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

Geothermal resource along borders: The Rwanda-DRC case

Jacques Varet
SARL Géo2D, France
j.varet@geo2d.com

Key words: *geothermal resource, Lake Kivu, Nyiragongo, active rift, Rwanda DRC border*

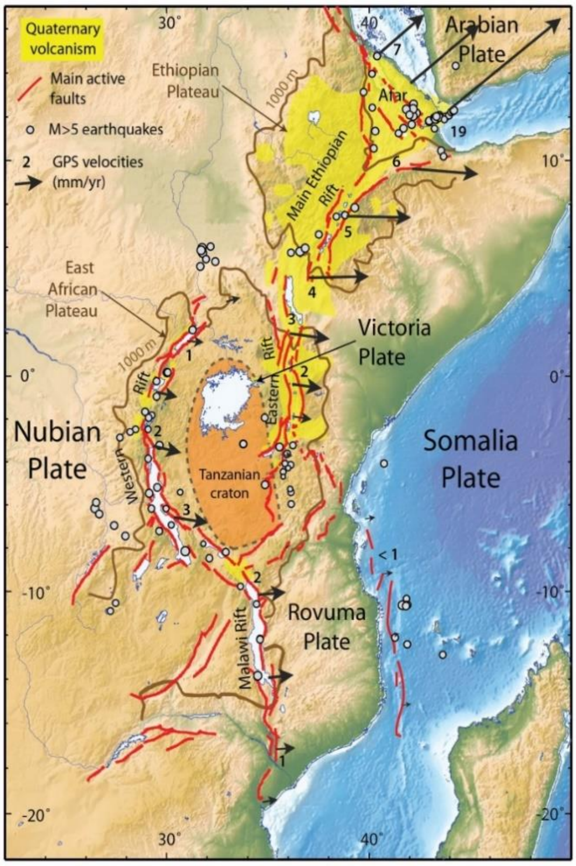
ABSTRACT

Boundaries may happen to develop along geographical features that then correspond to given geological structures. In the case of Rwanda and the Democratic Republic of Congo (DRC), the borderline fits the axis of the Lake Kivu, shared by the two countries, and extends onshore along the southern flank of Nyiragongo volcano in DRC. It happens that this is also the active axis of the Kivu Rift, along which a N-S trending fissure has opened at least twice historically, inducing injection of magma along a dike and some eruption of lava at the surface. Gas emissions are also known to occur along this axis, including CO_2 and CH_4 of mantle origin. It is also known that the stratification of Lake Kivu, with a more salty, higher temperature and gas-rich water at depth results from hydrothermal emissions at depth along the lake axis.

At present, the knowledge of geothermal resources in this promising area is limited to reconnaissance work and surface surveys engaged on both sides, but information regarding the most significant part of the geothermal system that is located along the borderline is still lacking. The engagement of a bilateral research project that would facilitate the filling of this information gap and help develop the understanding of the volcano-tectonic and hydrothermal context of the North Kivu Rift axis is therefore highly recommended. This approach would help promote the development of a joint geothermal resource exploration project including the identification of a heat source and a reservoir bearing fluids of economic interest. This paper argues about the attractive geothermal target of the area and describes the technical content of an exploration project to be engaged along this borderline.

1. The Western Rift: geological background and geothermal characteristics

The combination of Cenozoic up-doming and crustal deformation in the eastern sector of the African Plate associated with upper-mantle activity has produced an array of hyperthermal anomalies, volcanism, and local intrusions beneath the two >3000-km-long branches that constitute the East African Rift System (EARS). The Eastern Rift extends from the Red Sea and Gulf of Aden oceanic rifts in Afar (Eritrea, Ethiopia and Djibouti), to Northern Tanzania and traverses five countries in partly reactivated anisotropies of the late Proterozoic collisional Mozambique Belt. The Western Rift extends from Northern Uganda southward to Malawi through seven countries. Both rifts which separated in South Ethiopia meet again in South Tanzania (Hochstein, 2005). (See fig.1). From North to South, the EARS display a wide range of extensional tectonics and rift geometries. In the Main Ethiopian Rift, characteristics of the final stage of continental extension is observed up to seafloor spreading in Afar (where extension is mainly accommodated by dyke intrusions). Whereas in Mozambique, where normal faults drive crustal extension, nascent stages of continental extension is observed without volcanism.



Uplift, volcanism, and normal faulting in the EARS are hallmarks of one of the largest magmatic extensional provinces observed on Earth (Burke, 1996). The largely a-magmatic western branch contrast with the magmatically active eastern branch. Over 5000-km-long, the EARS has generated a series of transiently linked and isolated rift basins (Ebinger and Scholz, 2012). The extensive mantle anomaly that underlies the EARS (Simiyu and Keller, 1997; Ebinger and Sleep, 1998) explains the average elevations of +1000 m. Within this context of uplift, it formed a set of kinematically linked intracontinental rift basins whose development was initiated at least 30 Ma ago. Its evolution has been structurally controlled by extensional faults that have exploited rheologically weak rocks and pre-existing shear zones and foliations in the collision zone between the Archean Tanzania Craton and Proterozoic orogenic belts (Smith and Mosley, 1993).

Figure 1: The East African Rift system, with major fault systems, seismicity (M> 5), manifestations of Quaternary volcanism and plate-motion vectors with GPS velocities (mm/y) (Calais, 2016)

The Eastern Rift branch developed in Neoproterozoic orogenic belts (referred to as East African Orogen), whereas the Western Rift formed in Paleo- and Mesoproterozoic orogenic belts. As a consequence, the Western Rift is associated with thicker, stronger, and thermally less overprinted crust than the Eastern Rift. Demissie (2010) suggested that these different settings of the former orogenic belts were ultimately responsible for the different modes of upward transfer of mass and heat, determining the differences in the geothermal resources in both branches. The results of Begg et al. (2009) based on a continent-wide assessment of S-wave velocity in the uppermost 100-175 km of African lithosphere support this notion (Fig. 2).

A recent synopsis reveals a spatially disparate and diachronous evolution of Cenozoic rifting in East Africa, with clear differences in the onset of rifting in the western and eastern branches of the EARS (Torres Acosta et al., 2015). The timing and overall character of extension throughout East Africa likely reflects a large-scale, mantle-driven process. The uplift generated differential stresses and triggered the formation of rift basins in areas characterized by pronounced lithospheric and crustal-scale anisotropies and weakness. Variations in crustal strength and lithospheric thickness in both rift branches have been associated with differences in magmatic processes. In the western branch of the EARS the recent reactivation of the Virunga and Kivu volcanic provinces and the low rate of melt production and magma composition have been discussed in this context (Barberi, et al. 1982; Rogers et al. 1998). As confirmed by GPS velocities, the amount of extension is rather subdued in the western EARS (Bastow & Keir 2011, Calais, 2016). Overall, the plate-kinematic vectors in the region are oriented WNW-ESE (Sania et al., 2014), (Fig. 3).

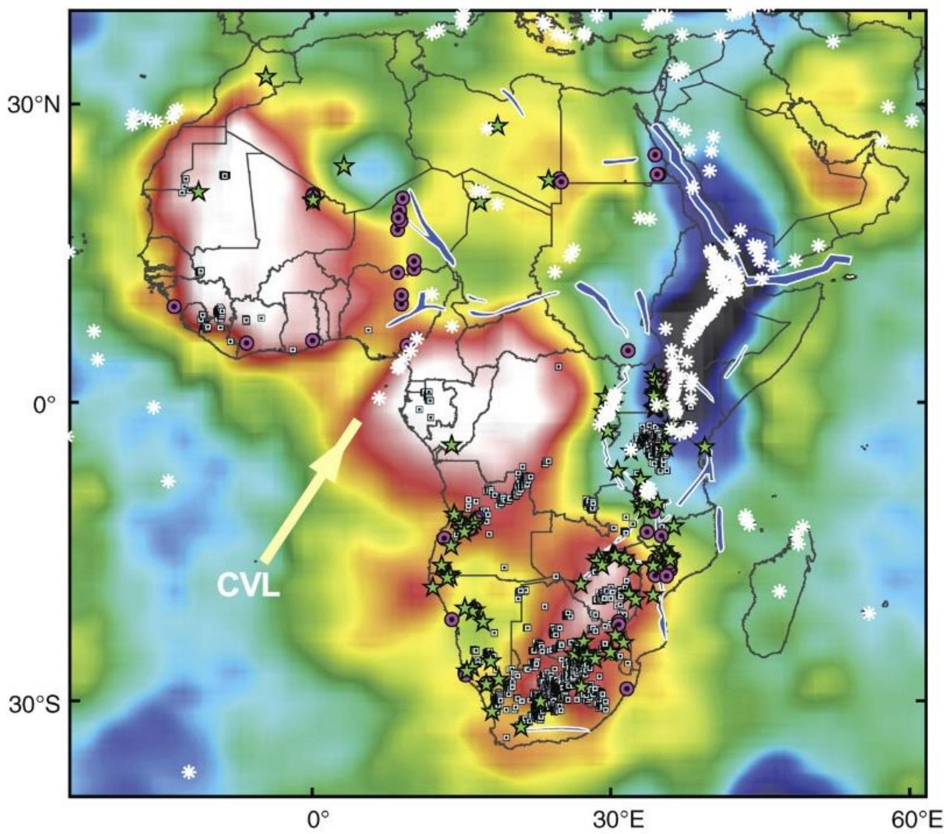
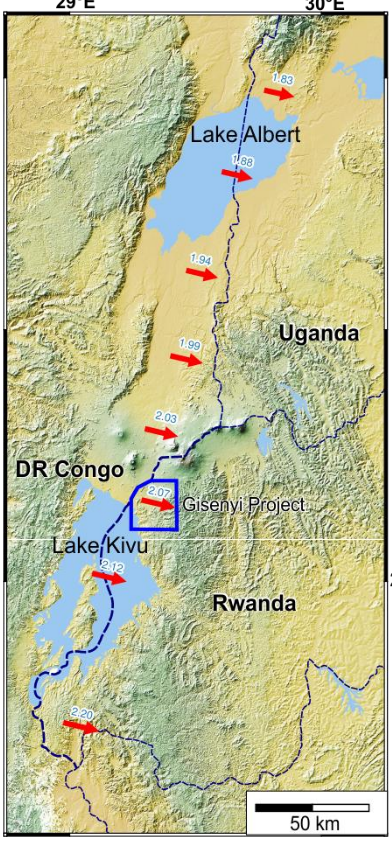


Figure 2: Distribution of low-volume melts (alkaline rocks, carbonatites, and kimberlites) and Mesozoic to Cenozoic rifts overprinting the velocity structure of cratonic blocks of Africa. Low velocities in blue to black, high velocities in red to white). Blue polygons = rifts; white asterisks = volcanoes; green stars = carbonatites; pink circles = nepheline syenites; white squares = kimberlites; CVL: Cameroon Volcanic Line. S-wave velocity (Vs) image is in the 100- to 175-km depth slice (from Begg et al. 2009).

There are pronounced differences between the two branches of the EARS concerning the level of crustal seismicity. Deprez et al. (2013) document a general trend toward increasing seismic activity in the EARS from north to south. This appears to reflect the style of extension. North, basaltic volcanism and dyke injections dominate the extension process in Afar (Barberi et al., 1972; Varet, 2018). Although at slower rates implying different magmatic evolutions (more alkalic, more abundant differentiated products), similar processes involving volcanism and dyke intrusions operate in the Ethiopian and Kenyan rifts where much of the present-day extension is accommodated by faulting rather than magmatic injection. This assessment is confirmed by the character of seismicity (Saemundsson, 2010). In contrast with the high-frequency/low-magnitude events in the Kenya Rift, seismicity levels of large magnitudes 6 to 7) and greater depths characterize the western branch. In general, seismicity in the Lake Kivu region and its northward transition into the Lake Albert area (Fig. 3) is closely associated with earthquakes along the western border faults and the volcano-tectonic axis in the west-central sector of the Kivu Basin (Fig. 4).

The differences between the Eastern Rift, linked with two domal uplifts, and the tectonically dominated, magmatically less active and sediment-filled Western Rift, regarding petrology and volcanology were emphasized by Barberi et al. (1982) (see Fig. 5). These authors showed that while transitional basalts associated with rather abundant peralkaline silicic products dominate the Ethiopian rift, alkali basalts associated with equally abundant sodic differentiates (peralkaline trachytes, rhyolites and phonolites) characterize the Kenya Rift. This differs from the western branch, where the rare mafic volcanics are K rich, rather undersaturated, and differentiates are the exception. These are thus very primitive, deeper mantle-derived rocks; they are also CO_2 rich, and associated with CO_2 and CH_4 emissions (Rosenthal et al., 2009).



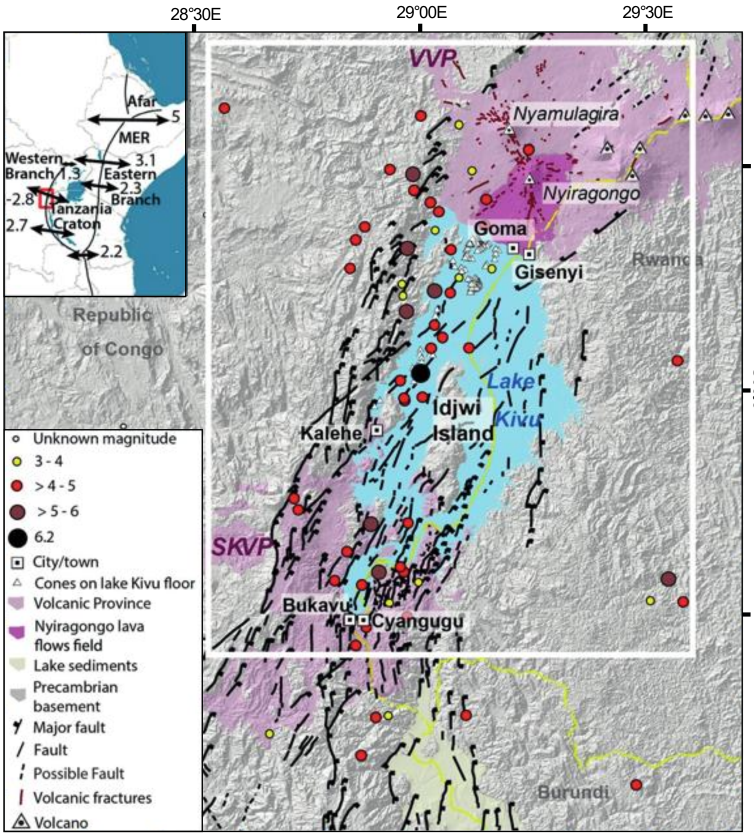


Figure 3 (Left): Plate-kinematic vectors for the Western Rift. Low rate of extension in a regional context characterizing the boundary between the Nubia and Victoria plates; in the Kivu area extension amounts to approximately 2.7mm/yr and active faulting is less developed (vectors calculated using Euler poles from Saria et al., 2014). Red arrows denote relative plate-slip vectors. Velocity in mm/yr.

Figure 4: Seismicity of Lake Kivu (in the period 1983-2009, from USGS), and volcano-structural data, showing the contrast between the active western (DRC) border and the rather aseismic eastern (Rwanda) shore (Wauthier et al., 2015). North of 2°, active seismic, tectonic and volcanic activity in Kivu Rift concentrated on the western side (DRC). The rift is an asymmetric half-graben-with the ealier faulted, deeply eroded Precambrian rocks of the Butare Horst on the Rwanda side gently dipping towards the lake in ist lower part, whereas the western side in DRC is characterized by active normal faults.

2. The northern Kivu Rift: a geothermal target

It appears that, in the western rift, the volcanically active part of the rift is in fact located in this Northern part of the Kivu Rift where 3 major volcanic units: Nyiragongo, Nyamuragira and Karisimbi are present. There relation with the active rift system is obvious but an in-depth study of this relation still needs to be engaged as it is a key to understand the characteristic of this geothermal province.
As shown by Chakrabarti et al. (2009) from an isotopic study of the lavas of the Virunga province, the origin of the magmas in Nyiragongo is particularly deep seated (up to 150 Km deep in the mantle), with limited differentiation or crustal influence (Fig.6).

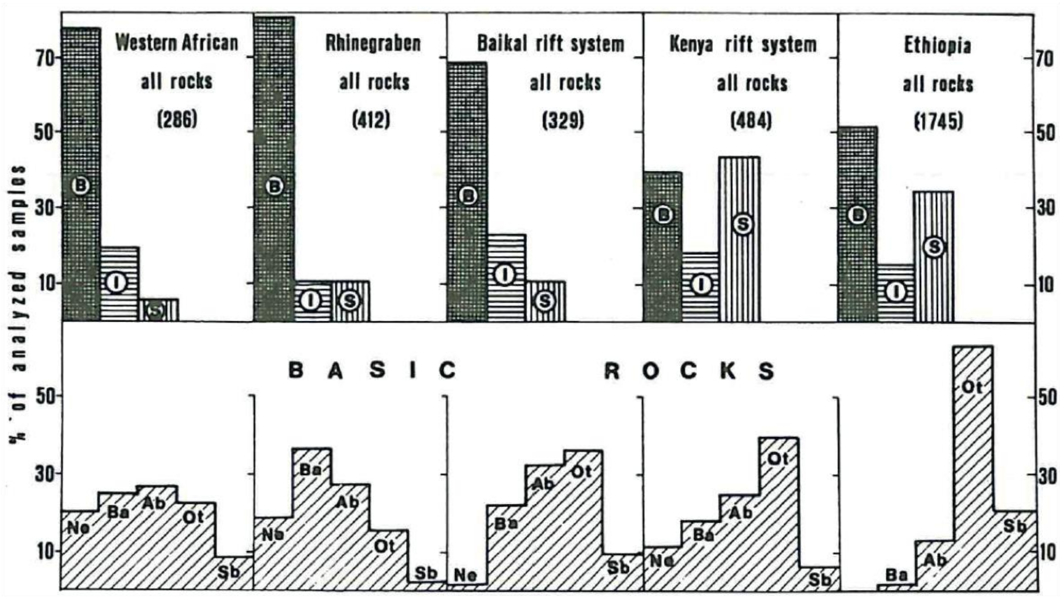


Figure 5: Comparison of the composition of volcanic rocks in 5 types of continental rift systems (West African rift, Rhinegraben rift, Baikal rift, Kenyan rift, Ethiopian rift including Afar): frequency histogram of available whole rock analysis. Plateau volcanics are included. In the upper figures, rocks are classified into basic (B), intermediate (I), and salic (S) according to an alkalies/silica plot. The lower figures refer to normative compositions, with nephelinites (Ne), basanites (Ba), alkali-basalts (Ab), olivine-tholeiites (Ot) and sub-alkaline basalts (Qz normative= Sb) (after Barberi, et al. **1982).**

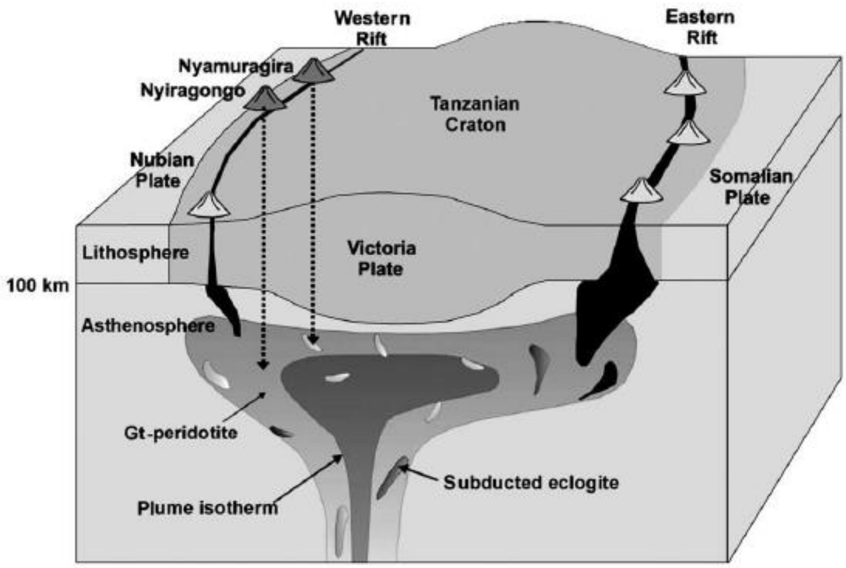


Figure 6: Diagram showing the model proposed by Chakrabarti et al. (2009) for the Virunga volcanics in the western rift, compared to the eastern rift. Nyiragongo lavas are shown to issue from 150 Km deep in the mantle without differentiation, whereas in the eastern rift, magma production and differentiation occur at much shallower depth in a thinned continental crust.

However, although limited, magmatic differentiation in magma chambers and interaction with the sialic crust may occur in the western branch; searching for it deserves further studies. Overall, the tectonic and magmatic evolution of the Kivu Rift area suggests a mechanically strong plate that has experienced limited thinning, with border faults penetrating the entire lower crust, consistent with the deep-seated seismicity. Our observations emphasize that the eastern margin results from important normal faulting having affected the Butare Horst at the early stage of rifting, with consequent downwarping forming hanging blocks at the foot of the major escarpment (Fig.7). The rift floor contains thin syn-rift volcanic and sedimentary fills, however associated with active diking along the rift axis north of Kivu Lake, as shown by the two recent volcano-tectonic events south of Nyiragongo (affecting Goma and Gisenyi townships along the Lake Kivu border, Fig.8). Geothermal surface manifestations are observed in various parts of the rift, but most commonly in form of warm or hot springs. Fumaroles are less common, with the noticeable exception of Virunga massif, the Nyiaragongo volcano, happily well followed by the Goma volcanological observatory and which needs to be better documented in view of a geothermal approach.

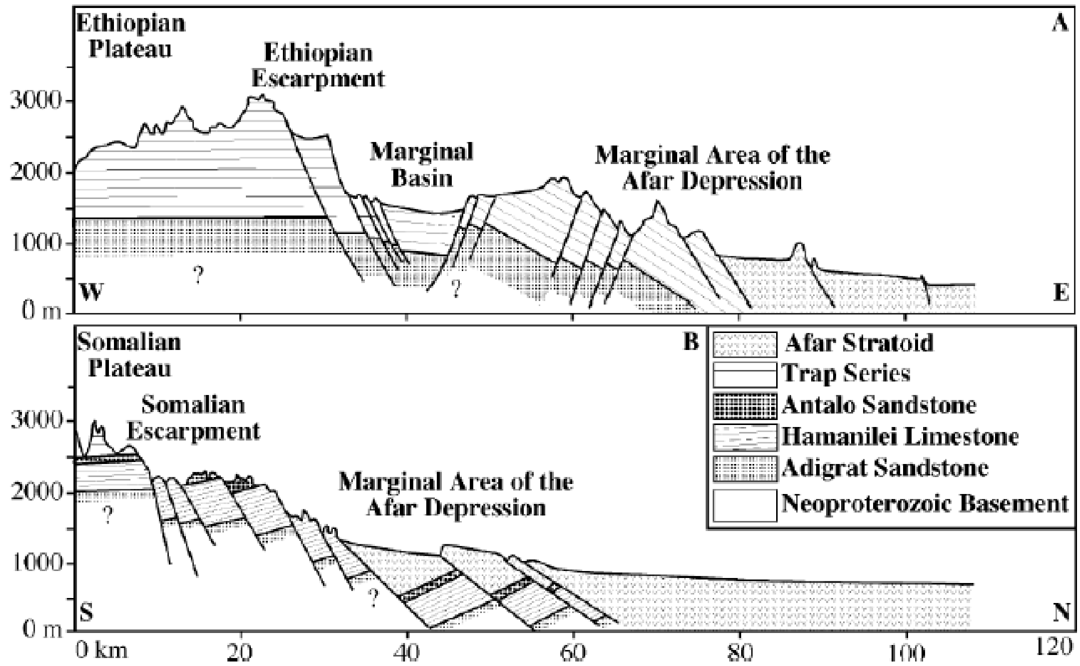


Figure 7: Stylized geological sections illustrating the two kinds of tectonics affecting the Eastern Rift at its early (i.e. Miocene) stage, along the Nubian (upper section) and Somalian escarpments (lower section), (from Beyene & Abdelsalam, 2005). Compared with the Kivu Rift, the upper figure (once reversed) is analogue to the Eastern Rwanda side, with marginal grabens observed along the escarpment of the Butare Horst and hanging blocks dipping towards the lake, whereas the lower figure is analogue to Western DRC side, and characterize most of the presently active system of the asymmetric Kivu Rift.

2.1 Looking for potential reservoir conditions in the basement rocks

The Lake Kivu region constitutes Precambrian metamorphic rocks intruded by granites. These rocks are found on both sides of the rift, uplifted at elevations spanning 1.465 m at Lake Kivu and more than 3.000 m in the Butare Horst in Rwanda, +500 m higher average elevation relative to the western rift side in eastern DRC (Fig.3) as a result of the East African mantle plume and associated tectonism that began impacting the region during the Tertiary. This higher elevation is attributed to crustal uplift over the thermal mantle anomaly. This uplift was followed by intense normal faulting at the early stage of rifting as observed from the numerous faults of NNW-SSE to N-S affecting the western side of the Butare Horst to the east of the project area. This resulted in the formation of hanging blocks along the foot of the escarpment in the downwrap area. Although less evident for geological observation than in the Eastern Rift where the basement is covered by sedimentary of volcanic strata (as shown in Fig.7), this major feature explains the present asymmetry of the Kivu rift, dominated in its presently active part by normal faulting with eastern dips, as observed on the DRC side (Fig. 4).

The formation of basement rocks commenced with the deposition of sediments and the emplacement of plutons between cratonic crust that had been evolving separately during the Archean (>2.5 Ga) through the accretion of granite-bearing rocks and greenstone belts resulting in the formation of mobile belts. Between 2.2 and 1.86 Ga this area was part of a supercontinent assembly during the Eburnean orogenic cycle. The supercontinent broke up during the post-orogenic Kibarian phase of crustal extension between 1.60 and 1.2 Ga. This resulted in a supercontinent assembly by the collision of continental blocks, culminating in the formation of the Panafrican orogenic belts straddling the margins of the Tanzania Craton.

The Kivu region is dominated by the “Zaire-Nile Crest” of the crystalline basement belonging to the Kibarian Orogen and comprises metasediments, metavolcanics, and granitic intrusions with younger granitic pegmatites. and abundant basic intrusions. All of these units have been heavily fractured by later orogenic and extensional processes. This fracturation allowed for the development of permeable formations, particularly in the pegmatites, providing potentially suitable conditions for geothermal reservoirs (GDC/Géo2D, 2017).

2.2 Structural control of the volcanic and thermal activity

The occurrence of volcanic centers, thermal springs, and associated normal faults in the Lake Kivu rift result from the effects of the extensive mantle anomaly underlying the East African dome region, at the place where the rift virgates from N-S (Kivu) to NE-SW (Albertine). The ages of the oldest Cenozoic volcanic and sedimentary suggest a south-westward propagation of rifting from the Albertine Rift (Fig. 3) at the Uganda-South Sudan border region toward Lake Kivu between about 16-12 Ma and 7 Ma (Mc Connel, 1972; Ebinger, 1989). The area is characterized by a complex set of Cenozoic structural features that include a N-S to NE-SW oriented graben system that host lakes Albert and Kivu (Figs. 3 & 4). Two other systems intersect the prospect area and determined the NE-SW trending volcanic axis Virunga – Kamatembe and the NW-SE-trending Bufumbira Bay - Karisimbi axis, both extending in the volcanically and seismically active volcanic districts of DRC. These fault-bounded areas are the site of geothermal manifestations, in the southern extremity of the Virunga volcanic province.

The Kivu rift appears as asymmetric:

1. Although well developed in the Butare Horst, the eastern fault scarp at the level of the Lake is topographically poorly expressed, lacking rectilinear shoreline (Fig. 8)
2. Bathymetric and seismic-reflection data indicate extensional block faulting on the western slope, a phenomenon not visible on the eastern DRC side (Fig. 9)
3. At the bottom of the Lake, the eastern basin has thicker sediments, than the western basin;
4. The seismic activity reveals frequent events along the western side of the lake and much less pronounced activity on the east (Fig. 4). Thermal activity also appears more developed.

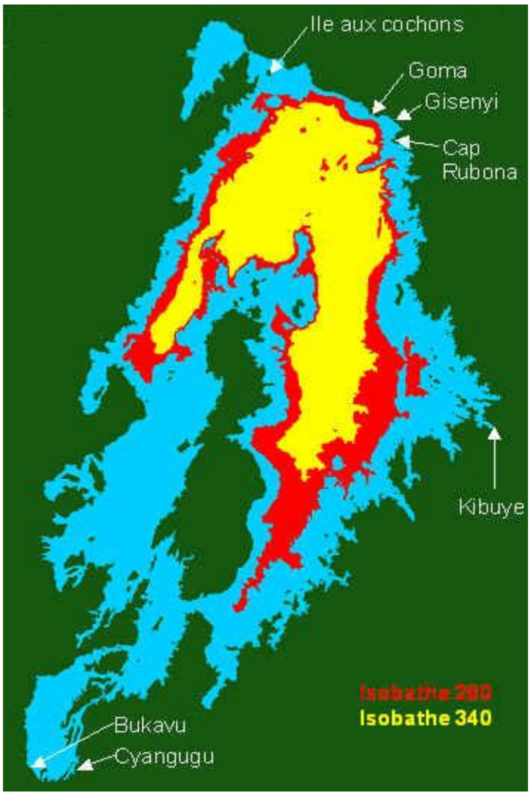
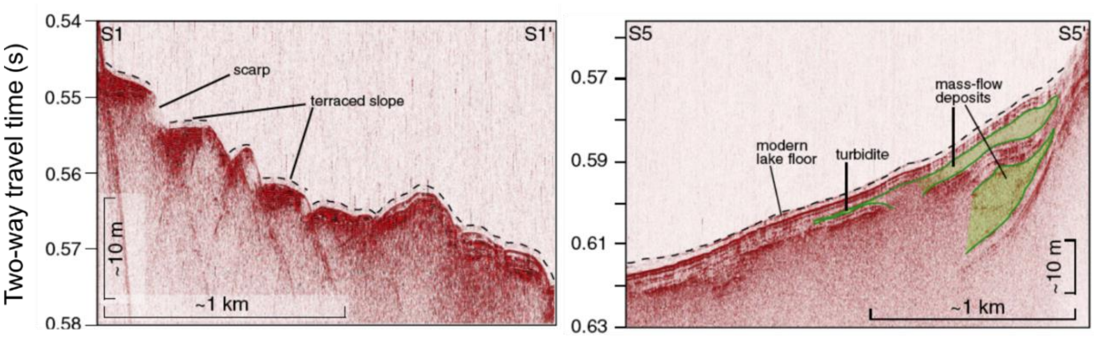


Figure 8: Bathymetry of Lake Kivu highlighting the contrast between the north-western basin, defined by NNE-SSW-striking faults, and the N-S-oriented eastern basin, which is delimited by less pronounced rectilinear, less faulted shorelines (from Lahmeyer and Osae, 1998) .

Figure 9 (below): Comparison of slopes along the western and eastern border of Lake Kivu as shown on seismic reflection profiles across the lake. Profile S5 does not reveal normal faults as observed on the western flank in profile S1, but thick sediments that include mass-flow deposits along a steep slope in the channels (from Ross et al. 2014)



2.3 Volcanological and hydrothermal context of the Kivu Lake

The youngest tectonic and volcanic features in the Lake Kivu area comprise Late Pleistocene and Holocene fault scarps, and numerous fissure systems, aligned eruptive centers and lava flows (Fig. 4) belonging to the Nyiragongo volcanic system. Bathymetric data from the northern end of Lake Kivu suggest that these manifestations - of Cenozoic and still active extensional processes - extend into the sub-lacustrine environment (Fig.10). At least one N-S dike and associated emissive fissure was active during the 1978 and 2002 volcanic eruptions that affected Goma (DRC) and Gisenyi (Rwanda), extending from Nyiragongo crater down to the Lake Kivu N-S axis. Volcanic activity has played an important role in the evolution of Lake Kivu. The cities of Goma (DRC) and Gisenyi located on the northern lakeshore are almost entirely built on Quaternary lava flows. The presence of phreatomagmatic cones along the shoreline, in particular the port of Goma, underscores the role of historic eruptive events at the lakeshore (Capaccioni et al., 2003). According to Habeeryan & Hecky (1987), Lake Kivu previously had an outflow to the north into Lake Edward, which was dammed by lavas of the Virunga province during the late Pliocene. 10 ky ago, the lake level rose, which finally caused a southward drainage reversal into Lake Tanganyika. At first sight it appears that the volcanic activity in the northern part of the Lake Kivu basin mainly developed on the western

(DRC) side. However, the 2002 eruption revealed the existence of an open fissure linking Nyiragongo volcano and the Kivu Lake rift axis, practically along the borderline, including the development emission of lava flows, magma injection along dikes, soil deformation, the formation of fumaroles and gas (CO_2 and CH_4) vents (Fig.11).

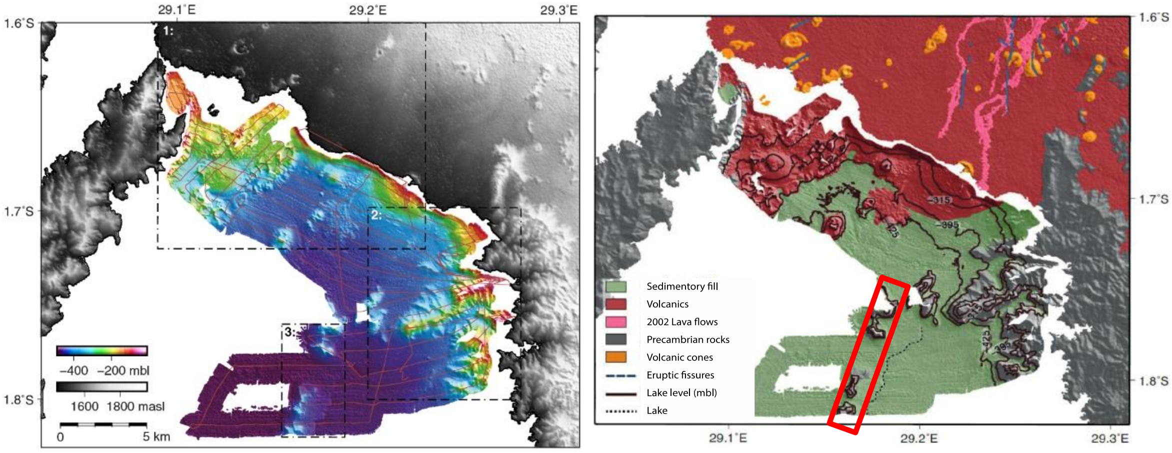


Figure 10: Detailed bathymetric survey (Ross et al., 2014) of the northern part of Lake Kivu showing the sub-lacustrine relief (left), and geological map of the same area (right). While, besides sediments, the Kivu rift floor appears to be affected by numerous volcanic manifestations in its northern part, volcanic centres aligned on a NNE fissure (dike). Underlined by the oblique red rectangle, this shows the active nature of the Kivu Rift axis.

Hydrothermal manifestations are known to occur on both sides of the lake, along normal faults bordering the graben, and even along the rift axis (see location on Fig.12). At least 3 thermal springs are known to occur along the western fault (Tingi, Sake and Kihira) and two along the rift axis (Musholosa and Kaputembo) in DRC (Muanza et al., 2015, Mahinda et al. 2016); and one on the Eastern side (Kilwa in Rwanda, GDC/géo22, 2017). Other thermal springs occur on the Lake Kivu floor, but their precise location and characteristics are still unknown. As shown by Zhang et al. (2009) if cold springs dominate in the upper 300 meters, hotter, saline springs are modelled at depths below -300m, with a total discharge of 0,15 km3/yr. Schmid et al. (2010) confirm this hypothesis, with the water column continuously warming between 2002 and 2007. Several "extreme hydrothermal events" are inferred from chemical fluctuations of the lake water; in particular at 5 and 1.0-0.8 ky BP, and perturbation of the thermohaline stratification at 0.6-0.4 ky was shown by Ross et al. (2014) to be linked to hydrothermal activity. The chemistry of the thermal springs shows a CO_2 rich composition consistent with the emanations CO_2 and CH_4 occurring in the deeper part of the lake. Their composition show a mantellic origin, but tectonics and magmatic controls of the geothermal reservoir feeding the surface hydrothermal manifestations need to be clarified. Geothermometres vary from 160 to 290°C.

2.4. A magmatic heat source: the Nyiragongo volcanic system

The Nyiragongo lava fields are characterized by a volcanic sequence highly enriched in potassium, with K-nepheline basanites, leucitite and melilite-bearing leucitites. Such a sequence is characteristic of a deep-seated origin (140 Km deep, Chakrabaty et al., 2009) related to a mantle source enriched in lithophile elements. The magmatic sequence underwent limited differentiation. These conditions do not indicate the existence of a shallow magmatic heat source. However, Nyiragongo is characterized by a permanent lava lake, and the nearby Nyiamuragira volcano also contains a periodically active lava lake, pointing to the existence of a shallow permanent magmatic heat source. In addition, Nyiragongo is associated with an active N-S-striking magmatic fissure along the axis of the Kivu-Nyiragongo Rift (Fig. 12).

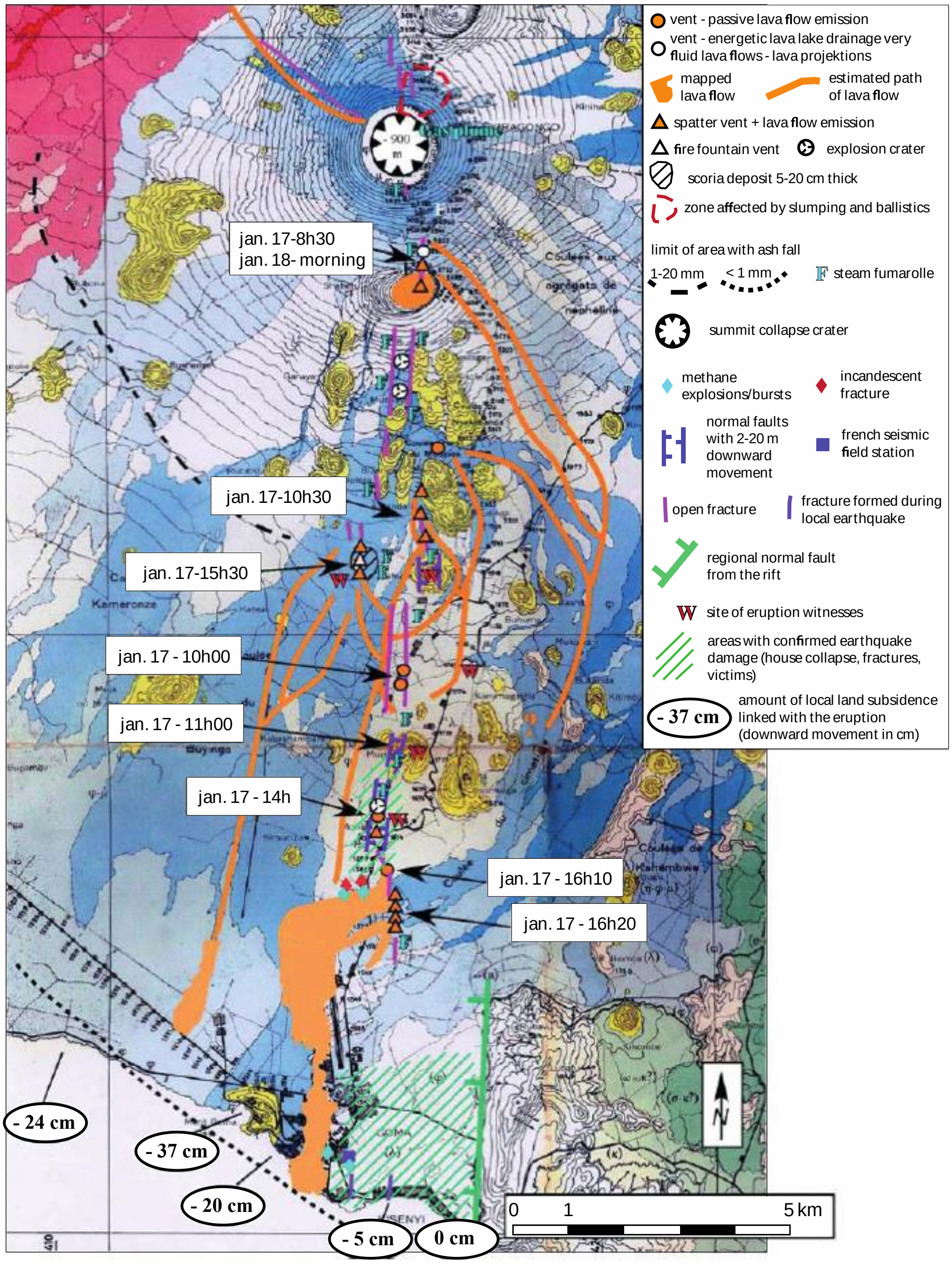


Figure 11: Synopsis of the 2002 eruptive Nyiragongo event showing the N-S fissure flank eruption and the extent of lava flows, the vertical deformation along the Lake Kivu shore, and the hydrothermal and gas-emission fissures that were active subsequent to the volcanic eruption. The 2002 event reveals an axial magmatic rift zone linking the Nyiragongo lava lake with the axis of the Kivu Rift. The same system was active during an eruptive episode in 1977.

Following the last eruption in 2002, new observations and measurements provided a better understanding of this region (Fig. 13), which involves the existence of a magmatic and hydrothermal system in the axial part of the Lake Kivu-Nyiragongo Rift. In terms of the regional geothermal potential the following aspects are noteworthy:

- volcanic eruptions and intrusions took place along a N-S-oriented axis extending from the crater to the lake;
- ground deformation with up to 37 cm vertical displacement was documented near the axis of eruption at lake level;
- fumarolic and gaseous emissions, including CO_2 and CH_4, followed the eruption;
- radar interferometry suggests diking operated at two different levels: in the volcanic edifice, from the crater to the southern flank, and a along a vertical zone extending southward from Nyiragongo to Lake Kivu at 8 to 2 Km depths (Fig. 12).

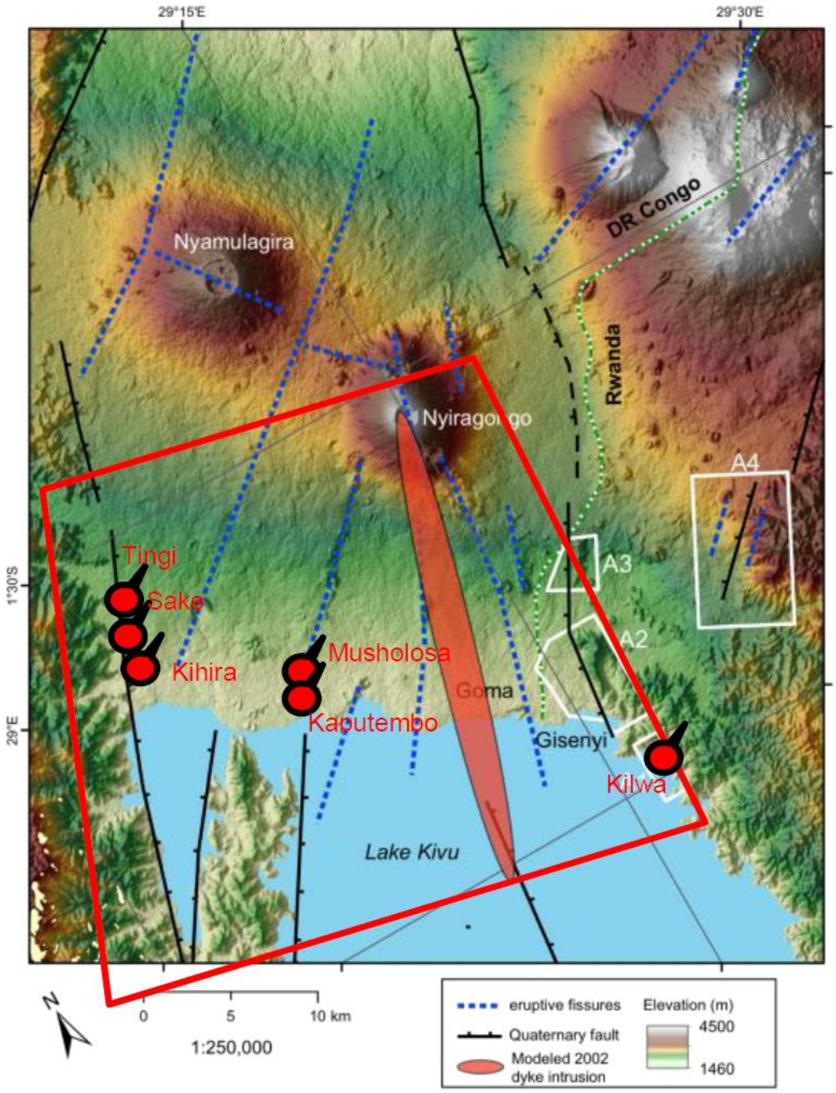


Figure 12: Topographic map (DEM model) showing the location of major faults and the 2002 dyke injection modelled to account for surface deformation based on radar interferometry (from Wauthier et al. 2015). Note the extent of the dike south of the volcano and its alignment with the axis of Lake Kivu at the latitude of the A1 hot springs (from GDC/Géo2D, 2017). A1 to A5 indicated the areas selected for detailed surveys during the geothermal exploration carried by EDCL in 2015-2017. Known hotsping occurrences are shown ( ). The red polygon indicate the limits of the area proposed for new geothermal investigations during the borderline survey proposed.

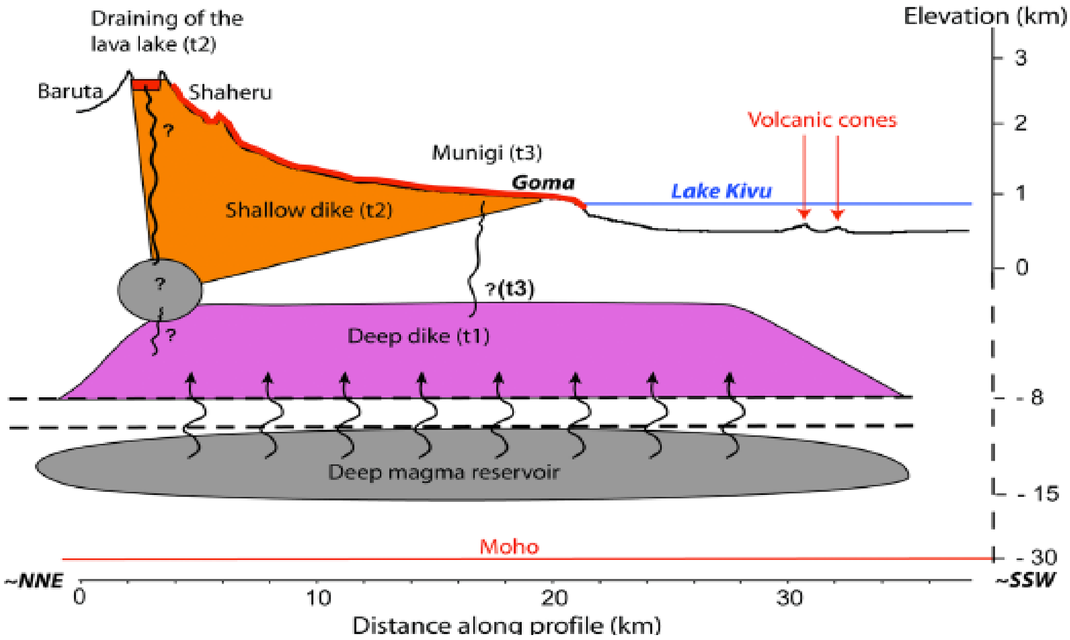


Figure 13: Modelling of two dykes to account for surface deformation based on radar interferometry (from Wauthier et al. 2015). Most probably, the deeding dike at 8 to 1 Km depth also connects to the surface manifestations along the shoreline and at lake bottom.

The 1-m-thick feeder dike is not large enough to be considered as a suitable heat source, but if the eruptive sequence is an integral part of a recurrent system, such events may indicate a persistent magmatic feeder of interest for geothermal considerations. In fact, another eruption, which occurred along the same fissure system in 1977 confirms that this is an active rift zone (Favalli et al., 2009). 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 along the borderline.

2.5. A potential geothermal target along the borderline

The data collected until now indicate that a geothermal system may have developed along the DRC-Rwanda border that would justify the engagement of a new ad-hoc exploration along the Nyarogongo-Kivu Lake axis that coincide with the limit between the two countries. Presently kept away from each country's investigation, this rather populated area mainly looked for the telluric risks may appear as of major economic interest for further power developments.

A preliminary conceptual model based on the presence of a deep seated magmatic dyke associated with the Nyiragongo- Kivu Rift, thus contributing to the hydrothermal system (convective fluids and heat contribution): this dyke thermally influences the sector of the Kivu Rift offshore and onshore and favors the development of geothermal reservoir in the deeply fractured environments. A panoramic view of the conceptual geothermal model of the Kivu Rift is provided in Fig. 14.

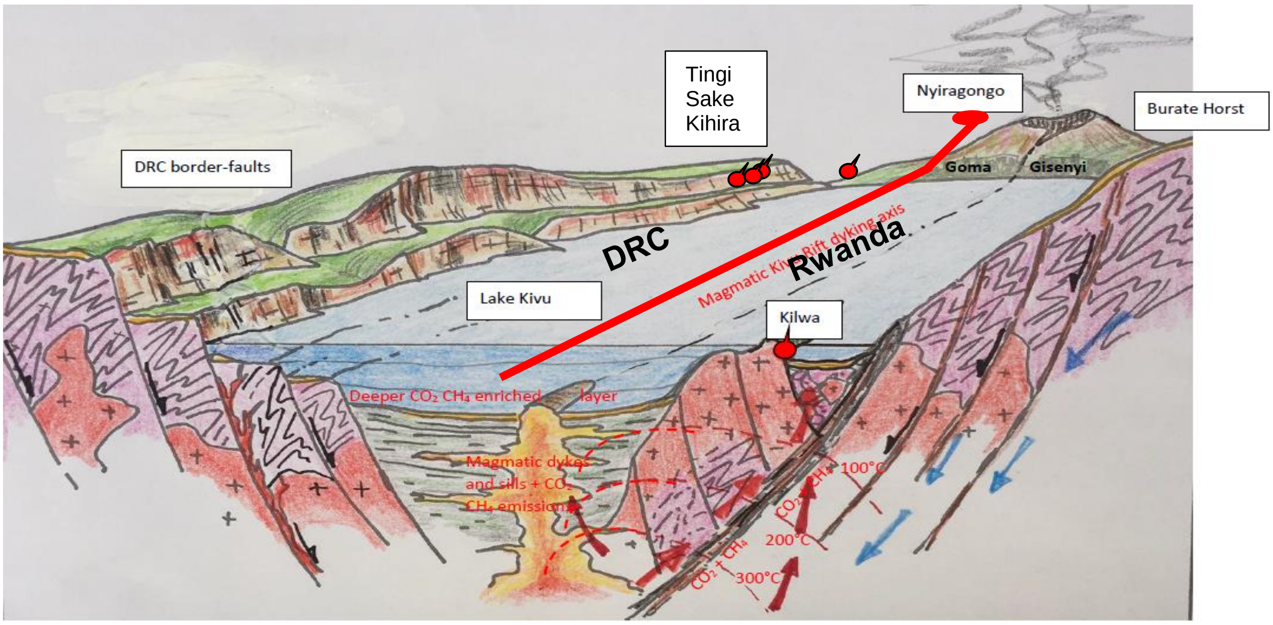


Figure 14: Block diagram showing the hypothetical Northern Kivu Rift geothermal conceptual model (drawing by Michel Villey in GDC/Géo2D, 2017, modified).

3. Conclusions and recommendations

Considering the geothermal potential of the area located along the DRC-Rwanda borderline, it is recommended to engage a regional project implying the public concerned institutions of both countries. The area to be investigated extends from the Nyiragongo summit crater down to the eastern and western shores of Lake Kivu. Age determinations of the successive volcanic events along this axis should be considered. Besides surface surveys onshore, the project should also include offshore studies, both along the faulted shore lines and along the N-S axis of the rift where the magmatic dike fed volcanic manifestations on the lake floor. Besides volcanic and tectonic studies, the survey should include mapping and analysis of all present and extinct thermal and gas surface manifestation, eventually with the help of an IR drone. Geophysical survey should include TM-MT survey, as well as gravimetry and micro-seismic studies.

4. Acknowledgments

The geoscientific data exposed in this paper are due to the work engaged with Manfred Strecker and Daniel Melnick under the GDC/Géo2D contract project: TCF IV-FED 2012/023-721. It also benefitted from exchanges with EDCL (Uwera Rutagarama in particular) and OGV-DRC (Celestin Mahinda Kasereka in particular) staff, and from the reviewer's comment (Peter Omenda). The author express warm thanks to all of them.

REFERENCES

Barberi, F., Santacroce, R., & Varet, J. "Chemical Aspects of Rift Magmatism". *In. G.Palmason (Editor). Continental and Oceanic Rifts. Geodynamics* (1982) 8, p. 223-258

Begg, G.C., et al. "The lithospheric architecture of Africa: Seismic tomography, mantle petrology, and tectonic evolution". *Geosphere*. (2009) 5-1, p. 23–50

Burke, K. “The African plate” *South African Journal of Geology* (1996), *99*(4),p. 341-409.

Déprez A., Doubre, C., Masson, F., Ulrich, P. “Seismic and aseismic deformation along the East African Rift System from a reanalysis of the GPS velocity field of Africa”. *Geophysical Journal International, Oxford University Press*, (2013) - 193 (3), p.1353 - 1369.

Demissie G., “Mantle Influence, Rifting and Magmatism in the East African Rift System (EARS): A Regional View of the Controls on Hydrothermal Activity”. *Proceedings World Geothermal Congress 2010 Bali, Indonesia*. (2010).

Ebinger, C., and Scholz C. A. “Continental Rift Basins: The East African Perspective”, in *Tectonics of Sedimentary Basins, John Wiley & Sons, Ltd*. p. 183-208, (2012).

Ebinger, C. J., and Sleep N. H. “Cenozoic magmatism throughout east Africa resulting from impact of a single plume”, *Nature,* (1998), *395*-6704, p.788-791.

Ebinger, C. J., T. Yemane, Harding, D. J. Tesfaye, S. Kelley S., and Rex D. C. “Rift deflection, migration, and propagation: Linkage of the Ethiopian and Eastern rifts, Africa”, *Geological Society of America Bulletin* (2000), 112-2, p.163-176.

Ebinger, C., Yemane, T., WoldeGabriel, G., Aronson, J. & Walter, R., “Eocene-recent volcanism and faulting in the southern Main Ethiopian rift”, *Geol. Soc. Lond*. (1993). 150, p. 99–108.

Favalli, M., G. Chirico, D. Papale, P. Pareschi, M. T. and Boschi, E. “Lava flow hazard at Nyiragongo volcano, DRC” *Bulletin of volcanology* (2009), *71*, p.363-374.

Hochstein, M.P., “Heat Transfer by Hydrothermal Systems in the East African Rifts”, *Proceedings of the World Geothermal Congress, Antalya, Turkey* (2005).

Mahinda K, Yalire M, Kavuke J., Nkokori N2 and Simpeze J. “Management and development issues of geothermal energy in the western branch of the frican rift system: case of the Democratic Republic of Congo”. *Proceedings, 6th African Rift Geothermal Conference Addis Ababa, Ethiopia,* (2016).

Muanza P.M. “Presentation of Geothermal Potential and the Status of Exploration in Democratic Republic of Congo”. *Proceedings World Geothermal Congress 2015. Melbourne, Australia,* (2015)

Mambo V. S., Mahinda, K., Mapendano, Y. and Mifundu. W. “Geochemical study of thermal springs in Eastern D.R. Congo”

Ross, K. A., Smets, B., De Batist, M., Hilbe, M., Schmid, M. and Anselmetti, F. S. “Lake-level rise in the late Pleistocene and active subaquatic volcanism since the Holocene in Lake Kivu, East African Rift”, *Geomorphology* (2014), 221, p.274-285.

Simiyu, S. M., and Keller G. R. “An integrated analysis of lithospheric structure across the East African plateau based on gravity anomalies and recent seismic studies”, *Tectonophysics,* (1997), *278*(1–4), p.291-313.

Wauthier, C., Cayol, V., Kervyn, F. and d'Oreye N. “Magma sources involved in the 2002 Nyiragongo eruption, as inferred from an InSAR analysis”, *Journal of Geophysical Research: Solid Earth,* (2012), *117*(B5).