RECOMMENDATIONS FOR GEOPHYSICAL STUDIES ON THREE GEOTHERMAL AREAS IN WEST AND SOUTH-WEST UGANDA

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ABSTRACT

A consultant geophysicist, under the project Geothermal Exploration UGA/92/002, went on a one month mission to Uganda in January 1994. The purpose of the mission was to visit three geothermal prospects in west and south west Uganda, evaluate existing geophysical data and make proposals for further geophysical studies of the prospects.

The three geothermal fields under consideration, Katwe-Kikorongo, Buranga and Kibiro, are all located in the northern part of the western branch of the East Africa rift system. The geothermal activity is connected to tectonics and recent volcanism in the rift.

In the present geothermal project geological and geochemical studies have been carried out with the aim of selecting one of the three geothermal areas under consideration for further studies. The Consultant Geophysicist shares the view that the results of the ongoing project do not provide firm enough basis for a conclusive ranking of the geothermal areas and that they must all be considered as potential geothermal prospects.

Based on site visits, evaluation of geological circumstances and inspection and evaluation of existing geophysical data, recommendations are made for geophysical investigation of the geothermal prospects and tentative survey plans are sketched for each of the three areas. In order to make the geophysical investigation more decisive, a multi-method approach is recommended, comprising resistivity, gravity and magnetic surveys.

Adequate expertise and equipment is found in Uganda for carrying out the gravity and magnetic surveys but foreign expertise is needed to assist in performing resistivity surveys.

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1. INTRODUCTION

The project "Geothermal Exploration - UGA/92/002" is funded by the Government of Uganda, UNDP, The OPEC Fund for International Development and the Government of Iceland. It is executed by the Department of Development and Social Management Services (DDSMS) in cooperation with the Geological Survey and Mines Department of the Ministry of Natural Resources in Uganda. The project is focused on three geothermal prospects in western Uganda and employs geological and geochemical methods with the aim to select one of the geothermal areas for further surface exploration and exploratory drilling.

On the 15th of January 1994, a consultant geophysicist under the project went on a one month mission to Uganda. The purpose of the mission was to visit the geothermal prospects, evaluate existing geophysical data and make proposals for further geophysical studies as is specified in the job description listed in appendix. The following report, which is submitted to the United Nations DDSMS contains the findings and recommendations resulting from the mission.

2. GENERAL GEOLOGICAL SETTING

The three geothermal areas under consideration are in the northern part of the western branch of the East African rift system. The rift is thought (McConnel, 1972) to have opened in the Pre-Cambrian rocks on Miocene time after the formation of the Uganda-Zaire dome. The rift runs (figure 1) from NW Uganda towards SW, through Lake Albert and the Semliki basin to the west of the Rwenzori mountains. South of the Rwenzori mountains it is shifted towards east, to Lake Edward. The Lake Edward part of the rift extends to NE but fades out at the Toro plateau to the east of the Rwenzori.

The Rwenzori mountains are of Pre-Cambrian rocks and reach the height of about 5110 m a.s.l., considerably higher than the Pre-Cambrian rocks bordering the rift, indicating that the rock mass between the overlapping branches of the rift has been subject to an up lift relative to the surrounding crust. Gravity and magnetic data (Kashambuzi, pers. comm.) indicate that the sedimentary layers in the Lake Albert rift have a thickness up to 5 km, but become gradually thinner toward SW under the Semliki plain and to the NE of Lake Albert. On the NW side the Rwenzori is bordered by steep fault planes of the Bwamba escarpment and the total vertical displacement of the faults seems to be up to 7-10 km. The SE slopes of the Rwenzori are more gentle than the NW slopes. In the Lake Edward part of the rift the sediments are about 3 km (Kashambuzi, pers. comm.) thick but get thinner towards NE, east of the Rwenzori.

The sediments in the Lake Edward and Lake Albert rifts are of lacustrine and fluvial origin and are divided (Harris et al., 1956) into the Kisegi (lower Miocene to Pliocene) and the Kaiso series (earlier Pleistocene) overlain by the Semliki series (mid Pleistocene). Some oil seepages are found on surface in the Lake Albert rift, indicating oil bearing sediments in the rift graben.

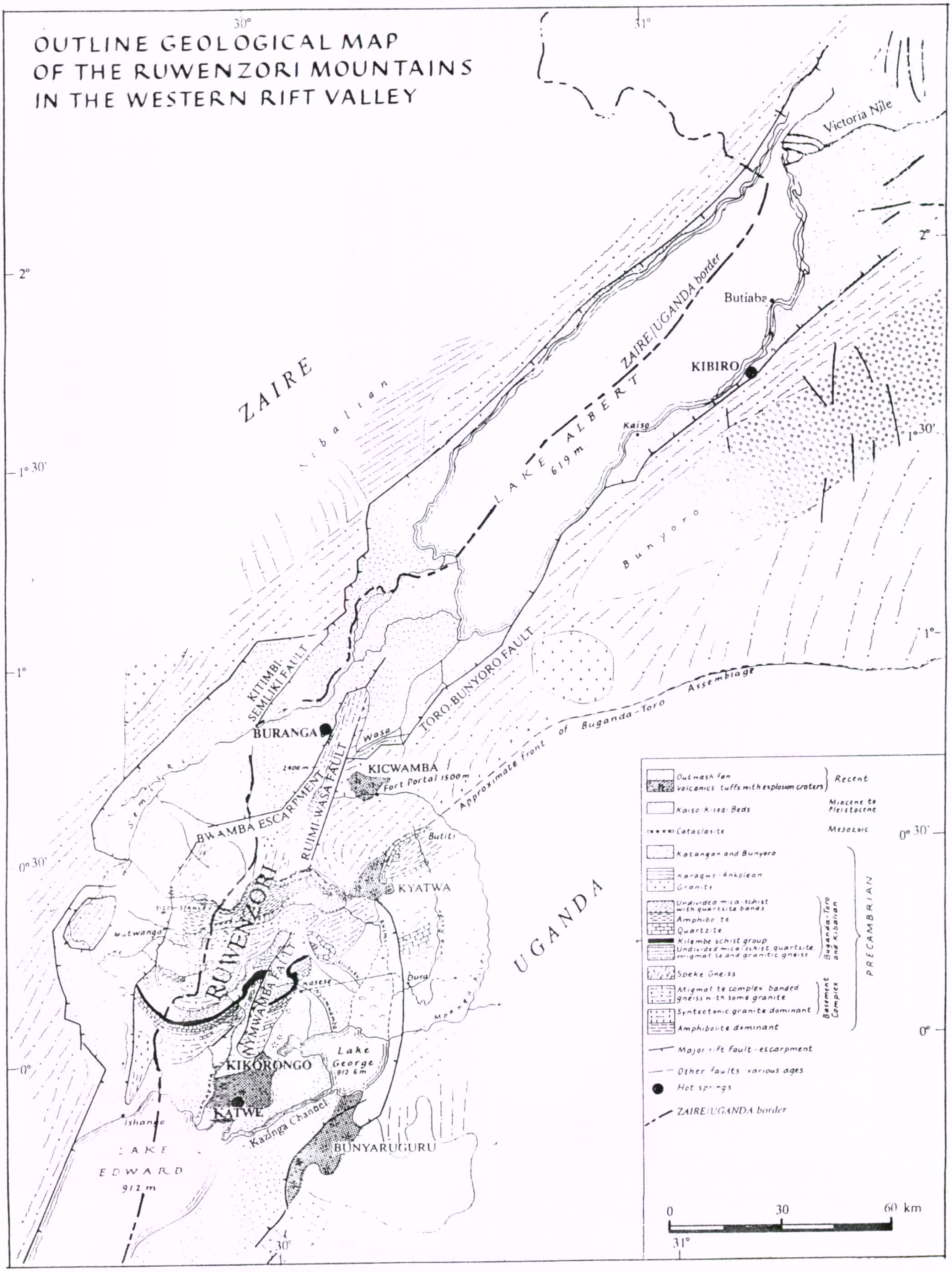

Figure-1. Geology of the northern part of the western rift (modified from McConnel, 1972)

Unlike the northern part of the eastern branch of the East Africa rift, which has extensive volcanism, the northern part of the western branch has sparse volcanism. In the Lake Edward and Lake Albert part of the rift, volcanic rocks are found on surface on the eastern side of the Rwenzori but aeromagnetic data from the area indicate possible volcanic intrusions in the sedimentary basins of the rifts (Kashambuzi, pers. comm.). More impressive volcanism is found further to the south, in Virunga and Tsibine at Lake Kivu in Zaire and Rwanda.

The volcanism east and immediately to the south of the Rwenzori is found in four relatively small separated areas between Lake Edward and Lake Albert (figure 1). Furthest to the SE is the Bunyaruguru area, which is on the SE escarpment of the Lake Edward rift, NE of Lake Edward, and extending north to Lake George. The other three volcanic areas are in the SE and E foothills of the Rwenzori. Furthest to the south is the Katwe-Kikorongo field, just north of Lake Edward and NW of the Kazinga Channel which connects Lake Edward and Lake George. The Kaytwa volcanic area is some 20 km south of Fort Portal and the Kicwamba area, just NW of Fort Portal, is the northern most volcanic area in the rift.

The volcanic activity is characterized by explosion craters and the ejecta is mainly phreatomagmatic pyroclastics and tuffs with abundant granite fragments and gneissic rocks from the basement. Only minor occurrences of lava are found, mainly in the northerly volcanic areas (Kicwamba and Kyatwa). The age of the volcanic activity is thought to be Pleistocene to Holocene (Musisi, 1991).

The northern part of the western rift branch and the area around the Rwenzori mountains is found to be one of the mosts seismically active areas of the East Africa rift system (Maasha, 1974). The area has been subject to devastating earthquakes and tremors. On 20th of March and 17th of May 1966, big earthquakes were on the Kitimbi-Semliki fault (figure 1), near the NW boundary of the Lake Albert-Semliki rift, west of the Rwenzori (Loupekine et al., 1966). The quakes which where of magnitude $M = 6.1$ and $M = 6.3$ respectively killed nearly 160 people and injured over 1000. The earthquakes were associated with surface faulting for about 40 km along the Kitimbi-Semliki fault with down throw of 30 cm and up to 2 m on the eastern side of the fault.

On the 6th of February 1994 an earthquake of magnitude 6.3 on the Richter scale struck the area around Fort Portal, NE of the Rwenzori. The quake killed 10 people and caused lot of damages. The epicenter was just south of Fort Portal. A number of after shocks occurred in the area, some with epicenter west of the Rwenzori (Gíslason, pers. comm.)

Maasha (1974) conducted a seismic survey in the Rwenzori region in the summer of 1973. He found the area to have more or less continuous micro-earthquake activity (8-15 events per day of magnitude -2 to 4). For the bulk of the quakes the epicentral locations and the focal mechanisms where found to accord with movements on normal faults around the Rwenzori mountains, reflecting east-west minimal stress (extension) across the rift system. Sub-crustal seismicity (depth of 25 to 40 km) beneath the Rwenzori Massif was also observed as well as indications that the northern part of the mountains is being uplifted relative to the southern part. The interesting observation was made that the seismic intensity seemed to increase at the onset of the rainy season which is in accordance with observations of the residents of the district. The volcanic areas to the east and SE of the Rwenzori mountains were found to be seismically active but the activity seemed to be in swarms.

The location of the geothermal areas under consideration are shown on figure 1. The southern most of these, the Katwe-Kikorongo area, is associated with volcanism. The main surface manifestations are hot springs found around and within the Lake Kitagata, which is one of the saline crater lakes in the area. The other two areas are associated with major fault escarpments. The Buranga field (also known as Sempaya) is found in the Semliki river basin under the Bwamba escarpment on the NW margin of the Rwenzori Massif. This field has the most impressive surface manifestations in Uganda, with numerous vigorous hot springs of temperatures up to 98 °C. The northernmost field is Kibiro which is located on a narrow plain under the escarpment of the Toro-Bunyoro fault which borders Lake Albert to the SE.

3. THE KATWE-KIKORONGO GEOTHERMAL FIELD

The Katwe-Kikorongo area (figure 2) is located in the Queen Elizabeth National Park, between Lake Edward and Lake George, SE of the Rwenzori Massif. The geological setting has been described by several authors (Combe 1939, Holms 1956, Lissanu and Ayele 1987) and is characterized by numerous explosion craters distributed over a NE-SW elongated area of about 10x20 km^2. The extruded volcanic material is mainly phreatomagmatic pyroclastics deposited on Pleistocene lacustrine and fluvial beds of the Kaiso and Semliki series, but probably directly on Pre-Cambrian rocks of the Kilembe series in some places in the NW part of the area. No lava flows are seen on surface but a few layers of laws, buried deep under the pyroclastic pile, outcrop in the Kitagata crater. Ejected blocks of ultra basic volcanic rocks as well as fragments of the granitic basement rocks are found in the erupted pile which rises some 400 m above the surrounding sedimentary planes.

The size of the craters varies from a few hundred meters to about 2 km in diameter. They normally have low outer walls and the larger ones have wide and flat floors. Seven craters are deeper than the present ground water level and host saline and carbonate rich crater lakes.

The nature of the volcanic activity in the Katwe-Kikorongo volcanic field has been a matter of dispute. Earlier investigators considered the volcanic activity to have been sub-aqueous (Combe 1930, Wayland 1934, Lissanu and Ayele 1987) but more recent investigators have considered it to be sub-aerial (Musisi, 1991; Lloyd et al., 1991). The eruption mechanism is also not clear. Holmes (1950) conjectured that the composition of the volcanic material and the explosive character of the eruptions were the result of a reaction between granitic rocks and magmatic carbonate producing large amounts of high pressure gases. Holmes (1956) studied carbon isotope ratios in CO_2 and carbonated rocks from Lake Katwe and interpreted the results as indicating a juvenile origin of the carbon and supporting his hypothesis of the nature of the volcanism.

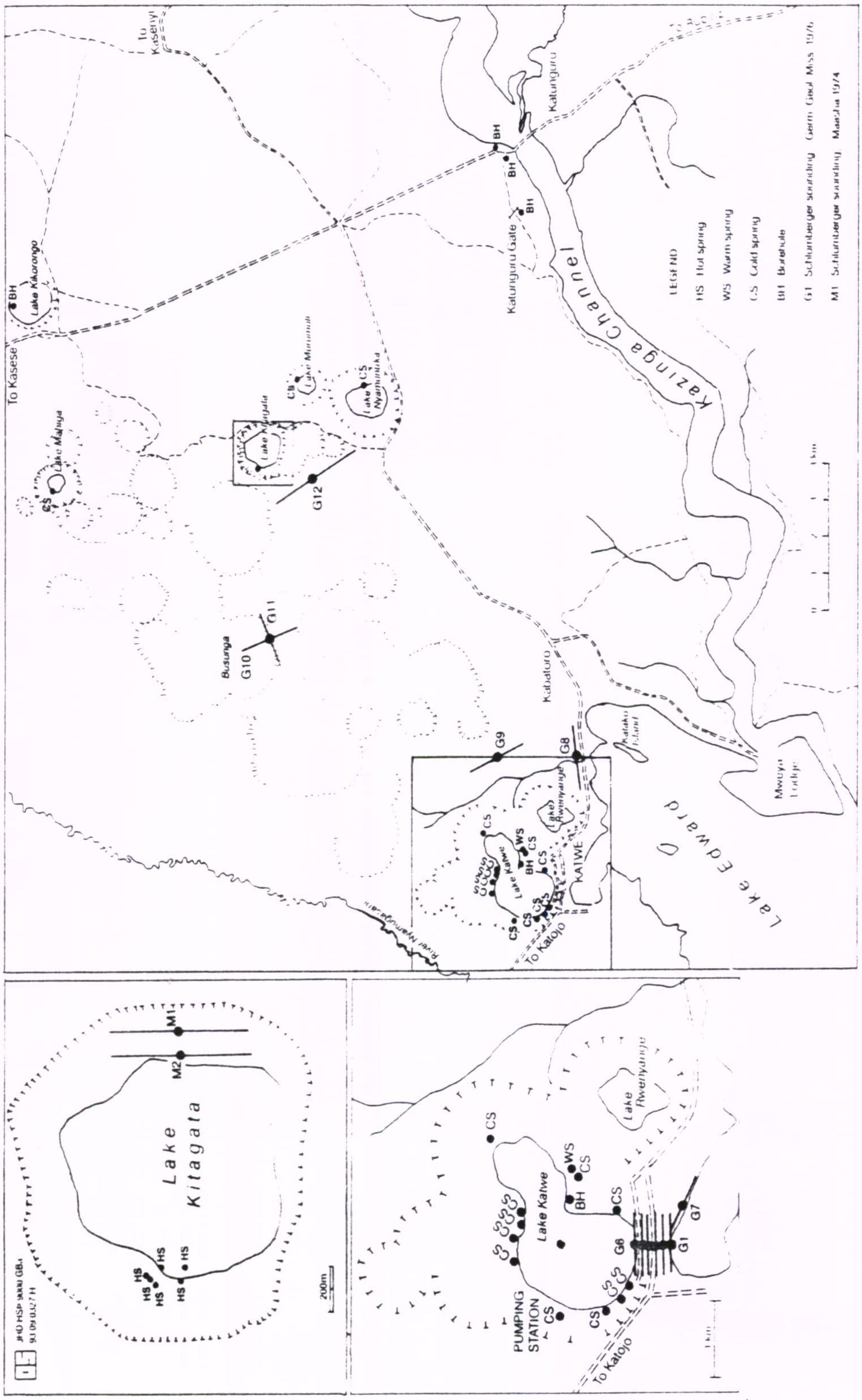

Figure-2. The Katwe-Kikorongo geothermal field.

Lissanu and Ayele (1987) put forward the hypothesis that the volcanic areas to the east and south-east of the Rwenzori are found where the rift intersects east-west trending transform faults, facilitating formation of magma chambers at shallow depths. They conjecture that the volcanic activity took place at the return of a wet climate where lacustrine waters would percolate through fractures and be turned into steam close to the magma, resulting in phreatic explosions.

Lloyd et al. (1991) took the large amount of volatiles (F, Cl, C and H) in spring water and volcanic glass, which they considered to be juvenile, as a support for gas fluidization process but also considered phreatomagmatic volcanism as possible. They concluded that the ultra mafic volcanic material can not be from "normal" mantle and suggest that the rift is underlain by alkali clinopyroxenite rich mantle. Relatively high heat flow in the rift results in magma and crustal thinning and uplift followed by volatile degassing in zones of crustal weaknesses.

Early investigators did not recognize evidence of tectonic activity in the Katwe-Kikorongo area. Recent studies (Gíslason et al., 1994) of areal photos and observations in the field have shown that the area has been subject to faulting after the volcanic activity. Numerous faults and fissures have been identified, most of them trending NE-SW, parallel to the main faults of the rift, but ESE-WNW trending faults are also observed. The two fault patterns or systems seem to intersect in the area around and to the NW of Lake Kitagata.

The main geothermal surface manifestations are found in Lake Kitagata, where five springs have been identified in the western part of the crater. Salt miners at Lake Katwe say that they have found hot springs discharging at the bottom of the lake and local people also say that they have found a fumarole within the crater are. Saline spring at the east side of Lake Katwe was found to be slightly warmer than other springs around the lake, having temperature about 30 °C (Gíslason et al., 1994). This is about 5 - 6 °C higher than the temperature of coldest springs and the annual mean temperature in the area. This spring may be the same as the one Stanley (1890) describes and reports measured temperatures up to 32.5 °C. Temperature measurements in shallow boreholes in Lake Katwe and Lake Kikorongo also show slightly elevated temperatures, 32.5 °C and 32.4 °C respectively (Gíslason et al., 1994).

In Lake Kitagata, the largest hot spring is found on the bottom of the lake, some 20 m form the west shore (figure 2), and discharges considerable amount of water. Temperature and flow rate is difficult to determine because of mixing with the lake water but temperatures up to 70 °C have been measured (Gíslason et al., 1994). The other springs are at the west shore or slightly uphill discharging only minor amount of water with temperatures up to 66.5 °C. The area in which the springs are found is slightly elongated in the N-S direction and is on the south prolongation of a fault which is seen in the northern rim of the crater, suggesting that they are associated with the fault.

The springs at Lake Kitagata discharge saline waters with conductivity in the range 25,000 to 48,000 μS/cm (Gíslason et al., 1994; Ármannsson, 1993) but the salinity of the lake water is much higher, with conductivity 132,000 μS/cm. The salinity of the warm spring, east of Lake Katwe is also high, with conductivity up to 79,000 μS/cm which is generally higher than for the colder springs at Lake Katwe. Large amounts of travertine have been deposited on the eastern side of Lake Katwe, strongly suggesting thermal component in the water. The water in Lake Katwe is saturated brine with conductivity of 170,000 $\mu S/cm$.

Cold springs are found in four of the craters lakes. Lakes Nyamununuka, Murumuli and Mahiga have cold springs which discharge minor amount of saline waters into the lakes which are more or less saturated brine because of evaporation. None of the crater lakes has surface outflow. Lake Katwe has numerous cold springs but with little discharge. The salinity of the springs in Katwe varies from nearly fresh to saline. The water of Lake Katwe is saturated brine and considerable amount of salt is mined from the lake, both from salt deposits at the bottom of the lake and from evaporation ponds. The level of Lake Katwe is about 30 m (880 m a.s.l.) lower than Lake Edward (910 m a.s.l.). The fresh springs at Lake Katwe are found on the western side of the lake some 18 m above the level of the lake. Earlier investigators considered them to be leakage from Lake Edward, but recent isotope studies (Ármannsson, 1994) show that their water originates more likely from the Nyamugasani river some 2.5 km NW of the lake.

Ármannsson (1993) and Gíslason (1994) sampled water from Lake Edward and the Kazinga Channel as well as from wells close to the bridge across the channel. The wells turned out to have brackish water with conductivity of 4000 - 5000 $\mu S/cm$, about 50 times that of the channel. Samples from wells in Lake Kikorongo and Lake Katwe had saline water, with higher salinity in Lake Kikorongo. Dyke (1954a) reports that water pumped from a borehole at the foothills of the northern Bunyaruguru volcanic area, to the SE of the Kazinga Channel was "found to be chemically unsuitable" for irrigation, which presumably means that it was brackish. It is therefore likely that groundwater in the Katwe-Kikorongo area is brackish but the saline springs seem to be confined to up flow areas in the crater lakes.

The saline spring waters in the Katwe-Kikorongo area have generally high concentration of CO_2 and dissolved silica (Ármannsson, 1993). The hot spring on the bottom of lake Kitagata and the warm spring east of Lake Katwe have by far the highest concentration of CO_2, over 11,000 mg/kg, and these springs also contain considerable amount of H_2S.

Ármannsson (1994) has applied geothermometry to water samples from the hot springs in Lake Kitagata. The chemistry of the thermal waters in Kitagata is quite anomalous as compared to other geothermal areas. Mixing with lake waters has further more made collection of representative samples from the main hot spring at the bottom of the lake difficult. All this has made the application of conventional geothermometers difficult and a wide range of results have been obtained. The best estimates seem to indicate likely subsurface temperature in the range of 140 to 200 °C but values as high as 260 °C have been obtained. The reservoir temperature in the Katwe-Kikorongo area must therefore be considered to be unknown and will probably only be determined by drilling.

The origin of the saline ground water in the Katwe-Kikorongo area, and especially in Lake Katwe has been debated and reviewed by Lissanu and Ayele (1987). Early hypothesis suggested that the salt was leached from the surrounding volcanic tuff by percolating water or that the craters were filled with saline water during Pleistocene volcanism. Lissanu and Ayele (1987) put forward the hypothesis that the interstitial brine in Lake Katwe could be from deep artesian ground water or water released from gypsum in the Kaiso series which is transformed into anhydrite but that some contribution could be from "volcanic" water due to heating of deep buried rocks. They speculate that geothermal heating of the water increases the leaching ability as well as convective forces that make the water rise up through deep fractures. They suggest that the circulation of the heated water through the thick non-marine sediments causes enrichment in Na, Cl, and sulphate through leaching of gypsum and organic rich sediments. As an explanation of the presence of H_2S they suggest bacterial oxidation of organic matter which reduces sulphate ions into H_2S and even elementary sulphur. Based on geochemical data from 13 boreholes drilled in the salt deposits of Lake Katwe, they further suggest that the brine rises from restricted vents. This is based on SSW-NNE linear trend seen in the concentration of Na and Cl ions which could be found to match with fault lines near the lake.

Lissanu and Ayele (1987) point out the similarity of the Katwe-Kikorongo area with saline crater lakes in southern Ethiopia, Kenya and Tanzania. These lakes are all alkaline soda lakes associated with young fissural volcanic fields in metamorphic terrain in the East Africa rift system. This, as well as the occurrence of CO_2 and H_2S, can be taken to suggest that the mineral salts in the water, which are high in carbonate salts, do originate from volatile degassing of magmatic intrusions. This idea gets support from carbon isotope ratios (Holmes, 1956) and high concentration of volatiles in the volcanic glass of the ejected material.

Lissanu and Ayele (1987) made a geohydrological study of the Lake Katwe area and Dyke (1954a) made a similar study in the area south of Lake George. They report numerous wells, generally 100 to 250 m deep, drilled in the Kaiso sediments to the east of the Katwe-Kikorongo volcanic area. Many of the wells turned out to be completely dry and some with water level well below surface but yielding only minor water during pumping. Some wells, and in some cases close to dry wells, struck permeable layers yielding artesian water. This indicates that the general permeability in the Kaiso sediments is low but localized permeable beds may carry artesian waters related to general ground water flow from north and north west.

The hydrology of Lake Katwe and its immediate surroundings is rather spectacular. The level of Lake Katwe is some 30 m below that of Lake Edward which is only 400 m to the south. Earlier investigators thought that the fresh water springs by Lake Katwe were leakage from Lake Edward but isotope ratios suggest that they originate from groundwater related to the Nyamugasani river to the west of the crater. The German Geological Mission of Uganda (Geological Survey of the Federal Republic of Germany, 1976) and Lissanu and Ayele (1987) addressed specifically the question whether Lake Katwe and Lake Edward are hydrologically connected and concluded that they are not. Lissanu and Ayele (1987) report a borehole drilled in the crater rim between the lakes with water level at 904 m only slightly lower than Lake Edward. It is therefore obvious that the hydrological system around Lake Katwe has had, and probably still has, efficient self sealing capability. The water level of the other crater lakes is somewhat variable from one lake to another (Gíslason et al., 1994) but is about or slightly lower than the level of Lake Edward, Lake George and the Kazinga Channel. This again suggests low permeability and complicated hydrology in the area.

There is reason to believe that the salinity of the springs and crater lakes in the Katwe-Kikorongo area is related to geothermal activity. The saline water is most likely ascending from depth as upwards convecting geothermal fluid along faults and fissures. Due to self sealing, which is clearly exemplified by the hydrological isolation of Lake Katwe from Lake Edward, the up flow zones are likely to be localized. The brackish nature of the surrounding ground water, as suggested by water samples from boreholes, is probably due to seepage of saline waters into the general groundwater system of the sediments in the rift.

3.1 Existing geophysical data

The earliest geophysical investigation that has relevance to the Katwe-Kikorongo area was done by Dyke (1954). He carried out a hydrological study to investigate possibilities of getting irrigation water for a proposed sugar planting in the area west of the northern part of the Bunyaruguru volcanic area, south of Lake George and the Kazinga Channel. He made 15 DC (Direct Current) electrical soundings using the Wenner configuration. The maximum current electrode spacing was 90 m (300 feet) and the depth of penetration was therefore limited (of the order of 50 m).

Dyke found that soundings at the foothills and in the Bunyaruguru volcanics showed relatively low resistivity, of the order of 10 Ωm, below 5 - 40 m thick surface layers. Further to the NW, in the vicinity of the Kazinga Channel, the resistivity below surface layers was found to be markedly higher, or of the order of 100 Ωm. This variation in the resistivity, even though not very conclusive because of the limited depth of penetration, is probably reflecting the influence of the Bunyaruguru volcanics. The lower resistivity towards the crater area is likely due to higher salinity and/or alteration minerals of geothermal origin.

The first reported surface geophysical work in the Katwe-Kikorongo area was carried out under the German Geological Mission to Uganda in the years 1970 - 1973 (Geological Survey of the Federal Republic of Germany, 1976). The mission was mainly focused on mineral exploration, but some work was devoted to hydro-geological and geothermal studies in the Katwe-Kikorongo area.

Nine Schlumberger electrical soundings were carried out in the vicinity of Lake Katwe. Three soundings were made further to the NE, one about 1 km SW of Lake Kitagata and two sited at the same spot, on the southern margin of the Busunga crater, but with the transmitting dipoles oriented perpendicular to each other (see figure 2). The maximum current electrode spacing was generally 600 - 1200 m but up to 2400 m at Lake Kitagata and the data seem to bee of high quality and reliable.

Six soundings were located on a profile across the barrier between Lake Katwe and Lake Edward just south of Lake Katwe. The purpose was to investigate possible hydraulic connection between the lakes as well as a possible existence of freshwater-saltwater interface. The resulting resistivity cross-section along the profile shows layers of relatively low resistivity, 10 - 25 Ωm, down to the level of Lake Katwe, 30 m below Lake Edward. Below the level of Lake Katwe the resistivity in the barrier is fairly homogeneous, 3 - 5 Ωm, all the way from Lake Edward and to the crater rim, but decreases to about 2 Ωm under the south shore of Lake Katwe.

Similar resistivity structure was observed in three soundings SE and E of Lake Katwe. The resistivity is generally higher than 10 Ωm, down to the level of Lake Katwe where it decreases to 4.5 - 5 Ωm. These findings can hardly be a mere coincidence, but reflect probably a general water-table of saline water at the level of Lake Katwe, about 880 m above sea level. The lower resistivity found at the shore of Katwe is probably either due to higher salinity or higher temperature at depth.

The three soundings to the NE of Lake Katwe were done to explore the geological structure and the geothermal activity in the Katwe-Kikorongo area. The two perpendicular soundings at the Busunga crater, some 4.5 km west of lake Kitagata, were to check for deviations from horizontal layering in the geological structure and they show some signs of anisotropy. Interpretation of these soundings shows resistivity higher than 70 Ωm to the depth of about 40 m, underlain by a about 200 m thick layer of about 40 Ωm. Below this layer, at about 900 m a.s.l., the resistivity drops sharply to about 2 - 3 Ωm. The sounding SW of Lake Kitagata has the largest current electrode spacings, up to 2400 m, and hence the gratest depth of penetration. It shows similar resistivities in the uppermost 40 m as at the soundings in Busunga but underlain by a 120 m thick layer with resistivity about 15 Ωm. Below this layer, at about 900 m a.s.l., the resistivity drops to 2 - 3 Ωm but increases sharply again at greater depths.

These resistivity data, although of limited extend, seem to indicate that the water level in the crater lakes represents a general level of saline ground-water in the area. The lower resistivity values found near Lake Kitagata, as compared to those near Lake Katwe, show that the resistivity of the low resistivity layer associated with the saline ground-water is not uniform throughout the area. The lower resistivity values probably reflect higher salt concentration and/or higher temperatures.

The resistive layer at depth found in the sounding at Lake Kitagata is of special interest. This layer could reflect the crystalline Pre-Cambrean basement below the sediments. The geological setting in the Katwe-Kikorongo area suggests that the depth to the Pre-Cambrean basement should decrease towards west. No sign of such resistive layer is seen in the soundings at Busunga, 5 km west of Lake Kitagata. These soundings have shorter maximum electrode spacings than the sounding at Kitagata and hence lesser depth of penetration, but the presence of the resistive layer at Kitagata is already observed at electrode spacings similar to those used at Busunga. It can therefore be concluded that resistive basement at similar or shallower depths under Busunga would have been observed. The resistive layer could reflect some hydrological or thermal infra structure in the geothermal system under Lake Kitagata. In high temperature geothermal systems in Iceland, resistivity is generally found to increase at depth, reflecting changes in alteration mineralogy at higher temperatures (Árnason and Flóvenz, 1992).

In 1973 Maasha (1974a) made two Schlumberger soundings at the east side of Lake Kitagata (for location see figure 2). The maximum current electrode spacings were only 480 m and the depth of penetration limited. Both soundings show low resistivity below surface layers. One of the soundings, which is right at the lake shore, shows resistivity of the order of 1 Ωm and a vague sign of increasing resistivity at the end of the sounding curve.

Resistivity measurements were done in connection with the exploration of the salt deposits in Lake Katwe in 1987 (Lissanu and Ayele, 1987; Tuhumwire, 1987). The study was focused on the barrier between Lake Edward and Lake Katwe and the immediate surroundings of Lake Katwe. It comprised 16 Schlumberger soundings, with maximum current electrode spacing of 1500 m, and resistivity profiling on three profiles along the barrier between the lakes. The profiling was done with Schlumberger array setup and two different current electrode spacings, 40 and 300 m. The quality of these data is sometimes rather poor and some of the soundings are seriously affected by malfunction in the instruments. The results of this survey seem to confirm the findings of the resistivity survey of the German Geological Mission around Lake Katwe.

Maasha (1974 and 1974a) studied the micro earthquake activity in the Katwe-Kikorongo volcanic area. He found the area to be seismically active and that the epicenters seemed to cluster some 10 km to the north of Lake Katwe. The focal mechanism of earthquakes in the rift, around the Rwenzori Massif, is predominantly of a normal fault type, but quakes in the Katwe-Kikorongo area were found to show "tensile cracking" mechanism. A similar type of micro-earthquake activity has been observed in the Hengill geothermal area in SW Iceland (Foulger, 1984; Foulger and Long, 1984) and has been interpreted as a result of tensile cracking of cooling rocks. The seismic activity in the Katwe-Kikorongo volcanic area can therefore be taken to indicate cooling heat source at depth.

4. THE BURANGA GEOTHERMAL FIELD

The Buranga geothermal field, also known as Sempaya field, is located in the Semliki Kaiso sedimentary basin some 300 to 600 m to the north west of the Bwamba escarpment which forms the NW boundary of the Rwenzori Massif (see Figure 1). Under the Bwamba fault, which strikes 20 - 40° to east and has a dip of 60 - 65° to the west, the sedimentary basin is covered with boulder beds and scree. The geothermal activity is found in an area of swamps and rain forest. Surface manifestations cover an area of about 120,000 m^2 and consists of three main hot spring areas: The Mumbuga springs, the Nyansimbe pool and the Kagoro springs. These three groups of springs lay approximately on a line extending some 550m along a strike N-35°-E, approximately parallel to the Bwamba fault (figure 3). In addition to these three hot spring groups, springs are found in an area extending some 350 m SE of the Nyansimbe pool.

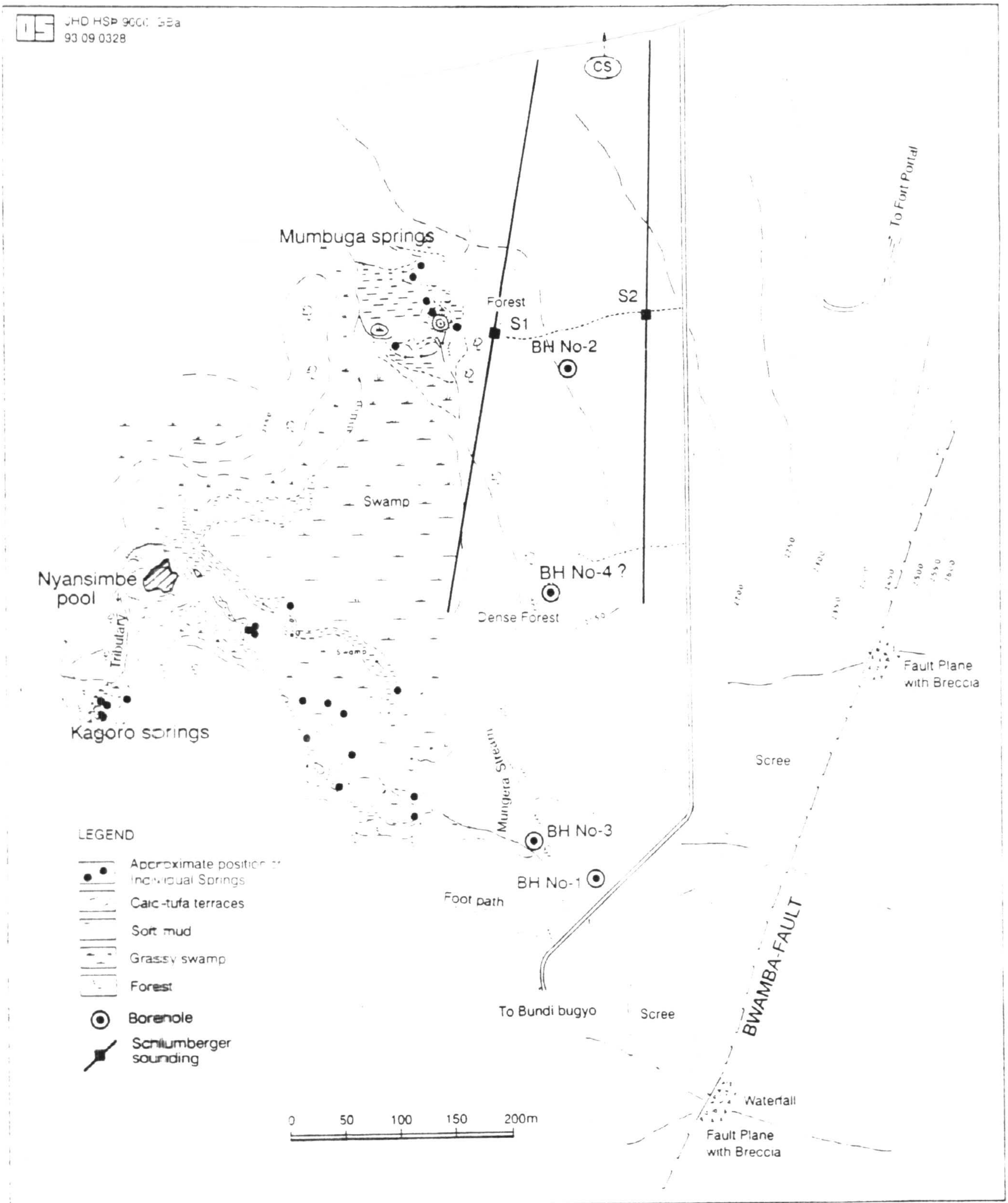

Figure-3. The Buranga geothermal field.

At the Mumbuga springs the bulk of the hot water is discharged from few large springs that have deposited large amounts of travertine. The largest spring has built a travertine cone about 1.5 m above the surrounding area and discharges water under pressure some 50 cm above the pool surface. The total flow from the Mumbuga springs has been estimated 6.5 l/s (Gíslason et al., 1994) and the temperature is as high as 95 °C. The Nyansimbe pool is built up of travertine, about 5 m above the surrounding swamp. It is about 15 m in diameter and more than 4 m deep. The total flow from the pool has been estimated 10 l/s and the temperature is 85.6 °C. The Kagoro spring area is the smallest of the three areas. The springs have built travertine cones, the highest 1.5 m. The total flow is estimated 3 l/s with temperatures ranging from 60 °C to 91 °C (Gíslason et al., 1994). The springs to the SE of the Nyansimbe pool discharge directly into the surrounding swamps making flow estimate impossible. This area hosts the hottest spring in Buranga with a temperature of 98.4 °C (Gíslason et al., 1994).

The thermal waters in Buranga are brackish. Ármannsson (1993 and 1994) reports results of chemical analysis of waters from the springs. The conductivity is fairly constant about 20,000 μS/cm. The CO_2 and SiO_2 content is also fairly constant, about 2,600 mg/kg and 65 - 90 mg/kg respectively. Some H_2S was measured in a sample from a spring in the Kagoro spring area and signs of sulphur deposits were found at the spring.

From earlier descriptions of the Buranga geothermal field (e.g. Pallister, 1952), it can be inferred that the surface activity has changed with time. After the earthquakes on 20th March and 17th May 1966, both of magnitude 6.1 - 6.3, pronounced changes in the surface activity was observed (Loupekine et al. 1966, Maasha 1974). The epicenters of these quakes were on the Kitimbi-Semliki fault, about 30 km SW of Buranga. Surface faulting occurred for some 40 km along the fault with down throw on the NE side, locally up to 2 m. Fore and after shock sequences were observed in a large area around the fault (Loupekine et al., 1966) and the changes in the Buranga geothermal activity show that movements have occurred on faults associated to the Bwamba escarpment. After the earthquake south of Fort Portal on the 6th of February 1994, of magnitude 6.3, and the after quakes, some probably west of the Rwenzori, changes have also been observed in the geothermal activity in Buranga. A new hot spring opened some 150 m east of the Nyansimbe pool, just east of the hottest spring in the area. The new spring is discharging 98.1 °C water into the swamps (Gíslason, pers. comm.). This shows clearly that the seismic activity in the area is sustaining permeability along faults.

Pallister (1952) considered the geothermal activity in Buranga to be connected with the tectonic activity in the rift but that the salinity of the water was not from leaching, but rather of magmatic origin. Following his recommendations, investigations of the Buranga area were continued. In 1953, some geophysical studies were carried out in the area as well as digging of pits, some of which resulted in escape of gas and inflow of hot water (Brown, 1953).

In 1954 three or four boreholes were drilled in the area. The location of the holes, as indicated on a map presumably prepaired by Brown (1954), is shown on figure 3.

Borehole No. 1 was drilled to the depth of 182 m and reached the basement rocks at the depth of 177 m, which were reported to be overlain by 5 m thick fault breccia (McConnel and Brown, 1954). The highest temperature in the well, 58 °C, was observed in the fault breccia. Borehole No. 2 was drilled some 100 m to the SE of the Mumbuga springs and to the depth of 349 m. According to Pallister (1954) the well did not reach down through the sediments and the highest measured temperature was 66 °C. Well No. 3, close to the south-easternmost hot springs, was drilled to the depth of 120 m. At the depth of 12 m, a zone, reported as a steam zone, was hit. This resulted in a blow-out which lasted for 10 minutes (Brown, 1954). According to the description, it must be considered likely that the blow-out was mainly due to gas rather than steam. No temperature log is available from the well but the returning drilling fluid was reported to have temperatures in the range 49 - 72 °C (Brown, 1954). Boreholes No. 1 and 3. have been located. Borehole No. 3 is flowing and the water has the temperature of 76 °C but no measurements have been made in well No. 1 (Gíslason et al., 1994). Borehole No. 4 was planned and its location decided (Brown, 1954) but no further reference has been found. A borehole has been located in the forest between wells No. 2 and 3, presumable well No. 4 (see figure 3), but no measurements have been made in the well.

The geothermal activity at Buranga is most likely linked to the tectonics at the Bwamba fault. The hot springs are presumably due to upwards convection of hot water after deep percolation along fault planes in the Pre-Cambrean basement rocks. The relatively large amounts of dissolved solids in the thermal water cause mineral deposition in the sedimentary layers above the basement, reducing permeability and confining the up flow to localized zones. Tectonic movements on the faults can open new flow paths both in the sediments and the basement, resulting in variations in surface activity with time.

The deeply convecting water is presumably mining heat from the generally high heat flow in the rift. The high concentration of CO_2 and the presence of H_2S do how ever strongly suggest the presence of magmatic heat source at depth and the salinity of the fluids is easily explained by volatile degassing of magmatic bodies. The salinity and the gas content of the thermal waters in Buranga could probably be explained by leaching and bacterial activity like Lissanu and Ayele (1987) did for the Katwe brine, but the magmatic origin seems more plausible.

The possible presence of magmatic bodies at depth gets further support from aeromagnetic data from the Lake Edward and Lake Albert parts of the rift. These data indicate thick sediments in the rift and show anomalies that have been interpreted as magmatic bodies in the sediments (Kashambuzi, pers. comm.). One of these postulated volcanic bodies is found in the sediments at the SW end of Lake Albert, in the vicinity of the Buranga field. Volcanic intrusions are commonly seen in seismic data from submarine sedimentary basins which have been subject to volcanic activity. The presence of magmatic heat sources in the sediments of the rift can therefore not be ruled out.

Ármannsson (1993 and 1994) sampled water from seven hot springs in Buranga. Chemical analysis and geothermometry of the samples indicates reservoir temperatures in the range of 120 to 130 °C. This rather low temperature can be taken as an indication that the heat source is the heat flow of the basement rocks. If the heat source is a magmatic body, this low temperature indicates that the geothermal system is probably in a late and declining phase.

4.1 Existing geophysical data

The earliest reported geophysical investigations in the Buranga area were gravity measurements performed by Bullard (1936) using swinging pendulums. The first geophysical work in Buranga, specially aimed at geothermal exploration was conducted by Brown (1953). The aim was to see if the geothermal activity could be associated with some near surface structures or "zones of weakness". The survey included gravity, magnetic and resistivity measurements as well as topographic surveying and leveling of the area.

The magnetic and resistivity parts of the survey were performed by L.J. Dyke at the Geological Survey of Uganda but these data, which were published as appendices to Browns report, are now missing. Brown (1953) summarizes the findings of these methods, saying that: "The magnetic measurements ..... give no indication of faulting or folding in the vicinity of the Buranga Hot Springs" but he points out that faults having nearly N-S direction, close to the magnetic meridian, would produce only minor anomalies because the small dip of the earths magnetic field at these latitudes. Brown further reports that: "The electrical measurements gave no indication that a near-surface structure exists" and that "at a short distance below the surface the sediments are waterlogged and practically homogeneous electrically in the vertical sense". He points out that such structures would be hard to detect because of limited depth of penetration which, for the electrical methods used at that time, was only some tens of meters.

The gravity data follow the report of Brown (1954), presented as a Bouger gravity map. The main features of the gravity map reflect, as Brown points out, rapid increase in the thickness of the Kaiso sediments towards the west and north. Apart from the gradient in the Bouger gravity, reflecting the increase in thickness of sediments, the map shows some gravity anomalies which Brown interprets as signs of buried fault striking about N-10°-E.

In 1973 two Schlumberger soundings were made at Buranga (Maasha, 1974a). The soundings were located between the Bwamba escarpment and the Mumbuga springs (for approximate location see figure 3), The transmitter dipoles were parallel to the escarpment and maximum current electrode spacing 526 m. The soundings show clearly that the resistivity in the sediments decreases towards the west, from the escarpment and to the springs. The lowest resistivity seen in the sounding S2, further to the east, is about 15 Ωm but about 3.5 Ωm in the sounding S1 close to the Mumbuga springs. A resistive basement is seen in both soundings and the depth to basement increase rapidly with distance from the escarpment.

The resistivity structure inferred from these soundings is in accordance with what is to be expected because the highest temperature measured in borehole No. 2, close to sounding S2, is lower than that of the Mumbuga springs and the depth to the resistive basement seems to agree roughly with the expected depth to the Pre-Cambrean basement rocks. It can therefore be inferred that the subsurface resistivity is a diagnostic parameter for the thermal and geological conditions in the Buranga area.

The seismicity at Buranga springs was also investigated in 1973, in connection with a more general study of the seismic activity of the rift around the Rwenzori Massif (Maasha, 1974 and 1974a). A micro-earthquake unit, with 4.5 Hz vertical geophone and capable of recording earthquakes in the magnitude range -2 to 4, was operated 30 m from the Mumbuga hot springs for 4 days. The unit did not record any micro-earthquakes nor ground noise at the springs, although it recorded numerous more distant events. This indicates that this part of the Bwamba fault is either not seismically active or, which is more likely, that the activity is unequally distributed in time. The recording may have coincided with a quite period of this part of the fault because at the same time other parts of the Bwamba fault were found to be active.

Recent ground based gravity and magnetic surveys have been carried out in the Lake Albert graben (Kashambuzi, pers. comm.) with the purpose of assessing possible hydrocarbon potentials in the sediments. A part of the Semliki basin, just north of Buranga, has been covered in these surveys and the resulting data will probably make a valuable background for geophysical studies of the Buranga geothermal field.

5. THE KIBIRO GEOTHERMAL FIELD

The Kibiro geothermal area is the northern most of the three areas under consideration. It is located on the SE shore of Lake Albert, on a narrow plane under the 300 m high Toro-Bunyoro escarpment forming the SE margin of the rift (figure 1). The Lake Albert part of the rift has more or less rectilinear boundary faults striking about N-50°-E but structures in the crystalline Pre-Cambrean basement are seen to be slightly oblique to the rift. The rift is about 40 km wide and the thickness of the sediments in the graben has been estimated, from gravity and magnetic data, to be as high as 5 km (Kashambuzi, pers. comm.). They have been divided into the Kaiso formation of quaternary lacustrine sands, shales and conglommerates, the Kisegi formation of tertiary fluvio-lacustrine sands and shales, underlain by the Waki formation of fluvio-lacustrine clastics. The Kibiro peninsula is an alluvial fan deposited onto the sediments in the basin.

The hot springs in Kibiro are found in three areas (figure 4). The most pronounced activity is at Mukabiga, in a ravine under the main escarpment. The geothermal springs in Mukabiga lie approximately on a line which seems to be associated with a fault slightly oblique to the main fault of the escarpment. The total flow from these springs is estimated about 4 l/s with temperatures in the range 57 - 86.4 °C (Gíslason et al., 1994).

Another group of hot springs is found some 200 m NW of Mukabiga. A number of small springs or seepages are found in this area but the estimated total flow is small, about 2.5 l/s, with temperatures in the range 33 - 71.7 °C. The third area is some 200 m due north of Mukabiga in an area called Muntere. The surface has been lowered to the ground water level and a number of seepages of water with slightly elevated temperatures up to 36 °C are found.

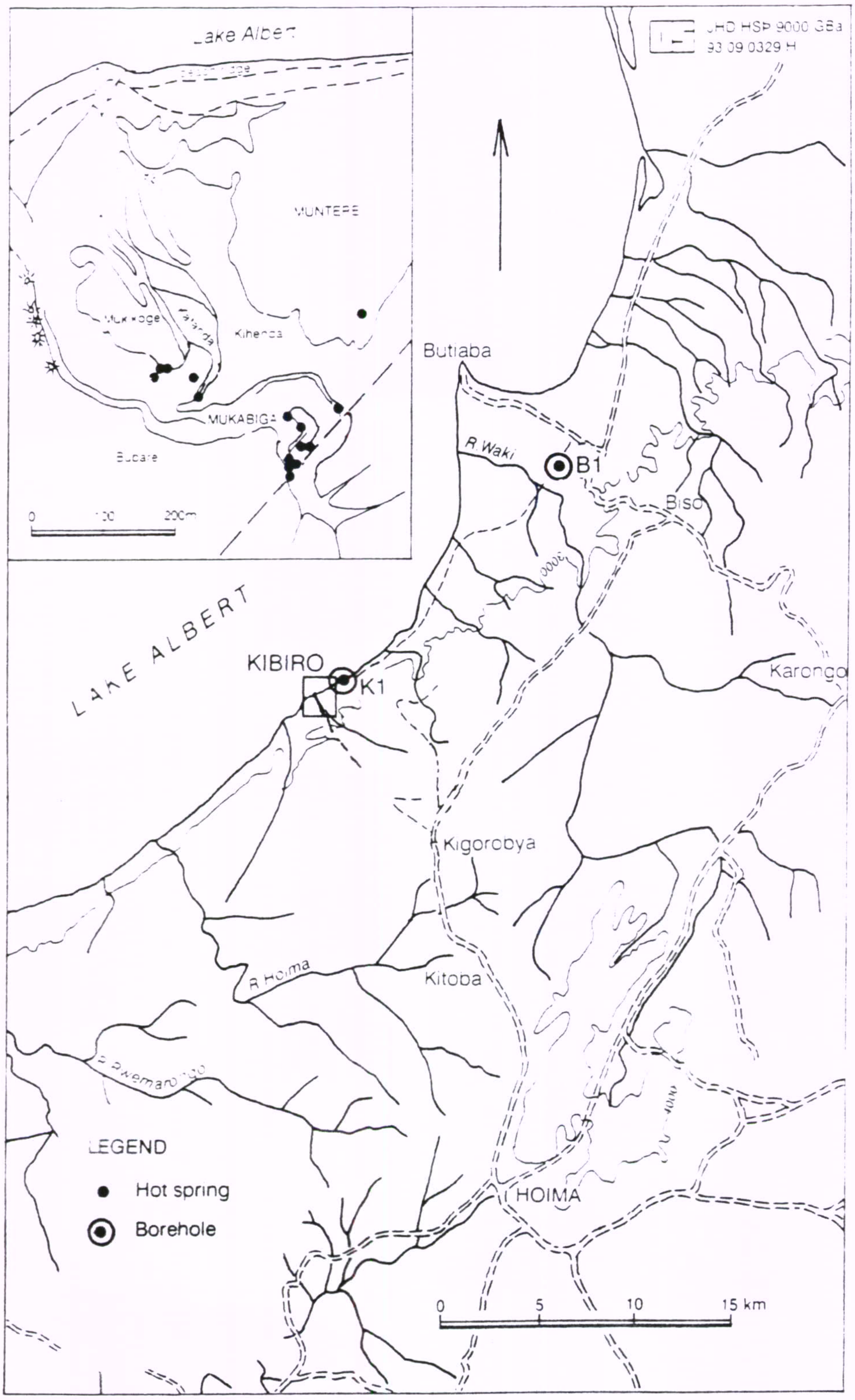

Figure-4. The Kibiro geothermal field.

Historical records indicate that the surface activity at Kibiro has changed with time. Wayland (1920) visited Kibiro in 1918 and described the springs similar or less active than they look today but refers to description of the geothermal activity made by Emin Pasha in 1885. According to this description, surface manifestations have been much more impressive at that time.

Ármannsson (1993 and 1994) sampled and analyzed thermal waters from four springs in Kibiro. The water is brackish, with conductivity about 7,600 $\mu S/cm$, and high silica content of about 120 mg/kg SiO_2. Concentrations of CO_2 are in the range of 110 - 240 mg/kg which is an order of magnitude lower than in Katwe-Kikorongo and Buranga areas. The H_2S is generally higher than 10 mg/kg and more than two orders of magnitude higher than in Katwe-Kikorongo and Buranga and considerable amounts of native sulphur is found at the Mukabiga springs. The large amounts of CH_4, about 90% in gas samples (Ármannsson, 1994), are unusual to geothermal waters. Oil is found to seep out of the sediments under the escarpment just NE of the Kibiro hot springs and the CH_4 can most likely be attributed to hydrocarbons in the sediments of the rift graben. Ármannsson (1994) applied geothermometry to the water samples form the Kibiro springs and found them to be a result of mixing of fresh and geothermal waters and that the temperature of the geothermal component is about 200 °C.

The salinity of the thermal water makes the ground water in the Kibiro peninsula saline. Salt is mined from the saline ground water in a rather unusual way which has been described by Connah et al. (1990). The surface is lowered to the ground water level and the salt is collected by capillary absorption and evaporation of the salt water in sand which is scattered over the salt gardens. The salt is then washed from the sand by water and concentrated and precipitated by boiling. The large areal extent of the salt gardens suggests that thermal waters enter the alluvial fan of the Kibiro peninsula in a larger area than indicated by surface springs.

Encouraged by oil seepages found in the Lake Albert graben, an oil exploration programme was initiated in 1938. A series of shallow holes and one deep well were drilled on the Butiaba peninsula about 20 km NE of Kibiro (see figure 4). The deep well, B1, was drilled to the depth of 1232 m and struck the basement at 1222 m (Petroconsultants, 1971). No signs of oil were observed but temperature measurements were made at several depths in the well (figure 5). Two wells, K1 and K2, were drilled under the escarpment about 1.5 km NE of Kibiro. K1 was drilled to the depth of 684 m, reaching the basement at 682 m. Above the basement, the well penetrated geothermally altered fault breccia. Two point measurements of temperature in the well exist and are shown on figure 5. K2 was drilled to the NE of K1, to the depth of 265 m encountering the rift fault at 261 m. The depths to basement found in these wells indicate that the dip of the main fault is about 70°.

Like in Buranga the most likely cause of the geothermal waters in Kibiro is deep circulation along the faults in the rift. The low thermal gradient in well B1 on the Butiaba peninsula and the much higher gradient in K1 strongly suggests convection cell in the faults at the escarpment. The low gradient in B1 is likely due to downwards percolating water and the springs in Kibiro and the high gradient in K1 due to the

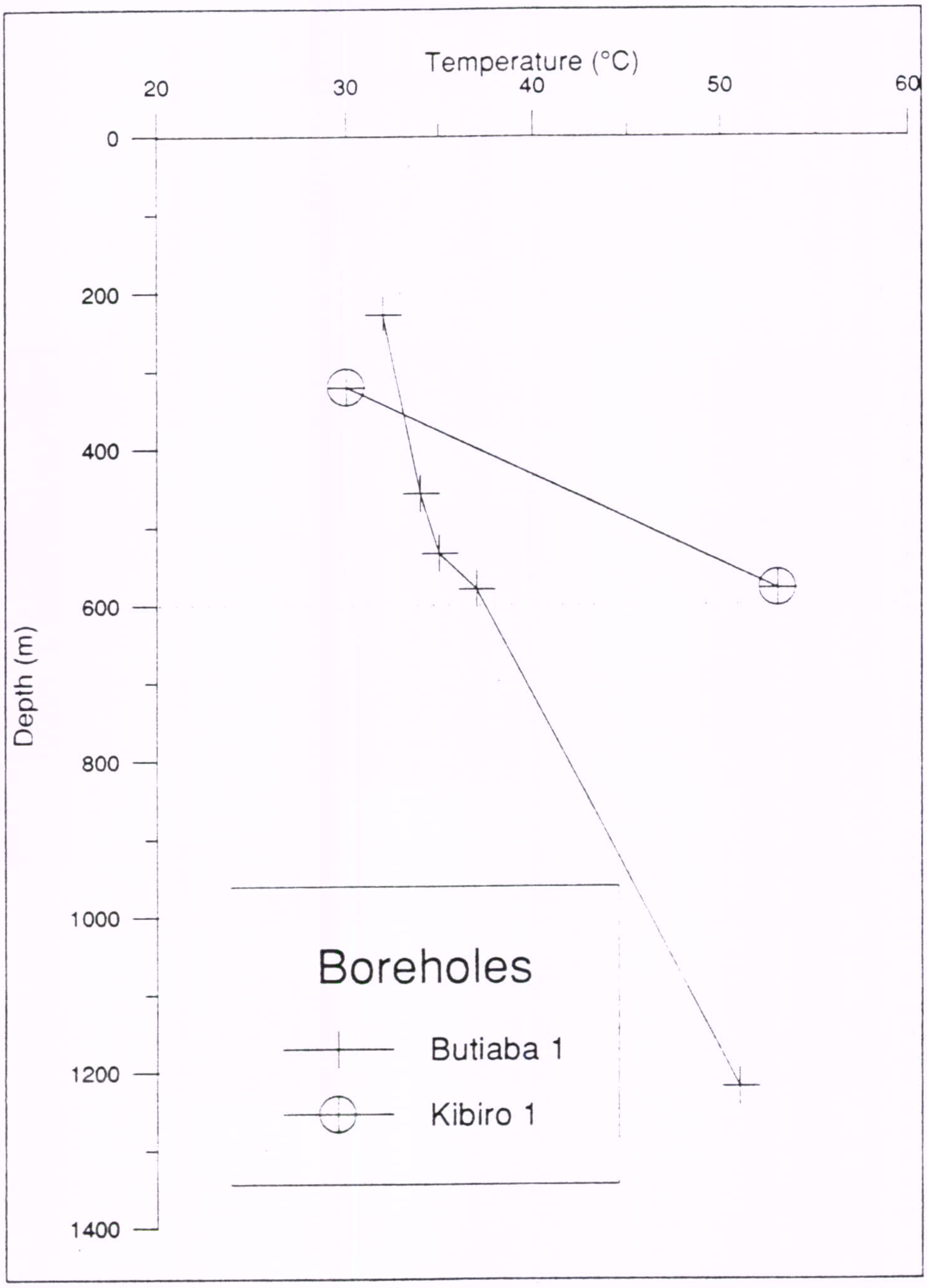

Figure-5. Temperature measurements in wells B1 and K1 in the Kibiro area (from Gíslason et al., 1994)

upwards convecting hot part of the cell. The low temperature at shallow depths in K1 indicates interference with cold ground water close to the surface which is in agreement with the chemical analysis of the spring waters in Kibiro which show mixing of cold and thermal waters.

The convection is most likely mining heat from the generally high heat flow in the rift. The salinity of the thermal waters, high H_2S content and native sulphur deposited near the springs might suggest degassing of magmatic heat source at depth but these occurrences could also be explained by leaching and bacterial activity in the sediments. The hypothesis of magmatic heat source gets support from aeromagnetic data from the Lake Albert graben which seem to indicate volcanic body embedded in the sedimentary basin close to Kibiro (Kashambuzi, pers. comm.)

5.1 Existing geophysical data

No surface geophysical work has been carried out in the Kibiro area, specifically aimed at geothermal exploration. During the study of the micro-earthquake activity of the rift, Maasha (1974) found the area at the SE side of Lake Albert to have seemingly more or less continuous seismic activity. He recorded on the average about 6 events per day on the Toro-Bunyoro fault on the SE margin of the rift.

Reconnaissance surveys have been carried out in the Lake Albert rift area in order to assess possible hydrocarbon potentials in the rift. This study comprises (Kashambuzi, pers. comm.) aeromagnetic survey, land based gravity and magnetic measurements as well as "marine" gravity survey on Lake Albert. The data from these surveys, which were designed to give information about the general geological structure of the rift graben, do not have sufficient resolution to reveal the small scale structure at Kibiro, but provide valuable background knowledge for more detailed studies.

6. EXISTING GEOPHYSICAL EXPERTISE AND EQUIPMENT

One of the objectives of Consultant Geophysicists mission to Uganda was to assess the manpower and expertise as well as existing relevant equipment that can be used for geophysical exploration of the geothermal prospects.

6.1 Manpower and expertise

The ongoing geothermal project is carried out under the Geological Survey and Mines Department (GSMD) of the Ministry of Natural Resources with offices in Entebbe. The project employs 10 people from GSMD: Two geologists, one geochemist, one technician, an account officer, a secretary, two drivers , an office messenger and a helper. The GSMD runs a chemical laboratory which is extensively used by the geothermal group.

The geochemist of the geothermal group at GSMD attended the United Nations University Geothermal Training Programme in Iceland in 1993, where he got six months of training in applying chemical methods in geothermal work. One of the geologists left at the end of January 1994, for ten months training at the Geothermal Institute of the University of Auckland in New Zealand and the other geologist is to attend the Geothermal training programme in Iceland in the summer of 1994. The geothermal group at GSMD was found to be very capable and likely to carry on effective work in geothermal exploration.

The geothermal group does not have a geophysicist on board, which would have been preferable and will be necessary when geothermal exploration in Uganda proceeds to applying geophysical methods. The GSMD employs four geophysicists who are at the moment mainly working on mineral exploration and earthquake studies. One of the geophysicists is at the moment being trained in seismological work at the University in Bergen Norway and another one is earning an MSc degree in geophysics in Holland. It would be preferable, in the future, that one of these geophysicists would be attached to the geothermal group or a new one employed.

The Petroleum Exploration and Production Department (PEPD) of the Ministry of Natural Resources has a geophysical group of three geophysicists, four geotechnicians and two geological assistants. The geophysical group at PEPD has been carrying out gravity and magnetic surveys in the Albertian rift with the purpose of assessing the hydrocarbon potential in the rift. The work performed in these surveys is found to be of high quality showing that the group is well qualified. The PEPD has offices next door to GSMD and it would be preferable that GSMD could call upon participation from the geophysical group at PEPD if major geophysical surveys are to be performed.

6.2 Geophysical equipment and computer facilities

The GSMD was found to possess the following geophysical instruments and computer facilities that are of relevance and could be available for geophysical exploration of geothermal resources.

Item	quantity
Scintrex IP and DC-resistivity equipment	
Tx: Scintrex TSQ-3 (3 kw)	1
Rx: Scintrex IPR-10	1
EG&G Geometrics proton magnetometers (G856)	2
Computers (PC-486, 33 MHz)	3
HP Design-Jet plotter (36" wide)	1
Digitizing board	1
Gray scale scanner (600-1200dpi)	1

Table-1. Existing geophysical equipment at GSMD.

One of the PC computers was bought by the ongoing geothermal project. In addition, the GSMD possesses equipments for conventional geodetic measurements.

The PEPD owns the following relevant equipment which could be available for geophysical work in geothermal exploration

Item	quantity
LaCoste & Romberg gravity meters	2
Scintrex CG3 gravity meters	2
EG&G Geometrics proton magnetometers	4
Theodolites	2
Electronic Distance Measurement Units	2
Global Positioning Systems (differential GPS capability)	3
Prismatic compasses	4
Walkie-Talkies	5
Field laptop computers	3
Computers (PC's, 500MB HD)	3
Color printers	2

Table-2. Existing geophysical equipment at PEPD.

7. RECOMMENDATIONS FOR FURTHER GEOPHYSICAL WORK

The consultant geophysicist shares the view of the Chief Technical Adviser of the ongoing geothermal project that existing information about the three geothermal prospects under consideration is not decisive enough to allow selection of only one of the geothermal areas for further studies. After completion of the present phase of geothermal investigations in Uganda, which is to be considered as the first (reconnaissance) phase of a systematic geothermal exploration, a well defined geophysical study of the prospect areas is the natural next step.

Since none of the geothermal areas has been specifically chosen for further studies, they must all be considered as potential prospects. Consequently a proposed survey plan will be sketched for each of the three areas.

7.1 Surface geophysics in geothermal exploration

The purpose of the geophysical study is to assist in further assessment of the geothermal potential by adding information about the likely spatial extent and infra structure of the reservoirs as well as to aid in siting of wells. It should be born in mind that surface geophysical exploration does generally not provide answers to questions about the temperature and permeability of the reservoir. If chemical analysis of surface springs does not give conclusive answers about expected temperature, this can only be determined by drilling. Geophysical methods will however point out places where drilling is likely to give good results and informative answers. Permeability is only determined by drilling and testing of wells and geothermal prospect is in general not proven feasible for exploitation until after successful drilling.

7.2 Recommended geophysical methods

A number of geophysical methods can and have been used in geothermal exploration (see eg. Wright et al., 1985; Hersir and Björnsson, 1991; Árnason and Flóvenz, 1992). These methods are often, but not unambiguously, divided into two categories. One category contains methods which are referred to as structural methods. These methods are used to study the geological structure of the subsurface in which the geothermal prospect is found. The most commonly used structural methods are the gravity and magnetic methods, but this category also contains active and passive seismic methods (seismic reflection, seismic refraction and earthquake monitoring). The other category contains methods which observe anomalies caused by the geothermal activity. The most common methods in this category are thermal methods (surface temperature and thermal gradient measurements) and resistivity methods.

An important factor of concern in geothermal exploration is cost-efficiency. The relatively low economical value of geothermal fluids as compared to e.g. hydrocarbons often prohibits the use of expensive exploration methods. The seismic reflection method, being the standard method in oil exploration, is capable of giving very detailed structural informations but it is expensive and seldom used in geothermal exploration. Because of the relatively high cost of drilling, thermal gradient methods are often only considered after narrowing down the target by less expensive methods.

Resistivity methods are probably the most widely used surface geophysical methods in geothermal exploration. The reason for this is that these methods are often very cost-effective and the subsurface resistivity is usually the most diagnostic parameter of subsurface geothermal activity that is measurable from the surface. The geothermal activity generally lowers the bulk resistivity of the rocks and the geothermal systems hence show up as low resistivity anomalies. This makes resistivity methods well suited to map the areal extent and the volume of the geothermal systems.

There are mainly three reasons for lower bulk resistivity of rocks hosting geothermal systems (Flóvenz et al. 1985). Firstly the ability to solve minerals and ions from the host rocks increases with temperature making geothermal waters generally richer of dissolved ions. In the case of volcanic heat sources, gases escaping from the magmatic bodies will further increase the salinity. Secondly the resistivity of electrolytic solutions decreases with temperature and thirdly, the water-rock interaction at elevated temperatures results in alteration minerals, many of which have much higher conductivity than the parent rocks (Árnason and Flóvenz, 1992).

The salinity of the fluids in the geothermal systems under consideration is thought to be deeply connected to the geothermal activity. It is likely due to volatile degassing of magmatic intrusions at depth and/or leaching by deeply convecting hot fluids. If the salinity of the geothermal fluid is higher than that of the general ground water, rocks hosting hot water will have lower resistivity than the surrounding rocks. Decreasing resistivity of electrolytic solutions with temperature will further amplify the resistivity anomaly. The existing resistivity data from the Katwe-Kikorongo and Buranga geothermal areas indicate that the subsurface resistivity structure is diagnostic for the geothermal activity of the areas. Hence resistivity surveys are recommended for further studies of the geothermal areas in western Uganda.

There exist various resistivity methods which have been used in geothermal exploration. Among the simplest and most commonly used methods to date is the Schlumberger method. The Magneto Telluric (MT) and Audiofrequency Magneto Telluric (AMT) methods have also been used quite extensively for deeper studies. The main advantage of the Schlumberger method is the relatively simple and inexpensive equipment needed, but the method suffers some disadvantages. It is based on the principle of injecting current into the ground and measuring how much of the current flows at the surface. The depth of investigation is increased by increasing the distance between the current electrodes. This can often cause problems. Firstly the injection of sufficient current can be very difficult in dry areas. Secondly, in order to obtain a depth of penetration of 600 - 800 m, the distance between the current electrodes has to be as large as 4 km. All this makes Schlumberger soundings time consuming and difficult to carry out in difficult terrain. The large electrode spacings needed to obtain sufficient depth of penetration do also cause difficulties in the interpretation of the soundings. The measured response depends on a very large volumes of rocks and lateral resistivity variations are difficult to resolve from variations with depth. This problem can only be dealt satisfactorily with by a time consuming and expensive two- or three-dimensional modeling of the sounding results.

The MT and AMT methods use variations in the earths magnetic field as source of electromagnetic signal. They do therefore not suffer the problems of current injection and large traverses needed to obtain sufficient depth of penetration as in Schlumberger soundings. The MT and AMT methods do on the other hand suffer the so called telluric shift problem. This problem has its roots in distortions of the sounding results caused by deviations form horizontal layering and can only be dealt with by complicated two- or three-dimensional modeling. It would therefore probably be difficult to get detailed picture of the resistivity structure of the geothermal prospects under consideration by MT methods but they might be considered for deeper studies in a later stage of geophysical investigation.

In recent years the so called Transient ElectroMagnetic (TEM) resistivity methods have gained increasing attention, especially the central-loop TEM method. The central-loop TEM method has been found to be in many ways superior to the more conventional Schlumberger soundings. Instead of injecting current into the ground, a source signal is produced by transmitting current into a loop of wire which is laid on the ground (for a description of the central-loop TEM method see eg. Kaufman and Keller, 1983; Fitterman and Stewart, 1986; Árnason, 1989). Central-loop TEM soundings with a square source loop of side length about 300 m have similar depth of exploration as Schlumberger soundings with current electrode spacings up to about 3.5 - 4 km. The TEM soundings also turn out to be much more downwards focused and less influenced by lateral resistivity variations than Schlumberger soundings. Comparison of these two methods has shown (Árnason, 1990) that a relatively straight forward one-dimensional inversion of TEM data gives similar resolution as a much more time consuming and computer demanding two-dimensional modeling of Schlumberger data.

All the above mentioned advantages of the central-loop TEM method are of relevance with regard to the geothermal prospects considered here. The relatively dry surface conditions in the Katwe-Kikorongo and Kibiro areas would be a problem in applying the Schlumberger method and the much smaller space needed for the TEM soundings is obviously a grate advantage in the Buranga and Kibiro areas. It is therefore, despite the fact that the necessary equipment for Schlumberger soundings exists in Uganda, recommended that the resistivity surveys are performed by applying central-loop TEM soundings. The benefits of using this method, both with regard to operational speed and data quality, will justify the investment in the necessary equipment.

The station spacings and the areal extent of the resistivity survey of each of the three geothermal areas should be such that the boundaries and the internal structure of the reservoirs is determined as well as possible. It is however recommended, in order to obtain efficiency, that detailed planning of the resistivity survey is kept flexible. Sounding results should be interpreted and the emerging resistivity structure continuously updated as field work progresses to ensure that soundings are sited where information is needed.

The hydrological structure of the geothermal systems under consideration is believed to be controlled by the tectonic activity in the rift. The general permeability of the sedimentary basins and the underlaying Pre-Cambrian basement rocks is considered to be low and that permeability is sustained by tectonic movements on faults. Therefore structural methods, capable of detecting buried faults and depth to basement, are of importance. Hence application of gravity and magnetic measurements is recommended.

The gravity and magnetic surveys should be conventional ground surveys. For the gravity survey it is essential that the elevation of the gravity stations is determined by leveling, with the accuracy of +/- 10 cm, in order to ensure sufficient resolution in Bouger gravity. It is furthermore important to perform careful topographic corrections to the gravity data, especially in the Buranga and Kibiro areas. The Magnetic survey should be ground survey measuring the total magnetic field corrected for diurnal variations of the external field. The areal extend and station density should be such that relevant anomalies, both of short and long wave lengths, are mapped properly. The survey lines of the gravity and magnetic surveys should be perpendicular to the geological strike. It is essential, in order to avoid spatial aliasing, that pilot profiles are measured both perpendicular and along strike before decisions about line spacings and station density along lines are made.

The three different geophysical methods proposed here map different physical properties of the subsurface rocks i.e. resistivity, density and magnetization. A joint interpretation of the survey results will therefore put more constraints on the resulting conceptual model of the geothermal system than would be obtained from any single method.

Sufficient expertise and equipment was found to exist at the Geological Survey and Mines Department and the Petroleum Exploration and Production Department of the Ministry of Natural Resources in Uganda, to carry out gravity and magnetic surveys. Foreign expertise and equipment is however needed to assist in carrying out resistivity surveys. It is therefore proposed that experts from Uganda carry out the gravity and magnetic part of the geophysical exploration and that foreign experts and equipments are brought in to assist with the resistivity surveys. The price of a complete set of instrumentation for central-loop TEM soundings is about 85,000 USD and monthly rental rate is about 8,000 USD.

In order to minimize risk of interruption in field work it is recommended that two trained experts in application of central-loop TEM soundings, preferably one geophysicist and one electronic engineer, will be in charge of the data collection. Processing and interpretation of the resistivity data should be performed by experienced geophysicist.

It is recommended that the Geological Survey and Mines Department provides a geophysicist as a counterpart in the resistivity surveys, both in field work and data processing and interpretation. Practical as well as theoretical training of the counterpart in application of resistivity methods in geothermal exploration should be an integrated part of the geophysical project.

In addition to the above discussed surveys, it is recommended that a soil temperature survey is performed in the Buranga geothermal area. Many of the springs in Buranga are found to emerge directly from the swamps without a mound of precipitated minerals. It is therefore likely that geothermal water is interfering with the ground water in the swamps in a larger area than is immediately evident on surface. By measuring the soil temperature, at the depth of about 0.5 m and in a regular grid, a good picture of the surface thermal activity could be obtained. Soil temperature maps often show lineaments which can give much clearer indications of up flow zones than the distribution of flowing springs. Soil temperature surveys are cheap and relatively straight forward and easy to carry out. It is recommended that such a survey is carried out by the people of the geothermal group at the Geological Survey and Mines Department in direct continuation of the ongoing geothermal project. The results of a soil temperature survey may turn out to be a valuable input for the planning and performing of further geophysical studies in Buranga. Besides manpower and equipment already existing in Uganda, the only thing that would be needed is a thermometer stick which is available for the price of about 1000 USD.

The seismicity of the rift around the Rwenzori is of special concern. The big earthquakes in 1966, killing nearly 160 people, and the recent earthquake on the 6th of February 1994, killing 10 people, call for a network of seismic stations to monitor the seismic activity in the area for Civil Defence purposes. The seismicity in the rift is so high that such a network would have to be based on telecommunications to head quarters and highly automatized location of seismic events in order to be of use for predicting major earthquakes. Such a monitoring system is expensive, both in construction and operation. Earthquake monitoring has been used as a tool in geothermal exploration but the proportion of the seismic activity in the rift, which has direct relevance to the geothermal activity, is probably too low to justify the investment in a monitoring system for the sole purpose of geothermal exploration. But once such a system is running it would, with little doubt, provide valuable information about the geothermal activity in the rift.

7.3 The Katwe-Kikorongo geothermal field

The Katwe-Kikorongo area is probably by far the largest of the three geothermal fields under consideration. The main purposes of a geophysical survey will be to determine the size of the reservoir and identify likely upflow zones. The areal extent of the uppermost 1 km of the reservoir will be determined by mapping the associated low resistivity anomaly. Resistivity variations within the anomaly will give information about infra structure in the geothermal system, related to variations in temperature and likely flow paths. The gravity and magnetic surveys are expected to give information about depth to crystalline basement, tectonic structure and faults and possible densification of the sediments, due to mineral deposition. A joint interpretation of the results from the resistivity, gravity and magnetic surveys will constrain the possible conceptual models and is expected to give fairly detailed and reliable picture of the geothermal system. When it comes to exploratory drilling, a careful investigation of faults observed on surface should be added and the wells sited such that they cut faults which are flow channels in the system. This is important because the general permeability in the sediments and the Pre-Cambrean basement is probably low.

Accessibility in the area is fairly good. Topography is generally gentle except for the craters, many of which are deep and with steep inner walls. The fact that the Katwe-Kikorongo geothermal area is situated in the Queen Elisabeth National Park needs a special attention and close consultation and cooperation with the relevant authorities is needed. Vegetation is mainly grass with scattered trees and bushes, except for many of the craters who have fairly dense forest. Only minor cutting of forest is expected to be necessary but off-road driving will be needed.

It is estimated that a geophysical survey in Katwe-Kikorongo will cover an area of about 10x20 km^2, elongated along tectonic strike. About 70 - 80 resistivity soundings and about 600 - 800 gravity and magnetic stations are needed to cover the survey area satisfactorily.

It is recommended that resistivity soundings are placed approximately in a rectangular grid. The grid axes should be along and perpendicular to the dominant fault strike so that resistivity cross-sections can be drawn, both along and perpendicular to the strike. It is recommended that station locations are not completely determined beforehand but kept flexible to a certain extent. Sounding curves should be interpreted at field camp and resistivity sections and maps continuously updated as field work progresses and soundings added where information is needed. Pilot profiles with relatively dense station spacings, no more than 2 km, should be run across the survey area, both along and perpendicular to strike, in order to get ideas about the magnitude and spatial wave length of the resistivity variations. Based on these pilot profiles, an appropriate station spacing should be determined and the survey area covered with relatively coarse grid, which can later be made more dense in areas where more details are needed.

The gravity and magnetic stations should be placed on survey lines running perpendicular to the tectonic strike. In order to avoid spatial aliasing, an appropriate station spacings along the lines and distance between survey lines has to be determined by pilot profiles, both along and perpendicular to the strike, and with small station spacings, no more than 100 m. The gravity and magnetic survey lines will probably have to be more densely spaced than the resistivity profiles but they should preferably be placed such that gravity and magnetic measurements are made along the resistivity profiles.

The time needed for field work in the resistivity survey is estimated 2.5 - 3 months and data processing and interpretation is estimated to take 2 - 3 months. The time needed for gravity and magnetic surveys is estimated to be similar to that of the resistivity survey. The surveys could be performed simultaneously if considered practical. A joint interpretation of all survey results and reporting is estimated to take about 1.5 - 2 months

7.4 The Buranga geothermal field

The geothermal water in Buranga is most likely ascending up through the sediments from buried faults in the crystalline basement. Because of interference with the abundant ground water in the area, the subsurface geothermal anomaly could be considerably larger than is immediately seen on surface. The purpose of a geophysical survey in the area is therefore to determine the areal extent of the thermal anomaly in the basement and try to locate the buried flow channels. Because of the water saturated sediments, it is not likely that geological investigations will be of much help in siting wells which have to be aimed at faults in the basement. This implies that the resolution in the geophysical survey has to be as high as possible.

It is recommended that a soil temperature survey is carried out prior to the application of the more expensive resistivity, gravity and magnetic surveys. Such a survey can reveal thermal anomalies and show lineaments which are not immediately recognized on surface, giving clues about up flow zones. Soil temperature survey is cheap and can easily be carried out by the geothermal group at GSMD as a direct continuation of the ongoing geothermal project. The only thing that will be needed is a thermometer stick which is available for about 1000 USD.

The soil temperature should be measured at the depth of about 0.5 m and it is important that this depth is kept the same within 10 cm. The temperature should be measured at about 5 m interval along survey lines perpendicular to the geological strike and the distance between survey lines should be about 25 m. The density of measuring points along lines and line spacing should be adjusted according to spatial dimensions of emerging anomalies. The survey should at least cover an area of about 1000x500 m^2 containing the surface manifestations and be extended as needed to trace observed anomalies.

A geophysical survey applying resistivity, gravity and magnetic measurements is expected to cover an area of about 3x8 km^2 comprising about 50 - 60 resistivity soundings and about 400 - 500 gravity and magnetic stations. The detailed planning of the survey should take into account the results of the soil temperature survey. In order to try to locate the up flow zones as well as possible, resistivity soundings should be carried out with short distance between stations in an area of about 1x2 km^2, elongated along the Bwamba escarpment and covering the surface manifestations. The soundings should be placed at about 200 m distance along profiles running from the foot of the escarpment and out to the sedimentary plane, perpendicular to the strike and the distance between profiles should be about 500 m. The sounding curves should be interpreted at field camp and distance between soundings reviewed according to the emerging resistivity structure. In order to map the possibly much larger thermal anomaly at depth, a more coarse grid of resistivity soundings should be measured, covering an area of about 3x8 km^2

Detailed gravity and magnetic maps should likewise be produced of an area of about 1x2 km^2 covering the surface manifestations. The measurements should be done along profiles perpendicular to the strike. In order to be able to detect faults in the basement and possible densification of sediments due to mineral deposition, station spacing along lines should be no more than 50 m where the sediments are thin, close to the escarpment but may probably be increased further out. Line spacing should be as small as 100 m, but it is recommended that pilot profiles are run both along and perpendicular to strike before station and line spacings are chosen. As for the resistivity measurements, a more coarse gravity and magnetic mapping is suggested for a larger area bordering the detailed map.

Accessibility in Buranga is rather difficult because the survey area is located in rain forest and swamps under steep hills of the Rwenzori mountains. Field work can only be carried out in the dry season. Survey equipment will have to be carried through most of the survey area which will slow fieldwork down and some cutting of forest will be necessary. The Buranga area is located within a forest reserve and close consultation and cooperation with the relevant authorities is necessary.

Field work is estimated to take about 2 months and data processing and interpretation about 1 - 2 months. This applies to both the resistivity and the gravity and magnetic surveys and they can be carried out simultaneously if considered practical. About 1 month is needed for joint interpretation of survey results and reporting.

7.5 The Kibiro geothermal field

The geothermal activity at Kibiro is most likely due to flow of hot water along tectonic flow paths associated with the Toro-Bunyoro fault. Geological investigations are likely to be of significant help in siting wells in the immediate vicinity of the springs. Geophysical methods can probably reveal structures hidden by the alluvial fan under the escarpment but equally important aspect is to see if geothermal activity is present in a larger area than is seen on surface, especially on the landward side of the escarpment.

Geophysical surveying at Kibiro is made somewhat difficult because of the limited space on land, under the escarpment. The survey should preferably cover an area extending some 8 km along the escarpment and some 2 km to each side of it. Accessibility on the south east side of the escarpment is relatively good, with gentle topography and vegetation characterized by grass and scattered trees and bushes. Most of the lake ward side of the preferred survey area is found to be in Lake Albert, except for the narrow planes at the foot of the escarpment.

Resistivity soundings on the lake are possible in calm weather but they might turn out to be difficult. This would be done by boats and the source loop either laid on the lake bottom or attached to a floating rope. The receiver coil would be mounted on a wooden float at the centre of the loop. Water born gravity measurements need specialized and expensive equipment and should not be considered but there is no problem in conducting magnetic survey on the lake. It is therefore recommended that an area of about 4x8 km^2 be mapped by magnetic measurements and the on land part of the area covered with gravity measurements. Resistivity survey should be carried out on land and extended as possible to the lake.

Resistivity soundings should be carried out with small station spacings, about 200 m, on the Kibiro peninsula and on the south east side of the escarpment in the vicinity of the hot springs. An area of about 2x8 km^2 on the landward side of the Toro-Bunyoro fault and along the shore of Lake Albert should be covered with more coarsely spaced resistivity soundings. If resistivity soundings on the lake turn out to be practical, an area of about 2x8 km^2 should be covered with relatively coarse station spacings.

Detailed gravity and magnetic maps should be produced, covering an area of about 1x2 km^2 on the Kibiro peninsula and to the south east of the hot springs. The measurements should be done with short station spacings, about 50 m, along lines perpendicular to the escarpment and with about 100 m between survey lines. A more coarse gravity and magnetic mapping should be performed in the surrounding area on land and magnetic measurements on the lake in the vicinity of Kibiro.

It is estimated that the geophysical survey at Kibiro will include about 40 - 60 resistivity soundings, depending on how easily sounding can be made on the lake, about 300 - 400 gravity stations and about 500 - 600 magnetic stations. Field work is estimated to take about 2 months for the resistivity survey and a similar time for the gravity and magnetic surveys. Data processing and interpretation is estimated to take about 1 - 2 months and joint interpretation and reporting about 1 month.

8. SUMMARY AND CONCLUSIONS

The three geothermal areas under consideration are in the western branch of the East African rift system in western Uganda. The geothermal activity is clearly related to the tectonic and volcanic activity of the rift which has higher heat flow than the surrounding Pre-Cambrian crust.

Geophysical exploration for geothermal resources in Uganda has been limited to date and existing geophysical data from the geothermal fields under consideration is sparse. Some gravity and magnetic data exists which may turn out to be a valuable back ground for further work.

The consultant geophysicist shares the view that the information provided by the ongoing geothermal project is not decisive enough to allow selection of one of the three geothermal areas under consideration for further studies. They must all be considered as potential prospects and hence a surface geophysical study is suggested and a survey plan is sketched for each of the three fields.

The recommended geophysical surveys comprise resistivity, gravity and magnetic measurements but prior to the application of these methods, it is recommended that the geothermal group at GSMD performs a soil temperature survey in Buranga. Adequate expertise and equipment is found in Uganda to carry out the gravity and magnetic part of the surveys but foreign expertise and equipment is needed for the resistivity part. The price of instruments needed for the resistivity surveys is about 85,000 USD and monthly rental rate is about 8,000 USD.

The following table summarizes the estimated time span and the amount of foreign expertise needed for the geophysical surveys:

	Katwe	Buranga	Kibiro	Total
Surveyed area (km^2)	200	24	32	256
Resistivity (months)				
Field work	2 - 3	2	2	6 - 7
Interpretation	2 - 3	1 - 2	1 - 2	4 - 7
Gravity and Magnetics (months)				
Field work	2 - 3	2	2	6 - 7
Interpretation	2 - 3	1 - 2	1 - 2	4 - 7
Joint interpretation and reporting (months)	1 - 2	1	1	3 - 4
Duration of survey (months)	5 - 8	4 - 5	4 - 5	13 - 18
Foreign experts (man-months)	7 - 11	6 - 7	6 - 7	19 - 25

Table-3. Estimated time span and work in geophysical surveys.

The time given for the total duration of the surveys is a minimum time supposing that the resistivity and the gravity and magnetic surveys are carried out simultaneously.

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APPENDIX

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JOB DESCRIPTION FOR CUNSULTANT GEOPHYSICIST