Geothermal Geology of Silali Volcano in Kenya

Marietta Mutonga

Geothermal Development Company, Nakuru, Kenya
mmutonga@gdc.co.ke or mariettamu@gmail.com

Keywords
Silali, geology, structures, evolution, geothermal

ABSTRACT

Silali is the largest and trachytic caldera volcano in the axis of the northern Kenya Rift Valley. This paper describes the results from examination of existing data and detailed geological exploration by the geology team of GDC. The study involved geological mapping of the rock formations, structural mapping and geothermal manifestations well as hydrogeological and volcanological studies of the volcano and sampling of rocks for thin section cutting and petrographic analysis. Fieldwork was carried out in the month of May and July 2010. Basalt is one of the most common types of lava in Silali, manifested mainly as flank fissure basalts and flood basalts. Basalts are aphiric or porphritic and vesicular. The Silali Trachytes are both silica-oversaturated and silica under saturated. In the post caldera group increasing differentiation is thought to have resulted in progressive silica under-saturation. The Blackhill Trachytes are among the youngest lavas are critically under-saturated with respect to silica. The latest activity from a satellite vent on the northern slopes of Silali is basaltic in composition and was erupted about 200-300 years BP. The presence of a still active heat source to sustain a geothermal system(s) indicates that there is a geothermal resource in the area that can be commercially exploited.

1.0 Introduction

Silali is the largest trachytic caldera volcano in the axis of the northern Kenya Rift Valley. It has is a broad low-angle shield with basal diameter of 30 km × 25 km slightly elongated in N-S direction and rises 760 m above the rift floor Smith et.al., (1995). The prospect had been earmarked as a target for detailed surface Geo-scientific exploration for the assessment of geothermal resources in Kenya.

Aspects of the geology of Silali volcano McCall (1968a, 1970), McCall and Hornung (1972) and were used in the compilation of the 1:125,000 scale geological map Truckle (1979a) as cited in Smith & Dunkley et.al., (1990a). A resurvey of Silali volcano was completed by the British geological survey and results were incorporated into a 1:50,000 scale geological map (Smith and Dunkley 1990a and a report by Dunkley et.al., 1994). However none of these studies were geared towards understanding the geothermal potential of the prospect. Therefore in 2010 geoscientific work was carried out towards this end.

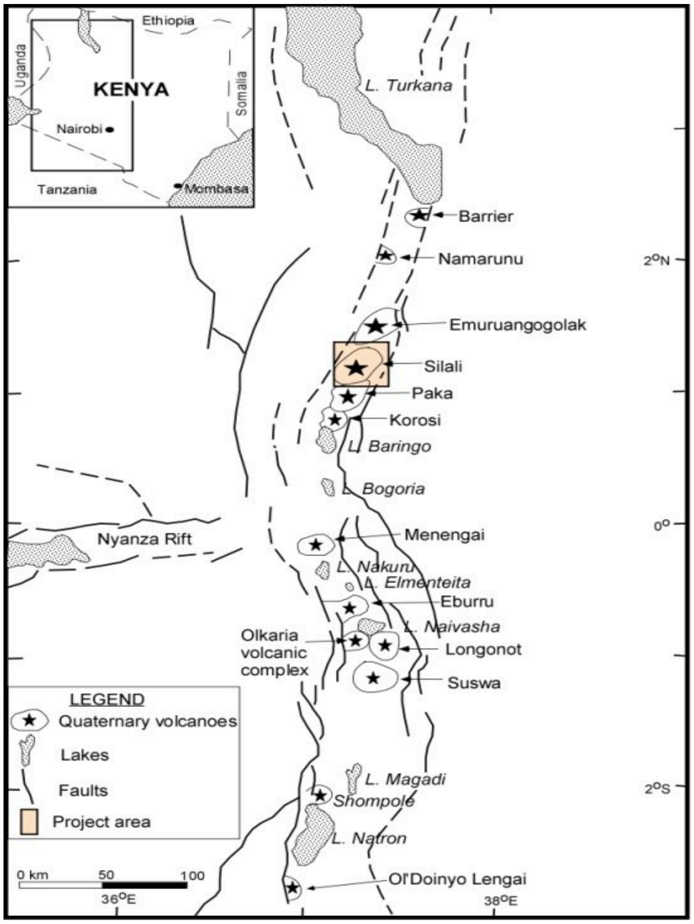

Figure 1. The Kenyan Rift.

1.1 Location

Silali is located in the northern Kenya rift. The prospect is located about 50 km north of Lake Baringo in the northern Kenya Rift at; 1º 2'21.173"- 1º 18' 38.064" N and 36º7'30.130-36º21'29.513"E. The spectacular caldera rim forms a complete circular cliff that breaks at few locations. The caldera floor, is fairly flat except for a few explosive crater cones covers. The area covered in the geo-scientific surveys measured about 900 km^2. (Fig.1).

1.2 Tectonic Setting

The East African Rift system (EARS) is expressed at the surface as a series of several 1000s km long aligned tectonic basins (rift valleys), separated from each other by relative topographic highs and generally bordered by uplifted rift shoulders (Fig.2).

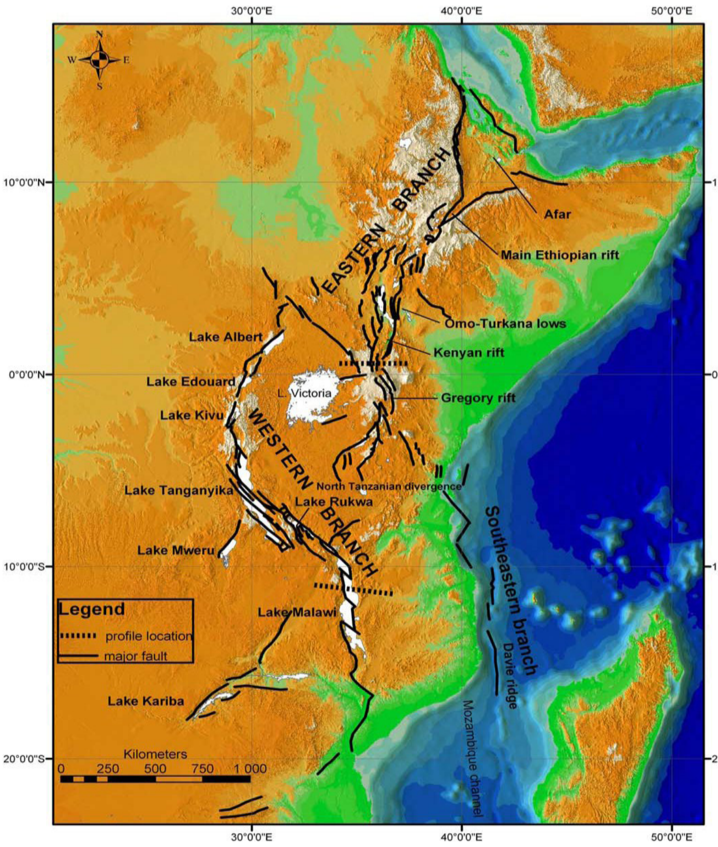

Figure 2. The East African rift system after Chorowizc 2005.

The EARs extends from the Red the Sea/Gulf of Aden in the north to Malawi, in the south. The EARS then splits into two main rift branches, the Western and the Eastern Rift.

The Eastern rift is more magmatically active than the western rift and Silali itself is one of the seven Quaternary volcanic centers in the Kenya Rift Valley. The volcanoes have divided into a northern set and a southern set been Williams et al., (1984), Macdonald (1987). The northern set consisting of Barrier, Emuangogolak, Silali, Paka and Korosi which are dominantly trachytic and basaltic. Caldera formation of these centers' was accompanied by only sparse pyroclastic activity (Fig.3). The southern set Menengai, Longonot and Suswa area almost entirely trachytic and are mainly as a result of Krakatoan activity. Caldera formation at Menengai is thought to have been Krakatoan type and was accompanied by voluminous ash flow and air fall tuff (McCall 1957; Leat 1984).

2.0 Geological Framework

2.1 Surface Geology

2.1.1 Basalt

Basalt is one of the most common type of lava in Silali. Basalts are manifested mainly as flank fissure basalts and flood basalts. Fissure eruptions were generated in the southern and south eastern flanks along a linear fracture or along an en echelon (parallel, but offset) fracture system. (Fig.4). Silali basalts are either aphyric or porphyritic and in some instances vesicular. The phenocrysts are composed of plagioclase, clinopyroxene, olivine, titamagnetite in a sub-ophitic or intersertal matrix. The youngest activity on Silali erupted porphyritic olivine basalt on the north-eastern flanks of the caldera from a series of small scoria cones. A lack of vegetation suggests that activity may have taken place 200-300 years ago (Dunkley et al., 1993).

2.1.2 Trachytes

(a) Lower Trachyte

Exposure of the Lower Trachyte lavas is limited, occurring around the western and southern sections of the caldera wall. The outcrops are mostly grey in color but are weathered to a reddish brown variety. The lower trachytes lavas maybe

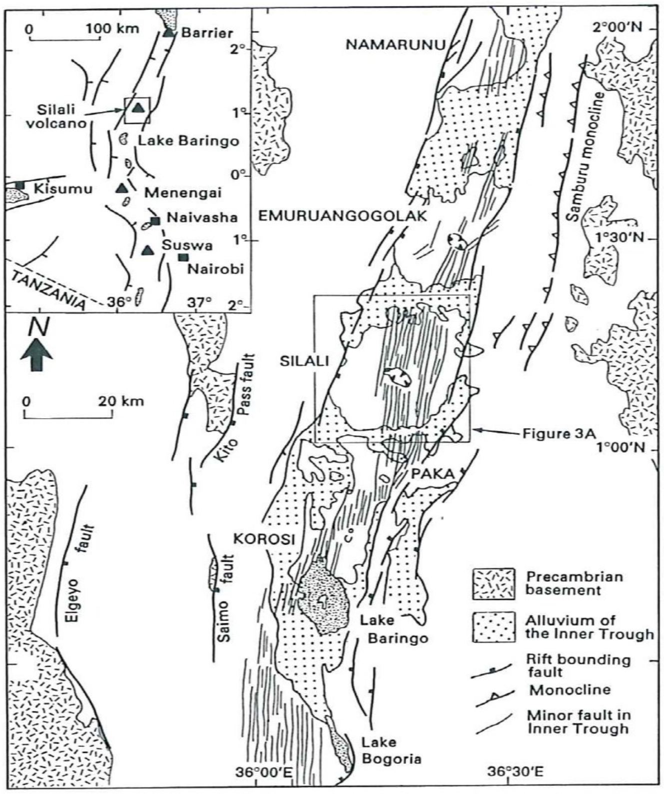

Figure 3. Geological setting of the Silali volcano and locality map of the late quaternary trachytic volcanoes, Kenya Rift (Smith et al.,1995).

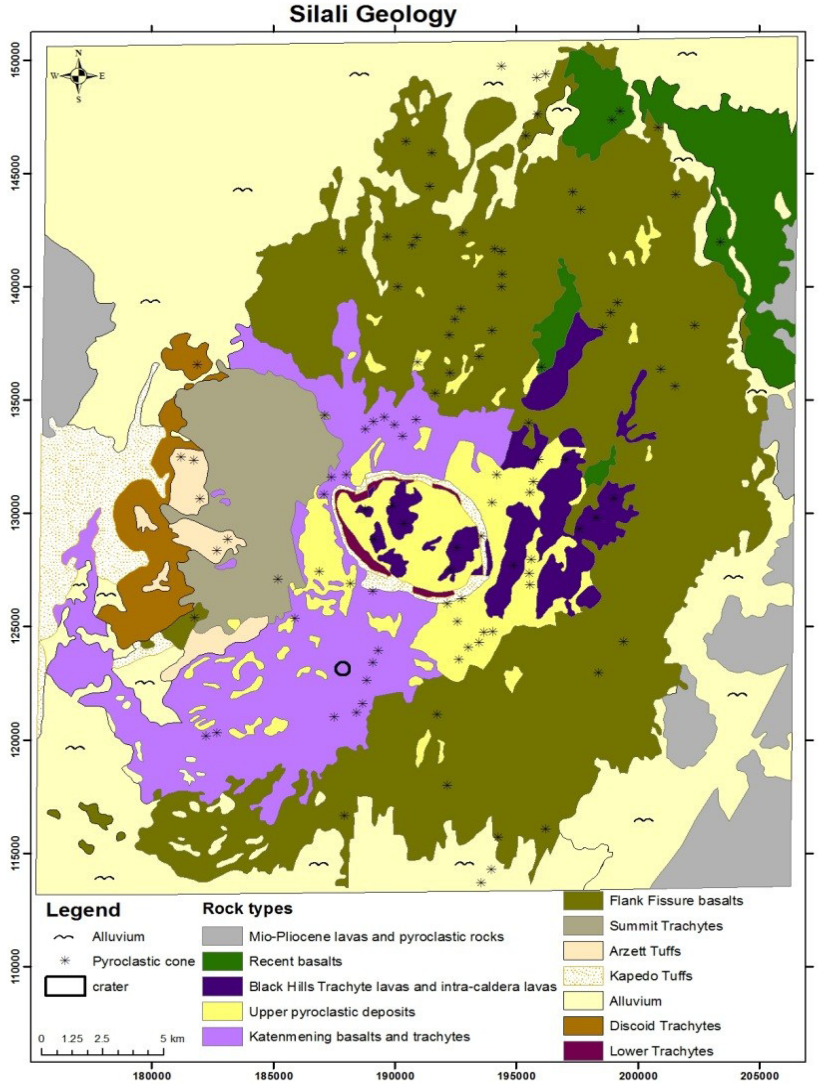

Figure 4. Geological Map of Silali modified from (Dunkley et al., 1993).

the actual shield building lavas and have been overlain by younger volcanics. The fine grained lavas are porphyritic in nature and contain phenocrysts of feldspars. Dunkley et. al., (1993) dated two samples of the Lower Trachyte formation and the lavas yielded an Ar^{40}/Ar^{38} date of 228±7 ka and 224 ± 9 ka. These lavas overlie the basalts.

(b) Discoid Trachyte

The Discoid Trachyte lavas crop out only on the western part of the caldera and based on lobate flow features the lavas were flowing in a westerly direction. The rocks overlie the Kapedo tuffs and are their estimated age is 133±3 ka Dunkley et al., (1993). Discoid trachytes are light grey to greenish and fine grained.

(c) Summit Trachyte

The Summit Trachytes are the most widespread trachyte in the region. Based on the stratigraphic correlation have an age younger than the Arzett tuffs and lavas of 117 ±5 ka. The source of these lavas is presumed to be arcuate fissures and domes situated to the west of the caldera. Lobate shaped lava front features clearly indicate a westerly direction of flow. The summit trachytes are highly fissile and fined grained with a high silica content.

(d) Blackhills Trachytes

The Blackhill trcahyte lavas are exposed on the upper eastern flanks of Silali where they form a linear belt 9 km long by 5 km wide. These lavas occur together with benmorites and phonolites, on the western side of the caldera. They are relatively young based on the fact that they are still glassy. Based on their flow fronts, the Blackhill trachytes likely flowed towards the east. The lavas are vesicular and unvegetated in some localities due to their young age. The blackhill trachytes are critically under-saturated with respect to silica. A general progression from two–feldspar trachytes to the dominant one–feldspar varieties is accompanied by a decrease in phenocryst abundances with more evolved trachytes tending to be aphyric and glassy.

2.1.3 Intermediate Lavas

Intermediate lavas exposed in the southern, northern and western walls of the caldera and include hawaiites, mugearites, benmorites and trachytes. In the west they rest conformably on the lower trachyte lavas but to the east they wedge out against lower pyroclastic deposits.

2.1.4 Pyroclastic Deposits

Pyroclastic deposits are 1-1.5m thick unconsolidated trachytic pumice and pumaceous lapili ash deposits which cover most of the caldera floor. The deposits also occur around the caldera rim and upper flanks of the caldera. Thickness variations and dispersal patterns indicate the main source was located on the upper eastern flanks but some may also have been erupted from the trachyte fissure on the caldera floor. Within the caldera walls the Kapedo tuffs locally make up to 80% of the section and comprise three distinct units. The upper and lower pyroclastic deposits are also present to the west of Silali around Kapedo and mantle the western margin of the rift.

2.1.5 Intrusive Rocks

Dykes occur mainly on the southern and the western parts of the caldera and are predominantly trachytic in composition although composite dykes of basalt and trachyte sometimes occur showing evidence of magma mixing. The dykes are up to 2 m in width and strike N101°E -N115°E and are closely related to a set of normal faults associated with post-emplacement brecciation and hydrothermal alteration. Generally, two phases of dyke injection are recognized: The early dykes intrude the Lower Pyroclastic Deposit and were feeders to the uppermost trachytes.

2.2 Petrochemistry

Analyses for oxides of major and trace elements of samples obtained from the Silali volcano were carried out by use of Atomic Absorption Spectroscopy (AAS).

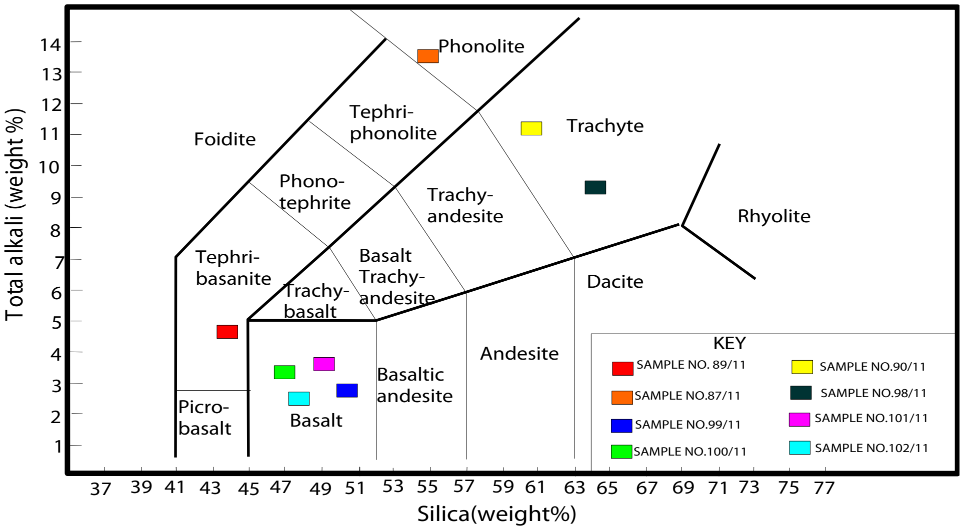

Figure 5. Graphical presentation of rock samples from the Silali based TAS diagram.

The analysis support that the Silali volcano is widely composed primarily of basaltic and trachytic rocks. Silali basalts are of high-Fe transitional affinity and range from plagioclase-phyric varieties, probably formed by selective accumulation to aphyric.

All Silali basalts are relatively evolved; with the primitive basalts probably being held close to the Moho, where they evolved by fractionation to produce basalts with less than 8% MgO. Fractionation was along a high-Fe trend through mugearite to metaluminous, two-feldspar trachyte and thence to peralkaline, one-feldspar, silica-oversaturated and silica-undersaturated trachytes. Magmas intermediate in composition between basalt and trachyte were very rarely erupted at Silali, but their evolution can be deduced from an extensive suite of dolerite blocks, which contain residual glasses varying from mugearitic to peralkaline phonolitic compositions. Magma mixing between basalt and trachyte has been common at Silali, implying complexity of the plumbing system. Evolution of the trachytes was by fractional crystallization combined with assimilation of crust during or after fractionation. Mixing of partially crystallized differentiates and reaction between late liquids (trachytic) and early formed crystalline phases (labradorite, olivine, augite) led to the development of hybrid flows such as trachybasalts.

2.3 Geological Evolution and Stratigraphy

The morphology of the present day floor of the Kenya Rift is due mainly to tectonic and volcanic events of the last 1Ma. According to Smith et.al., (1995) activity commenced at 400-220 ka (Fig.6a) with construction of a low relief lava shield whose summit area was subsequently modified by alternating periods of faulting subsidence and infilling associated with two major periods of explosive activity. This activity ceased around 133-131ka (Fig.6a, b, c) and was probably the result of fracturing and decompression of a high level magma chamber by regional extension and the injection of basaltic dykes below the volcano. Later eruptions (c.120 ka) along the western flanks migrated eastward with time and culminated in the eruption of viscous trachyte lavas from a circumferential fissure zone (Fig.6d).

The emplacement of basic dyke swarm to shallow crustal levels beneath Silali resulted in formation of a broad volcanic rift zone within which large volumes of fluid basalts being erupted onto the flanks of the volcano. This activity mainly predated but probably also overlapped with; incremental subsidence and asymmetric down sagging of the summit area and the propagation of a circumferential fissure zone. Basalt and trachyte erupted along the circumferential fissure zone and from a major summit fissure outward to form a series of flat summit benches and ponded in summit depressions before overflowing (Fig.6). The continuing inward collapse of the summit area and the lateral withdrawal of magma from a high level reservoir finally culminated in the formation of a large caldera at 64 ka (Fig.6e).

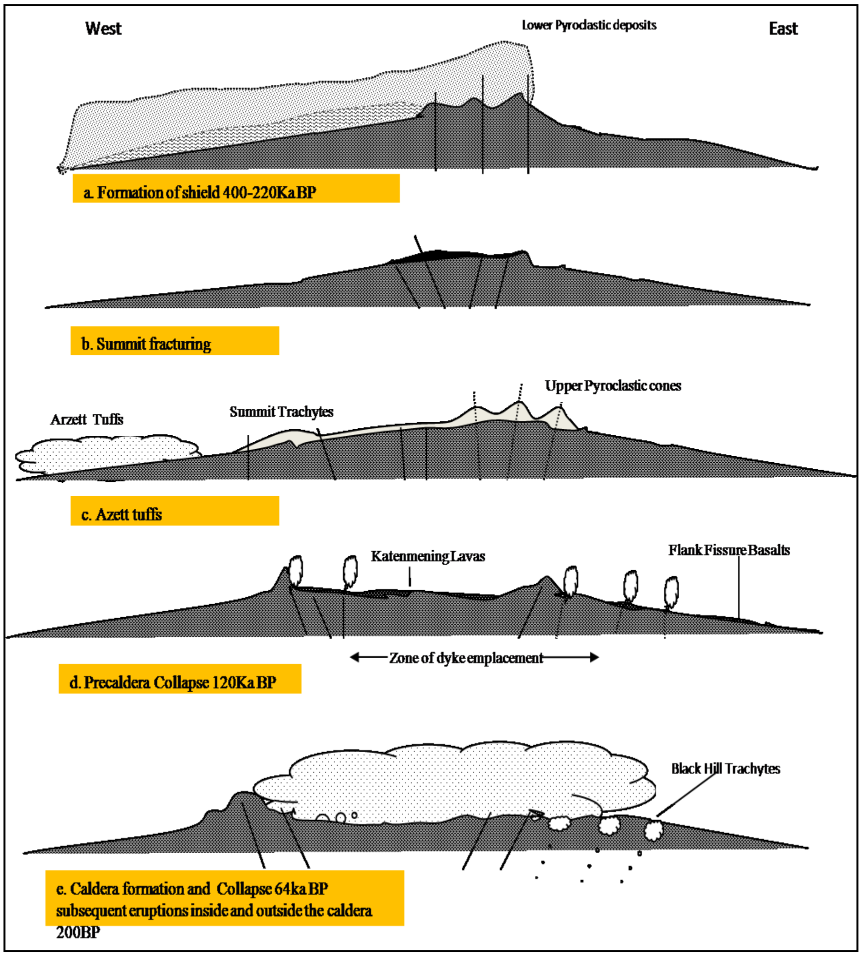

Figure 6. The evolution of Silali.

Table 1. Stratigraphy and evolution of the Silali volcano.

Event/Eruption	Age	Activity
Young Basalt lavas	4±2-10±2 ka	
Black Hill Trachyte lavas		
Late Pyroclastic Deposit		
Upper basalt and trachyte lavas	7±3 ka	
CALDERA FORMATION	63Ka	
FAULTING AND SUBISDENCE	64±2 ka	WESTERN FLANK ACTIVITY
Flank Fissure basalt Upper Pyroclastic Deposit	133±3 ka	Summit Trachyte Arzett Tuffs and Lavas Discoid Trachyte
FAULTING		
Intermediate Lavas Lower Pyroclastic Deposit Lower Trachyte Lavas Mission Basalt	224±9 ka	Kapedo Tuff

Post caldera activity utilized pre-existing weaknesses within the caldera, erupting basalt and trachyte lavas until around 7 ka within the caldera, and was contemporaneous with the eruption of trachyte lava domes (9-7 ka) Blackhills trachytes) on the eastern flanks and some late tongues of basalt on the outer slopes (undated). The above events can be summarized in the stratigraphic sequence in Table.1.

2.4 Structures

The northern, eastern and southern flanks of the volcano are cut by a prominent NNE-SSW trending volcanic rift zone that is 10 km wide and up to 30 km in length (Fig.7, Plate.1).

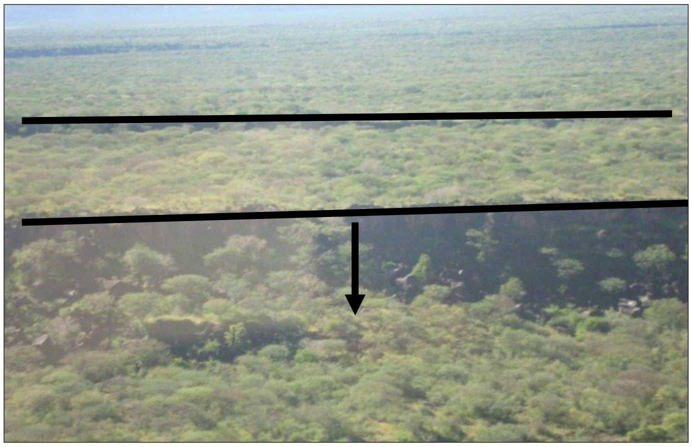

Plate 1. N-S Fracture zone.

This rift zone is characterized by numerous minor faults, tension cracks and fissures which are associated with the eruption of large volumes of basalt lava. This zone, which trends NNE-SSW across the volcano, is oblique to the adjacent rift margins and passes southwards into a zone of intense faulting on Paka volcano, but northwards dies out on the southern flanks of Emuruangogolak. The NNE structural trend parallels the grain of the underlying Precambrian Metamorphic rocks, thus attesting to the influence of the basement structures to the evolution of the rift. Volcanic activity that predates caldera collapse is controlled by the NNE trending fissures/faults. There is a lineament structure which trends NNW-SSE (Fig.7). It dissects the NNE-SSW fault in the South Eastern flanks which control geothermal outflow in the form of fumaroles. The caldera ring structure is also skewed in NW-SE direction probably reflecting influence of old basement structures on the evolution of the rift.

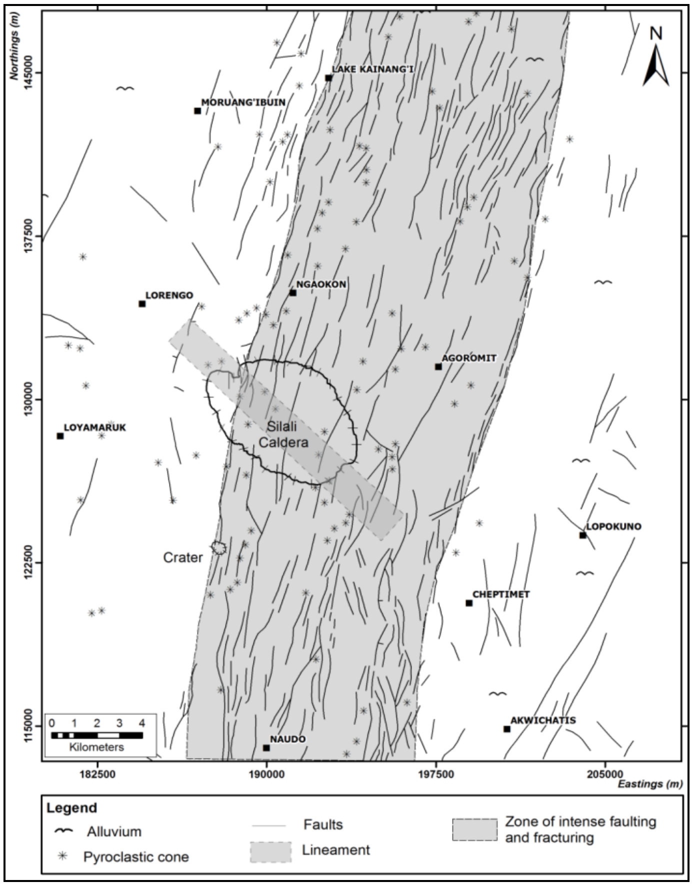

Figure 7. Silali Fracture Zone.

Adjacent to Silali faults and fractures are curvilinear with strike length up to 5 km. They define a series of short en echelon segments composed of symmetric grabens, asymmetric grabens and nested grabens linked by up-faulted tapering horsts of oblique relay faults. The grabens have widths ranging from 170 m to 550 m and are cut by swarms of vertical, open, tensile fractures, and linear trends of basaltic fissures and scoria cones.

The graben boundary faults have normal vertical displacements of between 10 m and 30 m (Plate 1). The faults described above cut all strata including the post caldera lavas and have a long of history of repeated movement, for example where they cut the flank fissure basalts individual faults are often buried by later basalts flows and have been subsequently reactivated. The trachyte eruptions that can be associated with the caldera formation flowed out of acruate structures on the western zone of the shield. Later basalts erupted through minor fissures observable on the southern and northern slopes.

2.5 Geothermal Manifestations

The major geothermal manifestations occur within the caldera floor and on the eastern highly faulted slopes of the volcano and cover an area of about 20 km^2. Some manifestations also occur along river Suguta to the west and along fractures in the far north of the volcano. Geothermal Manifestations occur in the form of altered grounds, steaming grounds, hot springs, fumaroles and geothermal grass (fimbristylis exilis(an example of vegetation that thrives at elevated temperatures in Kenya).

Plate 2. Lorusio Hot Springs.

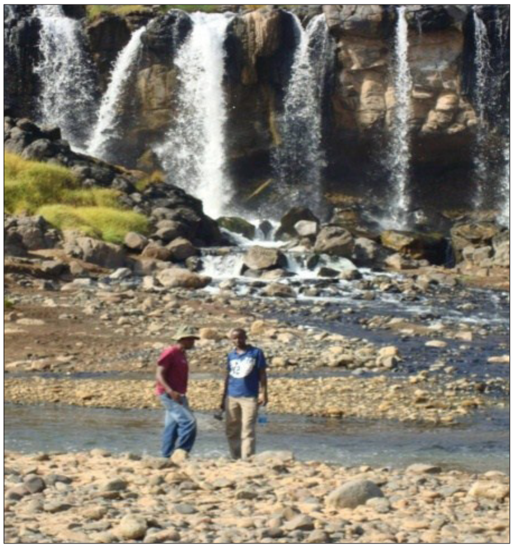

Plate 3. Kapedo Hot springs.

The highest temperature and most extensive activities occur in the eastern half of the caldera floor, here most hot altered grounds are aligned along the N-S fissure zone. At the foot of the South Eastern Walls highly altered grounds were mapped. Also on the walls at an elevation of about 200 m from the caldera floor active fumaroles were mapped. On the Eastern flanks of the caldera we also mapped fumaroles and hot ground mainly within the fissures trending N-S. These fumaroles have temperatures above 80ºC. Around Kapedo along the Suguta river is a fault zone directly below the Discoid Trachyte, I believe it could be the source of a series of hot springs(The Kapedo hot springs(P late.3). About 10 km North of Kapedo are Lorusio hot springs(Plate.2). The hot springs flow eastwards away from the west ranges of hills hosting dyke swarms and volcanic cones. There are about five springs occurring within a discharge area of about 1 km^2 of highly altered rock. They are probably due to upwelling of meteoric waters along a fissure/fault zone after contact with deep hot rocks.

2.6 Hydrogeology

Extraction and utilization of heat from the underground require a media to transport the heat to shallow depths. The heat is transferred from depth to shallow subsurface regions first by conduction and then by convection, with geothermal fluids action as a carrier in the later case. These fluids are essentially meteoric water that has penetrated into the Earth's crust and has been heated on contact by the hot rocks.

The generally N-S trending fault structures, the master rift faults and the fractured Plio-Pleistocene lavas within the rift floor influence the geothermal system of the Silali volcano by acting as conduits for recharging the system. The hydrogeology of the area is therefore characterized by recharge from master rift faults to the east and to some extent axially from the south (Fig.8). The interaction between lateral and axial flows is modified by rift floor fault network and dykes, which allows for recharge into the geo-

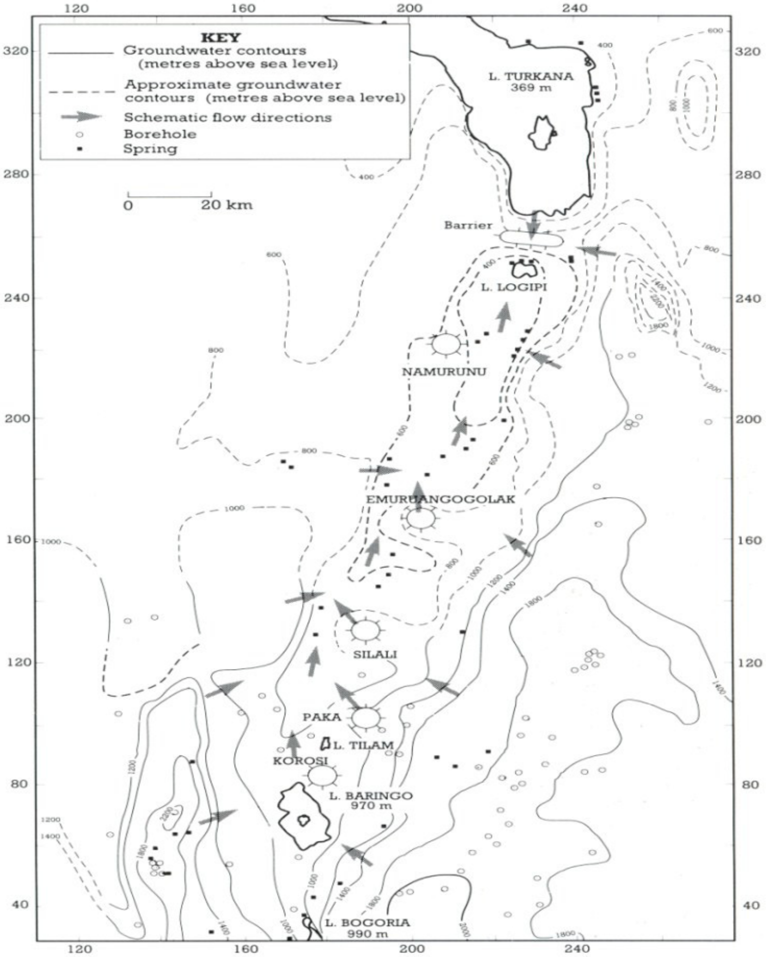

Figure 8. The potentiometric map between Lake Baringo and Lake Turkana (after Dunkley et. al, 1993).

thermal systems. Abundant meteoric fluids are very essential in the sustenance of a geothermal system. The height of the plateaus compared to the rift floor allows for sufficient hydraulic gradient to enable deep recharge to the heat source(s).

3.0 Discussion and Conclusion

Heat source: The continued eruptions (post, intra caldera) indicates that the magma body at Silali is still active (molten hot). The Blackhill Trachytes are among the youngest lavas in Silali. They are critically under-saturated with respect to silica. A general progression from two –feldspar trachytes to the dominant one–feldspar varieties is accompanied by a decrease in phenocryst abundances with more evolved trachytes tending to be aphyric and glassy. The youngest activity on Silali erupted porphyritic olivine basalt on the north-eastern flanks of the caldera from a series of small scoria cones. There is lack of vegetation here suggesting that activity is may have taken place as recent as 200-300years (Dunkley et.al., 1993).

Recharge: The Silali prospect is located on the rift floor where hydrogeologic recharge comes from the higher rift scarps mainly to the east i.e. the Laikipia ranges. The intense rift floor fracture/faulting in this area the creates NNE and some EW structures that control fluid flow. Water from the rift flanks penetrates deep into the crust towards the magma bodies under the rift floor and normal faults conducting hot fluids from deep into geothermal reservoirs at shallower depth. The NNW-SSE lineament and the NNE fissure swarm may be such important conduits of deep fluids thus significant for the geothermal prospect.

System Capping: Activity at Silali Volcano eruption included eruption of several extensive sheets of pyroclastics material. The spread of these is preferentially to the north and NW (Fig.4) as evidenced by the way the rift floor faults are masked in the area. Glassy pyroclastics are usually very susceptible to alteration forming hydrated clays that cause of self-sealing. The layered pyroclastics, therefore become very good capping for geothermal systems.

5.0 Acknowlegements

I wish to express my gratitude to the government of Kenya through the ministry of energy for funding the project and to the entire management of GDC for the assistance and advice they offered during the course of the project.

The good work of GDC geology field crew and technicians who worked tirelessly during fieldwork and laboratory work is sincerely acknowledged and appreciated. Last, but not least thanks go to all those who participated in one way or another in making the work a success.

6.0 References

Chorowicz J., 2005: The East African rift system. J. African Earth Sci., 43, 379–410.

Dunkley, P.N., Smith, M., Allen, D.J., and Darling, W.G., 1994. The geothermal activity and geology of the northern sector of the Kenya rift valley. British Geological survey, research report SC/93/1, keyworth Nottingham.

Leat, P.T.,1984 Geological evolution of the trachytic caldera volcano, Menegai, Kenya Rift Valley. Journal of Geological Society, London 141 1057-1069.

McCall,G.J.H 1957. The Menengai Caldera, Kenya colony. Proceedings of the 20th international Geological Congress, Mexico, Section 1 56-69.

McCall, G.J.H 1968a. Silali another major caldera volcano in the rift of Kenya. Proceedings of the geological Society of London, 1644 267-268.

McCall, G.J.H and Hornung, G.A., 1972. A geochemical study of Silali volcano, Kenya, with special reference to the origin of the intermediate acid eruptives of the central rift valley. Teconophysics, 15 97-113.

Macdonald, R. 1987. Quaternary peralkaline silicic rocks and caldera volcanoes in Kenya. In: Fitton, J.G. and Upton, B.G.J (eds) Alkaline igneous Rocks. Geological society of London, Special publications, 30, 313-333.

Macdonald, R., Davies, G.R., Upton, B.G.J., Dunkley, P.N., Smith, M., and Leat, P.T., 1995. Petrogenesis of Silali volcano, Gregory rift Kenya Journal of Geological Society London 152, 703-720.

Williams, L.A.J., Macdonald, R., and Chapman, G.R. 1984. Late Quaternary caldera volcanoes of the Kenya Rift. Journal of Geophysical research, 89, B10, 8553-8570.

Smith, M., and Dunkley, P.N. 1990a Geological map of Silali Volcano Ministry Of Energy, Government of Kenya.

Smith, M., Dunkley, A., Deino, A., Williams L.A.J., McCall, G.J.H., 1995. geochemistry stratigraphy and structural evolution of Silali volcano Gregory rift Kenya Journal of geol society of London Vol.152, pp 297-310.

Smith, M., and Dunkley, P.N., 1990b Geothermal activity of Silali Volcano Ministry of Energy, Government of Kenya.