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# Geophysical Exploration for Geothermal Resources: Rwanda's Experience

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## ABSTRACT

Karisimbi Volcano is located at the junction between three countries: Rwanda, Uganda and Democratic Republic of Congo. Karisimbi is one of the volcanoes making a series of geological features connected to the western African Rifting system; perpendicular to it by an accommodation zone whose geothermal manifestations come to surface. Geophysical methods used to survey the three prospects consisted of Transient Electromagnetic (TEM), Magnetotelluric (MT) and Micro-seismic study. This work discusses challenges encountered all along the surveys and solutions brought to them. The quality of data was evidence that these methods suit the surveys in North Western Rwanda Geothermal prospects. Geothermal Exploration started in Rwanda in 1982. The French bureau of geology and mines started the survey but the scope of work was limited to reconnaissance studies. In 2006, when Geothermal Energy Exploration in Rwanda became a priority for the Government; intensive geophysical survey began. The Germany Bureau of Geosciences (BGR) started the works in North-Western Rwanda with the sub-contract of KenGen (Kenya Electricity Generating Company). The first results of the survey sparked the geothermal resource exploration in Rwanda. Two more surveys followed with the aim of narrowing the area of geothermal resources and delineate them to a reduced area. Transient Electromagnetic (TEM) and Magnetotelluric (TM) among other geophysical direct methods (Heat flow) were used. The results are presented and discussed throughout this work. The final phase of Exploration was conducted by New Zealand Institute of Earth Science and Engineering (IESE). During that work, existing geophysics data were gathered and a desk top study was carried out to refine the existing reservoir conceptual model with the new data. The results were used to evaluate the heat source size, depth to the reservoir.

## 1. INTRODUCTION

Rwanda has today about 120 MWe of installed capacity. About 17% of households are connected to the grid and the demand for new connections is continuously increasing. The Government of Rwanda, through Ministry of Infrastructure and EWSA (Energy Water and Sanitation Authority) have been working tirelessly to increase the generation capacity by looking at new alternative ways to diversify sources of electricity. Geothermal potential that Rwanda is endowed along the Western branch of East-African Rift system came in first place among priorities. It presents a number of advantages in terms of Global Climate Change, technology and economy. Geothermal energy is a clean and reliable source of energy, which is not affected by short-term fluctuations in the weather or world producer prices of oil. The geothermal technology is well known and well developed and the risk is only limited to proving the resource size by drilling. Geophysical Exploration methods have been used to explore geothermal fields and giving more information that could not be obtained with other methods. This paper discusses methodology of geophysical exploration techniques and gives details and updates of geophysical survey in Rwanda for Geothermal Energy resources. It highlights challenges encountered and solutions.

## 2. GEOLOGIC SETTING

The Karisimbi, Kinigi and Gisenyi geothermal prospects are located at the Western branch of the East Africa Rift System (EARS) commonly referred to as the Albertine Rift (Figure 2). This region is considered a developing divergent, tectonic plate boundary. It divides the African Plate into two new plates, namely Nubian and Somalian subplates (Foley, 2005). The Western Rift hosts the higher volcanoes in altitude in Africa and contains deep rift valley lakes. They were formed as a result of the rifting.

The volcanic activity in the western branch commenced about 12 million years ago (Ebinger, 1989). The western branch is characterised by the abundance of potassic alkaline rocks that consists of K-basanites, leucites, nephelinites, K-mugeartes, K-benmoreiites and K-trachytes and other intermediate lavas in the Virunga area (Denaeyer, 1968). The nephelinites are deficient in silica. (Irabaruta et al, 2010). The volcanic cover which is estimated to be about 1 km overlies the Proterozoic metamorphic rocks that include granites, phyllites, orthoquartzites, metaquartzites and pegmatives (Demant; 1994). The deeper geothermal reservoirs are therefore expected to be within the metamorphic basement.

The major structures are in the NW-NE directions (Figure 3) associated with pre-rift, Proterozoic basement structures. The NE fault pattern is younger and is associated with the western rift (BGR, 2009). Another important structure includes the inferred NE trending accommodation fault zone which marks the boundary between the Proterozoic basement formation and the quaternary volcanic belt of the western rift. It is inferred that the NE structural patterns are also buried below the young volcanic rocks in the rift and the volcanic zone.

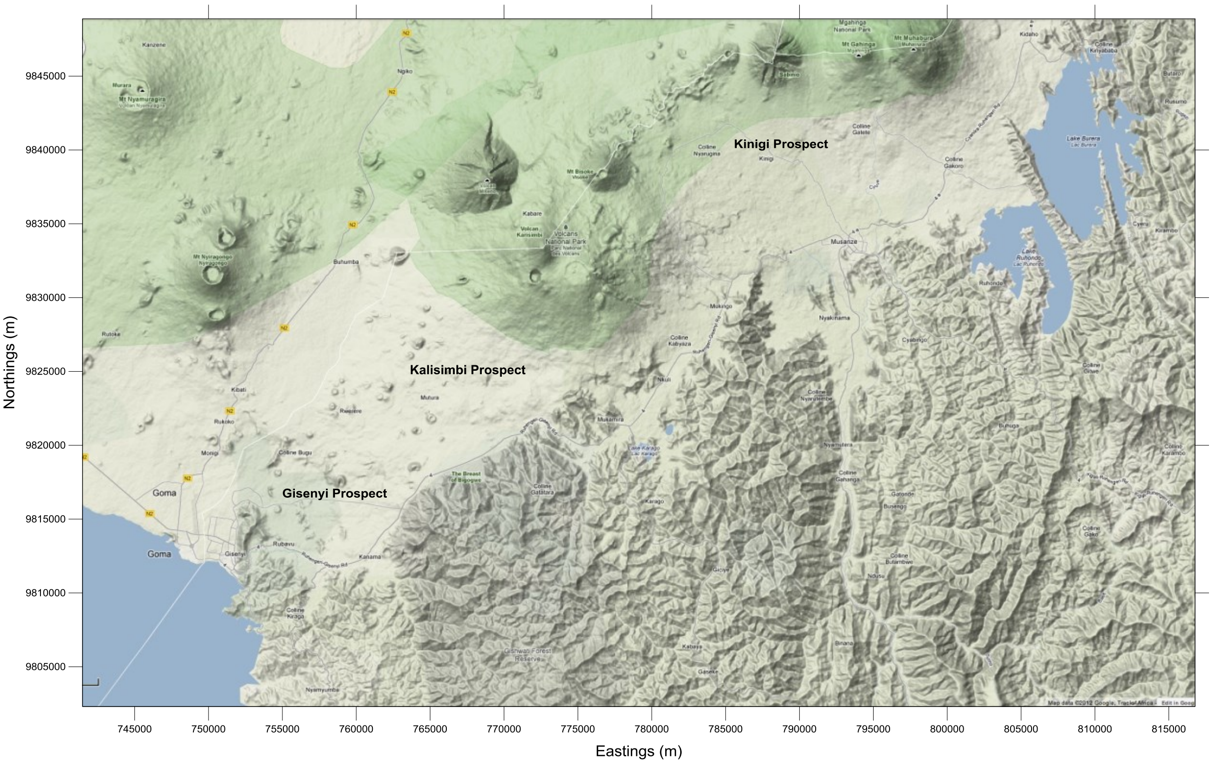


**Figure 1: Study area in North-Western Rwanda. (IESE 2012)**

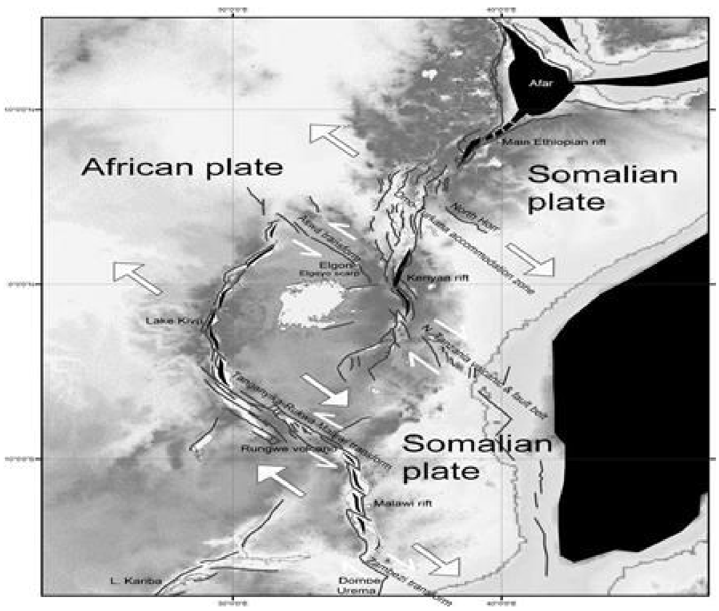


**Figure 2: African Plate into two plates African and Somalian (Foley, 2005)**

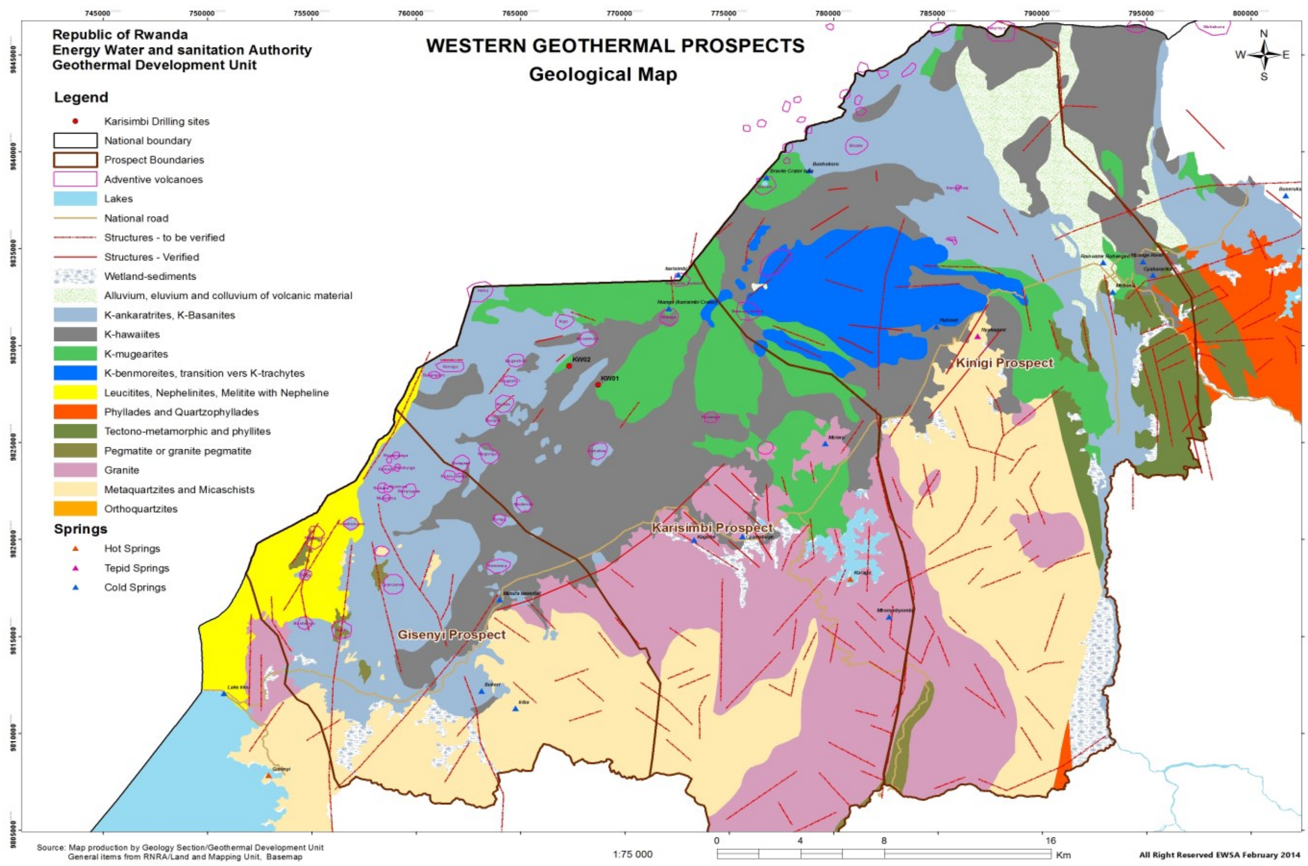


**Figure 3: Geology map of Kalisimbi, Gisenyi and Kinigi Geothermal Prospect**

## 3. METHODOLOGY

### 3.1.1. MT & TEM data acquisition surveys, data processing.

A total of 160 MT soundings were deployed in the Karisimbi, Kinigi and Gisenyi geothermal prospect areas (Figure 3). For these surveys, Phoenix's MTU-5A systems were used to record data from 400Hz 1000 seconds. Time-Domain TEM soundings (using In-loop arrays) were also carried out in these prospects using 200m x 200m source loops. The TDEM measurements were done at the same sites as the Magnetotelluric (MT) soundings using a Phoenix Geophysics TDEM system. MT and TEM ssoundings acquired by KenGen during the 2008 and 2009 field campaign were incorporated too.

### 3.1.4. MT & TEM processing and analysis

Using the program SSMT2000 (Phoenix Geophysics), the recorded time series were transformed into the frequency domain to determine the impedance tensor to be used in deriving apparent resistivity and phases at each site. The discrete Fourier Transforms (DFTs) were then reprocessed into cross powers. The cross powers stored in Plot files were edited using the MT Editor program and later converted to industry-standard EDI format for use with WinGLink geophysical interpretation software and WSINV3DMT-VTF-mpi (Siripunvaraporn, 2009) inversion code. TEM data (averaged stacks from TEM raw data) collected on same locations as the MT site were also exported to WinGLink program and 1-D MT equivalent models generated and used for static shift corrections.

The WinGLink program was used for 1-D and 2-D inversion of the MT data. Most of the soundings showed significant 3-D effects and only the 1-D and 2D models were used for interpretation in previous surveys. This conducted to a serious problem of missing out the changes in resistivity patterns in 3 dimensions. As results, the last survey took the issue into consideration and used a 3D code to reprocess the data.

3D inversions for the 3 prospects were based on 24 data periods over 3 decades. 8 complex impedances (real and imaginary) Zxx, Zxy, Zyx and Zyy, at 24 logarithmically spaced periods between 0.0044 and 90.901 seconds, were inverted. Adjustment was made to avoid noise contamination at the nominal 50 Hz mains frequency. 74 MT soundings were inverted for the Karisimbi prospect. The model contained 50, 70 and 50 500m blocks of in the x, y and z directions respectively. 56 MT soundings were inverted for the Gisenyi model. The model contained 40, 70 and 50 500m blocks in the x, y and z directions respectively. For the Kinigi model data from 59 MT soundings were inverted. The model contains 60, 60 and 31 500m blocks in the x, y and z directions respectively.

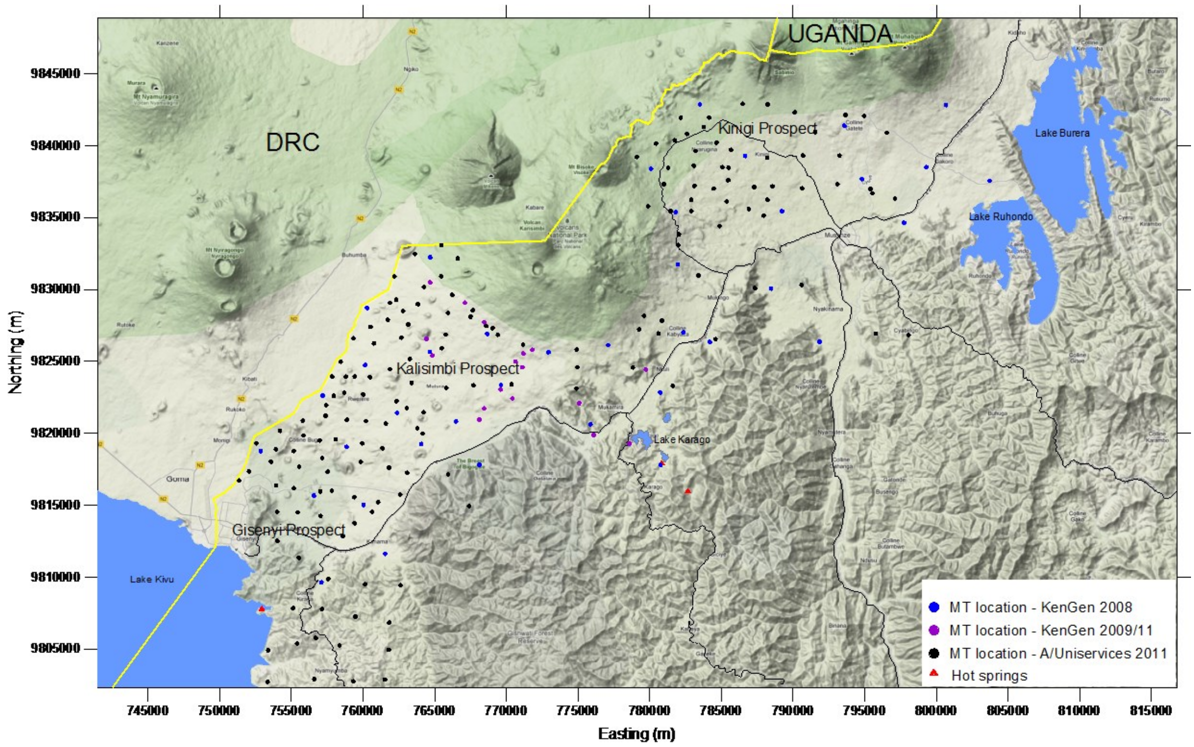


**Figure 3: Locations of MT and TEM in the Kalisimbi, Kinigi and Gisenyi prospect areas**

### 3.1.5. MT Results

<u>3.1.5.1 Karisimbi</u>

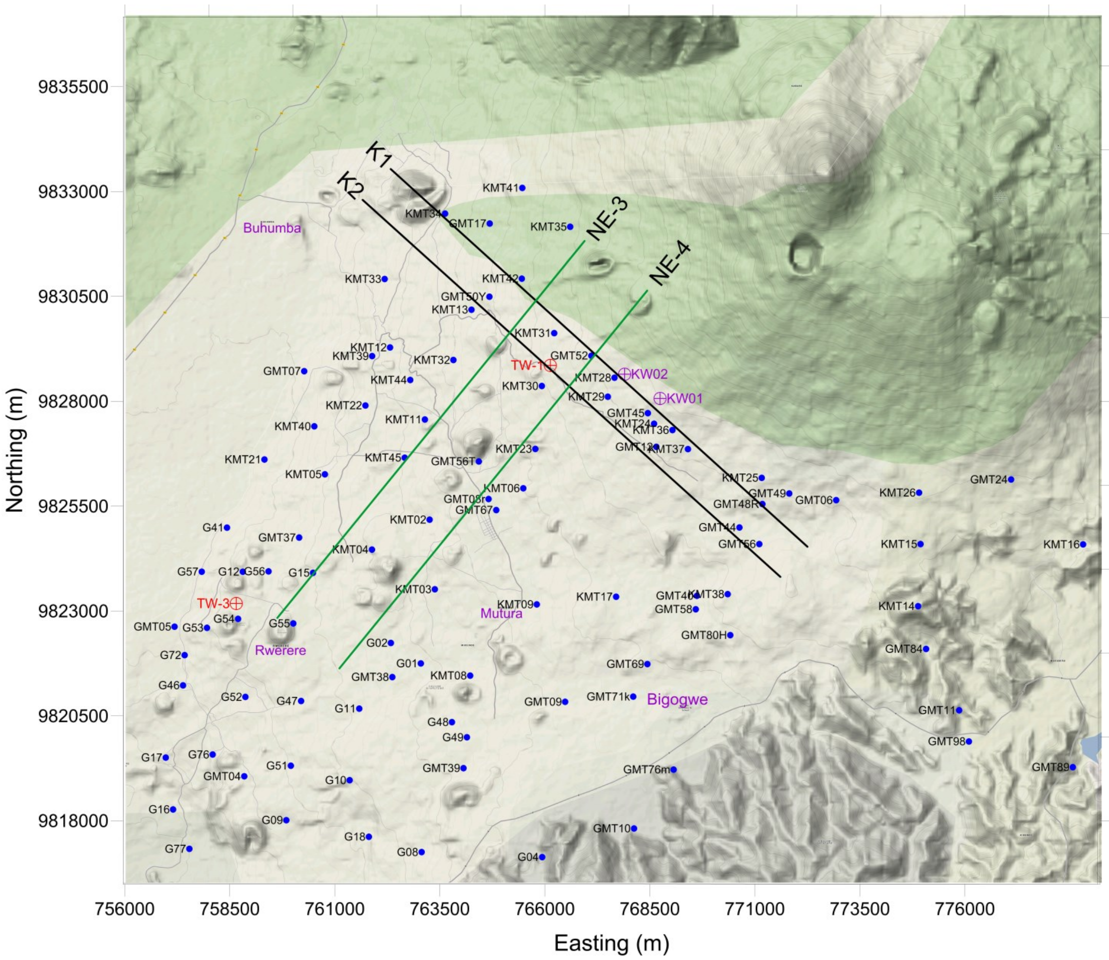


**Figure 4: Map showing sites of MT stations and location of interpreted 2D and 3D MT resistivity sections (Karisimbi sector)**

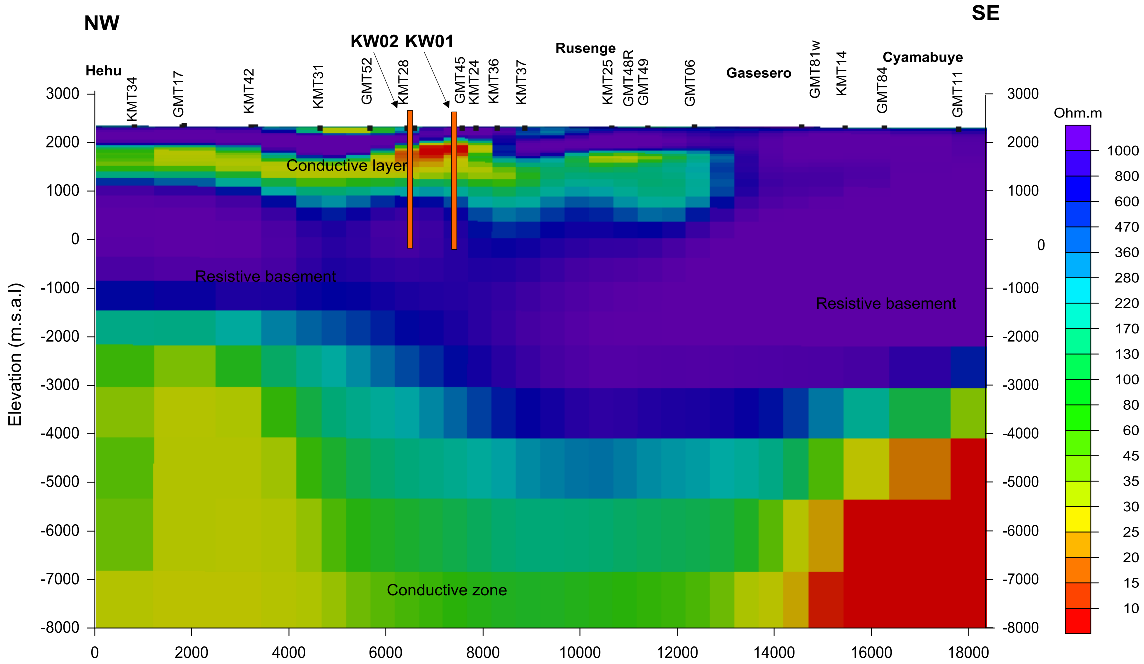


**Figure 5: 3D- resistivity cross section (IESE-UniServices) along profile K1**

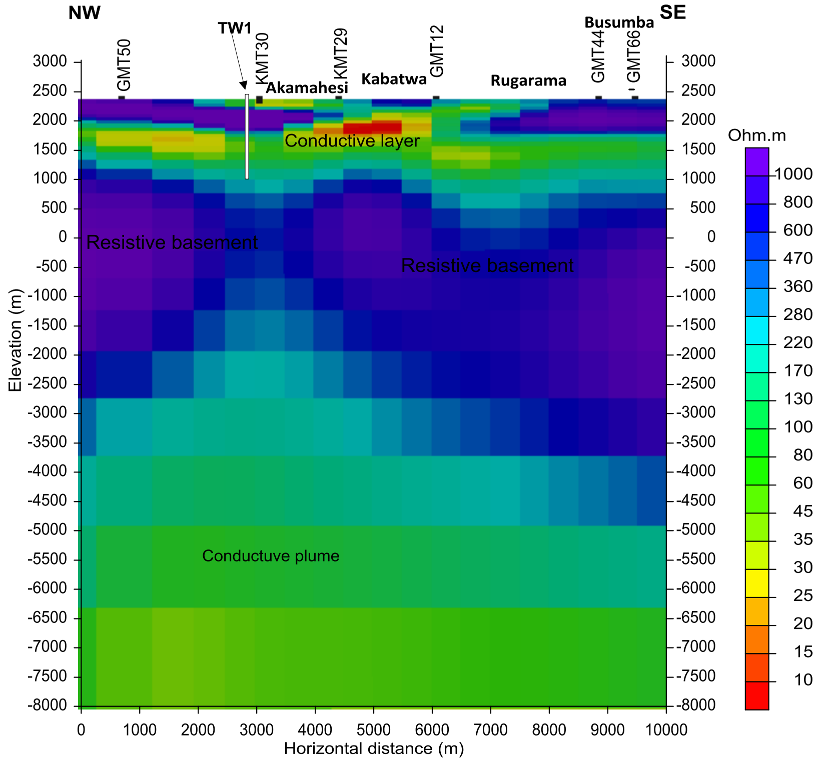


**Figure 6: 3D- resistivity cross section (IESE-UniServices) along profile K2**

3.1.5.2 Kinigi

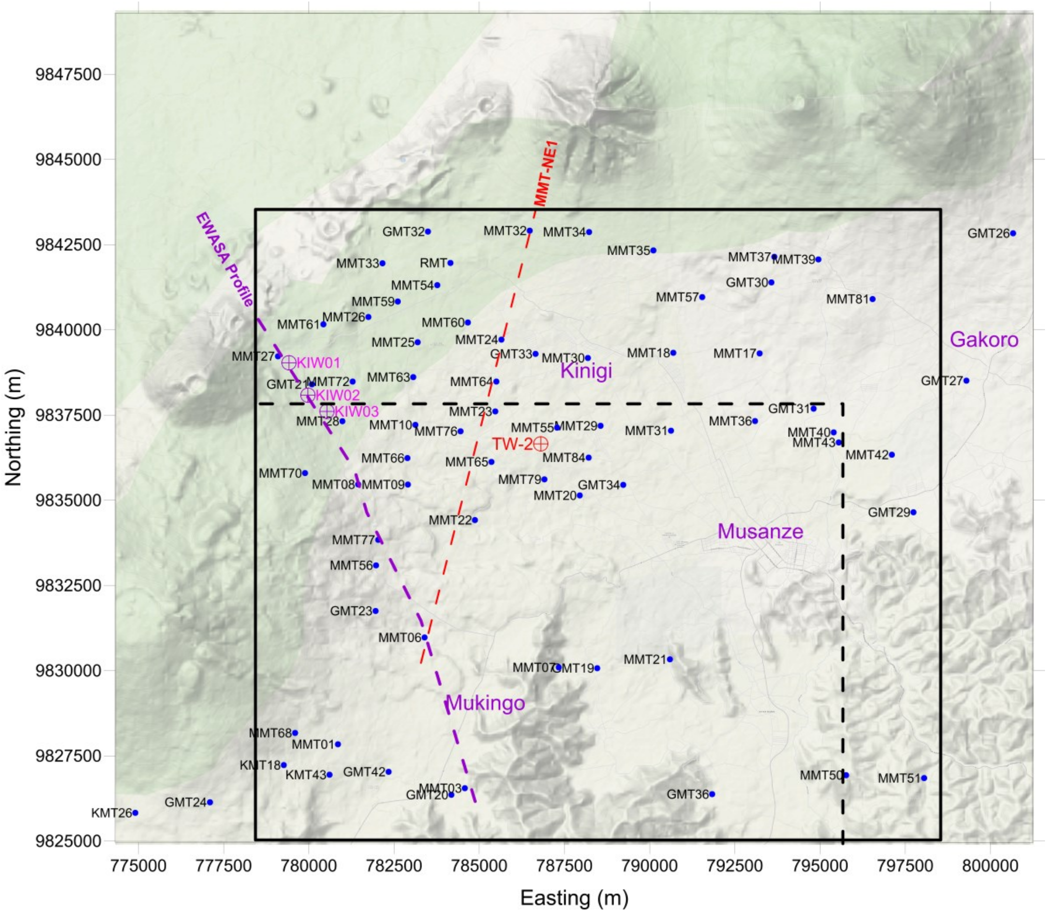


**Fig. 7: Map showing sites of MT stations and location of interpreted 2D and 3D MT resistivity sections (Kinigi sector)**

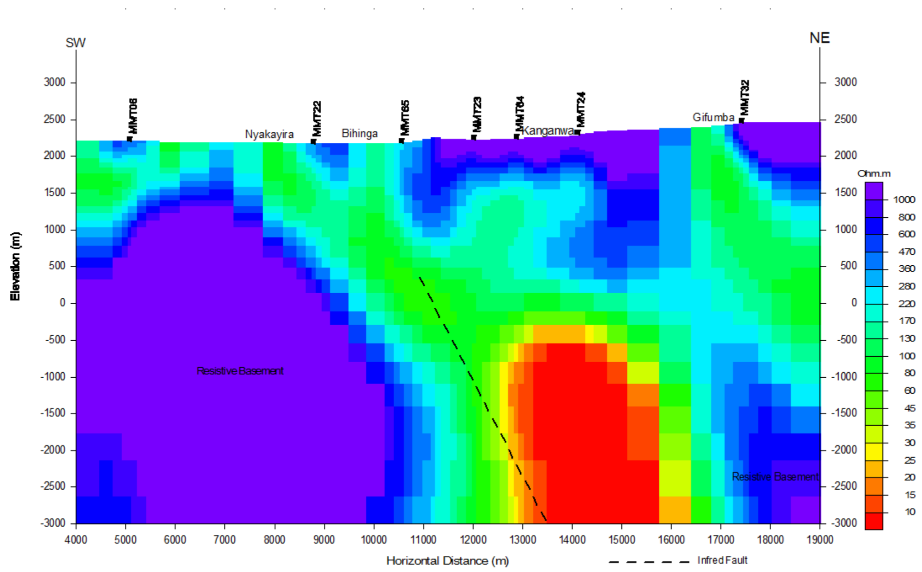


**Fig. 8: 2D- MT resistivity cross-section (IESE-UniServices) along profile NE-1**

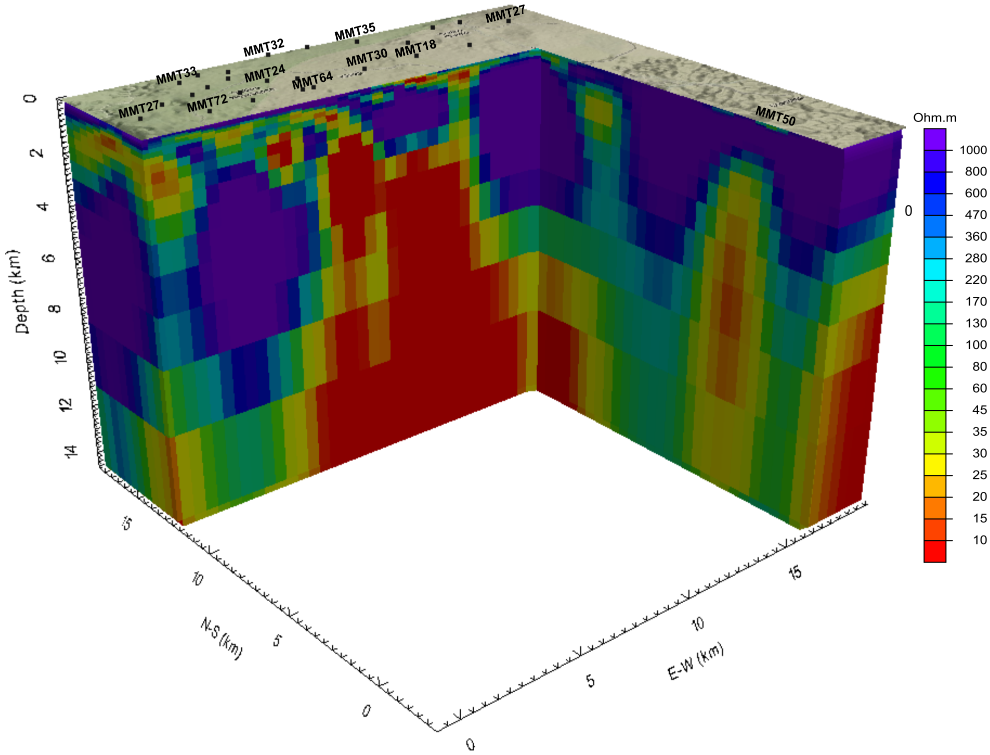


Fig. 9: 3D-MT perspective resistivity sections (IESE-UniServices) with cut-out quadrant shown in Fig.5

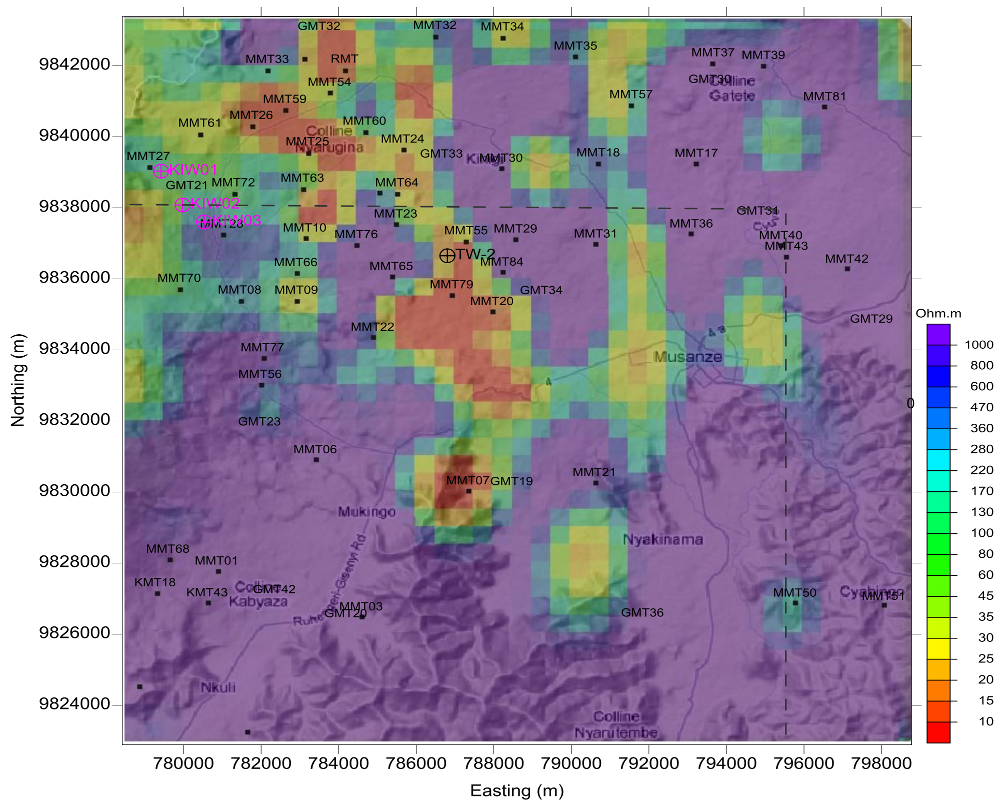


**Fig. 10: 3D- MT true resistivity, pixelled raster map' (IESE-UniServices) at sea level (c. 2.3 km av. depth beneath topography)**

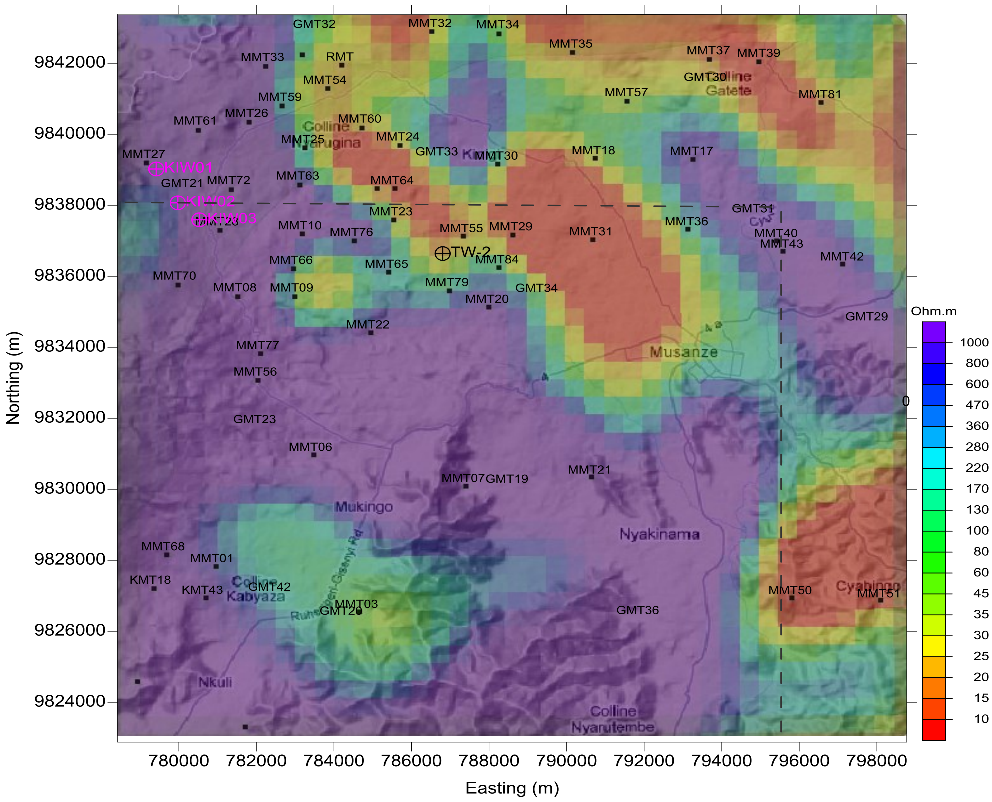


**Fig. 11: 3D- MT true resistivity, pixelled 'raster map' IESE-UniServices) at 3 km below sea level (c. 5.3 km av. depth beneath topography)**

### 3.2. Seismology studies

Seismology studies in Kalisimbi cover tightly Kalisimbi Geothermal Prospect. However, it did not contribute much in combining results from others geophysical methods. Because the events of micro earthquakes retrieved were insignificant to give inputs to the general picture of the subsurface. It is only referred to as one of the method used for Kalisimbi, Kinigi and Gisenyi Geothermal Prospect.

#### 3.2.1 Seismicity

A 12 station surface array was deployed in the Karisimbi area between October 2011 and January 2012, for a total of 108 days. Following a standard approach to geothermal area monitoring (Majer et al. 2007, and Dyer et al. 2008). Seismometer locations were chosen so that the stations would be evenly distributed around the target area to monitor the natural seismicity. During this deployment, the network recorded over 250 seismic events with ones occurring in the local area. Most seismic events recorded by the array were from regional events related to volcanic eruption in the Democratic Republic of Congo (DRC) about 10 km northwest of the survey area. The events were too small to bring information to the substructure of the area.

#### 3.2.2. Surface Station layout

Due to the large size of the survey area, it was impossible to cover the whole area with a dense seismic network. During the first 60 days of the deployment, the network covered the Karisimbi and Gisenyi with an average distance of 5-6 km between stations (station R01 to R 1 in figure 7). After 2 months, some of the stations were moved closer to the border with the DRC and to the Kinigi area (station R01 to R18 in figure 11). The relatively large distance between the facts that these were surface stations, limited the minimum size of detectable events to about 0.5 magnitudes.

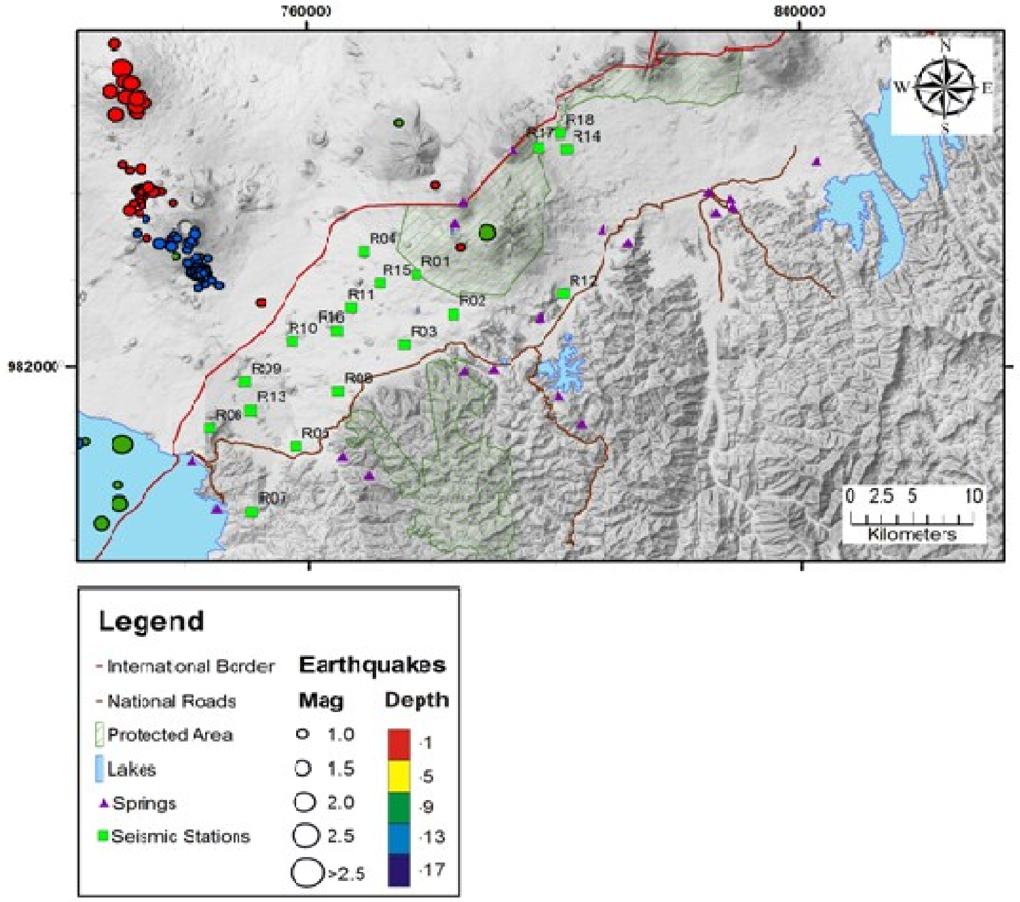


**Figure12: A total of 282 events were located by the network most of them related to the volcanic activity in the DRC. (IESE report, 2012)**

3.2.2. Results from analysis of micro earthquake

The Kalisimbi temporary network worked well for 14 weeks of deployment and recorded over 700 events with 282 located events; most of them recorded by the network were the result of volcanic activities north of the survey area in the DRC. Only two events located in the network footprint under Karisimbi volcano; stations R09, R10 and R11 recorded large and consistent shear-wave splitting showing potential large fracture density and permeability below these stations and toward the border. More seismic stations need to be conducted in the future.

## 4. DISCUSSION OF SURVEY RESULTS

### 4.1. MT

Resistivity structure of the three prospects, based on 3D interpretation, is made up of a resistive layer of unaltered lava flows cover most parts of the prospects. This layer is thicker (>300 m) at the base of the volcanoes and get thinner with increasing distance from the volcanoes. Underneath the top lava flows is a high to moderate resistivity layer of volcanic debris from earlier flows. Except for areas where the basements outcrops (eg Butare horst), this second layer comes into contact with the resistive basement at depths of about 1.5 km in Kalisimbi, 1 km in Kinigi and < 1 km in Gisenyi. Unlike in the Gisenyi and Kinigi prospects, lateral resistivity discontinuity in the basement (associated with fault zones) is limited to an area about 5 km SW of the Karisimbi volcano and along the northern edge of the Butare horst. Looking at the described patterns together, it appears that there is no evidence for a low resistivity structure associated with altered rocks of an active geothermal system driven by heat transfer and thermal fluids associated, in turn, with an even deeper cooling body (inferred cooling magma chamber beneath Karisimbi volcano, for example). The located deep, low resistivity bodies occur beneath young lava fields and in exposed Proterozoic basement rocks, away from the lava fields. The interpretation of the low resistivity bodies in terms of ancient, i.e. thermal palaeo alteration of an extinct thermal reservoir, concealed by the strato-volcanoes and their extensive young lava fields, is not convincing since similar structures are also hosted by outcropping basement rocks. A possible interpretation is the assumption of the occurrence of widespread 'cold', low resistivity bodies throughout the Proterozoic basement.

### 4.2. Seismology

The Kalisimbi temporary network worked well during the 15 weeks of deployment. The network recorded over 700 events with 282 located events. The actual number of events during the deployment period was probably twice as much, but the very high levels of cultural noise during the 12-hour working days, each day, reduced the detection threshold during these hours. Most of the events recorded by the network were the result of volcanic activities north of the survey area in the D.R. Congo. Only two events detected in the network footprint under the Karisimbi volcano. It is possible that more local events could have been located if the plan called for more seismic stations at a closer distance. Nevertheless, Kalisimbi seems to be less actively seismic than many geothermal areas. A deep swarm of seismic events 15 km below the surface under the Shaheru crater in the D.R. Congo was deep enough and close enough that the stations closest to it were in the shear-wave window. Stations S09, S10 and S11 recorded large and consistent shear-wave splitting. The most common cause for shear wave splitting (anisotropy) is aligned, near-vertical, fluid-filled cracks and fractures. Therefore, these observations show potential large fracture density and permeability below these stations and toward the Shaheru crater. The size of the delays and number of Summaries & Conceptual Model IESE - UniServices FINAL REPORT for EWSA 21 observations were most noticeable in station R10 recording with an average of 12% anisotropy and consistent fast shear-wave polarisation of 60 – 70 degrees azimuth.

## 5. CONCEPTUAL MODEL OF GEOLOGY AND VOLCANIC SETTING

The conceptual model of the Karisimbi area, including the Karisimbi and Gisenyi prospects, are consistent with our study results showing a relatively deep, young volcanic system. Figure 13 summaries schematically the components that support this model. As shown, the main elements are: (1) a differentiating mafic magmatic system at a depth greater than 10 km, originating from ultramafic mantle basanites, (2) a variable thickness cover of lavas and pyroclastics over a faulted old granitic basement, (3) a ground water system of variously mixed cold meteoric waters and basement circulating thermal fluids, and (4) significant fluxes of mantle CO2 and 3H. An essential feature of the model is the depth scale shown on the right of Figure 12. Our geophysical data are consistent with a recent volcanic cover in the order of 1 km thick. This overlies a more electrically resistive basement, the depth extent of which was not determined by our measurements. The basement is progressively faulted downwards along the margin of the Rift towards the west. The composition of volcanic rocks indicates their source is a >10 km deep volume of fractionating magma.

A key factor supporting this conceptual view of the Karisimbi area is its regional geological context, especially as it relates to the Virunga volcanic system and western arm of East African Rift system. The active Virunga volcano west of Karisimbi, Nyiragongo, is unique in the chemical composition, of its lavas with the lowest silica and highest potassium and sodium contents found anywhere in the world. It has been proposed that these lavas originate from below the mantle lithosphere, and hence represent the head of a deep mantle plume. Low silica rocks also occur closer to Karisimbi where they erupted from the many basalt cones, such as Mount Cyanzarwe. Summaries & Conceptual Model IESE - UniServices FINAL REPORT for EWSA 23 However, these rocks derived directly from the basanite magma in the mantle and did not undergo differentiation. They are not associated with any usable heat source. Lavas extruded from Mount Nyamuragira to the northwest of Karisimbi are of a different composition, reflecting a shallower source, similar to the one shown beneath Karisimbi in Figure 12. The Kinigi prospect is also dominated by volcanic rocks, mainly lavas and pyroclastics, but also debris flows derived from Visoke and Sabyinyo volcanoes. These younger volcanic rocks overlay the Proterozoic granites and gneisses. Limited geochemical evidence suggests that the lavas that erupted from Sabyinyo derived from a fractionating magma body present at an even greater depth than that below Karisimbi. The morphology of Sabyinyo volcano and sparse isotopic dating infers that that it is older than the Karisimbi and Visoko volcanoes.

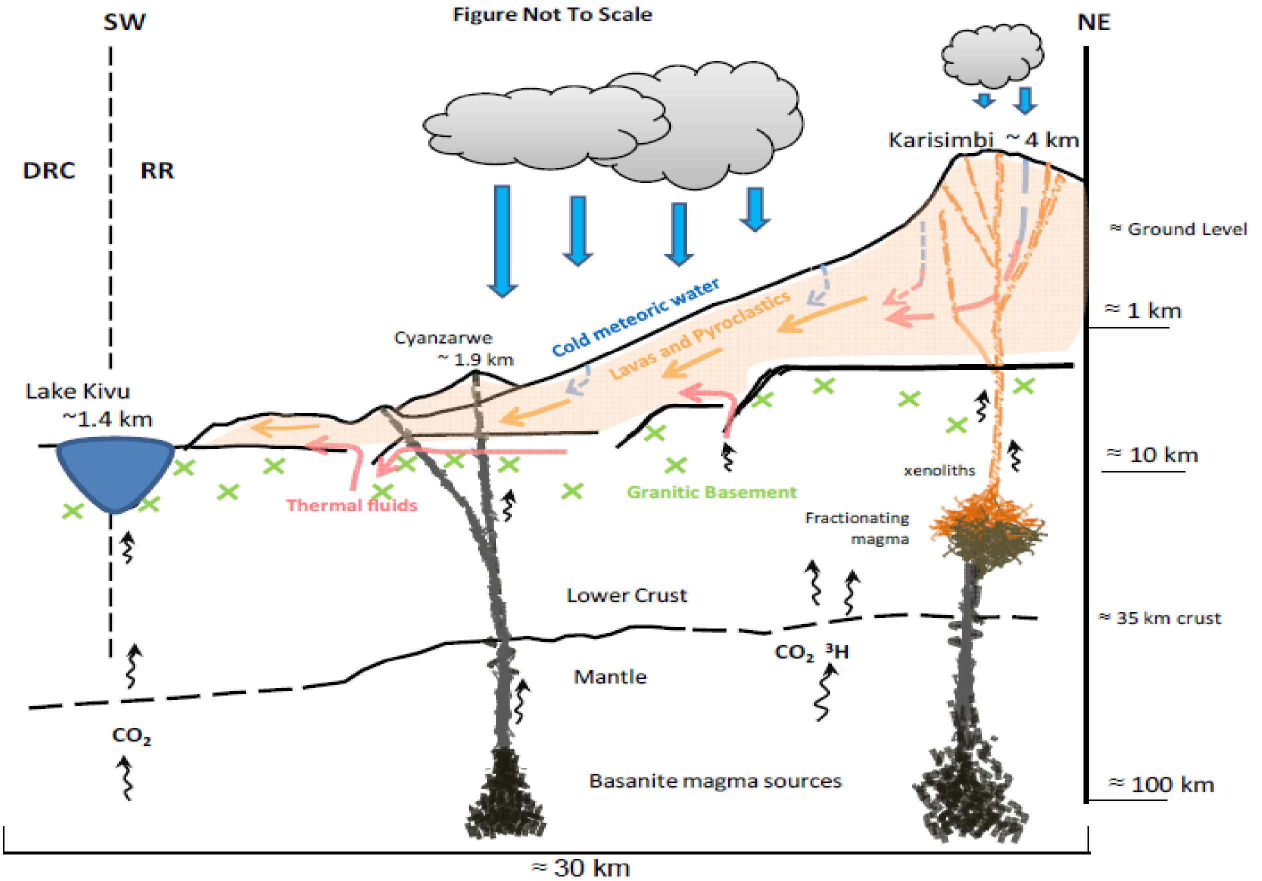


**Figure 13: Reservoir Conceptual model not to scale for Karisimbi geothermal prospect. (IESE, 2012)**

## 6. CONCLUSION

Most of the events recorded by the network were the result of volcanic activities north of the survey area in the D.R. Congo. Only two events detected in the network footprint under Karisimbi volcano. It is possible that more local events could have been located if the plan called for more seismic stations at a closer distance. Nevertheless, Kalisimbi seems to be less actively seismic than many geothermal areas. A deep swarm of seismic events 15 km below the surface under the Shaheru crater in the DRC was deep enough and close enough that the stations closest to it were in the shear-wave window. Stations S09, S10 and S11 recorded large and consistent shear wave splitting. The most common cause for shear wave splitting (anisotropy) is aligned, near-vertical, fluid-filled cracks and fractures. Therefore, these observations show potential large fracture density and permeability below these stations and toward the Shaheru crater. The size of the delays and number of observations were most noticeable in station R10 recording with an average of 12% anisotropy and consistent fast shear-wave polarisation of 60 – 70 degrees azimuth.

Pre-Paleozoic gneissic and granitic rocks cover the South half of the North Rwanda prospects; they also outcrop in the North foothills of the Virunga Range volcanoes in Uganda and further north where they constitute part of the East shoulder of the West rift. It can be assumed that Pre-Paleozoic rocks are continuous beneath the Virunga volcanoes and their lava fields. This implies that all deep, low resistivity bodies detected and inferred by interpretations of MT soundings over the Virunga prospect are hosted by Proterozoic rocks which exhibit rather ‘high’ resistivities of > 1,000 ohm m over stretches of gneissic and granitic outcrops in the South half of the prospect area. Occurrence of deep low resistivity basement rocks reflects some palaeo alteration of extinct thermal systems cannot be excluded. Other conductance mechanism can also explain the occurrence of low resistivity rocks in metamorphic basement rocks. Thin graphite layers within a set of shear zones can produce steeply dipping, low resistivity anomalies with apparent ‘plume’ structures as has been observed in the vicinity of a 9 km deep continental test hole in Germany. Viable electric conductance mechanisms which could explain the deep seated low resistivity rocks in the Virunga prospect appear to be conductive clays of inferred extinct geothermal system or linings of highly conductive graphite along metamorphic shear zones. In both cases the resultant low resistivity structures would not be associated with an anomalous thermal structure.

## ACKNOWLDGEMENT

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