Geology of Kibiro, Katwe and Buranga Geothermal Prospects of Uganda

James Francis Natukunda

Department of Geological Survey and Mines (DGSM), P.O. Box 9, Entebbe, Uganda.

jfnatukunda@gmail.com

Keywords: rifting, hot springs, fault permeability, geology

ABSTRACT
The three main Ugandan geothermal fields namely, Kibiro, Katwe and Buranga are located in the western arm (the Albertine Rift) of the East African Rift System (EARS). The general strike of the Albertine Rift is NE-SW. Geophysical surveys indicate 2500 to 3000m thickness of Pleistocene sediments in the rift floor.
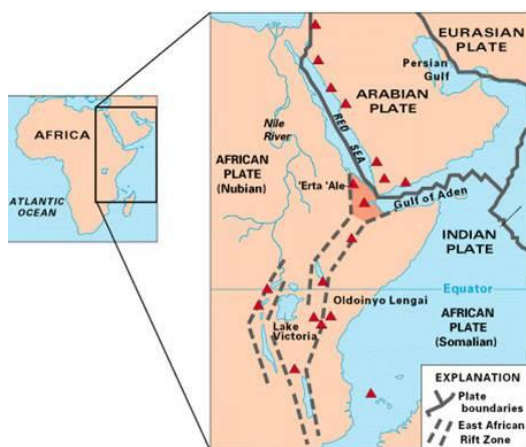
The Kibiro geothermal prospect, which is located at the Eastern escarpment of Albertine Rift is comprised of hot springs that emerge at the base of the escarpment at the intersection of three oblique faults. The escarpment forms a boundary between the old basement rocks (to the east) and the young sedimentary formation of the rift (to the west). The basement consists of Precambrian granites, granitic gneisses, gneisses and N-S striking basic amphibolite intrusives. Mylonitic gneisses characterise the fault-controlled valleys. The NE striking faults in the area are oblique to the main rift fault and crosscut E-W striking faults. All rocks are heavily fractured with crosscutting joints. The geothermal manifestations include; hot springs, solfatara, extinct clayey alterations and secondary hydrothermal minerals that include gypsum and calcite filling joints in altered mylonitic gneisses on the escarpment among others. The maximum temperature of the hot springs is 86.4^0C.

The Katwe volcanic field is on the SE of the Rwenzori massif and consists of 78 randomly distributed craters of which seven have water. The volcanics are deposited on Pleistocene sediments. Precambrian rocks of Toro system lie on the western side while on the eastern side; the sediments are underlain by Karagwe-Ankolean (K-A) metasediments. In the south-eastern side of Katwe field, there is Bunyaruguru volcanic field that consists of tuffs mixed with K-A rock fragments. The Katwe volcanics are mainly phreatomagmatic pyloclastic deposits consisting of ash, tuff, lapilli, volcanic bombs and xenoliths of basement rocks. Basaltic lava flows and ejected lava blocks occur around Kyemengo and Kitagata craters. The volcanic material pile rises up to 420m above surrounding sediments. NE-SW striking faults that characterize the field are parallel the strike of the main rift fault. Carbon dating puts the age of volcanism as Pleistocene to Holocene. The Katwe geothermal manifestations include travertine deposits that indicate extinct hot springs, warm springs (30^0C) at L. Katwe and hot springs (70^0C) at L. Kitagata.
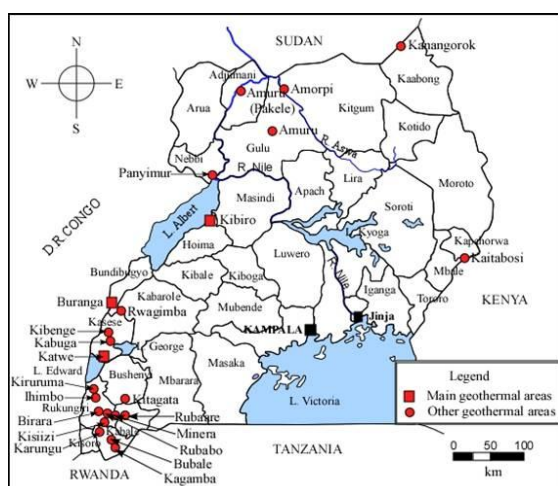
The Buranga field is located at the NW end of the Rwenzori massif near the base of Bwamba escarpment. The hot springs emerge through Pleistocene sediments. Precambrian rocks underlie the sediments. The main rift fault strikes 45^0 and dips 60^0-65^0. The three hot spring areas namely Mumbuga, Nyansimbe and Kagoro lie on a line striking 40^0 parallel to the main rift fault. Precambrian rocks form the northern half of the Rwenzori massif that strike 10^0-30^0 and consists of migmatites and gneisses. The sediments consist of fine to medium-grained, poorly consolidated sands and clays, some of which are coated with calcareous material. The geothermal manifestations of Buranga field include three hot spring areas with a maximum temperature of 98^0C, travertine cones and some sulphur deposits at Kagoro spring area. The area is seismically active and the frequent earthquakes in the region are reactivate and create new manifestations like new hot springs near Nyansimbe pool.
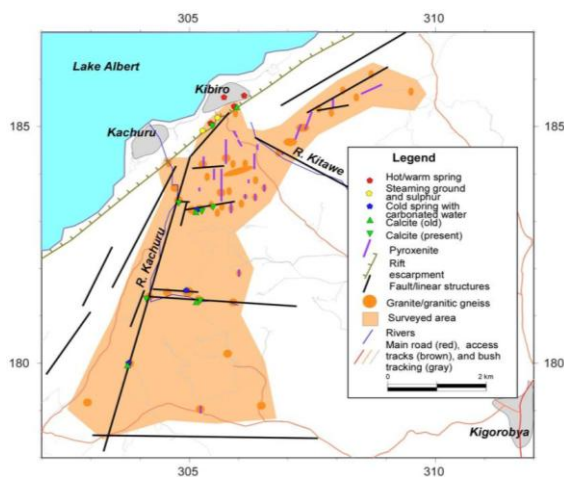
1.0 REGIONAL GEOLOGY
The geology of Uganda consists of an exposed pre-Cambrian basement dissected by the western branch of the East African Rift System in the western part of the country (Figure 1). The eastern branch, the Gregory Rift, passes through the central part of Kenya. The Western branch, the Albertine Rift, starts to the north along the Sudan border, and then curves to the west and then southwest along the border with the Democratic Republic of Congo, and south to Rwanda, Burundi and western Tanzania. Spreading began at least 15 million years ago in Miocene time. The western Rift is considered to be at an early stage in the development, and is younger (late Miocene-Recent) than the more mature eastern branch (Morley and Westcott, 1999). The Albertine Rift is seismically active, characterized by deep-seated (27–40km) large earthquakes. The region of the Rift has a markedly higher heat flow than the surrounding Pre-Cambrian terrain. Two different en echelon strands are found in the Western Rift Valley, separated by the Rwenzori Mountains, which rise from a base of less than 1,000m in the Rift to over 5,000m elevation. Within the Rift Valley there are thick layers of late Tertiary and Quaternary sediments, fresh water and saline crater lakes, volcanic, and plutonic bodies have been identified beneath L. Albert and L. Edward (EDICON, 1984). The three main geothermal areas of Uganda are Kibiro, Katwe, and Buranga.

Figure 1: The East African Rift System

2.0 LOCATION OF KIBIRO, KATWE AND BURANGA GEOTHERMAL AREAS

The Kibiro geothermal area is situated in Hoima District (Figure 2), on the eastern shore of Lake Albert. Kibiro is located at the foot of the escarpment of the western branch of the EARS. The escarpment rises over 300 m above Lake Albert.

The Katwe-Kikorongo (here after refered to as Katwe) geothermal prospect is one of three geothermal areas, which have been studied by the Ministry of Energy and Mineral Development (MEMD), the other two being Kibiro and Buranga in Hoima and Bundibugyo Districts respectively (Figure 2). Katwe is in the Kasese District. It is within the Queen Elizabeth National Park, south of the Rwenzori Massif and north of Lake Edward. Katwe is a volcanic area with many phreatic craters but very little lava at surface. Some of the craters have crater lakes. The most pronounced hot spring is on bottom of the crater lake in the Kitagata crater.

Being in a national park, the Katwe area is mostly uninhabited, except for the Katwe village, south of the saline Lake Katwe. Considerable salt mining takes place in Lake Katwe.

Figure 2: The geothermal areas of Uganda

3.0 THE GEOLOGY OF KIBIRO GEOTHERMAL FIELD

3.1 Introduction

The Kibiro area is located on the eastern escarpment of the western branch of EARS. It covers the small peninsula below the escarpment where the villages of Kachuru and Kibiro are located, the escarpment itself as well as the land extending from the escarpment shoulder towards the east. The area's altitude is from 620m above sea level (asl) at the rift floor and Lake Albert to 1,100m asl on the Rift shoulder. The area consists of deep and steep valleys (fault zones), especially closer to the escarpment. The temperature of the area is in the range of 32-38°C.

3.2 Description of Rock Units

The escarpment cuts through the field from SW to NE and divides the study area in two entirely different geological environments. To the east, the geology consists of crystalline basement, characterized by granites and granitic gneisses, whereas in the rift there are thick sequences of sediments. The best rock outcrops are found in the escarpment face, but the rock is usually highly transformed by the fault movements. Good outcrops are also found along the numerous fault-lines in the block-faulted rock and on the eastern side, the outcrops are restricted to a few outcrops on hills. These are the hardest rocks, and therefore resistive to weathering. The softer rocks have weathered and formed depressions in the undulating landscape (Gislason et al., 2004).

3.2.1 Granite and Gneiss

These Precambrian rocks form the entire basement east of the escarpment. They are fine to coarse-grained composed of quartz, feldspars, amphiboles (mainly hornblende) and biotite. Their colour ranges from grey to light brown and in some places pink hue depending on the type of feldspar present. Banding is common and is more pronounced closer to the escarpment, and usually dipping very steeply (60-90°), with the most common direction of the strike being close to N20°E although E-W direction is also common (Gislason et al., 2004). Close to the escarpment and in association with fault lines the granites are mylonitic or brecciated, typical of highly a faulted environment.

The stage of weathering or alteration of the granites depends strongly on the structure and location of the rock. The massive, un-banded granites tend to be very fresh, and generally, the rock is less altered with distance from the escarpment.

3.2.2 Amphibolite Dykes

Simmons (1921) was the first to describe dyke-forming intrusives within the present study area and referred to them as "pyroxenites" - a field term, but later authors (Kakenga et al., 1994) have referred to it as diorites. This formation is black, angular blocks on the surface, forming a small, elongated ridge in the landscape (Figure 3). These outcrops are usually 10-20m wide, but can be as long as a few km and are most common on the slopes and hilltops above Kibiro. Their strike varies from N-S to N20°E. In a hand specimen the rock is fine to medium-grained, dark grey in

colour and usually very fresh looking. No phenocrysts are seen, but joints are common. Microscopic examination of these intrusives in thin sections reveals that the rock is composed of quartz, pyroxene (orthopyroxene and clinopyroxene), apatite and relatively large amount of an opaque mineral (Gislason et al., 2004). The dykes appear unrelated to a heat source for the Kibiro geothermal system since there are no direct surface manifestations related to them (Natukunda, 2007).

Figure 3: Geology map of the Kibiro area

3.2.3 Rift Sediments

The studies that have been made on the sediments in the various parts of the EARS using geophysical methods indicate that the sediments are predominantly clastic, commonly fluvial and lacustrine deposits (Morley and Westcott, 1999). Little is known about the porosity and permeability of the rift sediments. Their age is between 10 and 15m.y. Although recent fluvial and lacustrine sediments usually have high porosity, with time these sediments become compacted and cemented, reducing their initial porosity and permeability. Wayland (1925) described the stratigraphy of the sediments of the Albertine Rift as consisting of three units: Epi-Kaiso gravels, predominantly arenaceous Kaiso beds and the underlying argillaceous Kisegi beds. In the Kibiro region, the Epi-Kaiso beds are about 20m thick, the Kaiso beds are 500m thick, and the total thickness is more than 1,200 m (Harris et al., 1956). The age of these two formations is uncertain, but Wayland (1925) considered the Kisegi to be possibly of Miocene age, and the upper part of the Kaiso beds to be late Pliocene or early Pleistocene.

A 684m deep well was drilled close to the oil seepage about 1.5km north of the Kibiro hot springs. The borehole log shows alternating layers of grey sand and grits with sandy clay and blue-green shales (Harris et al., 1956). At 120m the sediments are predominantly sand and gravel, but between 120 and 250m depth, layers of clayey sand and shales are dominant. Below 250m the proportion of sand is high, until the hole hits the basement rock at 1,222m.

3.3 Banding and Jointing

The granites in the area are usually without any banding, it is commonly associated with increasing faulting of the

granitic gneiss and mylonitic rocks. Several distinctive strike directions of banding have been observed, where east-west and N20°E are the most prominent. A less common strike direction is N130°E. The dip is usually very steep, in the range from 60° to vertical. Closer to the escarpment the bedding tends to have near vertical dip, but further "inland", the foliation in gneisses dips towards east and south. Banding is absent in the 'amphibolite' dykes. Joints are found in all rock types within the Kibiro, and have the same dominant direction as seen in the bedding. The joints and fissures are open or filled with secondary minerals such as quartz, calcite, kaolinite and sometimes pyrite.

A study of joints can reveal the stress field, which caused them. It shows the two prominent directions of joints in amphibolite outcrop, east-west and N20°E, intersecting at 60° angle. Also present is the less common joint with N130°E trend (Figure 4). A principal stress field with direction NW-SE, can explain this pattern of joints, more exactly with direction 140°E, which is exactly perpendicular to the direction of the rift in the area (N50°E) (Gislason et al., 2004).

Figure 4: Joints in amphibolite outcrop. The main joints form a 60° angle, and the main stress field is from NW-SE as per stress diagram to the right. (After Gislason et al., 2004)

3.4 Tectonics

The main faulting within the Kibiro area is the eastern escarpment of the rift, which cuts straight through the study area in N50°E. The visible vertical displacement at Kibiro from Lake Albert at 622m asl to about 960 masl. on the shoulder of the escarpment above Kibiro (340m). The land continues to rise towards the south-east, and at the village of Kigorobya the land elevation is about 1100m asl. Seismic refraction data in the rift shows that the total thickness of sediments at Kibiro-Butiaba is about 5.5km (PEPD, 2002), giving a displacement at Kibiro of at least 6km in total. The visible part of the escarpment fault - the extension belt - is restricted to a narrow band, not more than 1km, and often concentrated in one to two faults. Away from this narrow belt of rift faults no linear structures striking N50°E, i.e. the direction of the rift valley, have been found. The western branch of EARS is formed by series of half grabens, i.e. the main extension occurs on alternating sides of the rift, characterised by a dominant main boundary fault, but series of normal faults are hidden by lakes and sediments (Morley et al., 1999).

Drilling for oil north of Kibiro and at Butiaba showed that the escarpment dips at 65°E towards the rift (Harris et al., 1956). In the granites the most prominent landform within the study area is the valley of River Kachuru, which flows

off the escarpment to Lake Albert via Kachuru village, south of Kibiro. The valley cuts straight through the granites, very steep and narrow and 200m deep or more (Figure 5).

Figure 5: Kachuru fault-controlled valley viewed from its NE end

Its direction is N20°E, and parallel with it are a series of smaller valleys and linear alignments. This Kachuru Fault Zone (KFZ), is oblique to the main rift fault and intersects it at the villages of Kachuru and Kibiro. At this intersection several geothermal surface manifestations are located. Outcrops along the valley show strongly mylonitized rock, a characteristic fault rock, and the elongated fabric of the influenced rock is in the same direction as the fault. Mylonite is common in the vicinity of KFZ but is not found away from the fault zones. River Kachuru originates from a swampy area west of Kigorobya. It follows a direct course to the west until it flows into the Kachuru valley (Figure 5) where it turns NNE until it reaches the escarpment and flows into Lake Albert. The east-west direction of the upper parts of River Kachuru is a dominant linear structure in the study area, first described by Simmons (1921), who described an east-west fault just south of the study area and associated it with a bend in the Rift just south of the Kaiso Peninsula in Lake Albert. Simmons interpreted the two fault line directions (i.e. N20°E and E-W) in the granites as block faulting associated with the formation of the Rift. Simmons also mapped and described two East-West faults west of Kigorobya (Figure 3), and these have also been mapped by later authors (Kakenga et al., 1994 and Gislason et al., 2004).

River Kitawe follows a fault-controlled valley just north of the Kigorobya-Kibiro Road, and flows down the escarpment in a deep gully by the hot springs of Kibiro (Figure 3). The direction of this alignment is NW-SE (N120°E), intersecting the main escarpment at the Kibiro hot springs. Apparently, the NNE-trending Kachuru fault is the youngest one in the study area, as it cuts through the main rift escarpment. The Kachuru Fault apparently cuts off the east-west trending fault lines, indicating that they are older (Figure 3). On the other hand, the amphibolites, which have the same N-S trending lineament as the Kachuru Fault Zone, are clearly cut off by the E-W trending faults.

3.5 Geothermal Surface Manifestations

3.5.1 Hot and Warm Springs
There are three hot spring areas at Kibiro geothermal area. The main area of hot springs, Mukabiga, is located in a N-S trending ravine at the base of the main fault escarpment. A number of small springs issue from the boulder and gravel (Figure 6). Large amounts of gas escape from the springs, and there is a strong smell of H_2S in the air. There is little evidence of carbonate precipitation, but white thread-like algae are common in the stream. Close to the stream the threads are coloured black with sulphides. The springs are located on an elongated area, slightly oblique to the main fault. On the western side of the ravine is breccia outcrop related to a secondary fault, oblique to the main rift fault, and the springs are most likely controlled by the intersection of the two faults. Most of the springs drain into a small pool at the foot of the breccia outcrop, and gas bubbles continuously from the bottom of the pool. The total flow measured from the Mukabiga centre was 4 l/s, and the temperature range was between 57^0C and 86.4^0C.

A second group of hot or warm springs are found downstream, in an area of salt gardens called Mwibanda. The flow rate of 2.5 l/s is low, and the temperature range is 33^0C - 71.7^0C. Some of the seepages are on a straight N-S trending lineament, in a small dugout trench. Other springs are within the nearby Muntere salt gardens, which is directly north of the Mukabiga area. Its eastern side may be controlled by the secondary fault. Here the ground has been lowered down to the ground water level for the salt production. A number of small channels drain the area, and there are no well-defined springs. The highest recorded temperature at Muntere springs is 39.5^0C. Extinct clayey alterations occur in the breccia east of the Mukabiga hot spring area. They contain frequent colourless gypsum crystals.

Figure 6: A view of the main Mukabiga hot spring area. The springs emerge from a foot of a fault breccia

3.5.2 Steaming Ground and Solfatara - Surface Alteration
In the lower slopes of the fault escarpment there are several sites of outcrops of highly brecciated fault rock. A faint smell of H_2S is in the air and a thin film of sulphur covers the rocks. In cracks a well-formed sulphur crystals grow in clusters. Also present is a black tar-like hydrocarbon substance (Figure 7). No steam is seen rising, but the smell

and fresh deposits of sulphur demonstrate the presence of some gas being released. Calcite is found in cracks and fissures, indicating water discharge at earlier stages. A band of brecciated fault rock can be traced along the escarpment to both the north and south of this manifestation. About 175m to the north, and about 50m south of the track down the escarpment, the fault is well exposed in a shallow gully, and the rock is highly altered in a variety of colours. Sulphur and tar are present on rocks, but no smell is found. Another similar site is found on the same fault about 220m south of the school, where both sulphur and tar deposits are found.

Figure 7: Black tar-like hydrocarbon substance and extinct clayey alterations on escarpment face

3.5.3 Discharge into Lake Albert
From the salt works in the salt gardens of Kibiro, it is evident that some portion of the water seeps through the sediments towards the lake. It is therefore anticipated that some hot springs may occur in Lake Albert.

3.5.4 Carbonate Springs
In the KFZ, there are three locations of small perennial springs in the granitic zones away from the escarpment (Figure 3). They are all on the fault lines in the block-faulted area. In all cases, the flow is small (<1 l/sec.) and the pH of the water is between 9 and 10. Calcite precipitates from two of the springs and forms few cm thick deposits on rock surface downstream from the springs. The springs issue from fissures in cross-jointed rock outcrops.

3.5.5 Calcite deposits
Calcite is not a primary mineral in granitic rocks, and it is not expected to be present in the geological environment in the block-faulted granites. In this area it is present at some locations as secondary mineral in cracks and veins. Calcite is a common mineral in geothermal systems, especially in boiling zones and at the outer zones of the system. The calcite in the Kibiro area may be of geothermal origin, but this is yet to be proved. Three different formations of calcite occur. The first occurrence is calcite, which has formed from water flowing through joints and fissures in the rock, but the rock has now been brought to the surface due to fault movements and/or erosion. The second group is the calcite, which is currently being deposited at the carbonate springs. These two groups are here interpreted as

geothermal manifestations: the former may be fossil but the latter is active. The water in the headwaters of River Kachuru is saturated with calcite, and a thin film forms on rocks in the river. This calcite forms the third group, and as its origin is less certain than the former two groups, it has not been mapped. If the calcites are geothermal related, it is apparent that the east-west faults are playing an active role in the geothermal system (Gislason et al., 2004).
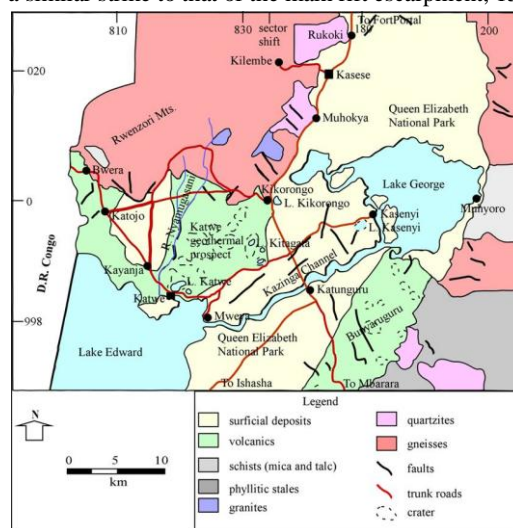
4.0 GEOLOGY OF THE KATWE GEOTHERMAL FIELD

4.1 Introduction
The Katwe-Kikorongo Volcanic Field (KKVF) is located on the western escarpment of the Rift, south of the Rwenzori Massif, which is a horst rising to an altitude of 5,109 m asl, with the equator running across the northern part of the field. Lake Edward and the Kazinga channel constitute the periphery of the Katwe field area in the south. In the east, the area reaches onto the flat plains of the Rift and in the west; the southern tail of the Rwenzoris borders it. Figure 8 shows a simplified geological map of the Katwe area. The geological history of the area begins from Precambrian base rock to Pleistocene-Pliocene volcanics to Quaternary lake sediments.

4.2 Basement Rock
The basement rock outcrops on the rift shoulders to east of the rift, adjacent to the Bunyaruguru volcanic field, and in the Rwenzori Massif, immediately to the north of the KKVF. To the east of the rift is the Karagwe-Ankolean System (quartzites, shales, phyllites intruded by granites). Reece (1955) studied accidental blocks occurring in the tuffs and craters that this formation underlies the Bunyaruguru volcanic field. The rocks of the southern part of the Rwenzori Massif belong to the Toro system, which consists of schists, quartzites and intrusive rocks such as granites, pegmatite, amphibolites and dolerites. The strike of bedding and foliation in the south-eastern Rwenzori has a similar strike to that of the main rift escarpment, 15°-70°.

Figure 8: Geology map of Katwe area and its surroundings

The Rwenzoris slope gently towards the south and their basement rock disappear under the volcanic pile of the

KKVF close to the equator. In this area the volcanics are deposited directly on the Precambrian rock, as outcrops can be seen in the northern part of the field like the northern inner slopes of the Mahiga crater. Towards the south, there is no direct evidence of the depth to the basement. The fresh water and temperature gradient boreholes drilled in the area have not intercepted the underlying basement rocks (Franzson, 2008).

4.3 Lake Sediments

The present day Rift floor is covered by an unknown thickness of lake sediments. Near the KKVF two major lakes are found, Lake George and Lake Edward, connected by the slow-flowing Kazinga channel. Through its evolution, the Rift Valley has hosted lakes to a varying extent, depending on prevailing climate and other controlling parameters. The present day Lakes Edward and George are small in comparison with earlier lakes, which sometimes covered the whole breadth of the rift. Flat lying sediments from these periods cover the Rift Valley floor, and the best outcrops are along the Kazinga channel, which connects the two lakes. At the Mweya Lodge, there is 20-30m high outcrop of lake sediments, fine silt or sand grain size with little or no layering and with no volcanics. The outcrop at the bridge at the Katunguru village consists of volcanic pyroclastics, partly welded to form a 70cm thick layer on top of the sediments. The land west of the crater area is outside the actual rift and is part of the southern slopes of the Rwenzori Mountains. Sediments can be seen in road cuttings and fault escarpments, and these are generally land deposits, inter-bedded with volcanic layers of pyroclastics, often rich of lapilli. In the crater area lake sediments are not exposed *in situ*, but can be found at few places as accidental fragments in the pyroclastics.

4.4 Volcanic Rocks

The KKVF is dominated by pyroclastic material with rare occurrence of lavas and ejected lava blocks as accidental fragments. Lloyd at al. (1991) estimated that the bulk volume of tephra was $63km^3$ but only $0.07km^3$ of lavas.

4.4.1 The Crater Area

The crater area is situated on the western escarpment of the rift, at the southern slopes of the Rwenzori Massif. The numerous craters are coarsely arranged in a north-easterly direction along the main rift alignment. The main crater area stretches over 30 km along the main fault lines, and is about 11km from north-east to south-west at its widest. A few craters are found outside the main crater area, as far as the town of Kasese in the north, making the total length from north to south about 45km. The craters are arranged very densely, often interlocking with each other, and many may be difficult to identify (Figure 10). A recent study identified over 140 eruptive centres within the Katwe area. The craters are generally of low relief, and were formed by a phreatic eruption, i.e. maars. Some of the craters, especially those on the lowland (Lake Katwe, Lake Kikorongo, and Lake Nyamunuka) or the deeper craters (Lake Kitagata and Lake Mahiga) have crater lakes, usually with high salinity waters due to evaporation. The phreatic nature of maars are caused by interaction of magma and shallow groundwater, leading to explosive type of eruption producing pyroclastic airborne deposits, often widely distributed and thus resulting in low crater rims composed by loose airborne material, often mixed with fragments from the host rock, i.e. accidental fragments. It is believed that many centres of phreatic eruption were active at the same time, producing large maar type flat-bottomed depressions (Gislason et al., 2008).

4.4.2 Pyroclastics

Most of the primary magma of the volcanic pile is represented by pyroclastics - mostly tuff - and to lesser extent lavas, but bombs are absent. This implies powerful explosions during eruptions, capable of tearing the magma to small particle sizes. The presence of lava flows with chemical composition identical to that of the tuffs shows that the explosive force is most likely due to external conditions such as direct contact of the parent magma with ground water. When magma and ground water interacts, the water is turned into steam, multiplying in volume, and breaking up the host rock formations where the interaction takes place. The angular forms of the abundant fragments of the basement rock in the pyroclastics indicate that the interaction takes place within the Precambrian basement (Gislason et al., 2008). Accidental fragments of the sedimentary formations are found at low levels of the pyroclastics in the Lake Katwe crater.

The pyroclastic outcrops have a yellowish appearance, and may vary in fragment size, although generally rather fine grained. On some locations no bedding can be seen in thick sections, but generally the pyroclastic outcrops show sorted, stratified airborne character. The drilling of borehole for temperature gradient measurements indicate that the pyroclastic material extend up to 132m depth (Natukunda, 2007). Commonly base surge structures are apparent, especially close to the crater of origin (Figure 9). No welding of the airborne material has been found, indicating lower temperatures, perhaps due to interaction of hot magma and cooler ground water (Gislason et al., 2008).

Figure 9: Surge structures in volcanic tuff

The most striking feature of the pyroclastic eruptions of the KKVF is the abundant occurrence of accidental fragments in the ejecta. The size of the fragments varies from being tiny fragments to over 3m in diameter. The largest rocks are always found near a crater, all stones larger than 10-15cm

in diameter are found within 50m distance from the nearest crater rim.

4.4.3 Lava Flows

Lavas make a very small part of the volcanic material of the KKVF. No lavas are seen on the present day surface, showing that the final volcanic phase was entirely of phreatomagmatic character. Lava flows can be seen *in situ* under a thick cover of pyroclastic material in four locations, in the inner slopes of two craters, namely the Lake Kitagata and Kyemengo craters. The main outcrops are on the northern side of the Nyabugando peak, which is located between the Kyemengo and Lake Kitagata. On its northern side, facing the Kyemengo crater at least six lava flows are exposed; their total thickness is about 120m. The flows have scoreacous tops and bottoms, and are sometimes separated by thin pyroclastic layers. The lava outcrop rests on pyroclastic deposits, and the lavas are buried under some 150m under the peak of the Nyabugando, which reaches to 1,225m asl. On the eastern side the lava pile terminates abruptly, as the outcrop is bordering the main fault of the KKVF Fault Field, forming the western side of the peak. On the eastern side of the Nyabugando peak, facing the

Lake Kitagata crater is another outcrop of lavas, at least 30m high, where four lava flows can be seen, and the steep wall is formed by the main fault of the KKVF. The hot springs of Lake Kitagata emerge at the foot of this. The third lava outcrop is found on the inner north wall of the Lake Kitagata crater. It is about 12m thick and is level with the second outcrop, but their contact is hidden by vegetation and scree, and the fault, which controls the hot springs, runs through this span. The outcrop seems to consist of one thick lava flow, but no correlation between the two neighbouring outcrops can be made. Holmes (1952) found one 20m thick lava flow in the Baboon cliff, which forms the western rim of the Kyemengo crater. The above locations are the only *in situ* lava flows, but lava blocks can be found in the ejecta of several of the craters surrounding the Lake Kitagata and Kyemengo craters. The blocks are angular and vary in size from few cm up to 2m in diameter.

Based on the chemical analysis of the rocks, which are low in silica ranging from 33.5 to 43.6 %, Holmes (1952) divided all the samples in two main groups based on the SiO_2/Al_2O_3-ratio. He identified the rock as being potash ankaratrites, leucite ankaratrites and melaleucitites. It is
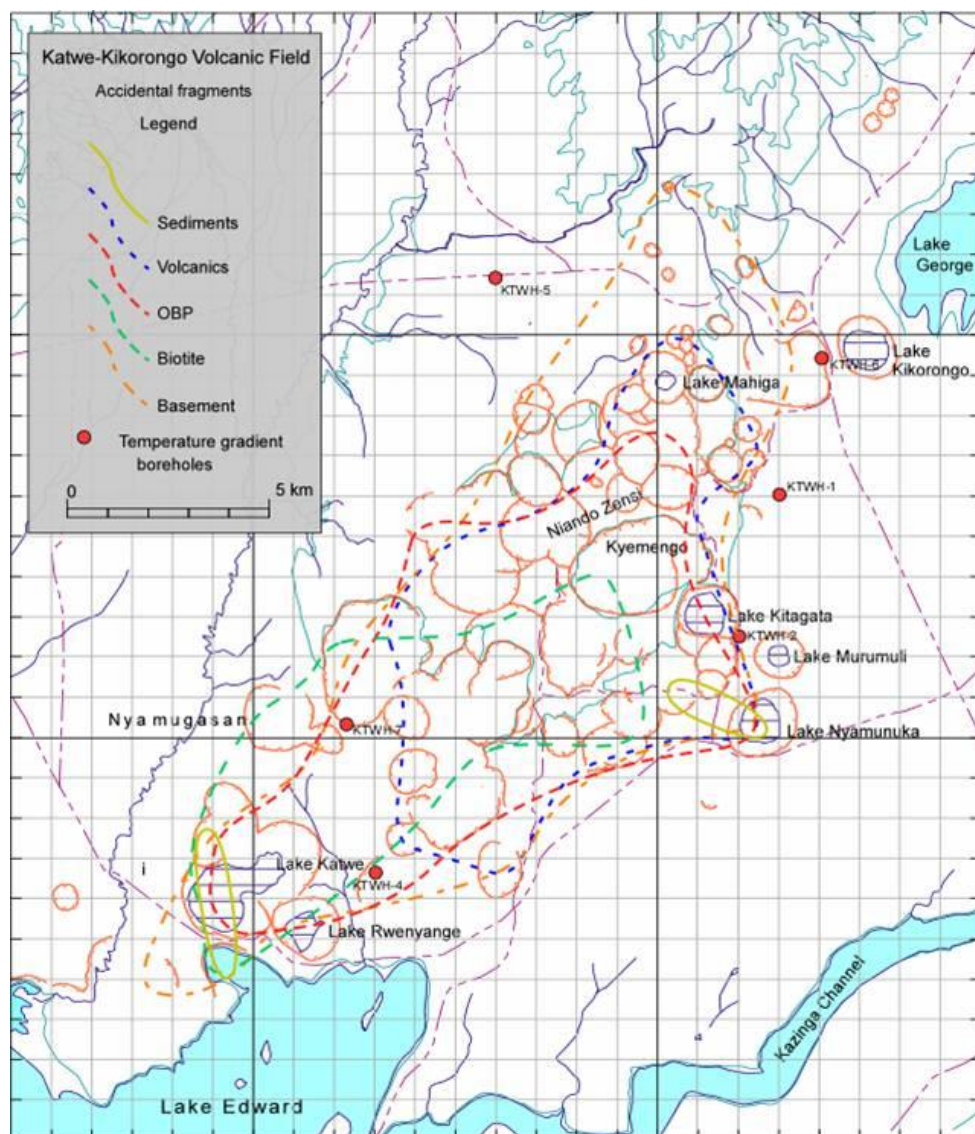
most likely that each lava block has been broken from its original place and ejected from the vent of the nearest crater.

4.4.4 O.B.P. Series

The ultrabasic volcanic rocks found in the pyroclastic ejecta as accidental fragments in the KKVF (Figure 10) as well as in other volcanic fields around the Rwenzori Massif, are referred to as the O.B.P. series (Holmes 1952). The fragments are composed of olivine and/or biotite and/or pyroxene, hence the name O.B.P. In the KKVF, O.B.P. is only found as fragments and never *in situ*. The crystals vary in size from fine grained to several cm in size, especially pyroxene and biotite. The latter is found as single crystals in the ejecta from many craters, up to 10cm in diameter. The O.B.P. fragments tend to be round in appearance opposite to the lava blocks which are often angular. This might indicate that at the time of the explosive eruption, the O.B.P. host rock was semi-solid, whereas the lavas in the root of the volcanic field was in a solid state (Gislason et al., 2008).

4.4.5 Accidental Fragments

The *maar* type of eruption, which is dominant in KKVF, is interpreted to be the product of an interaction between molten magma and groundwater, leading to violent steam explosions. The fragmented magma and voluminous steam tears lumps of material from the host rock where the explosion takes place and from the duct walls as the steam/tephra mixture rushes to the surface. The map (Figure 10) shows that the basement rocks underlie almost the whole crater area, except at the Lake Kikorongo crater where no basement fragments are found. The volcanic fragments are spread over the central part of the crater area, indicating that buried lava flows have formed a part of the volcanic pile in the central part of the volcanic system, but have not reached south to the Lake Katwe area, and the lavas have reached further north to Lake Mahiga. The O.B.P. series are shifted to the south compared to the lava distribution, and are found as far south as the Lake Katwe area, but are not found much north of the Kyemengo crater in the central part of KKVF. The large biotite crystals, which are presumed to be a part of the O.B.P. series, are found in the southern part of KKVF, but overlapping with the occurrence of the O.B.P. fragments (Gislason et al., 2008).

Figure 10: The Katwe-Kikorongo Volcanic Field. Outline of sub-surface distribution of rock formations as interpreted by distribution of accidental fragments in pyroclastics (after Gislason, 2008)

Lake sediments as accidental fragments are found in the Lake Katwe crater, and *in situ* under the pyroclastics in the Nyamunuka crater. The distribution of basement rocks not only shows that the basement underlies the whole of the crater area, but also that the interaction of magma and ground water takes place, at least to some extent, within the Precambrian basement formation. The distribution of lavas coincides with the area of highest production of volcanic material in the crater area.

4.4.6 Faulting
Faulting plays an important role in shaping the study area, as it is located on the rift shoulder of one of the branches of the EARS. The faults are draped by volcanics, and it appears that explosive volcanic activity was the latest events in the KKVF, covering any exposed faults. The Katwe faults have been mostly interpreted from aerial photographs, but in many cases confirmed by field observations. The dominant fault direction is parallel to the rift border, with a north-easterly direction. A major alignment in the Precambrian basement in the north-western corner of the study area runs with a N150ºE

direction under the volcanic field. This lineation marks the south end of the Rwenzori Massif. It is a product of foliation in schist, and faulting. South of this line the main faults of KKVZ have the direction N30ºE but to the north it changes to a more northerly direction, or N15ºE. Apparently, the intersection of these three structures influences the volcanic activity. The intersection coincides with the highest production of magma, and the distribution of lava blocks is centred on the intersection. It is also the location of lavas found *in situ* (Figure 10). The main hot springs of the area, i.e. the springs in the Lake Kitagata crater are clearly controlled by NE-SW faults, and are as well located above the underlying basement lineation. It may be interpreted that although the transport of magma is along the faults of the rift; the intrusive magma is injected at relatively shallow depth from the main NE-SW faults to SE along the weaknesses of the older basement fault. Here the magma interacts with considerable body of ground water to form the pyroclastic type of eruptions, only a small portion of the magma reaches the surface to form a normal lava flow (Gislason et al., 2008).

4.5 Geothermal manifestations

The geothermal surface manifestations in the Katwe prospect are hot springs located in the Lake Kitagata crater (Figure 11), and warm springs and travertine deposits that have built up tufas in the Lake Katwe crater, which is located 12km southwest of Lake Kitagata (Figure 10). The maximum surface temperatures in the hot springs in Lake Kitagata crater is 70°C, while in Lake Katwe Crater it is 32°C.

Figure 11: Kitagata crater in which lava flows occur under its highest Nyabugando peak and hot springs emerge at foothill and in the lake (eastern side of lake)

5.0 GEOLOGY OF BURANGA GEOTHERMAL PROSPECT

The Buranga geothermal area is located at the north-western base of the Rwenzori Mountains in the Western Rift Valley (Figure 12). Exploration for oil around Buranga showed a Tertiary succession of sands, clays and boulder beds with occasional tuffs. Geophysical surveys confirmed the presence of these rocks down to a depth of 1,524m. The boreholes showed that the Tertiary succession was terminated in the fault zone by a breccia cemented by calc-tuffs followed by mylonite (Harris et al., 1956). The clays are of various colours and the sands are fine to medium-grained, varying in colour between white, brown, grey and green. The most common binding material is clay, although this may be patchily replaced by calcium carbonate, giving rise to calcareous sandstones and grits. Pebble beds are of rare occurrence. There are no fossils apart from plant fragments.

South of Sempaya and close to the Buranga hot springs, a fault line (striking between 20° and 45° and dipping 60-65° westwards) is exposed (Johnson and McConnell, 1951). The presence of mylonite along the fault zone suggests movement along a very old fracture zone of compression. Traced further north, this fault system displays both a change of direction and reduction in magnitude. Step faulting is also present as per topographic features (Harris et al., 1956). The 13 structural lineament course is marked not only topographically, but also by masses of fossil calc-sinter covering 4km^2 between Kibuku and Buranga (Sharma, 1971). Kibuku is located approximately 10km north of Buranga hot springs.
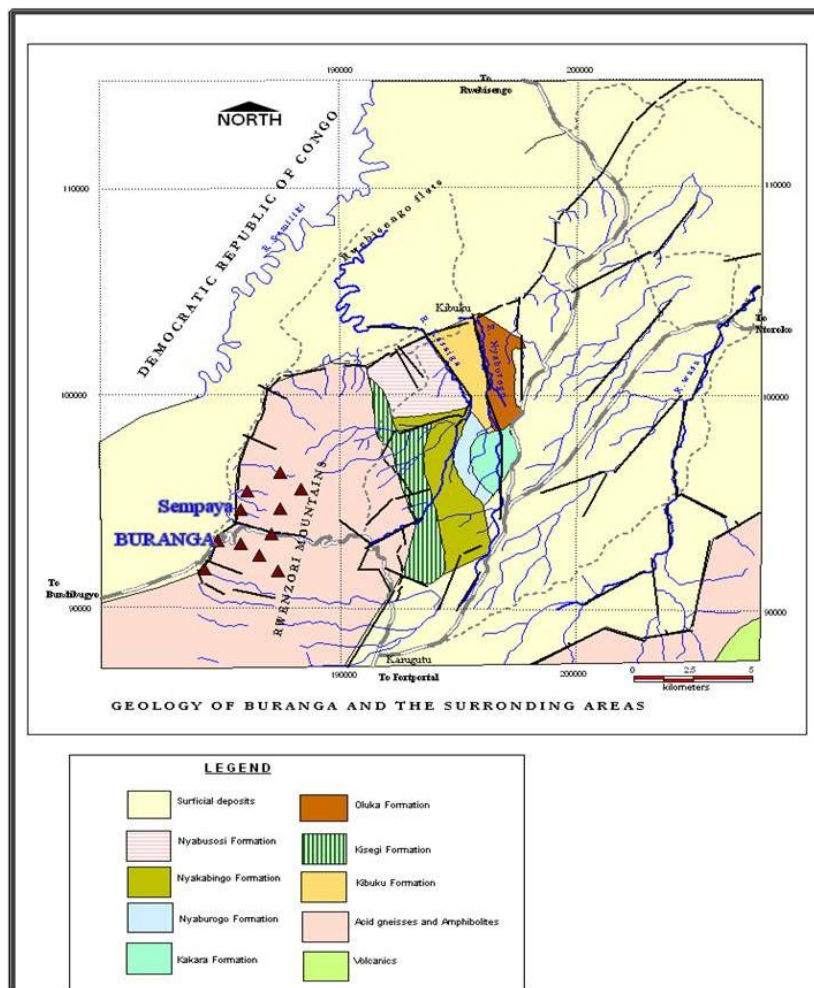
Figure 12: Geology map of Buranga showing location of hot springs

Unlike Katwe, Buranga has no evidence of volcanism but is highly tectonically active.

Geothermal surface activity is intensive, with sprouting hot springs and high gas flow (Figure 5).The manifestations are found at the foot of the escarpments in a swampy area enclosed by a dense rain forest. Surface alteration is scarce but most of the springs have developed traces and mounds of travertine. Surface and geological observations carried out under UGA/8/003 project indicate the presence of extinct thermal features (travertine) along a 10km stretch from Buranga hot springs to Kibuku. This shows that the area of thermal activity has been shifting from north to south and that the Buranga geothermal area may be somewhat larger.

5.1 Geothermal Manifestations of Buranga
Buranga has the most impressive surface geothermal manifestations i.e. hot springs (Figure 13) with a wide areal coverage in the whole of the western branch of the EARS. They include hot springs, calcareous tufa and recent surveys have reported small-scale seasonal fumaroles at Mumbuga spring area that appear in dry season when the water table is low. The surface temperature is close to 98˚C

and the flow is approximately 10-15 litres/second, an indication of high permeability.

Figure 13: The Mumbuga erupting hot spring in Buranga geothermal prospect. Note the developing travertine cone.

6.0 CONCLUSION
The Albertine Rift controls the geology of the three geothermal prospects. Katwe is the only prospect in a

68

volcanic environment while the geology of Kibiro and Buranga is dominated by crystalline basement and sedimentary formations. The fault system is most likely of the same age as the rift itself and results from the same forces. The tectonic pattern in the three areas is governed by the formation of the rift. The same forces that are tearing the Archaean shield apart in SE-NW direction and forming the Albertine Rift have block-faulted the semi-brittle granitic base rock east of Kibiro and Buranga prospects. In Katwe field, the geological evidence indicates that the magma-water interaction takes place within the Precambrian basement and that the forces of the eruption demand that the access to groundwater is considerable. The presence of ample water in Precambrian granites and gneisses suggests a secondary permeability, caused by the break up of the older formation during the evolution of the Rift Valley. The pre-requisites for the existence of geothermal reservoirs in the three prospects exist, namely: a heat source, permeability and rechargeable water. This is supported by the existence of hot springs, fractured basement glaciers on top of Rwenzori Mountain (for Buranga and Kibiro) and appropriate precipitation. In Katwe, the hot springs are right in the middle of the field, where the geological evidence points to the highest magma production, an intersection of large tectonic system and therefore the highest permeability.

REFERENCES

EDICON: Aeromagnetic interpretation of Lake Albert/Edward portion of the Western Rift Valley. *Unpubl. Report*, EDICON inc., Denver Colorado, (1984).

Fournier, R.O. and Potter, R.W. II..: A revised and expanded silica (quartz) geothermometer. *Geotherm. Res. Council Bull.*, 11, (1982), 3-9.

Franzson, H.: Uganda Kibiro – Katwe. Geology of thermal gradient wells. *Report*, Project No. ISOR, Iceland Geosurvey: 590-110, (2008), 1-12.

Gislason, G., Árnason, K., and Eysteinsson, H.: The Kibiro geothermal rospect; *Report,* on geophysical and geological survey prepared for Icelandic International Development Agency and Ministry of Energy and Mineral evelopment, Uganda, (2004),1-109.

Gislason, G., Árnason, K., Eysteinsson, H., and Magnússon I.Þ.: The Katwe geothermal prospect; *Report* on a geothermal survey prepared for Icelandic International Development Agency and Ministry of Energy and Mineral Development, Uganda, (2008), 1-101.

Harris, N., Pallister J.W., and Brown, J.M.: Oil in Uganda. *Memoir* No. IX, Geological Survey of Uganda, (1956), 1-33.

Holmes, A.: Transfusion of quartz xenoliths in alkail basic and ultrabasic lavas southwest Uganda. *Mineral Ma*gazine, 24, **155,** (1956), 408-421.

Holmes, A.: The potash ankaratrite-melaleucitite lavas of Nabugando and Mbuga craters, southwest Uganda. *Trans. Edinb. geoL Soc.,* 15, (1952), 187–213.

Johnson, R.J., and McConnel, R.B.: Notes on the Geology of the northern parts of the Rwenzori Mountains. *Geol. Ma*gazine 88, (1951), 249-256.

Kakenga, J.W., Rubondo, E.N.T., Kato, V., Kabanda, F., Namukoye, P.N., Ssentomero, W.D., and Namisi, S.: Geology of Kaiso Tonya area. *Unpublished geological map*, Petroleum Exploration and Production Department, Uganda, 1994.

Morley, C.K., Ngenoh, D.K., and Ego, J. K.: Introduction to the East African Rift System, *in* C. K. Morley ed., Geoscience of Rift Systems – Evolution of East Africa, *AAPG Studies in Geology,* 44, (1999), 1 – 18.

Morley, C.K., and Westcott, W.A.: Sedimentary Environments and Geometry of Sedimentary Dodies Determined from Subsurface Studies in East Africa, *in* Morley, C.K. ed., Geoscience of Rift Systems – Evolution of East Africa, *AAPG Studies in Geology* 44, (1999), 211 - 231.

Natukunda, J.F.: Geology of Kibiro and Katwe gradient boreholes, *Unpublished Report*, Department of Geological Survey and Mines, Uganda (2007), 1-14.

PEPD.: A Report on Geophysical Surveys carried out by the Geophysical Division between 17th October and 7th November in Hoima Basin, *Loose Minute*, Petroleum Exploration and Production Department, Ministry of Energy and Mineral Development, Uganda, (2002), 1-16.

Reece, A.W.: The Bunyaruguru volcanic field: Geological Survey of Uganda, *Records* for 1953, (1955), 29-47

Sharma, V.: Preliminary survey of thermal anomalies of Western Uganda for the possible development of Geothermal Energy, *Report* DGSM, (1971).

Simmons, W.C.: A Rapid Geological Survey of Part of Bunyoro. *Annual Report*, Geological Survey Department, Uganda, (1921), 29 – 34.

Wayland, E.J.: Petroleum in Uganda. *Memoir*, **1**, Geological Survey of Uganda, (1925), 61.