Proceedings, 7th African Rift Geothermal Conference
Kigali, Rwanda 31st October – 2nd November 2018

Conceptual model for Kilwa geothermal site

North East Kivu Lake, Rubavu, Rwanda

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Key words: surface study; geothermal conceptual model; Lake Kivu; Western Rift

ABSTRACT

The Government of Rwanda (GoR)engaged, with the support of the European Union (EU), a surface study of the Gisenyi geothermal prospect in the Rubavu area, along the North-Eastern border of Lake Kivu. The area is located in an active volcanic and tectonic environment, dominated by the North-South trending Kivu Rift. Along the shore of the lake, hydrothermal manifestations (with temperature of 70 ± 2 °C) occur in the Kilwa peninsula, emerging from detrital sediments forming the tombolo that links the island to the coast at the foot of a major normal fault. Structural studies show that the Kivu Rift is asymmetric with a major fault affecting the Western margin of the Butare Horst facing East towards the lake, whereas the lake area is characterized by block faulting facing West. This allows for a link at depth between Kilwa and the Kivu Rift axis, as deeply fractured pegmatites provide the necessary permeability for the up-flow of geothermal fluids. Reservoir temperature is estimated to be 160°Cat circa 2,000m depth, with shallow aquifers hosting fluids of >100°C at depths of circa 1,000m. Deep-seated magmatic dykes identified along the Nyiragongo-Kivu rift tectonic axis are considered as providing the heat source of the system.

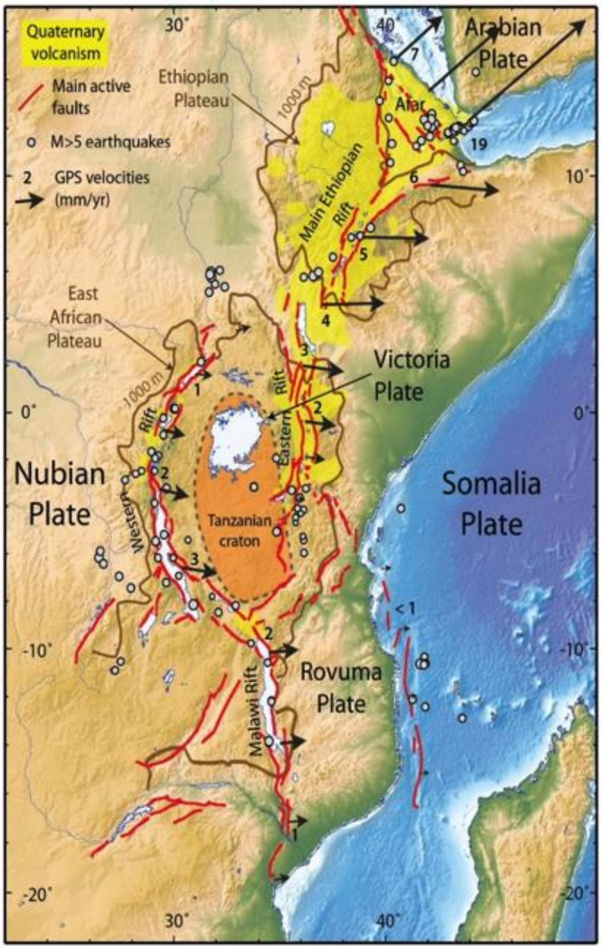
Kilwa should allow for generation of electricity using the Organic Ranking Cycle (ORC) technology, as well as answering direct uses such as agro-industrial (e.g. heat and CO_2 for the brewery), horticulture, aquaculture and a geothermal spa.

Besides this prime target, for which slim-hole drilling are recommended as well as complementary off-shore surface exploration, further geo-scientific work is proposed in the Nyiragongo-Kivu active volcano-tectonic axis along the Rwanda-Democratic Republic of Congo (DRC) border, in Base area and east of Caldera Bianca in the Karisimbi massif to investigate further possible geothermal resource potential.

1. Introduction: a project location that justify its geothermal interest

Geothermal energy development in Rwanda is currently at the exploration stage. There is no geothermal field that has been developed for power generation or direct use application. The basaltic lava fields south of Karisimbi is the only place where exploration drilling was carried out, however without success.

The approach engaged by the GoR with the Geothermal Development Company and Geo2D (GDC-Géo2D) team started with a comprehensive and in-depth study of all data available, focusing on any data of geothermal significance. This included an update of the geodynamic situation of this portion of the western rift in the context of the East Africa Rift Valley, EARV (Figure1), allowing to show that the rift is presently active with a spreading rate of 2.1 mm/y in the prospect area (Figure 2), that is the same order of magnitude as the central Kenya rift valley where major geothermal sites are identified and are being exploited



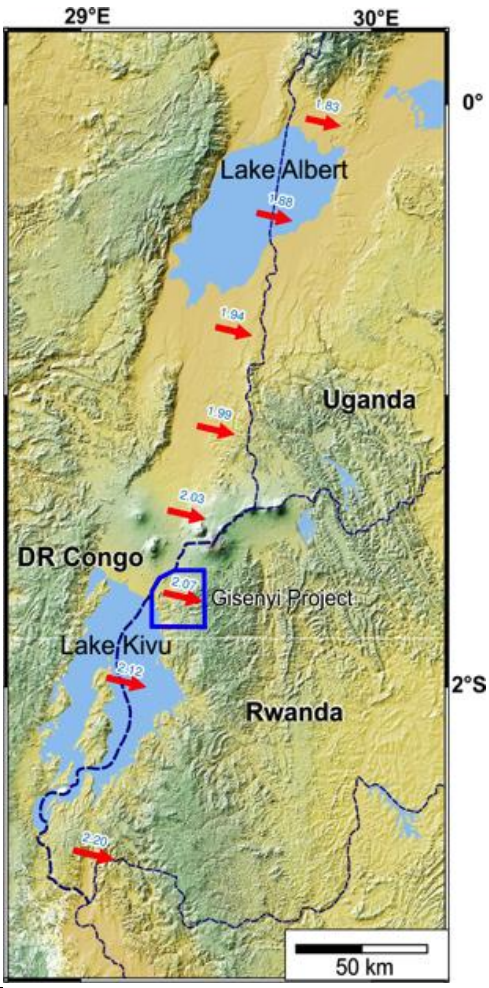


Figure 1 (left): The East African Rift system, with major fault systems, seismicity (M>5), and plate-motion vectors with GPS velocities (mm/y), from Calais (2016) From north to south, the spreading rate decreases along the Eastern Rift whereas it increases along the western rift. Observe the major contrast in manifestations of Quatenary volcanism abundant in the Eastern rift and rare in the western rift.

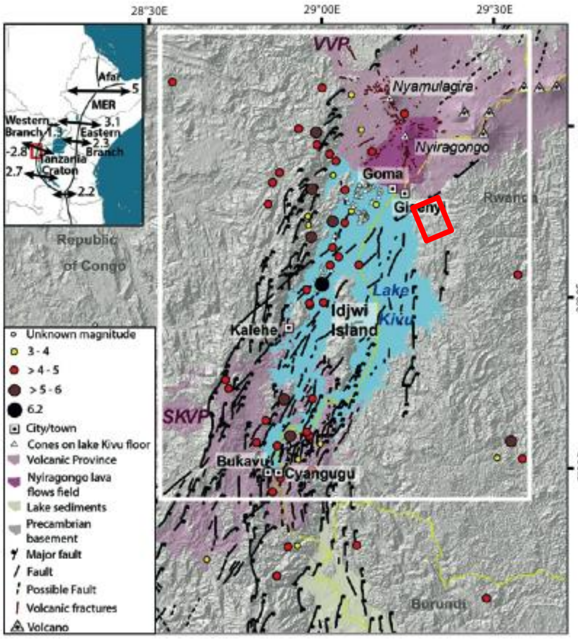
Figure 2 (right): Plate-kinematic vectors for the western Rift. In the Kivu area, extension amounts to approx. 2.1 mm/yr. red arrows denote relative plate-slip vectors. Velocity is in mm/yr. the prospect area is shown in blue.

Regional geological, structural, seismic and volcanological data have been combined with results obtained concerning the Lake Kivu, which is subject to detailed bathymetric, structural and geochemical investigations due to its natural stratification and the presently developing methane exploitation.

The site selected for the project is located on the NE border of Lake Kivu (Figures 2 and 3). It is bounded to the east by the (over 3,000 m high) Butare Horst made of faulted Precambrian basement, to the north by the lava fields of Nyiragongo and Karisimbi, and to the west by the Lake Kivu rift axis. As observed on Figure 3, this is not a particularly seismically active area, most of the activity is concentrated in the DRC, on the Western shore of Lake Kivu.

2. Geology of the geothermal site

Searching for a magma chamber that could provide a suitable heat source for a classical high enthalpy geothermal system did not provide obvious results in the prospect area. However, a volcano-tectonic feature drove our attention: The active North-South rift that links Nyiragongo volcano to Lake Kivu's axial graben fed by recurrent volcanic dikes (the last one active in 1977 and 2002), the geometry of which was well documented by interferometry studies following the last eruption (Figures 4 and 5). The eruptive activity did show an association of magma with fumaroles and gas (CO_2 and methane) similar to the ones feeding the deep Kivu lake strata. Convergent bathymetric, thermal and chemical studies have shown this hotter, gas rich strata resulted from the hydrothermal activity at depth (Figure 6). The presence of a magmatic heat source along the axis of the lake is therefore not excluded.



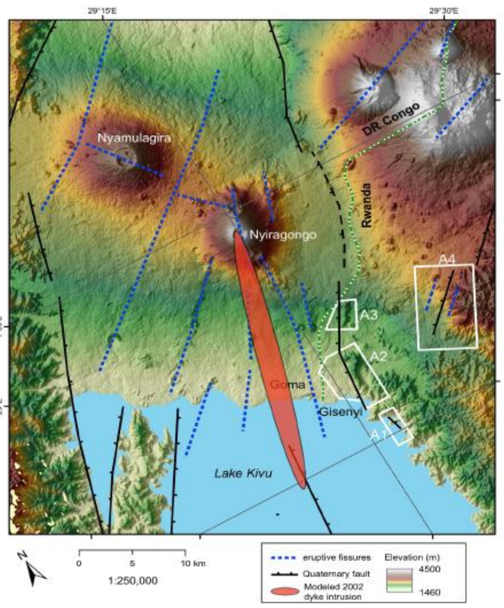


Figure 3 (left): Seismicity of Lake Kivu (from USGS), and volcano-structural data, showing the contrast between the active western (DRC) border and the aseismic north-eastern (Rwanda) shore (Wauthier et al., 2015). Figure 4 (right): Map showing the location of major faults and the 2002 dyke injection - modeled to account for surface deformation based on radar interferometry. Note the extent of the dike south of the volcano and its alignment with the axis of Lake Kivu at the latitude of the Kilwa (A1) hot springs (from GDC/Geo2D after Wauthier et al. 2015).

Let's underline– as shown in Fig.1 - that the geothermal systems under investigation radically differ from the model prevailing at present in the Eastern branch, where geothermal sites being developed are located in a well-defined and active volcanic environment (calderas, silicic domes, with associated hydrothermal activity).

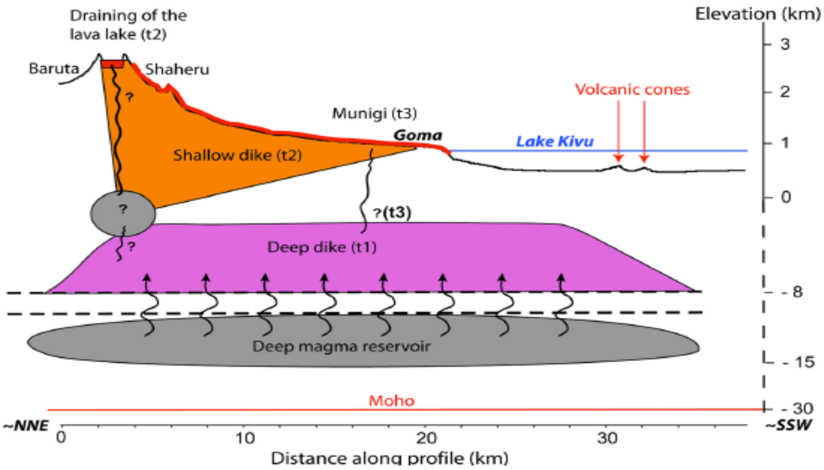


Figure 5: Modelling of two dykes to account for surface deformation based on radar interferometry (from Wauthier et al. 2015). The superficial one fed the 2002 eruption whereas the deeper one – at 3 to 8 Km depth - extends from south of the Nyiragongo volcano underneath the Lake Kivu rift axis, feeding therma manifestations under the Lake.

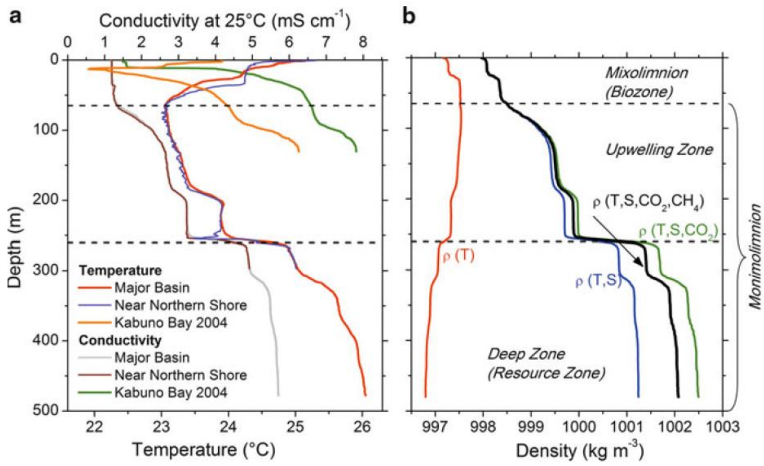


Figure 6: Vertical stratification (temperature, density, conductivity) in Lake Kivu as observed in different sub-basins, showing the temperature increase in the deeper zone associated with higher mineralisation, interpreted as resulting from thermal springs at depth.

The petrology of the volcanic rocks determined from thin-section study allow to discriminate between the lava fields of Nyiragongo (nepheline, leucite and melilite basanites) from the Karisimbi ones (potassium olivine basalts and mugearites), all lava of deep mantle origin. In the case of Karisimbi, magmatic differentiation occurred allowing for the production of important volume of trachyte, showing the presence of a shallow magma chamber in the Caldera Bianca area. Our volcanological and petrological investigations also indicated that volcanic units distinct from Nyiragongo and Karisimbi exist to the NE of the prospect area but did not allow to identify the presence of a local magmatic heat source.

The basement rocks were studied with attention concerning their lithology, structural geology and hydrothermal alteration, allowing to identify a mylonitized pegmatite – observed in the north and south of the prospect area (in particular hosting the hot-springs) - as a potential candidate for a geothermal reservoir of good permeability. Field and laboratory studies (petrology, XRD mineralogy of hydrothermal alteration products showing the importance of kaolinisation), complemented by detailed structural investigation of the recent fault system and of the volcanic emissive systems. indicate the possible existence of reservoir in the Precambrian basement. These geoscientific investigations allowed to show the Kilwa site as the most promising.

3. Hydrogeology and fluid geochemistry

Kilwa peninsula is a well-defined geographic structure; an island made of compact Precambrian basement (metasediments intruded by granites associated with pegmatites). Two hot-spring sites are found at the lake level on both sides of a narrow and small terrace that connects the peninsula with the eastern shore of Lake Kivu (Tombolo). The water temperatures at the springs vary from the lake temperature up to 73°C but did not vary with time as shown by successive studies: BRGM (1978), BGR (2009), KenGen (2010), Uniservices (2012), GDC/Geo2D (2017). These different springs reflects various degrees of mixing between the convective hydrothermal fluids (of Na-HCO3 type) with the Lake Kivu surface waters. The springs are associated with gaseous emissions with a slight H_2S smell, and iron sulphide is deposited, altered into iron hydroxide in atmospheric conditions. In the sections with the highest temperatures, the detrital lacustrine sediments are cemented by a matrix rich in sulphides, carbonates and silica.

The location of the hot springs is intimately associated with the NNW-SSE-striking Kilwa Fault (Fig. 7). The fault shows a high dip towards the east (i.e. opposite to the lake). In the footwall, the basement rocks – granites, metasediments and pegmatites – are virtually unaltered and a well-expressed fault plane is exposed immediately above the northern spring.

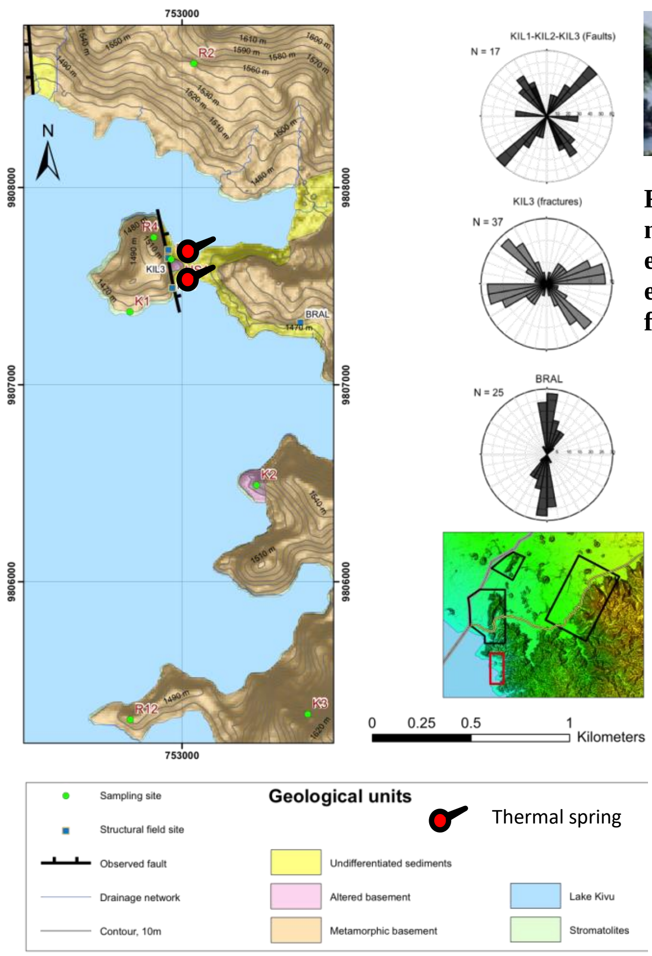


Fig. 7B. Photograph of the peninsula taken from the main shore North. The Kilwa Fault controls the emergence and the location of hot springs areas. An emerged stromatolite terrace is seen on the uplifted footwall block, cut by the fault.

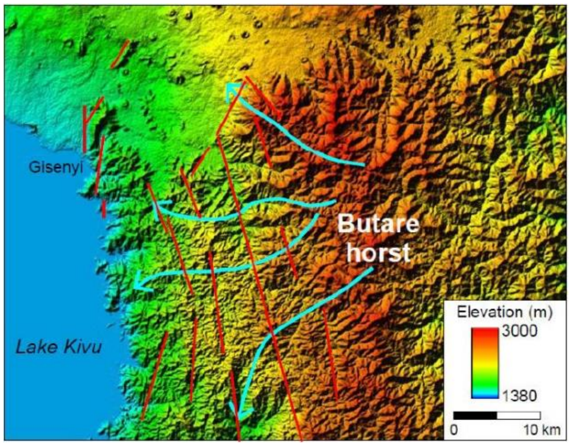


Figure 7C: Topographic map showing the inferred horizontal component of the advective flow pattern, from Butare Horst to the Gisenyi hot springs, and the normal faults (in red) that may drive the groundwater inflow.

Figure 7A: Schematic geological map of Kilwa Area showing the 2 hot-spring emergences and the hydrothermal alteration zone studied South at station K2. Note that these alterations are not observed in the next peninsula South. The rose diagrams show the strikes of faults. Note dominant NNW-SSE strikes, and different structural systems. The deformations that controls the thermal emergences are therefore limited in their extension North (1 Km max.) and South (3 Km max.). All taken from GDC/Géo2D.

If the geothermal fluids emerge from detrital coastal sediments of Lake Kivu, the exposed precambrian basement in the hanging wall exhibits rock formations that support the convective system. Here, a spectacular pegmatite cuts through the micaschists and metasediments that characterize the faulted and eroded hills limiting the lake to the east. Crystals of up to several decimetres in length are observed. The minerals include the dominant orthoclase, with muscovite, quartz and tourmaline also present. The pegmatite is pervasively fractured and thus furnishes a higher permeability of the host rock. This assessment is supported by hydrothermal processes that overprinted these rocks as shown by kaolinized zones within the pegmatite.

Away from the spring along the shore of Lake Kivu, extensive deposits coat shoreline conglomerates and protect them from erosion, are stromatolitic carbonates deposited by the Lake water. These are also found along a lacustrine terrace that is 8 m above the present-day water level and is inferred to have been uplifted and cut by the Kilwa fault (Fig. 7B). A boat survey of the neighbouring shorelines to the north and south showed that these deposits are extensive around the lake. A complex set of Cenozoic extensional structures belonging to the Kivu Rift system include locally a N-S to NNW-half graben controlling the thermal springs with brecciated pegmatite acting as a geothermal reservoir channeling the hydrothermal fluids. The N & S extension of the reservoir underneath the Lake surface would require further sub-lacustrine studies, but it should not exceed 1 Km N and 3 Km S (as shown in Fig. 7A).

The hydrogeological context of the site appears favorable, as high amount of rainfall with high permeability is found in the Butare horst, over 3.000 m asl compared with the altitude of 1.460 m asl for lake Kivu. (Fig. 7B). The porosity and permeability in basement rocks in the Butare escarpment is relatively high due to contrasting lithologies and successive deformational events. The Butare horst hence display all characteristics of a powerful recharge area for the Kilwa geothermal site.

The geothermal system appears as a fault-hosted geothermal circulation system allowing for the presence of an intermediate temperature liquid dominated reservoir hosted in basement rocks controlled by the Kilwa Fault System dipping in the opposite direction and controlling the hydrothermal upflow zone.

The Kilwa site is deprived of any visible recent volcanic activity in its nearby surrounding. It therefore lacks evidence for the presence of a shallow magmatic heat source, although it could be influenced by the magmatically and hydrothermally active axis of the Kivu rift located 10 km away as hypothesized from the active magmatic and hydrothermal axis (as seen in Fig. 4, 5 & 6). The feeder dyke is not large enough to be considered as a magma chamber, but if the eruptive sequence is an integral part of a recurrent system, such events may induce a magmatic heat source at depth that could be of interest for geothermal considerations. But more information needs to be collected regarding previous eruptions to better document these recurrent multi-decadal diking events to unambiguously show that there is a heat source of geothermal significance (see Varet, this volume).

An appreciable concentration of He is present in selected samples of Kilwa gases albeit varying orders of magnitude of atmospheric air contamination. The possible source of He in the N_2-He-Ar trilinear diagram is from the mantle and the crust. $^3He/^4He$ ratios of 0.16 R_A indicate a mixture of atmospheric source with He generated from radioactive decay of U- and Th- series of radionuclides in the crust (basement rocks). It can therefore be postulated that the geothermal system benefits from heat that might be emanating from a deeper magmatic dyke although heat emanating from radioactive decay in the crustal rocks cannot be ruled out (GDC/Geo2D, 2017).

Also, it can be deduced that the presence of appreciably high CO_2 fluxes localized in the hot springs area with Carbon of mantellic origin. The maximum depth to which the meteoric water descends is constrained by the geothermometric temperature of the hot springs (100 to 164 ºC). Assuming twice the normal shallow adiabatic geothermal gradient of 66 ºC/Km, this implies a circulation depth of 1.4 to 2.1 km. A deep geothermal reservoir is hence expected at a temperature of 160°C or more at circa 2 Km depth. A secondary shallower reservoir is postulated to be hosted by the fractured basement along Kilwa fault with a conservative temperature of ≥ 100 ºC at depths of 800 ± 200 m (GDC and Geo2D, 2017).

In addition, based on the association of the hot springs with brecciated pegmatite and the fact that the adjacent highly fractured basement regions to the east and northeast of the Butare Horst are located at high elevation and receive ample rainfall, it is hypothesized that enhanced fluid flow may occur in the basement rocks at depth, away from the Butare Horst, toward the W underneath the Kivu Lake surface. This setting thus suggests that the Kilwa site is an integral part of a regionally more extensive hydrothermal system developed along the lake shore. Other thermal springs are known to occur in the lake at greater depth although their exact location has not yet been precisely identified. Several extreme hydrothermal events were inferred from associated chemical fluctuations of the lake water, in particular around 5 and 1.0-0.8 ky BP. Hydrothermal activity also resulted in the perturbation of the thermohaline stratification at 0.6-0.4 Ky (Ross *et al*. 2014).

To conclude, a classical geochemical model can be generated considering the equilibrium temperatures computed by use of water and gas geothermometers, with relatively deep reservoir of about 160ºC and a shallow secondary reservoir of 100ºC. The parent geothermal water is likely to have high temperatures and cools through mixing with cold water during the fluid ascent from the shallow reservoir to the surface. Possibility of existence of a more deep-seated reservoir with temperatures greater than 200 ºC should not be ruled out as reflected by the hydrocarbon geothermometers and high values of the apparent gas-gas equilibrium temperatures (GDC/GéO2D, 2017).

4. Geophysical studies

The magnetic survey conducted by GDC/Geo2D (2017) shows a magnetic low to the east and west of the mapped fault intercepted by a magnetic high near the fault area. The magnetic low near the fault is not well constrained and may partly result from electrical power effect on few points that are near the houses at that location. Transient Electromagnetic (TEM) data show a 500 m wide low resistivity anomaly sandwiched between high resistivity (Fig. 8) interpreted as a hydrothermally altered brecciated fault zone controlling the geothermal fluid upwelling.

In order to mitigate the limitation in TEM method, the use of DC resistivity was added to the surveys in order to mitigate the pollution by power lines. The Schlumberger array was used with the potential electrode spacing fixed while the current electrode spacing increased at intervals. Current was injected into the ground and the potential drop across the electrodes is obtained for every station. The resistivity of the respective subsurface layers and their thicknesses are obtained from the apparent resistivity modelling.

The 1D-DC resistivity models show low resistivity zones that confirm the existence of a fractured area up to 500 m wide that extends at depth in the basement rocks along the foot of the fault line observed at the surface. The extend of the fault to the north and south could not be measured from these results, but is certainly more than 1 Km long. This hydrothermally altered fracture zone host the geothermal fluids that issue at the hot-spring locations on its wertern margin. The regions away from the fault zone show high resistivity suggesting low porosity and permeability in the less altered Precambrian metamorphic and granitic basement.

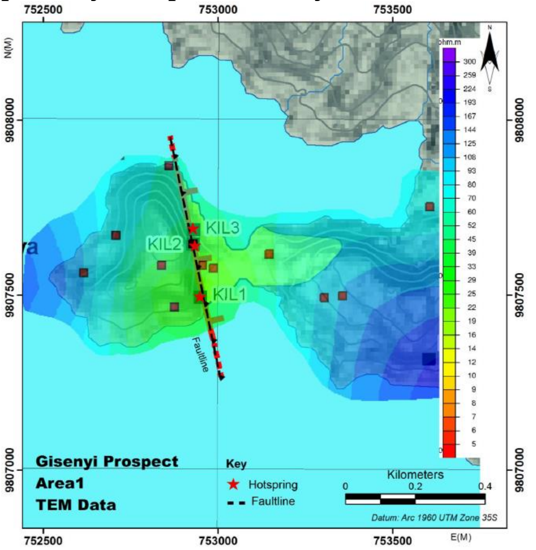
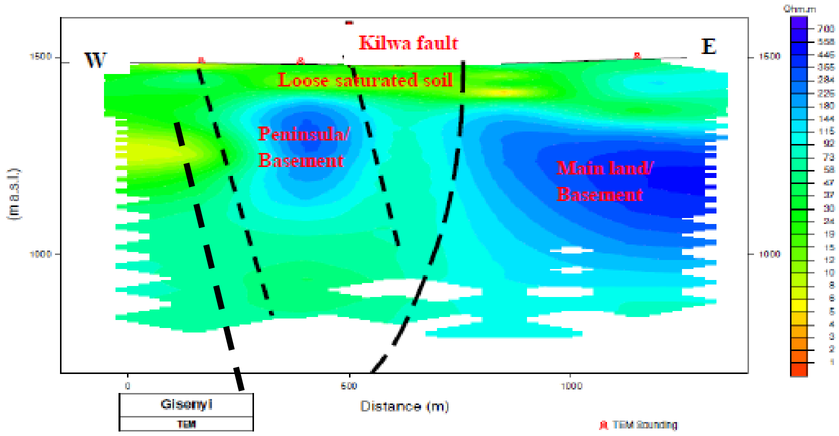


Fig. 8: Resistivity map outlining the geothermal resource at Kilwa Peninsula. The low resistivity zone is a hydrothermally altered, fractured pegmatite that is channeling the convective geothermal fluids. Hot-springs occur along the fault line.

High resistivities are measured in the surrounding unfractured basement (GDC/Geo2D, 2017).

A high resistivity above a low resistivity is observed in the Kilwa peninsula (Fig.9); it corresponds with the compact Precambrian basement observed at the surface, thickness of which is shown nit to excced 1 Km. Below this impermeable basement, the more conductive layer may indicate a fractured area at depth where the thermal fluids are stored and eventually circulate from depth underneath the lake (eventually from Kivu rift axis?) towards the surface at Kilwa.

Figure 9: 1D TEM resistivity inversion model cross section along E-W profile line at Kilwa. The black dashed lines are the interpreted faults marked by resistivity offset. Green-yellow zones are low resistivity and blues are the high resistivity (GDC/Geo2D, 2017).



As both magnetic and TEM measurements are affected by powerlines present at the vicinity of the fracture zone holding the geothermal fluids, it was worthwile to conduct gravity field measurement and to produce a map of contrasting densities. The sampling frequency was aimed at defining the boundaries of the low density fracture zone with a few meters accuracy. The Instrument readings were processed to remove the effect of topography to Simple Bouguer anomalies reflecting the local geological structures (Figure 10). Data shows a high gravity anomaly related to the unfractured basement rocks on the peninsula and the main land, and in the central region a low gravity anomaly sandwiched between these gravity highs. This low density zone related to the fracture zone correlates with a low resistivity zone, which suggest that the thermal water is stored and circulate within this fracture zone.

As a whole, geophysical data show concordant low magnetic, resistivity and gravity anomalies interpreted as a fractured zone marked hydrothermal mineral alteration together with the upwelling of thermal fluids. The extend of this permeable area to the north and south could not be estimated from the geophysical results, but certainly exceed 1 Km, with a maximum length of 4 Km considering the constrains provided by the geology. The regions located east and west away from this fractured hydrothermal zone are resistive to electrical currents thus showing low porosity and permeability, coherent with the observed basement rocks in these areas. Data allow to estimate the extension at depth of this potential geothermal reservoir down to at least 800 m, but could not be investigated deeper. The source of the heat could not be evaluated from the available geophysical data.

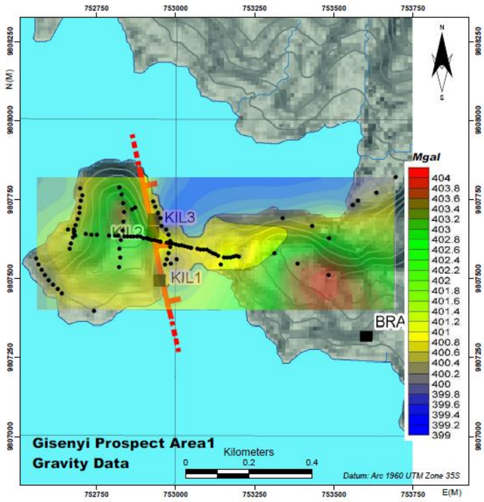


Figure 10: Simple Bouguer anomaly overlain on the topographic map of Kilwa Area. The red shows the high while the blue low gravity anomalies. The black dots are the gravity measurement points the red line if the mapped fault in this region.

5. Geothermal conceptual model

5.1. Geothermal heat source

It is speculated that thermal fluids circulating in the Gisenyi geothermal system transport the heat that might be originating from deeper sources. $\delta^{13}C\text{-}CO_2$ values of hot springs reflect the deep provenance of CO_2. It is therefore considered that the geothermal system transports heat that might be originating from magmatic source along the active (circa 2mm/y that is 2m by millennium) Kivu Rift axis that can connect with Kilwa through convective transfer along deeper normal faulting, with heat also partly emanating from deep normal gradient basement and radioactive decay in crustal rocks. We have seen from the geological sudies that the feeding dike of the last Nyiragongo eruption extended at depth of 3 to 8 Km underneath the Kivu rift axis. Despite the distance, recurrent magmatic injections along tis diking axis may have influenced the Kilwa site through the faulted substratum of the lake as shown by some of the isotopic data.

5.2. Reservoir permeability

The Precambrian basement, made of meta-sediments intruded by granites and associated pegmatites, particularly abundant in the Gisenyi-Butare area, was shown to be heavily fractured and faulted due to several orogenic events. The pegmatites, particularly brittle with their crystals of decimetric size, were deeply affected by mynlolitization. In addition, the extensive normal faulting that affected the area since the rift initiated in Miocene increased the permeability of these pegmatites which were therefore affected by hydrothermal alteration. The deep seated faulting along the eastern escarpment allowed for down-wrapping of the hanging blocks as the one observed at Kilwa and sub-lacustrine surroundings.

The Kivu Rift appears asymmetrical, and structural conditions imply that important and deep normal faulting affected the whole area, with development of lateral grabens and hanging blocks favouring deep penetration of the meteoritic water in the Precambrian basement (Figure 11).

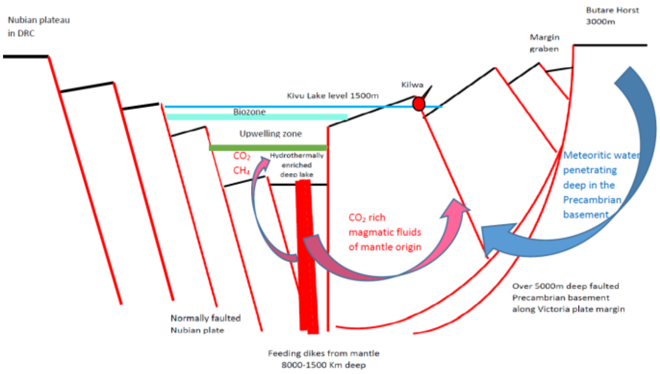


Figure 11 : Schematic E-W structural section at the level of Kilwa showing the two possible heat sources: a magmatic and hydrothermal convective system along rift axis of Kivu Lake driven by CO_2 rich gas of mantellic origin and normal gradient from Precambrian Victoria plate margin affected by faulting favouring deep water circulation of meteoritic origin and hydrothermal convection through normal gradient basement.

Given the penetrative character of the pegmatite veins at regional scale, the upper part of the granite plutons underlying the metamorphic units could reflect enhanced permeability conditions, rendering the granite to act as a regional reservoir. The ubiquitous, highly brecciated pegmatite veins facilitate fluid flow.

5.3. Source of Fluids and Reservoir(s) Recharge

Geochemical interpretation of the δ^2H and δ^{18}O values of H_2O rain ground water and thermal springs have shown that the source of parent geothermal liquid is a mixture of local meteoric water infiltrating from relatively high altitude and deeper magmatic fluids. The elevated Victoria plate border at Butare horst (above 3,000 m high), is with normal faults of N-S direction parallel to the rift axis offers channelling options for deep seated water circulations.

5.4.Temperature of the Geothermal Reservoir(s)

Data suggest that a deep geothermal reservoir hosting an intermediate-temperature liquid phase is present in the Kilwa area. The iso-chemical geothermometric mixing model demonstrates that the geothermal endmember hosted in a deep source at a temperature of 164°C, as indicated by convergence of the SiO_2 and Na/K geothermometers whereas H_2-Ar geothermometer is 156°C. The Powell and Cumming (2010) diagram of log (H_2/Ar) vs. log(CO_2/Ar) yields a conservative temperature of 160°C. It therefore follows that these temperatures are representative of the deep parts of the geothermal reservoir. Possible existence of a more deep seated reservoir with temperatures greater than 200°C should not be ruled out as reflected by the hydrocarbon geothermometer GDC/Géo2D, 2017).

Lower temperatures of a shallow reservoir with temperatures ≥ 100°C is indicated by the iso-chemical geothermometric convergence of the K-Mg and silica. This reservoir directly corresponds with the thermal emergences at Kilwa. The presence of appreciably high CO_2 fluxes at the hot spring areas is in good agreement with the presence of faults cutting the basement acting as conduit for the ascending fluids. Both are hosted by the fractured basement, the fractured pegmatites fracture zone developed east along the Kilwa fault.

5.5.Chemical Characteristics of the Deep Reservoir Liquid

According to the approach of the iso-chemical geothermometric mixing model, the deep reservoir liquid of Gisenyi is preferentially enriched in Na-HCO_3 components (Na = 1091 mg/kg, HCO_3 =1055 mg/kg) with a chloride content of 500 mg/kg, K = 54 mg/kg. The preferential enrichment of Gisenyi reservoir liquid with Na-HCO_3 suggest the involvement of magmatic fluids in its origin in addition to meteoric water, due to the strong prevalence of aqueous CO_2 which is in agreement with δ^2H and δ^{18}O values of H_2O and δ^{13}C values in CO_2.

Similarly, the surface discharge fluids also show a preponderance of Na-HCO_3, the source of which is mainly due to interaction of water with rocks, sustained by conversion of magmatic CO_2 to HCO_3. Geochemical modeling shows that Na-HCO_3 type water from Gisenyi hot springs and Lake Kivu are positioned along the same linear trend indicating that the progressive acquisition of HCO_3 is accompanied by a gradual gain of Cl and SO_4. This implies that the two hydro facies have similar mineralization processes with Gisenyi end member having high TIS (Total Ionic Salinity) values ≥ 20 meq/kg. The source of the solutes/salinity for the two end members is to be found in the basement and in the magmatic dikes of mantle origin respectively.

The gases accessible to sampling have CO_2 accounting for 66 ±26 mol% of the total gases, nitrogen represents the second major constituent, with concentrations up to 26 ± 20 mol% depending on the varying orders of magnitude of air contamination. The trilinear CO_2-H_2S-CH_4 modelling generally shows that the chemical composition of these gases is typical of travertine spring gases (it compares for instance with gas from Rungwe Volcanic Province in Tanzania.

The interpretation of the available δ^{13}C-CO_2 values, suggest that CO_2 is greatly supplied to the aqueous solution by deep sources, such as mantle degassing along Kivu rift axis. Isotopic signatures show large negative sign for δ^{13}C in CH_4 for the Kilwa samples that clearly demonstrates significant biogenic origin of CH_4. These deductions are in agreement with the source of CH_4 in Lake Kivu, which is generated through conversion of geogenic source of CO_2 through biological processes.

Albeit varying orders of magnitude of atmospheric air contamination, there is appreciable concentration of He in selected sample of gases from Kilwa. N_2-He-Ar trilinear diagram and ^{3}He/^{4}He ratios indicate that the source of helium may be a mixture between atmospheric helium and He generated from radioactive decay of U and Th radionuclides in the basement rocks.

5.6. Geometry of the Geothermal Reservoir

Geophysical investigations help to predict the depth and some part of the geometry of two areas at depth that can be interpreted as geothermal reservoirs. Resistivity methods provide a coherent picture that supports the existence of a shallow reservoir located in the 500 m wide area that is between the Kilwa fault and the main coastline. This depth cannot be fully constrained due to the limitation of the methods used.

Alternatively, the P_{CO2} of the Gisenyi reservoir liquid is 5.9 bar as indicated by the K-Ca P_{CO2}-indicator at 164°C. This gives an indication of the depth: calculation shows that 160°C would be reached at ~2 km; 200°C would be reached at ~3 km depth. The same calculation provides a depth of ~1 km for 100°C, but convection may allow to attain 100°C at shallower depth.

From the above findings, a model can be generated implying a shallow geothermal reservoir at 100°C and the deep reservoir develops at a temperature of ~160°C with deepest part at 200°C. The model (Figure 12) shows the hydrodynamics such as recharge regime, outflow and isotherms of the reservoir. A meteoric-water recharge derives from the high-elevation Butare horst, with infiltration taking place along the pervasively fractured Precambrian with circulation in the fractured and altered granite and pegmatites that underlie the metasediments at depth. Upward migration of fluids takes place along tectonically active faults and deep-seated fractures that limit the Kivu asymmetric graben to the east. As a whole, the model indicates the possible existence of a usable medium temperature geothermal resource (GDC/Géo2D, 2017).

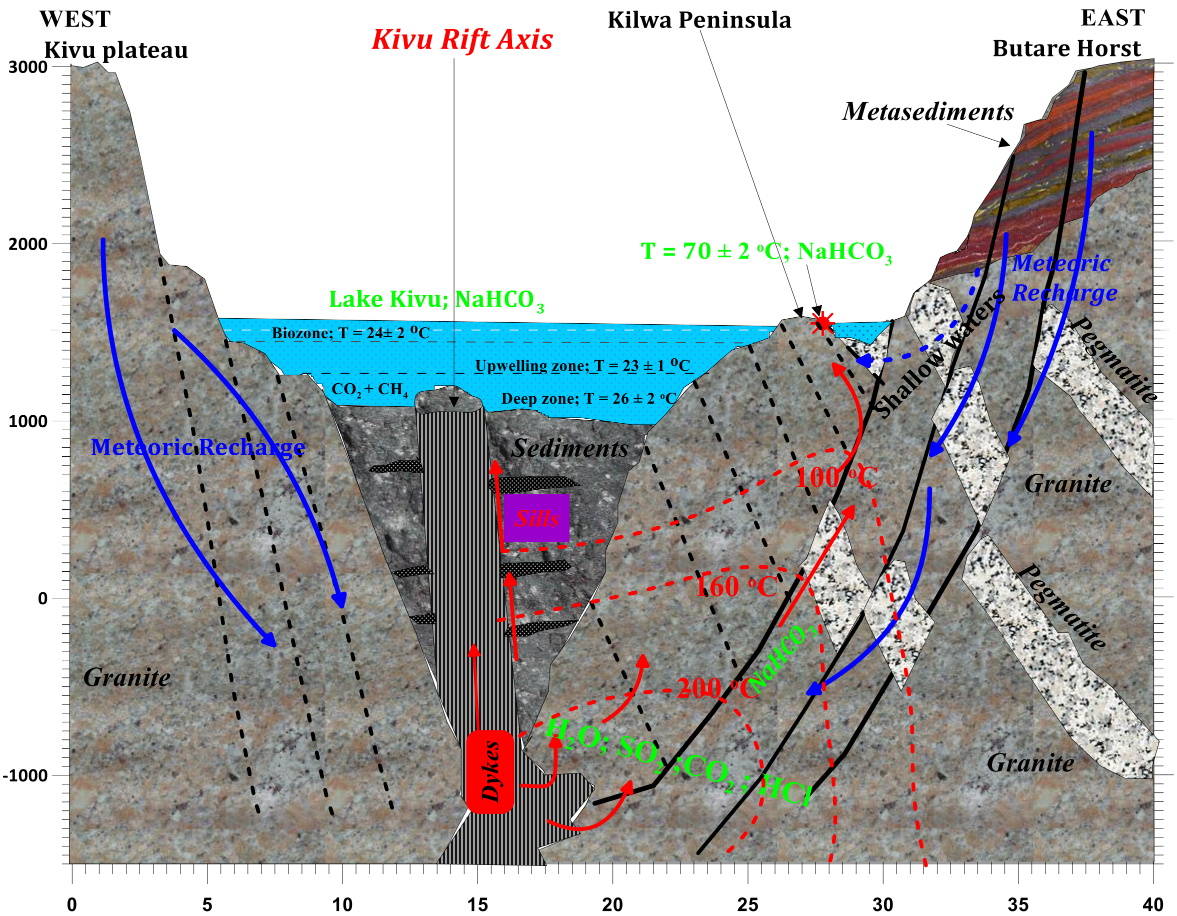


Figure 12: Conceptual geothermal model for Kilwa area (GDC/Géo2D, 2017), including the main source of meteoric water in the Butare horst (3,000m high); infiltration (blue arrows) along major faults and fractures in the basement limiting the Kivu graben to the East. Ascent of hot waters (red arrows) along pervasively brecciated pegmatite veins in the metamorphic basement; and migration of CO_2 (+ brine?) generated along the active axis of the Kivu Rift favouring the ascent of heated and gas lifted thermal fluids The vertical scale is in metres, the horizontal one in Km, the vertical exaggeration is circa 20. While a shallow reservoir at 100°C and 800 ±200 meters depth is expected to be found in the tombolo area within the V shape fractured pegmatites resulting of the crossing of the Kilwa fault with the main Butare horst fault, a deeper reservoir (2000 ± 300 m deep) at a temperature of 160°C (and eventually up to 200° at ~3000 ±300) is expected to extend to the west of the Kilwa fault underneath the peninsula.

The conceptual model supports the presence of a deep seated magmatic dyke along the Nyiragongo- Kivu Rift contributing to the hydrothermal system (fluids and heat contribution).

Conclusion

The next phase being engaged by EDCL is to complete the exploration with slim-hole wells that would confirm the conceptual model and the geothermal reservoir. Their location and characteristics will be precised with further surface complementary investigations:

- A MT survey allowing to precise the 3D geometry of the low resistivity zone(s) at depth providing the necessary precisions on the deeper part of the geothermal reservoir. It will require appropriate filtering techniques to get rid of the surface noise in the area (power generator and electric lines).
- A micro-seismic survey is also considered to delineate and monitor the active faults and permeable zones. Seismometers of high resolution are required to successfully achieve the target.
- A sub lacustrine survey should allow to map the extend of Kilwa fault and associated hydrothermal manifestations underneath the lake Kivu north and south of the peninsula. This should allow to quantify the geometry, structure, and extension (hence power) of the hydrothermal system.
- An environmental and social study will be engaged as required by national environmental and social laws. Considering that direct use applications will be encouraged given the medium enthalpy resources, a detailed study of the socio-economic demand (for applications like agro-industry and tourism/hydrotherapy) will be engaged. , in order to facilitate the implementation of the project to the next stage.

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