extensional system: Ihimbo geothermal system is an amagmatic (non-magmatic) deep circulation extensional geothermal system which is fault-hosted. It typifies other deep circulation extensional systems (horst and graben complexes) which derive their heat from heated continental crust by upwelling mantle. According to Moeck (2013) classification, Ihimbo qualifies to be extensional domain play type –CV3.

Heat source: The heat source is ascribed to anomalous heat flow due to mantle upwelling into continental crust related to crustal extension and thinning. This is a non-magmatic geothermal system similar to Basin and Range in Nevada, USA. Deep circulation along rift faults results in generation of geothermal water if there is heat source related to high heat flow because the crust is thin.

Permeability: Permeability is controlled by rift main faults. There is a strong relationship between faults and permeability. Faults have high permeability but fault intersections have increased permeability hence were key geothermal exploration targets. Deep circulation of meteoric water is favored by zones of high permeability like fault zones along rift boundaries.

Seismically active: The presence of recorded seismic activity indicates that the region is tectonically active, with active faults and hence likely to possess a suitable resource.

7.0 Recommendations

- **TDEM surveys**: Although MT surveys provide a powerful means for accessing information about the deep subsurface, heat sources and regional fluids flow pathways, swallow level resistivity surveys (TDEM) are needed in order to identify drilling targets. In this way, focused TDEM surveys are admirable complements of an exploration program in Ihimbo.
- **Data gap closure**: Data so far collected provide some indication of a geological anomaly, but the data were not sufficient to delineate a target. Focused data gap closure (geological-Structural analysis, geophysical, and geochemical) is recommended to provide a rigorous subsurface model.
- **Temperature Gradient Measurements**: TGH should be drilled and data integrated prior to committing expensive full diameter exploration wells.
- **Reflection Seismology**: Oil and gas data acquired during oil exploration should be used to map deep reaching faults presumed to control geothermal activity.
- **Geothermal Conceptual model**: When geo-scientific surveys have been completed, it is necessary to synthesize all the acquired data and to draw conclusions based on totality of the evidence. It is advisable to integrate geology, geochemistry, geophysics and geothermic data into a comprehensive geothermal conceptual model (synthesis map & cross sections) and drill the model. This after synthesis and interpretation.
- **LiDAR Mapping**: This is recommended to delineate faults, create high resolution DEMs, quantify fault kinematics and develop linear maps.
- **Noble gas isotope geochemistry**: This is recommended to confirm the heat source whether magmatic or amagmatic.

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