Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Quaternary Volcanism System in Uganda and its Associated Geothermal Significance

Vincent Kato

P. O. Box 9 Entebbe, Uganda

kato_vicent@hotmail.com

Keywords: Basaltic volcanism, kamafugite, silica under saturation, silicic volcanism, magma chambers, thermal anomalies, extensional type geothermal system, magmatically heated geothermal systems

ABSTRACT

Geothermal resources are usually genetically related to areas of recently active volcanic centers. Young volcanic activity and thermal anomalies indicate geothermal potential. Accordingly, such areas are considered viable geothermal exploration targets and are given priority. Uganda volcanism is of basaltic type (purely basic volcanic system). Mid-Miocene to Recent lavas in the Western Branch of the East African Rift are confined to four intra-basinal accommodation zones (Ebinger, 1989; Pasteels et al., 1989; Furman, 1995) and Pouclet et al. (1983) noted a trend towards increasing potassium and C02 coupled with increasing silica-under-saturation towards the north, where carbonatites also occur (Barker and Nixon, 1989; Stoppa et al., 2000). Quaternary volcanic fields occur to the east and south-east of the Ruwenzori massif along the border between Uganda and Congo. The volcanic edifices of this area are the type locality of kamafugite: pyroclastics dominate over lavas (Holmes and Harwood, 1932) due to the extremely volatile-rich, explosive nature of the volcanism. Magmatism was active in the Upper Pleistocene and continued intermittently until recent times (Holmes, 1950; Lloyd et al., 1991). According to K-Ar and Ar-Ar age determinations all the volcanics are younger than 50 ka (Boven et al., 1998). Generally, the basaltic terrain rarely form *thermal anomalies* of economic interest, whereas silicic volcanic system probably do if they are large enough. In oceanic systems there is admitted possibility of the existence of high level basic magma chambers (Reykanes and Kilauea Volcano Hawaii). Purely basic volcanic system of Uganda (Kalsilite-bearing lava and ejecta) are of Kamafugite series. Kamafugites represent primitive ultrapotassic rocks which are extremely rare but widespread. Reece (1955) noted that volcanic activity probably continued into historical times.

Kamafugites are characterized by $Si0_2$ under-saturation, low AI, moderately high K but extremely high Ca content and as a consequence of this unusual major element composition modal kalsilite, melilite and perovskite frequently occur. Basaltic lava has low viscosity and can flow long distances. These basaltic magmas originate deep from upper mantle melt (30-50km) and most of them rises relatively rapidly to the earth's surface and reacts very little with crustal rocks because of its low viscosity. Basaltic materials are more fluid than Rhyolites, andesites and dacites which contain more silica. The basalts rise rapidly from the mantle to the surface through pre-existing weakness zones in the crust. As a result their heat was dispersed rather than stored and does not provide useful geothermal concentration (Smith and Shaw, 1975). This is not the case with high silicic variety (which are lacking in Uganda), which are highly viscous and commonly associated with magma chambers at shallow levels (long lived heat source) in crust (Smith and Shaw, 1975). Uganda's basaltic magma unlike silicic magma cannot sustain *high temperature conventional systems* for thousands of years. Due to basaltic nature of Uganda's volcanism, the existence of high level magma storage chambers in the upper 10m of the crust is less likely. Many large geothermal systems appear to be associated with young silicic volcanism. The heat source of Uganda's geothermal systems is related to conduction dominated environments ascribed to extension and thinning of the crust as opposed to high level magma chambers. High heat flow is related to thinned crust and high temperature mantle. The high level magma chambers are presumed not to be the ultimate heat source of Uganda geothermal systems in volcanic terrain. The volcanic rocks of Uganda are fresh with no visible exposure to high temperatures and thermal influence.

It can be presumed that Uganda's geothermal systems are *extensional-type geothermal systems* as opposed to magmatically heated geothermal system notwithstanding the existence of recent volcanism in tectonically active rift zone. This observation is consistent with conventional wisdom that suggests that basaltic provinces are poor targets for *high temperature geothermal exploration* because of low viscosity of basalts results in rapid flow to the surface along narrow conduits rather than forming shallow magma chambers that are large enough to support high temperature fluid convection. Uganda is presumed to host low to medium grade (lower temperature) geothermal resources which are fault-hosted largely due to its basaltic terrain.

1. INTRODUCTION

Geothermal energy is present everywhere beneath the earth's surface, although the most desirable high-temperature resources are concentrated in regions of active or geologically young volcanoes. High heat flow is associated with areas of recent volcanic activity and earthquakes. Thus geologically young volcanic terrains are exploration targets for geothermal resources and fertile fields for exploration. The magma that feeds volcanoes originate deep in the mantle, and considerable heat accompanies the rising magma as it intrudes into the volcanoes in magmatic driven systems. Much of the intruding magma remains in the crust resulting into shallow magma storage chambers and constitute an intense high-temperature geothermal heat sources for periods of thousands of millions of years, depending on depth, volume and frequency of intrusion (John Harvey Sass et al, 1991).

Geologically young volcanic rocks are associated with hot springs the world over. In Iceland, the plate boundary is the locus of many earthquakes, active volcanoes and associated high-temperature geothermal systems. Because the entire country is consist of geologically young volcanic rocks, geothermal resources are almost everywhere in Iceland.

The volcanically active and earthquake-prone zone "Ring of Fire" is associated with high-temperature geothermal resources. Magma in the crust can provide the heat for high-temperature geothermal resources. Uganda has an earthquake prone zones with geologically young volcanoes. The author attempts to analyze the geothermal significance of these volcanic terrain in Uganda.

2. WESTERN RIFT VALLEY

The Western Rift Valley is ascribed lateral extension and thinning of the crust. The crust below active rifts is thin (20-30km) compared to regional thickness (35-45km; Beaumont et al, 1982). As the brittle crust pulled apart during stretching, it fractured forming steeply dipping rift bounding normal faults that are perpendicular to the direction of extension (Glassley W. E, 2012). As a result Grabens and Horst were formed. The high angle normal rift faults extended to considerable depth in some cases aiding magma eruption. The thinning of the lithosphere, likely at a rapid pace, causes pressure release, melting of the mantle (Morgan, 1983) and generation of basaltic magmas and high thermal gradient. This is the origin of explosion craters characterizing the western rift valley. Zones of thinned crust corresponds to regions of upwelling asthenosphere and high heat flow where Moho has moved closer to the surface. Magma ascent through fault conduits was in response to decrease in lithospheric pressure caused by crustal extension and thinning. Heat flow increases following the rise of mantle isotherm and crustal thinning. This process resulted into formation of geothermal systems (elevated heat flow related to upwelling asthenosphere) along rift bounding faults.

Alternatively, when magma is emplaced into shallow crust, heat from intrusion is thus either convected to the earth's surface or it forms a hydrothermal reservoir at some intermediate depth. Magma storage chambers or intrusion can support geothermal resources in magmatic driven systems. In this initial phase of rifting, magmatism encompasses the rift, with volcanic activity affecting the rift depression, the major boundary faults and limited portions of the rift shoulders (off-axis volcanism; Corti et al, 2012).

Uganda's geothermal systems are classified as fault-bounded system (Brophy Type E). They are extensional driven type geothermal system (as defined by Koening and McNITT, 1983, Wisian et al 1999) as opposed high-temperature magmatic driven geothermal systems. Under hydrological continuity, they rely on deep circulation of meteoric waters along high angle rift bounding faults into the thermal zone where they are heated and rise by buoyancy to the surface as hot springs. They are low to medium temperature geothermal systems. The Western rift valley is known to be seismically active both from felt and instrumental information on earthquake occurrences (Loupekine, I. S et al, 1966). Bi-modial quaternary igneous activity is not documented in the western rift presumably ruling out possibility of silicic rocks formation. Rocks like, silicic tuffs, silicic lahars, silicic lavas, obsidian and pumice are not documented in the Western rift. In contrast to the widespread volcanism observed in the eastern or Gregory (Kenya) rift system, volcanic province in the western rift are areally, volumetrically small leaving the vast majority of western rift devoid of magmatism.

2.1 The Role of Volcanic Geology in Geothermal Investigations

High-temperature geothermal resources occur primarily in zones of active volcanism along spreading ridges, above subduction zones, at intraplate melting anomalies and at slab windows (Muffler et al, 1976). In all these plate-tectonic environments, conductive transfer of thermal energy is greatly enhanced by coupled magma movement and hydrothermal circulation, thus providing near surface high-temperature thermal anomalies that constitute attractive targets for geothermal exploration (Muffler et al, 1976). Geothermal resources on the basis of their origin can be classified as two main category (Muffler, 1976).

Many of the electric-power producing geothermal reservoirs in the world occur in or near young silicic volcanic fields. Magma storage zones (chambers) that feed rhyolite volcanoes are commonly large and located in shallow crust. If the rhyolitic magma chambers have not cooled substantially, they offer a heat source within the range of modern drilling technology (Smith and Shaw, 1975). Basalts fields are fed by narrow dikes extending from great depth and are less favorable geothermal targets, although some places like Iceland and Hawaii they form important geothermal concentrations.

2.1.1 Geothermal Resources Associated with Igneous Intrusion in The Upper Crust

These require emplacement of magma in the upper crust. There must be some suitable barrier or cap to prevent magma from erupting. When magma from the lower crust or the upper mantle quickly reaches the earth's surface, it quickly loses all its heat to the atmosphere without forming producing significant geothermal resources (Harsh K, Gupta et al,). However, a body of magma confined at some depth from the earth's surface dissipates its heat by a variety conductive and convective processes, giving rise to geothermal resources. Partial melting of crustal materials produces silicic magma and intermediate rocks. There must be intrusion of large volume of molten rocks into the shallow crust. The magma itself is a potential resource. After intrusion magma loses heat by conduction and convection.

2.1.2 Resource Associated with Deep Circulation of Meteoric Waters

These are characterized by warm water springs associated with regions of normal or even low geothermal gradients. There are located in regions not associated with Cenozoic volcanism. Geothermometry does not reveal elevated temperatures at shallow depth. Such warm springs appear to be related to deep circulation of meteoric waters. A good example are the warm springs of the Basin & Range Province of USA, Western Turkey ascribed to extensive normal faulting

2.2 Western Rift Volcanism

The Volcanic terrains are characterized by silica-under-saturated mafic volcanism and local development of evolved products (hyper sodic, ultra-potassic and carbonatites). Volcanic terrains are located within accommodation zones where presumably deep faulting taps magmatic reservoir. Mid-Miocene to Recent lavas in the western rift branch of the EARS are confined to four intra-basinal accommodation zones (Ebinger, 1989; Pasteels et al, 1989; Furman, 1995 ;). Pouclet et al (1983) noted a trend towards increasing potassium and CO_2 coupled with increasing silica under saturation towards the north where carbonatites also occur (Baker and Nixon, 1989; Stoppa et al, 2000). In the Toro-Ankole Volcanic field, ultra-potassic rocks are common. Several Quaternary volcanic fields occur to east and south east of Mt. Rwenzori. The volcanic edifices of this area are reported to be kamafugite; pyroclastics dominate over lavas (Holmes and Harwood, 1932) due to extremely volatile-rich explosive nature of the volcanism.

Potassic alkaline magmatism was active in the Upper Pleistocene and continued intermittently until recent times (Holmes, 1950; Lloydet al 1991). According to age dating (K-Ar and Ar-Ar), all volcanics are younger than 50ka (Boven et al., 1989). According to Nixon (1973), the age of Fort Portal volcanic activity is thought to be Upper Pleistocene to Recent by analogy with the other fields further south where carters are latter than the Middle Pleistocene Kaiso Rift Sediments. All craters are barely eroded, and as Wayland first pointed out belong the very late phase in volcano-tectnonic history of western rift. Bailey and Collier (2000) concluded that a thick lithosphere, low geothermal gradient, extensional tectonics and an important role for volatiles are essential for kamafugite magmatism. Reece (1955) noted recency of volcanic activity probably continued into historic times.

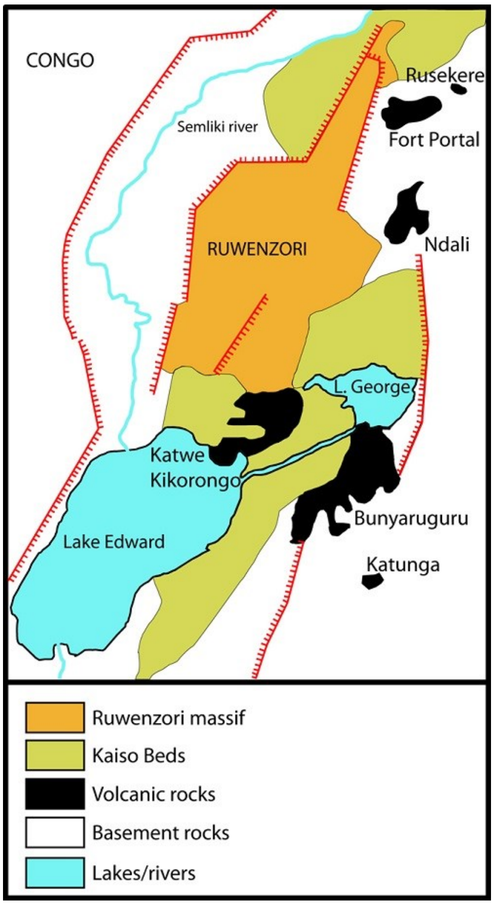

Figure 1: Map showing volcanic centers in Black

2.2.1 The Katwe-Kikorongo Volcanic Field

The Katwe-Kikorongo volcanic field consist of at least seventy-eight (78) explosion craters in an area of about 21km2 (Matthews, P. E., 1953). Two recency groups can be recognized; an older group filled by the ultra-potassic volcanic dust and ash. The other group is younger with sharp rims and steep crater walls. There are seven (7) crater Lakes with varying degrees of blackish water and an encrustation of salt is usually found around the edges. At Katwe, the saline water is saturated with salt precipitates. The lavas and tuffs of this field are strongly silica under-saturated and potassic to ultra-potassic in composition (kamafigute affinity of Sharma, 1974). These fields are the type area of the three primary magmas of Holmes (1965) that comprise the kamafugite affinity; ugandite (primary minerals are olivine, pyroxene, leucite); mafurite (primary minerals olivine, pyroxene, kalsilite); katungite (primary minerals olivine, melilite, kalsilite, leucite) (Nelson et al,). The field consist of pyroclastic ring-craters, lavas are rare (Nelson et al, 2016). Lloyd et al (1991) estimated the field consists of 0.07 km3 of small lava flow and lava piles and 63km3 of ash. Stoppa et al (2000) reported carbonite lapilli and bombs in Murumuli crater indicating carbonatite magma were present. The craters resulted from a series of violent explosions of volcanic gas and steam. Explosions were more or less simultaneous and all must have taken place within a short time of one another. An explosive phase is the precursor to any volcanic episode and it is followed by the outflow of lava which builds up a volcanic cone around the center of eruption. In Katwe the second phase did not occur. Except for three very limited occurrence no lava flows are known (Matthews, P. E., 1953). Explosive materials include very fine dust, ash and small fragments of rock (granite, dark amphibolite) blasted in the process. Explosion craters are of recent date similar to Fort Portal and Kichwamba (Matthews, P.E., 1953).

2.2.2 Fort Portal-Kasekere Volcanic Field

Fort Portal volcanic field was described by; Holmes and Harwood (1932), von Knorring, and Du Bois (1961), Bell and Powell (1969), Nixon and Hornung (1973), and Baker and Nixon (1989) among others. It is a magmatic tectonic geological setting. Volcanic activity at Fort Portal occurred between 6,000-4,000 years ago (Vinogradov et al, 1980) and resulted in the formation of monogenic cones, comprises of lapilli tuffs. This small field consist of forty nine (49) caters with rings of friable (extrusive carbonatites) lapilli tuffs. The volcanoes lie along a linear N.W. trending zone. The tuffs are either friable lapilli or are welded and flaggy. The volcanic history included an explosive phase, possibly kimberlitic, followed by eruption of lapilli, bombs and fragmental material, with only occasional eruption of lava and dyke rock. The age of the volcanicity is thought to be Upper Pleistocene to Recent by analogy with other fields further south (Nixon P. H. et al 1973). All craters are barely eroded and as Wayland first pointed out, belong to a very late phase in the volcano-tectonic history of the Western Rift. Fort Portal volcanic rocks occupy an area approximately 142km2 and those of Kasekere approximately 2.5km2. They have a total volume of 0.25km3. The most spectacular occurrence is the one to five meter thick lava flow at Kalyango (Nixon, P.E. et al, 1973). It has very little SiO_2 and alkalis. Tuffs are the predominant volcanic rock type. Carbonate from former hot springs or fumarole are reported at Nyabusozi, Kasekere and Saka volcano (Nixon, P.H, 1973). The lapilli tuffs are poorer in silica and richer in carbonate. Throughout the main eruptions, the magma is represented by bombs and only occasional lava and dyke rock. This sparse distribution is probably explained by a rapid and violent exsolution of gases in the magma near surface producing a turbulent boiling of fluidization resulting in lapilli formation. Analysis revealed the following minerals; olivine, clino-pyroxene, phlogopite and titanomagnetite.

2.2.3 Bunyaruguru Volcanic Field

Bunyaruguru consist of over 130 craters which have been blown through sub-aqueous tuffs (Nixon, P.H. 1967). Twenty seven (27) contain lakes. Bunyaruguru contains extrusive carbonatites (Baker and Nixon, 1989), attesting to importance of CO_2 in the source. The carbonatite lavas and tuffs of the Bunyaruguru field overlie the youngest rift sediments and are affected by faulting. Barker and Nixon (1989) considered the Bunyaruguru volcanics to be Late Pleistocene to Recent in age. Boven et al. [1998] showed that eruptions in the Toro-Ankole province started at about 50 ka and continued until 4 ka. Although age data are scarce, the field relationships underscore the very young age of the Bunyaruguru volcanics. Bunyaruguru rocks consist of mainly tuffs and agglomerates which were formed from middle Pleistocene to quaternary (Reece, 1954a). Bunyaruguru volcanism involved frank eruption and discharge. Volcanic activity occurred late in the Pleistocene and it was explosive in character with minor effusive lava flows (Reece, 1953). Only five occurrence of lava are known (Nixon, P.H. 1967). Wayland (1921) recognized the sub-aqueous and calcareous nature of the volcanic ash flow tuffs (explosive). Two eruption episodes were recognized since craters drilled through older tuffs. The tuffs in places are greater than 122m. Analysis revealed the following minerals; olivine, leucite, clinopyroxene, cr-spinelide and phlogopite. Some 16km to the south east of the Bunyaruguru field is the isolated volcano of Katunga (north of Bushenyi). This is a volcano with a crater lake and from which a lava of unique composition was extruded (Nixon, P.H. 1967). Surface geothermal manifestations include travertine deposits which is located along main bounding fault (Kichwamba border fault) indicating past geothermal activity. Other evidence include volcanic craters (off axis volcanism). Previous studies by Reece (1954b) have documented surface manifestations of geothermal activity like hot spring deposits around the Kyambura gorge and in crater rims. According to Sebastian et al, 2003, the rock samples analysed from Bunyaruguru indicates rocks Mafurite, K-Ankarite, and Ugandite. These kamafugite represents primitive ultra-potassic rocks which are extreemly rare but widespread. They are characterized by silica under-saturation, low Al, moderately high K but extremely high Ca content and as consequence of this unusual major element composition modal kalsite, melilite and perovskite frequently occur (Sebastain et al, 2003).

2.2.4 Ndale (Kyatwe) Field

About seventy craters are present showing similar charactertincs to those of Kichwamba. The craters are aligned along a NE-SW axis which corresponds to the strike of the underlying rocks (Nixon, P.H. 1967). No lavas or even lava bombs are known. The tuffs are reported to be radioactive due to presence of betafite (Nixon, P.H. 1967). Maximum thickness of the pyroclasts is probably of the order of 30 – 91m. These largely basaltic terraisn are not generally considered to be viable exploration targets for high temperature geothermal system. There is paucity of geothermal surface indicators in these volcanic terrain.

2.2.5 Birunga (Bufumbira) Volcanoes

These lie in the depression of the Edward-Kivu rift which is part of Western Rift. These were described by Combe and Simmons (1933); Holmes and Harwood (1937). Bufumbira field is comprised of intercalated lavas and pyroclastics, 34 small cones mainly composed of pyroclastics and 11 pyrocltastic domes and ridges (Lioyd et al 1991). Lavas are more abundant than pyroclastics. The most primitive mafic rocks are basanites. In Uganda these include; Sabinio (3,658m), Mgabinga (3,475m) and Muhavura (4,114m). Sabinio is the oldest volcano. There are an additional 34 separate (and probably of later date) smaller volcanoes. Also there are ash ridges due to eruption through fissures (Nixon, P.H. 1967). These small volcanoes are built of ash and extremely frothy types of lava. All are steep sided and rise to no more than 152m above the surrounding land. This field while also pottasic shows much lower degree of K-enrichment. In many cases the cone appears to have been built up of ash followed by extrusive (in some volcanoes, an intrusive) lava phase. Sabinio boulder debris consist of lava boulders set in much finer volcanic debris. The lavas are characterized by a composition in which $K_2O > Na_2O$. They fall into roughly four groups; Leucitities (leucite + pyroxene); leucite basanite (leucite, olivine, pyroxene, feldspar); Saturated K-rocks (orthoclase + plagioclase + little or no leucite, olivine or augite); oversaturated types with feldspar and quartz, especially hypersthene latite (Nixon, P. H. 1967).

Table 1: Origin of the volcanic rocks in Uganda (Nixon, P.H. 1967)

South→North

	S. Kivu	Birunga	Katwe, Kichwamba, Katunga, Ndale, Kasenyi crater	Fort Portal
Chemical composition		Potassic mafics and felsic rocks, mildly potassic region	Ultra-potassic volcanics, strongly potassic region	Extrusive carbonatites
Rock type	Olivine basalt subordinate trachyte, rhyolite	K-rich lavas, leucite bearing felspathic types present	K-rich ultrabasic lavas, bombs and lapillae	Highly carbonate rich ultra-basic lavas
Origin	Primary uncontaminated olivine basalt + differentiation products	Olivine basalts + Sial (granite) + carbonatite → K-rich lavas	Carbonitite magma + G(crustal xenolith) →OPB+K	Carbonatite magma +G (crustal xenolith)→ OPB+K
Theory to propose uplift at nodes along rift	Eclogite → basalt	Eclogite → basalt + introduction of carbonatite magma	Introduction of carbonatite magma	Introduction of carbonatite magma
Volcanic products		Lava flows, tephra, scoria, bombs	Tuffs, ashes, bombs, lavaflows	Lava and tuffs

While lavas contain crustal material, the generally low silica content suggest crustal contamination is limited. Basaltic magmas are more fluid than andesite and dacite and react very little with crustal rocks because of its low viscosity.

3. BASALTIC VERSUS SILICIC VOLCANISM AND THEIR GEOTHERMAL SIGNIFICANCE

Types of magmas: There are generally three (3) types of magmas (see table 2); *Basaltic magma* -- SiO_2 45-55 wt%, high in Fe, Mg, Ca, low in K, Na; *Andesitic magma* -- SiO_2 55-65 wt%, intermediate. in Fe, Mg, Ca, Na, K and *Rhyolitic magma* -- SiO_2 65-75%, low in Fe, Mg, Ca, high in K, Na.

Gases in Magmas: At depth in the earth nearly all magmas contain gas dissolved in the liquid, but the gas forms a separate vapor phase when pressure is decreased as magma rises toward the surface of the earth. The composition of the gases in magma are mostly H_2O (water vapor) & some CO_2 (carbon dioxide) and minor amounts of Sulfur, Chlorine, and Fluorine gases. Rhyolitic magmas usually have higher gas contents than basaltic magmas.

Viscosity of Magmas: Viscosity is the resistance to flow (opposite of fluidity). Viscosity depends on primarily on the composition of the magma, and temperature. Higher SiO_2 (silica) content magmas have higher viscosity than lower SiO_2 content magmas (viscosity increases with increasing SiO_2 concentration in the magma). Lower temperature magmas have higher viscosity than higher temperature magmas (viscosity decreases with increasing temperature of the magma).

Summary Table 2

Solidified Rock	Chemical Composition	Temperature	Viscosity	Gas Content
Basalt	45-55 SiO_2 %, high in Fe, Mg, Ca, low in K, Na	1000 - 1200 °C	Low	Low
Andesite	55-65 SiO_2 %, intermediate in Fe, Mg, Ca, Na, K	800 - 1000 °C	Intermediate	Intermediate
Rhyolite	65-75 SiO_2 %, low in Fe, Mg, Ca, high in K, Na.	650 - 800 °C	High	High

Basaltic magmas is commonly produced by direct melting of the earth's mantle and rise quickly to the surface. Magmatic differentiation in the lower crust produces rhyolitic magmas probably caused by intrusion of basaltic magmas (see diagram 1 below). In some cases the rise is rapid that they don't react with crust because of low viscosity. Their silica under-saturation means there was limited assimilation of xenolith rocks or magmatic differentiation.

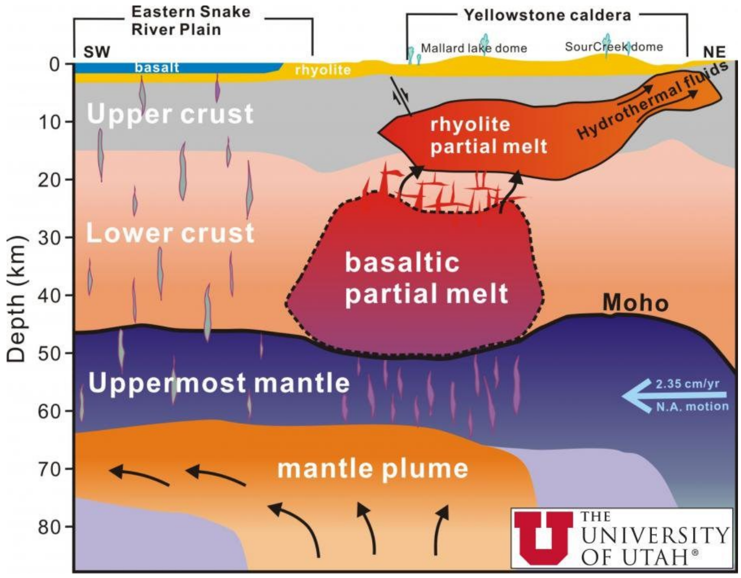

Diagram 1: Showing magmatic differentiation (Adopted from The University of Utah)

The volcanic explosivity Index of basaltic lava is low compared to rhyolitic lava. Young volcanic system in Western Rift are predominantly composed of silica under-saturated basaltic rocks and related magmatic products. Most of the associated volcanism is basaltic and primarily effusive. Under some conditions basaltic lavas are potential indicators of buried high-level silicic bodies (intrusion of magma deposition at shallower depth) with no obvious surface manifestations. Differentiation from mantle derived basalts to rhyolite occurs in dikes and sills at relatively shallow depths (5-10km).

Silicic magma forms when mafic magma stalls (lodge) in the shallow crust forming shallow magma chambers, and erupts either explosively to generate ash falls and flows, or effusively to produce lava flows and domes. Bimodal volcanic activity that is associated basaltic and silicic volcanism is not documented in western rift. Bimodal volcanic activity is common in Iceland (Silicic and mafic eruptions at Katla and Hekla). There are well documented geothermal systems in areas of Basaltic volcanism without associated rhyolites (Kilanea Volcano, Hawaii, Reykjanes in Iceland). This could be attributed to partial melting altered basalts. Felsic melts could have formed by magma differentiation. Without a thermal boost, silicic magma chambers cool and solidify, they never reach the upper crust. Silicic volcanic rocks are not documented anywhere neither rocks like pumice and obsidian mapped in Western rift valley.

As indicated by Smith and Shaw (1975), the basalts that form most volcanoes have probably risen rapidly from the mantle to the surface during volcanic eruption. As a result, their heat is dispersed rather than stored and does not provide useful geothermal concentrations. Heat is directly related to magma storage chambers in the shallow crust of the earth (Smith & Shaw, 1975). The high silica variety of volcanic rocks, perhaps because of very high viscosity, are commonly associated with magma storage chambers at shallow levels in the crust (perhaps 2-10km) but most commonly about 4km (Smith & Shaw, 1975) and can sustain high temperature convection systems for many thousands of years. Many large geothermal systems appear to be associated with young silicic volcanic rocks. Smith and Shaw (1975) pointed out that basalt is channeled rapidly from depth to the surface through fractures forming dikes that cool rapidly. In contrast rhyolite magmas commonly form large voluminous sub-surface magma storage chambers in shallow crust and are therefore more capable of providing a larger and longer lived heat source for hydrothermal circulation.

In Uganda, there is paucity or limited occurrence of geothermal surface indicators in volcanic terrains. Young obsidian or pumice flows are lacking unlike in Kenya and Ethiopia. Most high grade recoverable geothermal energy is likely to be associated with silicic young volcanic systems active in the past 1 million years. Purely basic volcanism rarely form geothermal anomalies of economic interest, whereas silicic volcanic systems probably always do if they are large and volumetrically big. In some oceanic systems, there is the admitted possibility of the existence of high level basic magma storage chambers.

Finally, single basaltic / ultra-basic magma eruption are considered to be immature volcanic evolution. Volcanoes which erupt magmatic products from multiple basaltic/ ultra-basaltic to andesitic and up to rhyolite magma products are considered as mature volcanoes. Immature volcanic systems are characterized by fissure vents, simple monogenetic cones, mafic magma and stromboli / volcanic eruption thin lava flows. In contrast mature volcanic systems are characterized by central and parasitic vents, multiple cones / cones/ calderas, intermediate to silicic magmas, active fumaroles and hot springs with areas of acidic alteration, Plinian and pelean eruptions, pyroclastic flows and ash falls, silica domes, (Wohletz et al 1992).

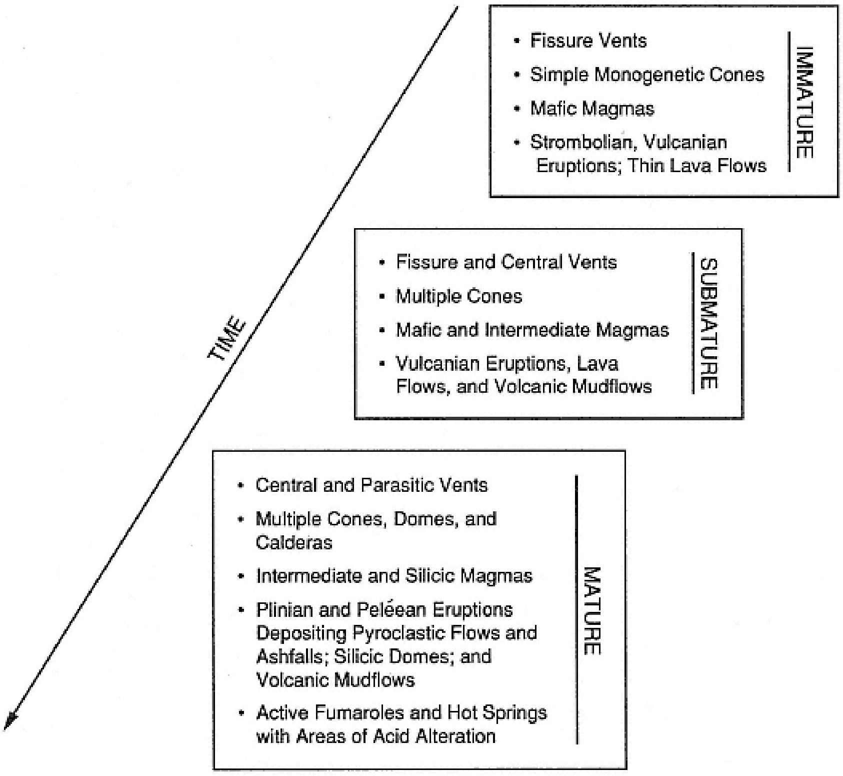

Figure 2: The evolution and geothermal potential of composite cones (Kenneth Wohletz)

Composite cones usually evolve through time, as is displayed in Fig. 3 each successive eruption involves increased silica content in the magmas, shallower crustal magma bodies, and more energy. This process may last over several hundred thousand years but certainly less than a million years.

4. CONCLUSION

The Western Uganda volcanic terrain is characterized by silica-under-saturated mafic rocks and local development of evolved products (hyper sodic, ultra-potassic and carbonatites). Basaltic volcanism in western branch is geologically recent and the area is tectonically active (young faults). The province is volcanic geologic extensional terrain.

The basaltic magmas probably escaped magmatic differentiation or crustal contamination to produce young silicic magmas at shallow depth. The basalts probably rose rapidly from the mantle to the surface during volcanic eruption. As a result, it is likely their heat was dispersed rather than stored to provide useful geothermal concentrations. There is paucity of or limited occurrence of surface indicators in volcanic terrains. No young pumice or obsidian flow nor bi-modal volcanism is documented in volcanic terrains in Uganda ruling young silicic magmatism. There are no widespread occurrence of young silicic rocks in these volcanic terrains. Lava flows are limited with reported immature magmatic evolution.

In contrast the high silica variety of volcanic rocks, perhaps because of very high viscosity, commonly are associated with magma storage chambers at shallow levels in the crust (perhaps 2-10km) but most commonly about 4km and can sustain high temperature convection systems for many thousands of years. Many large geothermal systems appear to be associated with young silicic volcanic rocks. Basalt magma is channeled rapidly from depth to the surface through fractures forming dikes that cool rapidly. In contrast rhyolite magmas commonly form sub-surface storage chambers in shallow crust and are therefore more capable of providing a larger and longer lived heat source for hydrothermal circulation

Geothermal regimes in volcanic fields of Uganda presumably don't owe their existence to young high-silica intrusions (sub-surface shallow magma chambers) though the data is still insufficient. These are resource associated with deep circulation of meteoric waters. The magma storage chambers are presumably not the ultimate source of heat for these systems. Shallow level source of geothermal heat would have altered the rocks in the area. This working hypothesis invite further geophysical studies to conclusively prove or disapprove shallow magma storage chambers under these volcanic terrains.

REFERENCES

Barker, D.S. and Nixon, P.H.: High-Ca, low-alkali carbonatite volcanism at Fort Portal, Uganda. *Contrib. Mineral. Petrol.,* (1989). 103, 166-177.

Bailey, D.K. and Collier, J.D.: Carbonatite-melilitite association in the Italian collision zone and the Ugandan rifted craton: significant common factors. *Mineral. Mag.,* (2000), (64, 675-682.

Bailey K, Lloyd F, Kearns S, Stoppa F, Eby N, Woolley A.: Melilitite at Fort Portal, Uganda: another dimension to the carbonate volcanism. *Lithos*, (2005), 85: 15-25.

Barker D S, Nixon P H.: High-Ca, low-alkali carbonatite volcanism at Fort Portal, Uganda. *Contr Mineral Petr*, (1989), 103: 166-177.

Bell, K. and Powell, J.L.: Strontium isotopic studies of alkali rocks; potassium rich lavas of the Birunga and Toro-Ankole regions, east and central equatorial Africa. *J. Petrology (1969), 10: 536-572.*

Boven, et al.: Quaternary perpotassic magmatism in Uganda (Toro-Ankole volcanic province), age assessment and significance for magmatic evolution along East African Rift, Afri. Earth Sci., (1989), 26, 463-476.

Combe, A.D. and Simmons, W.C.: The volcanic area of Bufumbira Part 1: The Geology of the volcani area of Bufumbira, south-west Uganda, Memoir, Geol. Surv. Uganda (1933).

Combe A. D.: The Katunga volcano S.W Uganda Geol. Mag 74 (1937) 190-200

Delvaux, D.: Structural development and fault kinematics of the Western Branch of the EARS (2016).

Delvaux, D.: Structural development and fault kinematics of the Western Branch of the EARS and their controls on geothermal resources (2016).

Ebinger, C. J.: Tectonic development of the western branch of the East Aji• ican rift system. Geol. Soc. Am. Bull., (1989), 101, 885-903.

Furman, T.: Melting of metasomatized sub-continental lithosphere: under-saturated mafic lavas from Rungwe, Tanzania. Contrib. Mineral Petrol., (1995), 122, 97-1 15

Giacomo, Corti.: Evolution and characteristics of continental rifting, Analog modeling –inspired view and comparison with examples from East African Rift System, Tectonophysics (2011).

Giacomo, Corti.: Continental rift evolution: From rift initiation to incipient break-up in the MainEthiopian Rift, East Africa, Earth-Science Reviews (2012).

Harsh, K. Gupta. et al.: Geothermal Energy: an alternative resource for 21st century; Elsevier (2017)

Holmes, A.: Petrogenesis of katungite and its associates. Am. Mineral., 35, 772-792. -, (1952) - The Potash Ankaratrite-Melaleucitite Lavas of Nabugando and Mbuga Craters, South-West Uganda. Trans. Edin. Geol. Soc., (1950), 15, 187213.

Holmes A, Harwood H F.: Petrology of the volcanic fields east and south-east of Ruwenzori, Uganda. Quart J Geol Soc London, (1932), 88: 370-442.

Holmes, A. and Harwood, H.F.: The petrology of volcanic area of Bufumbira, south-west Uganda. Memoir Geol. Surv. Uganda, (1937), 3:1-300

John, Harvey. Sass. et al.: Geothermal Energy: Clean power from the earth's heat, USGS (1991).

Koenig, J.B. and McNitt, J.R., 1983, Controls on the location and intensity of magmatic and non-magmatic geothermal systems in the Basin and Range province: Geothermal Resources Council, Special Report No. 13, p. 93.

Lloyd, et al.: Phanerozoic Volcanism of Southwest Uganda: A case for regional K and LILE enrichment of the Lithosphere beneath a domed and rifted Continental Plate, in Kampunzu, A.B., and Lubala, R.T., eds ., Magmatism in Extensional Structural Settings : the Phanerozoic African Plate: Berlin, Springer, (1991), 23-72

Lloyd F. E. et al.: Rift valley magmatism is their evidence for laterally variable alkali clinopyroxene mantle. Geolines (1999), 9: 76-83.

Loupekine, I. S.: The Toro earthquake of 20 march 1966, earthquake reconnaissance mission UNESCO (1996).

Matthews, P.E.: The Katwe-Kikorongo explosion craters in the Queen Elizabeth National Park, Toro, Uganda, Geological Survey of Uganda Report PEM/10 (1953).

Muffler et al.: The role of volcanic geology in the exploration of geothermal energy (1976).

Muffler, L.J.P.: Tectonic and hydrologic control of the nature and distribution of geothermal resources; Processings of the 2nd United Nations Symposium on development and use of geothermal resources 20-29 May 1975, San Francisco, California, Vol 1 Washington D.C (1976).

Nelson, E. G.: Geochemistry and mantle sources for carbonatittic and potassic lavas western branch of the East African Rift System, SW Uganda. Geolines 15 (2003)

Nixon P H, Hornung G.: The carbonatite lavas and tuffs near Fort Portal, western Uganda. Overseas Geol Min Res, (1973), 41: 168-179

Nixon, P.H. 1967. Notes on volcanicity in the western rift in Uganda. Geol. Surv. Of Uganda (1967).

Nixon, P.H.: The Geology of the Fort Portal and Kasekere volcanic fields, Rep. Geol. Surv. Uganda, No. PHN/15 (Unpubl., 1967)

Pasteels, P. et al.: Timing of the volcanism of the southern Kivu province: implications for the evolution of the western branch of the East African Rift system. Earth Planet. Sci. Lett., (1989), 94, 353-363.

Patrick Muffler L. J and Wendel A. Duffield.: The Role of volcanic geology in the exploration for geothermal energy (1976)

Peter Stelling. Nick Hinz, Lisa Shevenell, William Cumming, Mark Coolbaugh, Glen Melosh: Volcanic features and geothermal potential (2016).

Pouclet, A. et al.: Le magmatisme alcalin potassique de l 'a ire volcanique des Viringa (Rift occidentale de l'Afrique de l'Est). Une approche statistique dnasla re cherche des fi liations magmatiques et des nuicanismes de differenciation. Bull. Mineral., (1983), 106, 607-622

Reece, A. W.: The Bunyaruguru volcanic field, Records of Geological Survey of Uganda, (1953), pp 29-47.

Sebastian et al.: The Kamafugite of Uganda. A mineralogical and geochemical comparison with their Italian and Brazilian analogues (2003).

Smith, R.L., and Shaw, H.R., 1975, Igneous-related geothermal systems, in White, D.F., and Williams, D.L., eds., Assessment of geothermal resources of the United States— 1975: U.S. Geological Survey Circular 726, p. 58-83

Stoppa, F. et al.: Carbonatite lapilli-bearing tuffs and a dolomite carbontite bomb from Murumuri crater, Katwe Volcanic Field, Uganda, Mineral, Mg. (2000), 64: 641-650.

Vinogradov, V. I et al.: Carbon 13/Carbon 14; oxygen 18/oxygen 16, carbon 14 concentration in the carbonitite of the Kalyango volcani area in East Africa, Int. Geol. Res. (1980), 22: 51-57.

Von Knorring. O. and DuBois. C.G.B.: Carbonatitic lava from Fort Portal area in western Uganda. Nature 192 (1961), : 1064-1065.

William, E. Glassley.: Geothermal Energy: Renewable Energy and the Environment, (2012), 2nd Edition, CRS Press.

Wisian K. W. Blackwell D.D. and Richards M.: Heat flow in the western US and extensional geothermal systems; Proceedings 24th Workshop on Geothermal Reserviour Engineering, Stardford C. A P 219-226 (1999).

Wohletz, K. & Heiken, G.: Volcanology and geothermal energy; Berkeley University of California, (1992), Press 432p.