GEOTHERMAL RESOURCE INDICATIONS OF THE GEOLOGIC DEVELOPMENT AND HYDROTHERMAL ACTIVITIES OF D.R.C.

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ABSTRACT

Published sources report the occurrence of more than 135 thermal springs in D.R.C. All occur in the eastern part of the country, in association with the Western rift and the associated rifted and faulted terrains lying to its west. Limited information was available on the characteristics of the thermal features and the natural conditions under which they occur. Literature study of the regional distribution of these features and of the few relatively better known thermal spring areas, coupled with the evaluation of the gross geologic conditions yielded encouraging results. The occurrence of the anomalously large number of thermal springs is attributed to the prevalence of abnormally high temperature conditions in the upper crust induced by a particularly high standing region of anomalously hot asthenosphere. Among the 29 thermal springs the locations of which could be determined, eight higher temperature features which occur in six geologic environments were found to warrant further investigation. The thermal springs occur in all geologic terrains. Thermal fluid ascent from depth is generally influenced by faulting while its emergence at the surface is controlled by the near-surface hydrology. These factors allow the adoption of simple hydrothermal fluid circulation models which can guide exploration. Field observations and thermal water sampling for chemical analyses are recommended for acquiring the data which will allow the selection of the most promising prospects for detailed, integrated multidisciplinary exploration. An order of priorities is suggested based on economic and technical criteria.

Keywords: Hydrothermal activities, Eastern D.R.C,

INTRODUCTION

The information which was available for this study was incomplete and mostly old. Moreover, it was believed that the systematic study of hydrothermal features from the geothermal energy development aspect was unlikely to have been carried out to date. Under circumstances where information on the occurrence and characteristics of hydrothermal features is insufficient to allow their study and the discovery of the associated geothermal resources, exploration is most effectively progressed by starting with the review of the available literature, the compilation of geologic information and hydrothermal feature inventory.

This paper aims to contribute to the literature research effort. It aims to provide a gross view of the subsurface geothermal conditions which are indicated by the occurrence of numerous thermal springs, and to identify areas where follow-up work may be warranted.

The effort involved:

- the compilation of hydrothermal feature occurrences based on published information;
- the review of this information in the context of the geologic settings of the activities; and,
- the identification of areas where follow-up work would be warranted to determine the most attractive sites for follow-up studies.

The work relied solely on literature research. However, the paucity of published information deterred the full characterization of the thermal springs and the prediction of the sub-surface conditions from which they derive. Moreover, the locations of only 29 thermal springs could be determined. The approach which was adopted was thus both general, to allow the appreciation of the gross subsurface geothermal conditions, and focused, taking advantage of the availability of some basic information on a few thermal spring areas.

The work resulted in the listing of 70 named thermal springs and of the general locations of another more than 65 un-named features. These are listed in the appendix. All features are situated in the eastern part of the country. The work also enabled an understanding of the large scale natural conditions which gave rise to this anomalously high concentration of hydrothermal features in that region. The features were found to be diagnostic of the hyper-thermalism of the subsurface under the region as inferred from its geologic, geophysical and physiographic characters. Of the areas where thermal springs were reported to have more than 50OC temperature, locations could be determined for only six. These are proposed to be the focal features around which further studies should be carried out. It is suggested that brief geologic reconnaissance surveys, and hydrothermal fluid sampling and chemical analyses be carried out in these areas in order to determine whether detailed investigations would be justified.

BACKGROUND: GEOLOGIC DEVELOPMENT OF EASTERN D.R.C.

Hydrothermal features occur in all tectonic terrains which date from as early as during the Archean. It is thus useful to gain an appreciation of the geologic development of D.R.C. since those times. Figure 1 shows the main tectonic terrains, lithologic types and structures of Eastern D.R.C. This geologic framework owes its origins to successive phases of continent construction and breakup.

Pre-East African Rift System (EARS) Developments.

The long history of geologic development of the D.R.C. till the Paleogene resulted in the creation of the basement terrain and structural framework on which took place the Neogene and Quaternary processes which determined the crustal geothermal conditions.

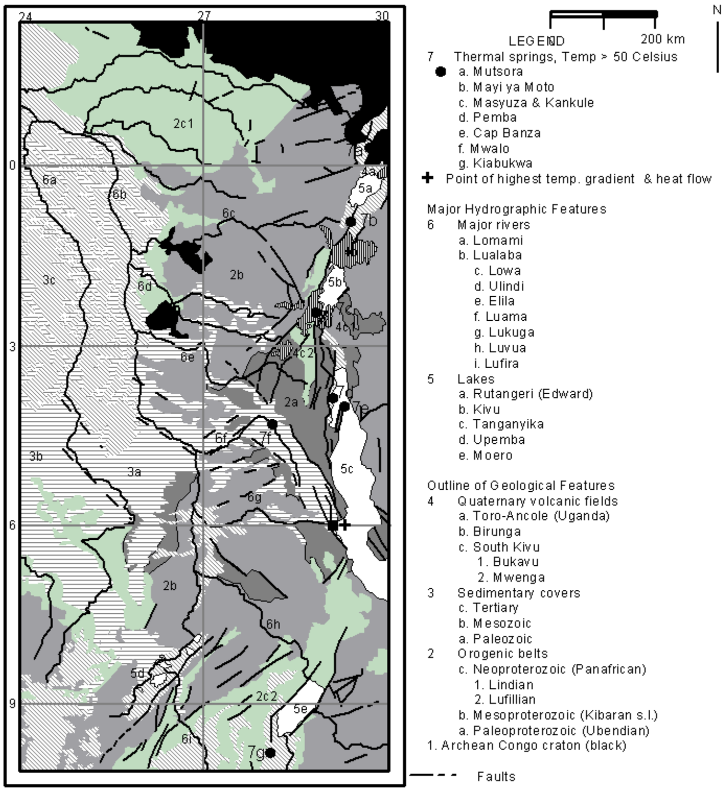
Congo craton (unit #1 in Fig. 1) formed during the Archean and served as the core around which this part of Africa was assembled during a succession of three major orogenic cycles. In D.R.C., the craton is mostly covered by sediments and outcrops in only a few places.

The Ubendian orogeny (2a) took place during the Paleoproterozoic and joined the Congo and Tanzanian cratons. The globally widespread Mesoproterozoic Kibaran orogenic belt (2b, in this wider sense also comprising other coeval orogens) formed during Rodinia supercontinent assembly during 1.36-1.00Ga. Rodinia broke up at the end of the period. During 800-550Ma, the Panafrican orogens, in D.R.C. comprising the Lindian (2c1) and Damaran-Lufilian (Katangan, 2c2) were raised between the Congo, Kalahari and East Saharan cratons resulting in the assembly of part of Gondwana supercontinent in the D.R.C. region.

The lithologic units which formed during these three orogenic cycles make up the Precambrian basement in most of the region of present interest. A protuberance of Congo craton occupies the northeast and extends into Uganda and C.A.R. The Ubendian and Kibaran make up the extensive Mitumba Mountains of Eastern D.R.C. and have contributed to determining the manner of Western rift development and the associated hydrothermal processes. The Panafrican orogenic belts occur in the north as part of the East Saharan Metacraton and host the Upemba and Moero rift zones in the south.

During the Cambrian to Carboniferous, the southern and equatorial regions of Africa were tectonically largely stable, remained above sea level and subjected to the denudation of high-standing orogenic ranges and sedimentation in low lying areas in and around Congo craton.

Fig. 1: Geologic outline, drainage and high temperature thermal spring areas in Eastern D.R.C. (modified from UNESCO/CGMW, 1985)



From the late Carboniferous onwards, Gondwanaland entered extensional tectonic phases which entailed a long period of intracontinental rifting followed by drifting phases during the Jurassic and early Cretaceous which respectively opened the Indian and Atlantic oceans. Extensive sedimentation took place in the rift basins. The Karoo continental sediments (3a) were deposited during the Carboniferous to Permian followed by the laying down of marine transgressive sediments during the Jurassic and Cretaceous (3b). These sediments are presently found in the Congo basin in the west and in the failed rifts of Eastern D.R.C. The sedimentary basins are reputed to host widespread hydrothermal activity.

The tectonic activities also resulted in the eruption of kimberlite in Southwest D.R.C. during the Jurassic and, during the Cretaceous, in the initiation of the periodic emplacement of small lava fields in Southern L. Kivu region.

Neogene and Later Developments

By the end of the Paleogene, Africa had attained its present outline. Since the Miocene however, as the core remnant from Gondwana breakup, it continued to rift and fragment along the Proterozoic orogenic belts in the context of EARS development.

Geodynamic studies show that much of the African lithosphere is underlain by a region of anomalously hot and upwelling asthenosphere, which was probably extant since about 45Ma, judging from the earliest volcanism in Northeast Africa which can be attributed to it. Asthenosphere upwelling heated and expanded a large region of the African lithosphere and caused it to isostaticaly rise to the high elevations, the "African Superswell", which especially characterize the region lying between Southern and Northeastern Africa. Eastern D.R.C. is situated on a particularly elevated part of the Superswell.

Seismic shear wave velocity tomography shows the asthenospheric temperature structure to rise to progressively shallower depths northeast-ward from Southern Africa. In the two regions where the upwelling has risen to shallow depths, it has spawned two mantle plumes which preferentially rose to still sallower depths along the Panafrican orogenic belts, the youngest and most mobile in the region. Mantle plume impact on the lithosphere caused further heating of the lithosphere which rose in isostatic adjustment to form the Ethiopian and East African domes. The two plumes are responsible for the extensive volcanism which characterized these regions starting during the Eocene. The Eastern rift developed on the softened and stretched terrains of these two domes starting during the middle of the Miocene. Plume driven within-rift volcanism has remained highly active since then. While much of it lies within the African Superswell, the Western rift developed outside the region of direct plume influence. This has given it a history of tectonic and magmatic development which is distinct from that of the Eastern rift.

The Western rift opened in a region occupied by diverse tectonic regimes. Its northern part lies in the Archean terrain of the Congo craton. Paleo- to Meso-Proterozoic orogenic belts make up its middle and southern parts while its southwestern branches developed in Neoproterozoic terrains. Its initiation is generally accepted as 10Ma: late Miocene, which appears to be the case for its central and southern parts. However, Abeinomugisha and Mugisha (2004) give an end-Oligocene to beginning-Miocene date for the initiation of its northernmost sector, the L. Albert rift, on the basis of the ages of rift bound sediments. Western rift development involved the opening of new rift zones following pre-existing rock fabrics in the metamorphic basement and the reactivation of structures that were initially setup during late Paleozoic and Mesozoic periods of crust extension. In addition to its main conspicuous physiographic expression lying between D.R.C and its eastern neighbors, the greater Western rift system also has a number of secondary rifted and faulted zones on its western side extending up to the eastern margin of Congo craton. This tectonic regime accounts for the great majority of the hydrothermal features of the country.

A distinctive feature of the Western rift is that it is segmented. It comprises rift zones, mostly half grabens which are separated from each other by rift-transverse faults. Quaternary volcanism took place solely along these faults while the interior parts of the rift segments remain amagmatic. In D.R.C., the Birunga and S. Kivu volcanic provinces are, from north to south, found between Lakes Rutangeri, Kivu and Tanganyika rift zones. To the north, the Toro-Ankole volcanic province in Uganda separates the Rutangeri and Albert rift zones.

The northernmost thermal springs in D.R.C. occur in L. Albert rift, a full graben which opened in Congo cratonic terrain. It is believed that this northernmost part of the Western rift is opening passively, with no in-field stress involved. Transform faulting along Aswa shear zone, which terminates the Western rift in the north, is believed to have transferred crustal movement from the Eastern rift. The tectonic event reported by Abeinomugisha and Mugisha (2004) predates the initiation of the main Kenya rift but rifting and volcanism in Turkana rift zone were already ongoing at that time. The Miocene age alkaline-carbonatite eruption centers in Eastern Uganda, e.g. Mt. Elgon, (Barifaijo, 2001) resulted from movement along this structure. The initiation of rifting by the agency of Aswa shear zone is thus plausible.

On the other hand, the high Mitumba Mountains region of Eastern D.R.C. is the part of the "African Superswell" which has undergone the most thermal uplift. The Ubendian basement terrain reaches 3,200m elevation along the Western rift margin on the western side of northern L. Tanganyika. This is the highest standing basement terrain of Africa attributed to thermal uplift. It is also marked by a regional gravity minimum (<-160mgal), a reflection of crustal density reduction by thermal expansion over tumescent asthenosphere.

In the region lying between Bukavu in the north and Kalemie about 400km to the south, the Western rift exhibits a complex structural pattern where faults of its three arms interact*:*

- a Northeastern arm: the L. Kivu rift zone which, in segmented form, extends to the northeastern termination of the rift branch at the Aswa shear zone in NW Uganda;
- a Southeastern arm: the Tanganyika-Rukwa-Malawi (TRM) rift zone which trends NW-SE to NNW-SSE; and,

- the Ruzizi rift zone: The N-S oriented structure which hosts the Ruzizi River and the northern L. Tanganyika basins and links the above two rift arms.

The L. Kivu rift zone is a half-graben extending from the NNE to the SSW between the Birunga and South Kivu volcanic fields. The earliest border faults are dated at between 7.5 and 4Ma (Furman and Graham, 1999). The WNW border faults extend to the region of Kamitunga in the Elila River basin in the SSW. Two lava fields are mapped as occurring in this rift zone: in Bukavu area and in Mwenga area situated about 100kms to the southwest.

A major NE-SW oriented, NW-facing regional fault could be discerned on SRTM-DEM of the L. Kivu-Elila River basin region. It extends from L. Kivu, where it forms the lake's southeastern coastline, to the northeastern border fault of Luama graben in the southwest. Its inferred disposition is shown in Figure 4. The fault appears to be more important than the NW border faults in forming an asymmetric graben in which Mwenga volcanic field is situated (here tentatively referred to as Elila graben). The graben is seismically active, discernibly more so in its southeastern part where this major fault is inferred to be situated. This fault may have contributed to the localization of volcanism in the Mwenga area, and possibly also in Bukavu area. The upper Elila River basin occupies the graben and is reported to be populated by 23 thermal springs of which the locations of only two, Kitutu (#24) and Kilenga (#31), could be determined. This inferred fault (here tentatively referred to as the S.E. Kivu fault) appears to form the northwestern structural boundary of the uplifted Ubendian basement.

The 200km wide TRM rift extends over a distance of 1,000km in the NE-SW to NNW-SSE direction between the southern part of L. Kivu rift and the northern end of Malawi rift, via L. Rukwa rift zone. It opened during Permo-Carboniferous times (Delvaux and Kervyn, 2004) following the Ubendian rock fabric, skirting the southwestern side of the Tanzanian craton. Crust extension across the TRM resulted in the opening of L. Rukwa graben in SW Tanzania and, in D.R.C. on the western side of the lake, the half graben which forms the upper Luama River basin. Permian Karoo and Cretaceous sediments were deposited in both rift zones. The opening of the part of TRM rift which houses L. Tanganyika's southeastern basin was initiated during late Miocene. The lake owes its formation to both crust extension and dextral displacement. The TRM was involved in transform movements at various times. The timing of these movements is subject to debate. As such, similarly to its northern counterpart, the Aswa shear zone, this structure is considered to be a transfer structure (CGMW, 2009) which facilitated the southward propagation of the EARS to by-pass the deep rooted and mechanically strong Tanzanian craton across which the Eastern rift failed to propagate. The structure is marked by late Miocene to Holocene volcanism in the areas where it terminates the L. Kivu and L. Malawi rift sectors.

The faults of Ruzizi rift zone have N-S trend, plausibly facilitating rifting to take place along the line of least mechanical resistance to link the above two rift arms. This rift zone includes the northern basin of L. Tanganyika which is characterized by N-S faulting extending as far south as Kalemie area. This basin is about 1,300m deep and it is separated from the lake's southeastern basin by a structural high where the depth of the lake is less than 750m (ILEC, 2009). From the structures which exist on both sides of the lake, it is evident that this structural high is cut by NW-SE trending faults which extend from the lake's northeastern side in Tanzania to Luama graben on the D.R.C. side in the northwest. Seismicity is particularly high in this zone (Fig.3).

The three sets of faults cross in the Kalemie-Bukavu region. Due to the above tectonic architecture, the Western rift exhibits an east-facing concave outline, with the Tanzanian craton nestled in the concave. This structural condition has given this part of the Western rift and its associated structures a distinctive geothermal character as discussed in Section 4 below. It is speculated here that the three fault systems form the structural framework within which the extraordinary thermal uplift of the Ubendian basement by about 2kms above the surrounding basement terrain occurred over a particularly buoyant sub-lithosphere region. The uplift of the Mitumba Mountains is greater in this area than elsewhere along the Western rift and cannot be accounted for solely by the rift shoulder uplift which is commonly said to accompany passive rifting. If this speculation is borne out to reflect the actual situation, it may explain why an anomalous geothermal regime prevails in this region, giving rise to a high density of hydrothermal activity and the occurrence of primary magmatic brines of very deep origin.

In the southeastern region of D.R.C., the incipient NE-SW trending Upemba and Moero rift branches are undergoing extension in the NW-SE direction (Fairthead, 1977). The structural development of the region dates from northeastward thrusting and the raising of the Lufilian Arc (Fig. 2) during the Panafrican orogeny. The Damaran-Lufilian orogenic belt is characterized by extensive faulting of this age with strikes oriented NE-SW, the direction of thrust. The structures which evolved to become rift faults thus seem to be attributable to Panafrican structuring. In contrast to other rift zones in the region (Luama, Rukwa, Malawi, Luangwa and Zambezi) these rift branches do not seem to contain Permian and Cretaceous sediments and thus appear to be newly opened during the EARS tectonic phase. Although situated in the mobile Neoproterozoic Lufilian (Katangan) greenstone belt, which is inherently most amenable to deformation, these two rift branches have failed to further propagate to the southwest. This is mainly attributable to the rheological barrier imposed across the otherwise preferred path of rift propagation by the cross-cutting Lufilian Arc. Otherwise the rift zones exhibit a high level of seismic activity and extensional stress. A large number of areas of hydrothermal activity are reported to occur in the rifts and in the basins of the rivers in the region. During the early 1950s, Kiabukwa, situated in the southern L. Moero rift zone, was the site of the first geothermal power plant in Africa (Hochstein, 2000).

SUMMARY OF THE FINDINGS

Regional Distribution of Hydrothermal Activities.

All of the geologic terrains described above exhibit hydrothermal activity. Except for the fumaroles of Nyiragongo and Nyamulagira volcanoes, all other known hydrothermal features in D.R.C. are thermal springs. All of the features are found in the eastern part of the country, extending over nearly all of its latitudinal extent (Fig.2). None are reported to occur to the west of 24OE longitude.

The westernmost thermal spring, Tshapona (#35 in The appendix), discharges in the upper Kasai River drainage basin. Three others, Kibimbi, Lufubu and Piani Mimba (#25-27), occur close to Lualaba River. All of the rest are found to the east of that river. Of those features for which the locations are known, Kasongo occurs close to R. Lualaba but all of the rest are situated to the east of 28OE longitude. This distribution of most of the thermal springs indicates their large scale tectonic affiliation to the highlands of Eastern D.R.C.

Several thermal springs are found within the Western rift basin, including most of those that are hotter than 50OC. The largest number of the features is however found in the Mitumba Mountains region lying to the north of R. Lukuga, and most of them occur in the basins of the numerous rivers which drain westward into Lualaba River. In the southeast, numerous thermal springs are reported to occur in river and lake basins found in the Proterozoic terrain which makes up the plateaus and rifts of Katanga.

Sub-lithospheric Influence on the Hydrothermal Activities.

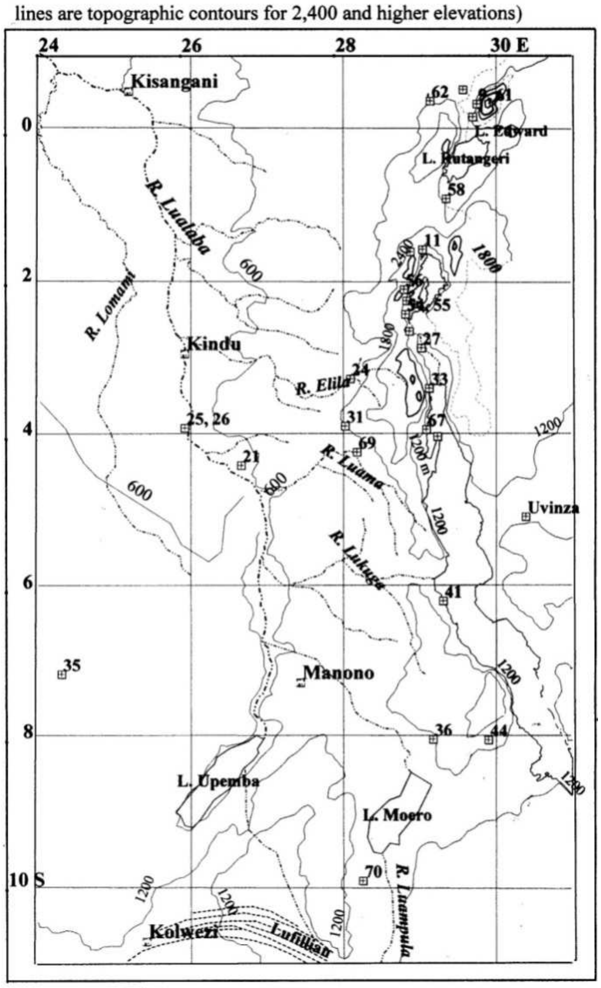
The different stages of tectonic and magmatic development reached by the various rift zones are due to the different degrees of sub-lithospheric influence which itself evolves in time. This is relevant to understanding the nature and characteristics of the hydrothermal features of the EARS in general and those of the Western rift in particular, including their associated geothermal resources (Getahun Demissie, 2010). The geothermal resource development prospects in Eastern D.R.C. are thus best viewed in this light.

The northernmost part of the Western rift lies outside and to the northwest of the East African dome, the region of direct mantle plume influence. The asthenospheric temperature structure has a more subdued aspect which is more akin to that prevailing in the Saharan zones of moderate thermal uplift. The gravity field is also similar to the pattern along these zones and matches the lower elevations which prevail in this part of the rift than further to the south. This part of the Western rift is situated in a region of old, thick and cooler crust than elsewhere and is undergoing a truly passive rifting process involving little or no in-field stress. Mantle influence is limited solely to the emission of volatile components released during the degassing of newly un-muffled mantle. There has not been any magmatism in the form of melt production.

On the other hand, in the Birunga and S. Kivu parts of the Western rift, asthenospheric impact is believed to occur, signaling two evolutionary stages of rift

Fig. 2: The known thermal spring locations of D.R.C.

(Thermal spring numbers are as in the appendix. Bold full lines are topographic contours for 2,400 and higher elevations)



development. As further discussed under 3.3.4 below, the dominantly Potassic alkaline affinity of the volcanic rocks in the Birunga field (Rogers et al, 1998) represent the earliest phase of small scale melt production in a still passively rifting state. The mode of melt generation is metasomatic and not adiabatic melting which requires a higher more advanced scale of lithosphere structuring. On the other hand, volcanic petrogenetic data from Bukavu lava field (Furman and Graham, 1999) indicate the magma sources to be situated at the base of an already attenuating lithosphere at an estimated 65km depth, the shallowest depth in the Western Rift outside the Rungwe volcanic field in SW Tanzania. This state of lithosphere breaching can be taken as signaling the transition of Kivu rifting from the passive to the early active phase. The picture is broadly consistent with results from seismic shear wave velocity modelling work by Simiyu and Keller (1997) and Nyblade et al (2000). The models indicate the existence of a deep seated mantle plume arm rising westward from a plume head situated under the Tanzanian craton. Nyblade's model shows the plume arm apparently penetrating the lower lithosphere under the region of the Western Rift lying to the south of Kivu volcanic province. This may account for the significant extent of sub-lithospheric erosion which the petrogenetic evidence implies.

An evidence for this situation prevailing under Eastern D.R.C. is the occurrence of an anomalously large number of hydrothermal features, surpassed in density of activity only by regions of Africa which are traversed by the eastern and northern EARS sectors, the middle Zambezi rift and the Atlas Mountains belt of currently ongoing orogeny. The juvenile brine springs in the Ruzizi rift zone, indicate rifting in this region to be more advanced than in most other parts of the Western rift.

Crustal Influences on Hydrothermal Activity

<u>Some Geophysical Features of the East D.R.C. Crust</u>

Seismicity

Figure 3 shows the distribution of earthquake epicenters for the period 1973 to 2009 (NEIC, 2009). The three tectonic elements of the Lakes Kivu and Tanganyika region, discussed in 2.2 above, and the Upemba and Moero rift zones are schematically shown. Except for Upemba rift zone where the situation is unknown, most of the higher temperature thermal springs of Eastern D.R.C are hosted within this tectonic framework. The thickness of the seismogenic layer in the region is generally 33kms, showing the crust to be largely un-attenuated.

From the distribution of seismic epicenters, it is evident that the crust in the region is tectonically active. The high epicenter density shows not only that active faulting prevails in the rift zones that were newly opened during the late Miocene but also along the TRM fault system most parts of which date from the late Paleozoic and the Mesozoic.

The close association of areas of thermal spring activity in Eastern D.R.C. with these fault systems is discussed in 3.3.2 below and indicates that faults serve as channels of geothermal fluid ascent to the surface.

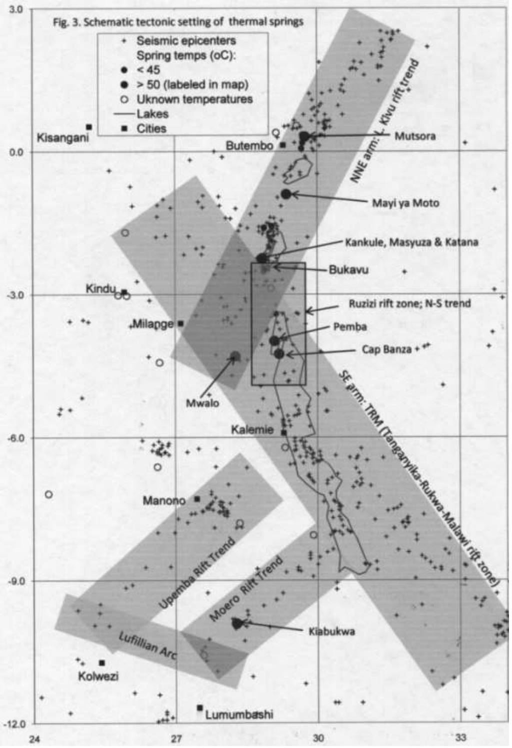


Fig. 3. Schematic tectonic setting of thermal springs

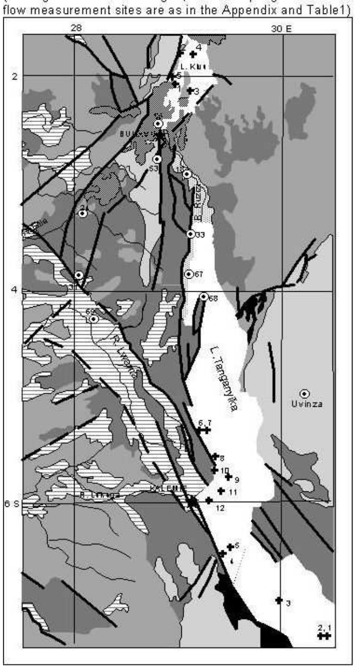
Heat Flow

Sebagenzi et. al. (1993, cited in Sebagenzi et. al., 2004) provided the two only known heat flow values on land in D.R.C.: 65mWm-*2* is reported for the rifted Kundelungu plateau terrain and 40mWm-*2* from Congo craton. These are comparable to values reported by Nyblade (1990, 1997) for the adjacent regions: 67+/-7mWm-2 for the Kibaran belt on the southwest side of L. Victoria, 76+/-14 mWm-2 for the Mesozoic Luangwa and Zambezi rifts in Zambia and 34+/-4mWm-2 for the Tanzanian craton.

The international heat flow data base contains only 17 values, all from Lakes Tanganyika and Kivu (Fig. 4, Table 1). Heat flow values range widely for both lakes, respectively from 17 to 151mWm-*2*, and 17 to 185mWm-*2*. Heat production values are 5.6 and 5.8µWm-*3* for L. Kivu and 3.3 to 3.5µWm-*3* for L. Tanganyika. There is no information on what rocks were tested for heat output. Therefore, it is not known if the higher values from L. Kivu are due to measurement in the young Panafrican rocks which occur in the lake's northwestern part. Granitic rocks in the Panafrican basement are much younger than the Ubendian and Kibaran rocks which make up the basement of L. Tanganyika and would still retain much of their original radio-element contents. In the data from both lakes, there is no correlation between heat production and heat flow. Heat flow may thus have deeper sources and also appears to reflect the influence of faults. In L. Kivu, the higher values are from the zones of two east-facing faults: 99mWm-2 near a rift border fault to the east of Kabuno Bay and 181mWm-2 near the eastern border fault of Idjwi horst.

In L. Tanganyika, temperature gradient shows a wide range, all but one value exceeding the global average of 30*O*C/km. There is a linear relationship between heat flow and temperature gradient indicating the absence of near-surface influences. The highest temperature gradient and heat flow, respectively 190OC/km and 151mWm-2, are both from the shallow zone which separates the lake's two basins. This contrasts with usual sub-lacustrine heat flow value distributions in rift zones where the higher values typically are from the deeper parts the lakes, e.g. L. Baikal, Russia (Lysak and Sherman, 2002). This indicates that the high heat flow is due to a NW-SE trend fault which crosses this block. Another value of 57mWm-2 is from a nearby location on this block. The difference between these values seems attributable to the measurement points being located at different distances from fault zones.

Figure 4. Geology, known thermal spring locations and heat flow measurement points in Lakes Kivu-Tanganyika region.
(Geologic units are as in Fig. 1, Thermal spring and heat flow measurement sites are as in the Appendix and Table1)



The Influence of Crustal Structures

As outlined under Section 2 above, the region of Eastern D.R.C. has a long history of structural development, mainly dating from Gondwana supercontinent rifting and break up during the late Carboniferous to Cretaceous. The dominant structural trends during those times appear to have been oriented NW-SE and NE-SW. This is discernible in the structural patterns engraved on the Proterozoic terrains and marking the outlines of sedimentary rock exposures. These structures also determine sections of the courses of the numerous rivers which drain the Mitumba Mountains. The latest phase of structural development however dates from the late Miocene initiation of EARS tectonics.

From the locations of thermal spring activity along fault zones and in the graben structures which house river basins, it is evident that faults serve as the preferred paths for thermal fluid up-flow from depth. This is particularly well illustrated by the locations of the sub-lacustrine juvenile brine springs of Pemba and Cap Banza (#67, 68). Tiercelin et al (1993) report that these features occur at the intersections of NW-SE and N-S trending faults, respectively designated above as the TRM and Ruzizi fault systems. Uvinza brine spring in Tanzania (Fig. 3) also occurs on a fault of the TRM system, and is believed to be of similar juvenile origin. Alleman et al (2003) reported water stratification in L. Tanganyika which is due to poor mixing. Hydrothermal fluid contribution to the deep lake water and particulate chemistry was seen to occur in the northern basin, from either upward fluid flow from beneath the basin itself or outflow from sources in the north. In either case, the importance of the N-S structures as conduits of hydrothermal fluids is demonstrated.

Table 1: Heat flow data from D.R.C.

A. From the IASPEI-IHFC database: Lakes Kivu (L-K) and Tanganyika (L-T),

Site	Location		Heat Production	Temperature Gradient	Heat Flow
No.	Long	Lat	μW m-3	oC km-1	mW m-2
L-K001	29.02	-1.99	-	-	41
L-K002	29.02	-1.75	5.8	-	99
L-K003	29.15	-2.13	5.6	-	185
L-K004	29.17	-1.80	5.8	-	25
L-K005	28.98	-1.93	5.6	-	17
L-T001	30.27	-7.22	3.4	49.0	35
L-T002	30.23	-7.22	3.3	54.5	39
L-T003	29.97	-6.85	3.4	77.0	55
L-T004	29.54	-6.44	3.5	24.0	17
L-T005	29.58	-6.38	3.4	33.0	22
L-T006	29.25	-5.33	3.3	48.0	35

L-T007	29.35	-5.30	3.3	57.0	67
L-T008	29.47	-5.54	3.3	58.0	41
L-T009	29.58	-5.77	3.3	55.0	39
L-T010	29.42	-5.73	3.5	65.5	46
L-T011	29.53	-5.92	3.3	72.0	57
L-T012	29.45	-5.97	3.4	190.0	151
B. From Sebangezi et al, 2004 (unspecified location coordinates)					
Kundulungu plateau,			-	-	65
Congo craton overlain by Paleozoic sediments				-	40

While the preceding accounts for the tectonic control on individual thermal spring occurrences, their general distribution in the key region affected by the above fault systems may be viewed in terms of the larger scale of crustal structural control. In this respect, the present perception is that the high standing block of Ubendian basement may be considered as a focal structural unit of geothermal anomaly with regional significance. This basement is believed to have been heated and thermally uplifted over a particularly tumescent mantle structure. The resulting thermal expansion and consequent density reduction of the Ubendian crust is reflected in a very strong negative gravity anomaly, as discussed in 2.2 above. This tectonic setting leads to the inference that the uplifted block has an anomalously high subsurface temperature. Its high internal heat content may be advectively flushed outwards by hydrothermal fluid flow which would have given rise to the numerous thermal springs which occur in the lower lying faulted areas of the surrounding region. Its conductive heating by a high standing mantle hot plate may also be augmented by the upward rise of juvenile hydrothermal fluids in the areas affected by the Ruzizi and TRM fault systems, elements of which are seen to extend into the uplifted block. The path of magma rise from lower lithosphere regions may have been refracted away from the uplifted block and into the faulted zone in the northwest to engender the volcanism of Bukavu and Mwenga areas. In this respect, the faults of Elila graben appear to be more amenable to the upward leakage of hot lower lithospheric materials, in the form of melt, than those of the amagmatic Ruzizi and TRM systems which facilitated only volatile component rise. From this may be inferred the possible geothermal attraction of Elila graben.

The Role of the Sedimentary Basins

Successive vertical movements have been followed by the erosion of uplifted blocks and sedimentation in tectonically subsided and rifted zones especially during the late Paleozoic and Mesozoic (lithologic units 3a and 3b in Fig. 1). The rivers which drain the Mitumba Mountains region lying between the latitudes of Bukavu and Kalemie wholly or partially flow in these sedimentary terrains. A number of the numerous thermal springs that are reported to occur in these river basins can thus be expected to be hosted in these structurally controlled sedimentary basins. The only thermal spring known to have such occurrence is Mwalo. It is reported to exhibit high energy of discharge. Continental clastic sedimentary basins tend to be associated with higher permeability than igneous and metamorphic terrains and to attain more extensive lateral continuity. They may thus support energetic hydrothermal activity as at Mwalo. If geothermal resources are hosted in such basins, as is supposed here to be generally the case on the western flank of the Mitumba Mountains, it can be expected that both the stored resources and well productivities may be sufficiently large to warrant economic geothermal resource exploitation. Deep sedimentary basins are also known to host geopressured geothermal resources which do not have surface expressions. The rift bound Paleozoic to Mesozoic sedimentary piles may thus also host such blind resources.

The influence of magmatism

As indicated earlier, coupled with it's more recent initiation than that of the Eastern branch, rifting in the thick and strong Paleo- to Mesoproterozoic crust in Eastern D.R.C. is insufficiently developed to trigger high volume adiabatic magma generation in the mantle. Rifting and crustal attenuation are thus at too early stages of development to engender the large scale and evolved magmatism which characterizes the more developed eastern and northern EARS sectors. Only small scale volcanism took place in the Birunga and South Kivu volcanic fields.

The oldest volcano in the Birunga volcanic field (unit 4b in Fig.1) is Mikeno and has been dated at 2.6Ma **(**Ranson and Demange, 1983**).** Two active volcanoes, Nyiragongo and Nyamulagira are of late Pleistocene age. These three volcanoes occur in the D.R.C. part of the volcanic field. Karisimbi and five other recently inactive volcanoes of similar age occur on the D.R.C.-Rwanda border. The Birunga field is characterized by alkaline, dominantly potassic, volcanism with limited total volume and areal distribution of eruptive products. The chemical and mineralogic compositions of the volcanic rocks in most cases show derivation from small fraction metasomatic partial melting in the mantle and very little sign of magma differentiation or interaction with crustal rocks. Magma is thus believed to rise to the surface without undergoing significant intermediate storage in the crust.

Karisimbi, which is most favorably situated on the eastern rift border where it is crossed by a rift-transverse structure, shows a degree of magma differentiation reflected in the eruption of trachytic lava (Rogers et al, 1998). It is the only one which exhibits the possible presence of magma storage in the upper crust. Gisenyi thermal spring in Rwanda (70OC) may be associated with the magmatism which produced Karisimbi. The volcano's recent inactivity and the small volume of the total erupted products however indicate that magma size may not be large or to still be at high temperature. The other, warm, thermal springs which occur in the adjacent areas to the north of L. Kivu may owe their geneses to the circulation of meteoric waters in upper crustal regions that are heated conductively and by heat loss from ascending magma, and their mixing with hot juvenile volatile fluids which are common features of the Western rift region.

The nature of volcanism at Mayi ya Moto, situated to the north of the Birunga field, is not known although its tectonic setting suggests it to be an offshoot of that volcanic field and to broadly share its petrologic, and therefore genetic, characteristics. Its association with highly dynamic hydrothermal activity however lends it distinction which should be accounted for.

In the Southern Lake Kivu volcanic province, numerous episodes of small scale alkaline volcanism have been dated from as early as 70Ma (late Cretaceous) forming a pre-rift tholeiite flood basalt plateau (Ranson and Demange, 1983). The late Miocene lavas however date from the initiation of Kivu half graben opening at about 7.5Ma. The more evolved lavas are from Bukavu area (unit 4c1) where the above described three fault systems interact. The volcanic province is almost entirely made up of fissure lava flows with only a few relatively small volcanic centers occurring along the northwestern border faults. Tshibinda is the more prominent of these centers. Its last eruption was at 10Ka, at the same time as a small eruption on Idjwi Island.

The volcanic field in the general area of Mwenga (4c2) situated about 100 kms from Bukavu, forms the isolated, southernmost field of the South Kivu volcanic province. It is found in the area which is affected by the SW extensions of Kivu half graben border faults which, together with the S.E. Kivu fault described above form a graben. Information on the nature of the volcanic rocks was not available for this study.

A number of carbonate bodies, sometimes described as carbonatite, occur within and outside the rift basins. Evidence from Kibuye in Rwanda (Lavreau and Buyagu, 1989) shows it to be a product of hydrothermal remobilization of carbonates in the metamorphic and sedimentary rocks, rather than originating from metasomatic carbonatite volcanism. Thus, the many thermal springs which deposit travertine fronds should be viewed in this light for better understanding their geneses and chemical evolution.

Lithologic Affiliations of Hydrothermal Activity.

Hydrothermal activity takes place in areas made up of lithologic types of all ages.

<u>Thermal Springs of the Volcanic Fields</u>

Two of the high temperature spring areas, Mayi ya Moto and the Mahyuza-Kankule group, (respectively #58 and 54-55 in the appendix), occur in the areas of hydrologic discharge situated in Quaternary volcanic provinces.

The low temperature springs, Tingi, Sake, Kihira (collectively #11) and Kikingi (#63) occur on the northwestern shore of L. Kivu. It is uncertain if they are heated under the Birunga volcanic field to emerge on or near the lake shore at the lower end of the local hydrologic gradient, or if the waters rise from depth along the border fault limiting Kabuno Bay on the west. Published results (e.g. by Tietze et al, 1980; Tassi et al, 2005) show that L. Kivu discharges large volumes of CO_2 and CH_4, especially in Kabuno Bay. The CO_2 is of juvenile origin. Katana (#12) and Maziba (#56) occur near the northern end of the Bukavu sector of S. Kivu volcanic field, probably owing their location to the outer rift border faults. Nyangezi (#53) occurs near the southern edge of the lava field.

Kitutu (#24) is situated near Mwenga. It is the only thermal feature which may possibly be related to the volcanism there. Of the other 22 reported thermal springs in the Elila River basin, some may have similar association while others may be expected to occur in the graben marginal metamorphic or graben filling sedimentary rocks. No information was available on these thermal springs.

<u>Thermal Springs of the Sedimentary Basins</u>

The only thermal spring for which the location coordinates are known and that is believed to be situated in an area occupied by sediments is Mwalo (#69). It occurs in the upper Luama River basin in the piedmontain area on the northeastern side of the Luama half graben. Waring has reported the occurrence of 17 other thermal springs in this river basin (#28, 29 and the #29a group of 15 features). The main course of Luama River is situated within the extensive late Paleozoic and overlying Mesozoic graben filling sediments. Thus many of the features may issue from these rocks. Two alternative modes of subsurface hot water circulation may tentatively be considered. Hot water may rise to the surface along faults from a reservoir situated within the sedimentary basin, or, it may emerge from a thermal water outflow structure originating from a heating and upwelling area situated under the high standing block of Ubendian metamorphic rocks lying to the northeast.

Pakundi spring (# 34) is reported to occur in the Lukuga River basin which is partly occupied by the same sedimentary rocks. Waring also reports that 7 named (#14-16 and 21-24) and 27 un-named thermal springs occur in the Ulindi and Elila River basins. The courses of these rivers traverse similar sedimentary basins as R. Luama. Thermal springs may thus discharge from sedimentary rocks if they happened to be situated in close proximity with the rivers in their middle courses. Others may issue from the metamorphic rocks which occupy the upper and lowermost parts of the river basins.

Thermal Springs of the Proterozoic Terrains

Many thermal springs, including half of those known to issue at high temperature (#68: Pemba, 69: Cap Banza and 70: Kiabukwa) occur in Proterozoic basement terrains. They rise from depth along crossing, rift forming faults and emerge where the near-surface hydrologic conditions allow them to occur. Pemba and Cap Banza brine springs occur in Ubendian basement rising along deep reaching faults, as discussed in the last paragraph of 2.3.2 above. Kiabukwa occurs in Panafrican terrain near the northwesters border fault of Moero rift zone.

A number of the thermal springs which are described by Waring as occurring in the Lowa (#10a group of 14 features), Luika (#30, 31), Luvua (#36-40) and Lufira (49-52) river basins as well as in the areas of Lakes Rutanzigi, Upemba and Tanganyika seem to all occur in similar terrains and under similar tectonic and hydrologic controls. Those features which occur in the non-volcanic, rift shoulder area to the northwest of L. Kivu (#64-66) seem to occur in areas of Kibaran basement. Some of the thermal springs in these areas may issue from Neogene sediments which may cover the basement rocks, as in Semliki River valley.

The thermal springs of Ruzizi valley (#17-20, 53) as well as Mutambula and Uvira (#32, 33) occur in Proterozoic metamorphic terrain. The hot waters issue from the border faults of the high standing metamorphics lying to the west. It is presently unknown whether, alternatively, the northernmost springs in this zone issue from hot water outflows from the Bukavu volcanic field to the north.

Thermal Springs of the Archean Terrain

Fourteen thermal springs (#1-9, 59-63) are reported to occur in areas of rifted Archean basement situated to the south, west and north of the Ruwenzori Mountains. The northern group (#1-4) are reported to occur in the vicinity of L. Albert but at unknown locations. Two of these (#1 and 2) are described as hot and sulfurous. Goda (#3) is reported to issue petroleum with its thermal water, which co-occurrence of the two fluids is reminiscent of Kibiro thermal spring area on the Ugandan side of the L. Albert rift zone. The southern group (#5-9, 59-63) are in the Semliki valley and are all reported to be sulfurous. The highest temperature, 57OC, was measured at Mutsora while for the rest of the #59-63 group temperatures range 39-43OC. No thermal water discharge rate is reported. No information is available for the #5-9 sub-group except for the location of Mutwanga (#9). The area found to the west of the Rwenzori Mountains is a low lying rift floor which is drained by R. Semliki which flows from L. Rutangeri to L. Albert in the north-northeast. Granted that temperatures are lower, the tectonic and hydrologic setting of this group is similar to those at Buranga in the Bundibugyo area of Uganda (Armannsson, 1994).

Other thermal springs of Unknown Affiliations

Tshapona (#35), the westernmost known thermal spring in D.R.C., occurs in a region of Mesozoic sediments. Kibimbi, Lufubu and Piani Mimba (#25-27) occur in Kibombo area near the Lualaba River. The area is made up of sediments which range in age from late Paleozoic to Quaternary. However, Piani Mimba (#27) is reported to issue from achiest (Kibaran?). Kasongo appears to be located about 100kms to the southeast of Kibombo and about 20kms east of Lualaba River. However, Waring reported it as occurring in Elila River basin, which is situated more than 200kms to the north.

These five areas are the westernmost places of thermal spring occurrence, far removed from the Mitumba Mountains region of high geothermal anomaly. It may be speculated that they owe their temperatures to crustal heat sources: either radioactive heat sources in the underlying basement rocks, or, exothermic diagenetic processes taking place in the sediments which may host some of them.

DISCUSSION

The information that was available for this study was insufficient to support conclusive interpretations. The principal source for hydrothermal feature occurrence was Waring (1965) who based his work on Belgian sources dating from 1879-1936. The available more recent information was bare on details. There had been a professional paper on the thermal springs of D.R.C. by A. Le Bail and M. Buchstein which was presented at the International Geological Congress in 1969 under the title “Les sources thermales et thermo-minerales de la republique democratique du Congo.”. The effort to locate a copy was not successful.

In spite of these shortcomings, a discussion of the findings of this study is believed to be useful for describing the picture which arose from it and for proposing explanations for the surface expressions of the subsurface geothermal situation. The testing and improvement of these explanations and the provision of answers to the uncertainties expressed by this study can provide a starting point for the systematic study of the hydrothermal manifestations.

It is evident that thermal spring occurrence in Eastern D.R.C. is associated with a variety of lithologic types. Overall, there is no fundamental distinction in the geneses of the thermal springs which is attributable to lithologic affiliation. A shared feature among the thermal springs is the combined control of fault tectonics and shallow subsurface hydrology on their regional distribution and individual occurrences.

The thermal springs which occur in the Archean cratonic and Quaternary volcanic terrains are the better known groups as they occur in the northeastern part of the country in areas of high population density and which are also the less challenging to field surveys by geoscientists from Kivu and elsewhere. Together these better known thermal springs make up about 20% of the reported number of thermal springs in D.R.C. More of these 20% occur in areas of Archean basement than in those of Quaternary volcanism. The least known thermal springs are those which occur on the western flank of the Mitumba Mountains which is highly dissected by the numerous rivers which descend toward Lualaba River, are sparsely populated and difficult of access. However, according to Waring’s sources, about 50% of the thermal springs of the country occur in these river valleys. Another 30% occur in the river and lake basins of Katanga and Ruzizi valley. Thus about 80% of the thermal springs of D.R.C occur in areas made up of faulted Proterozoic metamorphic or Phanerozoic sedimentary rocks. A larger number of the known, most dynamic hydrothermal features occur in these terrains rather than in the volcanic fields. This is convincing evidence of the fact that magmatic melt transported to, and stored in, the upper crust, may account for the heating of only a few, if at all, of the hydrothermal features. Thus, magma storage in the shallow subsurface is not essential for the occurrence of high energy thermal spring activity in Eastern D.R.C. and, by extension, for engendering and maintaining the geothermal systems which they may indicate to exist in the subsurface.

Experience from within the region includes that from the better studied high temperature and high discharge thermal springs issuing in areas of no volcanic activity of any age: the Buranga and Kibiro thermal spring areas in Uganda. Experience from other parts of the world, includes that from the Basin and Range tectonic province of the Western United States (Edmiston and Benoit, 1984) which shows that Recent volcanism is either absent or of small volume and unrelated to the heating of the numerous medium and high temperature geothermal fields that have been successfully developed in the region. It is thus argued here that, while the question of to what extent various modes of magmatism may be involved in heating hydrothermal fluids should be addressed while exploring for geothermal resources in the volcanic fields of Eastern D.R.C., emphasis should also be given to exploring areas of high energy hydrothermal activity in the non-volcanic areas.

Crustal tectonic conditions which develop over regions of active tumescent mantle-crust interactions give rise to high temperature conditions in the upper crust. Meteoric waters which circulate in such crustal regions pick up heat from conductively heated crust, by the flushing of any residual heat transferred to country rocks during magma ascent to the surface, and by mixing with hot volatile components which are released during mantle degassing. These may give rise to hydrothermal features on the surface which may be associated with geothermal resources in the subsurface which may be economically exploitable.

Based on the information that was available for this study, thermal springs at eight named and two un-named areas are either described as “hot” or reported to issue at higher than 50OC temperature. However, only the locations of the eight features that are listed in Table 2 could be determined. It is possible that a more complete inventory would identify other high temperature hydrothermal features. A full inventory of these features in the whole of D.R.C. is essential and should be carried out in due course in order to create the basic data base which is needed for use in geothermal resource development.

However, the aim of the present exercise is to contribute to expeditious progression toward the identification of areas of most promising geothermal resource development prospect. It is thus found useful to focus present attention on starting with the existing state of knowledge of the high temperature thermal springs. It is proposed that this knowledge should be expanded by the follow-up study of the known features and others that may be found to share their tectonic and hydrologic settings.

The eight thermal springs occur in terrains occupied by the four lithologic units discussed under 3.4 above. They may thus be considered to be representative of other high temperature and high discharge springs which may be found under the same or similar natural conditions elsewhere and which may be included in the suggested studies. Table 2 is compiled with these objectives and scope in mind.

Table 2: Areas of the hottest known and related thermal spring activities in Eastern D. R. C.

No.	Main thermal springs	Unknown but possibly related thermal spring areas
54, 55	Mahyuza and Kankule	None
58	Mayi ya Moto	Waring's Kabusi volcano
61	Mutsora	Others in R. Semliki and L. Albert rift basins
68, 69	Pemba and Cap Banza	None others known
70	Mwalo	The easternmost of: 18 springs in R. Luama basin, 23 in R. Elila basin and Pakundi in R. Lukuga basin
71	Kiabukwa	17 named and 10 un-named thermal spring areas in Luvua and Lufira river basins and Upemba rift

The high temperature thermal springs of the volcanic areas

The Kankule-Mahyuza group

Vikandy's map of the area shows that the thermal springs occur near the southwestern shore of L. Kivu, near Bukavu, where Ruzizi River leaves the lake to flow south to L. Tanganyika.

Mahyuza, lies close to the lake shore and has a somewhat lower temperature (66OC) than Kankule springs (72OC) most likely due to cooling by mixing with cold water infiltrating from the lake. The springs produce near-neutral (pH 7.3) waters with TDS concentrations of less than 1,500ppm. The dominant ions are of Na and HCO_3 with the respective concentrations being about 200 and 800ppm. No travertine deposition is reported.

Their geologic setting indicates that the springs may be located closest to the focal area of geothermal water upwelling in the Bukavu lava field which is more centrally situated than the other parts of the volcanic field. Quaternary volcanism concentrated along the western Kivu rift border fault. Small volume Holocene volcanism occurred at Tshibinda situated about 15kms distance to the southwest and at a higher level of the local hydrologic gradient. Rancon and Demange (1983) report that some of the volcanic rocks in Bukavu area are products of differentiation from alkaline parent magma. However, the small volume of the volcanic rocks of Quaternary age and, as discussed above, the paucity of eruptive centers which are made up of magma differentiation products preclude the possible existence of a significant magmatic heat source.

The significance of the rifting and magmatic development in S. Kivu area seems to be less in its potential for spawning significant magma storage in the shallow subsurface, but more in its potential for installing a high temperature regime in the upper crust without significant contribution by magmatic mass and heat transport from sub-crustal sources. This region may be considered to be the exception in the Western rift in that it is situated over a sufficiently high standing mantle temperature structure which serves as a hot plate which maintains high upward thermal conduction through the overlying thinned lithosphere and as a source region for the upward leaking mantle volatiles as well as the small volumes of melt. Apart from heating conductively and by volatile fluid upwelling, the area may also contain residual heat that is released to the country rocks by magma rising to feed the Holocene volcanic eruptions at Tshibinda and Idjiwe. Circulating ground water may flush this stored heat over extended periods of time and sustain thermal springs.

Mayi ya Moto

The occurrence of these hydrothermal features in a discrete tectonic, volcanic and hydrologic setting lends the study of the features with a straightforward starting model which links them with the subsurface regions heated in connection with the activity of the presumably Holocene age Mayi ya Moto volcanic center and the hydrologic system maintained by Lakes Kivu and Rutangeri and River Rutshuru. Although the thermal water and steam output (natural heat energy release) is unknown, it appears that the hydrothermal activity may qualify as one of the most important volcanic field related activities of the Western rift. Hochstein (2000) reported that both hot water and steam discharges. Another spring, Bitangola (#10) which Waring reports as occurring in this river basin is at an unknown location.

Mayi ya Moto hydrothermal features occur along a major east-facing fault against which a within-rift horst is up-thrown in the west. The main body of Mayi ya Moto volcanic center is situated on the horst while the lower part of its eastern flank has been downthrown by the fault. It seems obvious that this structure controls the emergence of the thermal water at the surface. The springs occur in the western part of the Rutshuru River basin. The river starts in the uplands of the area of Rutshuru town and the eastern rift shoulder and flows north into L. Rutangeri. Ground water conditions in the area mirror the surface drainage pattern and are determined by the levels of Lakes Kivu and Rutangeri which respectively stand at elevations of 1,460 and 910 m a.s.l. Because of its impoundment in the north by the Birunga volcanic field since the Pleistocene, L. Kivu has stopped draining northward into L. Rutangeri and the Nile River system. However, there is a north-sloping ground water gradient.

This subsurface hydrologic regime may be thought to be favorable for the recharge of any subsurface geothermal reservoir that may be associated with the Mayi ya Moto hydrothermal features. An outstanding question is whether thermal springs occur on the southern shore of L. Rutangeri, being products of the northward flushing of thermal water from Mayi ya Moto area along this inferred ground water gradient.

Vikandy et al (2008) reported some major ion chemical analyses data. The field survey team does not seem to have been equipped to carry out on-site volatile component analyses. Additionally, a number of key components were not reported: SiO2, CO_2, CO_3, H_2S, and CH4. It is not known if the wide ranges in the reported chemical concentrations are due to sampling at different sources or during different seasons. However, all of the surveyed thermal springs surveyed are reported to be rich in CO_2, and this presumably includes those at Mayi ya Moto. However, travertine deposition, common among Western Rift thermal springs, is not reported, perhaps being absent due to low Ca concentration.

The pH of the thermal spring waters ranges 7.99 – 8.94. The lower range of temperatures reported, 94.5 - 96.4OC, are at the approximate boiling temperature of water for the elevation of the springs (about 1,000 m. asl). The reported 100OC temperature represents superheat but its significance is currently unknown. Laboratory analyses results show high concentrations of Na (2,170-2,745ppm), HCO_3 (3,400-5,096 ppm), Cl (1,070-1,140ppm) and SO_4 (400-590 ppm). Ca and Mg concentration s are low (respectively 1-9.6 and 0.9-2.0ppm). The higher of the above concentrations together with the very low concentrations of F, Br, NH_4 in comparison with Na and K show the waters to be of peripheral character to primary NaCl type waters and are of meteoric origin. Na/K geothermometer values of 163-177OC were calculated which are within the range for thermal springs with such chemical compositions.

The petrogenetic affiliations of the products of Mayi ya Moto volcanic center are not known. It is thus not possible to evaluate the likely heating mechanism for the hydrothermal fluids.

The Sedimentary Basin Hosted Thermal Springs: Mwalo and Others.

Mwalo was reported by Hochstein (2000, 2005) as one of the important areas of hydrothermal activity which were distinguished from other features by spring temperature and total heat energy output being respectively higher than 75OC and 3 MWt. There is no specific information on the characteristics of the thermal spring activity or on its geologic setting. Resort will thus be made to regional and generalized considerations for justifying the view that Mwalo may be the site of key hydrothermal activity.

The three major rivers: from north to south Ulindi, Elila and Luama drain the region of the thermally uplifted block of Ubendian metamorphic rocks, the highest standing range of the Mitumba Mountains. This region has a concentration of higher temperature springs and may be considered to be a regionally anomalous zone of hearting. Together, the three river basins account for the occurrence of a reported total of 54 thermal springs. The Locations of only three of these, Kitutu, Kilenga and Mwalo, are known and they are all located in the upper reaches of the river basins. The distribution of earthquake epicenters indicates that many of the structures which control the river valleys are active. These structures have potential for hosting thermal water flow and, under hydrologic influence, may give rise to widespread thermal spring occurrences, by a westward flushing of the high subsurface heat flux taking place in the east.

The regional drainage pattern in Eastern D.R.C. shows that the high topographic gradient descending toward R. Lualaba imposes a steep subsurface hydrologic gradient in that direction. The prevalence of high subsurface temperatures under the high standing block inferred from its geotectonic setting, suggests that the main heating areas of the hydrothermal features lie toward the east. It can be inferred from the above that the easternmost thermal; springs would be closer to their areas of heating and would be the hottest. Those lying toward the west may be expected, at least mostly, to emerge at the surface from subsurface hot water outflow structures from the east. The upper reaches of some of the river basins are situated in sediment filled basins in faulted Proterozoic basement and the easternmost thermal springs may issue from the sedimentary rocks. Any high temperature thermal springs which may be thus situated would have potential for high flow from aquifers which may sometimes be permeable and have large lateral extensions. Many of the thermal springs may share similar characteristics and it would thus be useful to carry out a survey of this group of thermal springs which appear to constitute a distinct generic type.

In the above generalized scheme, thermal spring activity at Mwalo offers one of the most promising starting points for the study of the geothermal resources associated with the river basins which traverse sedimentary rocks in their upper reaches. The reported large natural heat output at Mwalo indicates the prevalence of high permeability in the zone of hot water ascent to the surface and the existence of a voluminous source region in the subsurface. Its occurrence in an area of sedimentary infill in a reactivated half graben structure makes it attractive in that there is a possibility for the existence of a high temperature hot water reservoir system within the sedimentary sequences. There is also the possibility of such a reservoir system being replenished with hot water as active faulting would keep channels of fluid ascent open and facilitate the rise of deep circulating geothermal waters to these levels.

High Temperature Thermal Springs of the Proterozoic Metamorphic Terrains

Cap Banza and Pemba brine springs

RIGFC (1982) quote a temperature of 96OC, pH 6.5 and SiO_2 concentration of about 210ppm for Cap Banza thermal spring (#68). It issues 1 l/s of NaCl type water along faults which define a narrow horst which is disposed in the N-S direction and projects into the northern part of L. Tanganyika from the D.R.C. side. Tiercelain et al (1993) report the occurrence of sub-lacustrine hydrothermal chimneys topped by vents at Cap Banza where aragonite and pyrite deposition is taking place. At Pemba (#67), located to the north of Cap Banza, Springs issue $NaHCO_3$ type water which deposits iron sulfide minerals. Temperatures of up to 103°C were measured. Chemical geothermometers yield temperatures at depth of 179 and 219°C respectively for Cap Banza and Pemba. Isotope data from the CO_2 released at the two sites show the gas to be of juvenile origin. The hydrothermal fluids emerge where TRM and Ruzizi trend faults cross. Hydrothermal fluids characteristically emerge above or at the levels of cold water bodies due to the low densities induced in them by thermal expansion and their usually dilute chemical contents. The Banza and Pemba brines issue below lake level because of their high density which is due to their high dissolved mineral content. These brines are typical of to ore transporting and depositing primary magmatic fluids. They are the precursors of near surface geothermal fluids, which result from the mixing of these parent fluids with much larger volumes of meteoric waters in the sub-surface. Thermodynamic evolutionary processes modify their original chemical and physical characteristics during their circulation and mixing in the subsurface.

The deposition of metal sulfides and carbonates at these features is analogous to mineral sulfide deposition from deep geothermal well discharges at Gale le Koma in the Asal Rift in Djibouti. Asal rift is the most advanced stage of EARS development. Mantle melt is estimated to undergo crystallization at about 4-5kms depth. The mineral content of the brine there is attributed to the exsolution of the volatile magma components (mainly water) together with metals which do not readily go into silicate mineral formation during magma crystallization. The segregated fluids leak upwards along fractures. Drill holes reduce the confining lithostatic pressures on the fluid and allow it to expand and rise. Mineral deposition occurs when brine density is reduced by boiling upon pressure release on brine entry into the geothermal well or upon its venting at the surface, in analogy to the natural processes of ore transport and deposition from primary magmatic fluids. The Banza and Pemba brines occur under favorable natural tectonic conditions. Deep reaching faulting allowed the buoyant rise to the surface of the primary magmatic fluids in a region of thick crust. Asal rift and the northern L. Tanganyika rift zone are the only two known zones of the EARS where primary brines reach the surface. The differences in the type of minerals that are deposited at Banza, Pemba and Asal are attributable to their initial chemical compositions as well as to the different brines having differently evolved during their rise from depth, including their internal chemical thermodynamic evolutions and, in the case of the former two features, their interactions with wall rocks and thermophylic microbial action.

The significance of the Banza and Pemba brines with respect to geothermal resource development does not lie in themselves or in the structures along which they rise to the surface. Their mode and places of occurrence make resource exploitation by drilling logistically impractical. Similarly to the situation in the Asal rift, the primitive chemistries of the brines are likely to render them challenging for direct utilization in economic power generation. Such fluids are economically exploitable for power generation where they are found lower down along their evolutionary paths. They are thus potentially important for their potential for spawning exploitable derivative geothermal resources and for the information which they may provide regarding the geothermal conditions in the larger area of Northern L. Tanganyika. The brines rise along Ruzizi and TRM structures. The importance of these structures as possible conduits for the primary brines into the adjacent areas may be important if, by mixing with meteoric waters in the subsurface, the brines generate derivative high temperature geothermal fluids suited to economic exploitation. It may be queried whether the numerous thermal springs which discharge to the west of Northern L. Tanganyika may have genetic relations with such deeply sourced primary fluids.

Kiabukwa

Kiabukwa (#70) has the distinction of having been the site of the earliest geothermal power plant in Africa but which has stopped operating at some unknown time in the past. It is reported to have had a generation capacity of 200kW. Although no other information is available on the resource, the fact that it had been developed in the past renders it significant.

Thermal Springs of the Archean Terrain: Mutsora and Others

As pointed out in 3.4.4 above, the 14 reported thermal springs which occur in this part of Eastern D.R.C. respectively share some of the hydrothermal fluid characteristics of Kibiro, in the case of the northern group, and the tectonic and hydrologic settings of Buranga, in the case of the southern group. These situations present opportunities for the exchange of experiences which can benefit the study of Mutsora and the region's other thermal springs.

CONCLUSIONS AND RECOMENDATIONS

The findings of the study encourage the conclusion that a number of thermal spring areas in Eastern D.R.C. warrant further study. It is recommended that the full complement of basic data on the hydrothermal activities which is essential for gaining greater certainty of the prospectivity of these areas should be collected. An order of priorities is also proposed among these areas based on need for geothermal power development and the likelihood of success in satisfying that need.

Candidate Prospects of High Priority

The priority areas are Mayi ya Moto, Kankule-Mahyuza and Mwalo and are the candidate targets which at this stage seem to offer better prospects for the discovery of exploitable geothermal reservoirs and also are important from the point of view of need for geothermal power generation, if possible.

Situations allowing, it is recommended that preliminary field and laboratory works be carried out consisting of geologic observations in the field and recording of conditions of thermal spring activity and their sampling for chemical analyses. In addition to these generic geoscientific due diligence surveys which apply to all three areas, it is recommended that studies be made in each area to clarify issues that are specific to it as follows:

Mayi ya Moto

A volcanic petrogenetic study should be carried out to determine if significant and sustained magma differentiation takes place at shallow crustal depth from which may be concluded that a geothermal resource which is associated with a shallow magma body heat source may exist. This will involve the sampling of young lava flow and pyroclastic units for major and trace element analyses.

The Mwalo-Bukavu-Kalemi Region

Two approaches are proposed for this region: a) specifically addressing the two high temperature thermal spring areas and, b) combining this with a preliminary evaluation of the regional context in which they occur.

Mwalo

Mwalo is a potentially attractive prospect, possibly together with other thermal springs which occur in Luama graben, not only because of its favorable attributes, but also because its position in the regional tectonic framework renders it important. An evaluation of the sedimentary stratigraphy which may influence the occurrence and character of the thermal water, estimation of sediment thickness, and determination of the character of contact areas with the metamorphic rocks would be of specific interest at Mwalo.

Kankule-Mahsyuza

Research on the volcanism of Bukavu area has provided good quality data which should be viewed in detail for the geothermal implications. Similar work should be carried out for the volcanic field in Mwenga area, especially in light of the integrated regional approach proposed below. Structural continuity between L. Kivu and the middle basins of Elila and Luama rivers justifies the adoption of an overall view of a unified geothermal system.

Regional Survey

The regional approach is based on the perception expressed in the last paragraph of 3.3.2 and encompasses the region described in 2.2 above. If that perception can be shown to be viable, a regional focal geothermal regime centered on the uplifted Ubendian terrain may give rise to the thermal springs which occur in the Ruzizi, Elila and Luama river basins and to those found along the western coast of L. Tanganyika's northern basin. This approach, while giving individual emphasis to the study of Mwalo and Kankule areas, would also involve the sampling of all of the thermal springs for chemical analyses and the cursory assessment of their geologic and hydrologic settings. This will contribute to the better understanding of the hydrothermal features of focal interest by viewing them in theirs regional context, at the same time that it clarifies the regional geothermal regime.

The Lower Priority High Temperature Thermal Spring Areas

Mutsora

The thermal springs of the region of Archean basement in North Kivu share a number of characteristics and geologic associations with those of the Buranga and Kibiro thermal springs in Uganda. The active effort to progress exploration work in these Ugandan prospect areas may produce results which work in North Kivu can learn from. It is believed to be useful to delay the investigation of the region of Mutsora area until that time, also with a view to deploying effort more gainfully in the high priority areas.

Kiabukwa

For reasons given under 4.3.3 above, Kiabukwa may be considered technically attractive. However, because its region is one of the most industrially developed in D.R.C., it is expected that hydro-electric power generation is well developed and there may not be a justification for granting priority to developing geothermal resources in the region in the short term.

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Appendix. The known thermal springs of D.R.C.

No.	Feature Name	Temp. OC	Reported Location, District l Province		Coordinates*		Observations; chemical features
					Long.	Lat.	
1	Kaswa	"Hot"	1. Vicinity of L. Albert				Deposits of sulfur
2	Mount Laba	"Hot"					Sulfurous
3	Goda						Water and petroleum
4	Pandju						Saline
5	Zumbia (Kwanjwa?)		2. Similiki River valley				
6	Molinglingo						Sulfurous
7	Katuka						
8	Vyatungo						
9	Mutwanga				29.750	0.351	
10	Bitagoha		3. Rutshuru	N. Kivu			
10a	*Un-named: 14 springs*		*4. Lowa River basin*				
11	Tingi/ Sake/ Kihira	30	5. L. Kivu volcanic area		29.041	-1.571	
12	Katana (Kakondo)				28.833	-2.225	Travertine deposit
13	Luiro						
13a	*Un-named: 1 spring*	*60*	*-do- Nr Kabusi volcano*				*Free CO_2, large travertine deposit*
14	Nyaluindja		6. Ulindi River basin				Sulfurous
15	Lualatshi						
16	Lubuka						
16a	*Un-named: 8 springs*						
17	Luwangi		7. Ruzizi River valley				
18	Luvungi				29.027	-2.871	
19	Mokindwa						
20	Minyove						
21	Mount Kasongo		8. Elila River basin		28.430	-3.543	
22	Pene Kabonde						
23	Tchavula						
24	Kitutu				28.100	-3.280	
24a	Un-named: 19 springs						

Appendix. The known thermal springs of D.R.C. (Continued)

No.	Feature Name	Temp. OC	Reported Location, District l Province		Coordinates*		Reported chemical features
			District	Province	Long.	Lat.	
25	Kibimbi		9. Lualaba River basin, near Kibombo. Piani Mimba issues from schist		25.93?	-3.93?	
26	Lufubu				25.93?	-3.93?	Saline
27	Piani Mimba (Pene Sibo)						TDS: 33,360 ppm 55%NaCl, 11% $CaCl_2$, 5%$CaSO_4$
28	Basikabusi		10. Luama River basin				Sulfurous
29	Basimakule						
29a	*Un-named: 15 springs*						
30	Muesse		11. Luika River basin				
31	Kilenga				28.031	-3.908	
32	Mutambula	50	12. NW L. Tanganyika				Sulfurous
33	Uvira	44	Uvira	S Kivu	29.129	-3.406	
34	Pakundi		13. Lukuga River basin				
35	Tshapona		14 R. Lomami/ Luembe		24.317	-7.183	
36	Kisabi		15. Luvua River basin		29.181	-8.044	Saline
37	Luona						
38	Mbalai						
39	Sanga						
40	Luiboso						
41	Rutuku		16. South L. Tanganyika		29.314	-6.219	Saline
42	Kayungwa						
43	Kakonta						
44	Kianza (Near Tampa)				29.905	-8.055	
45	N'Ganza						
46	Kafungwe		17. L. Upemba area				Sulfurous
47	Katapena						
48	Konkula						
48a	*Un-name:10 springs*						

Appendix. The known thermal springs of D.R.C. (Continued)

No.	Feature Name	Temp. OC	Reported Location, District l Province		Coordinates*		Reported chemical features
					Long.	Lat.	
49	Moashia		18. Lufira River basin				
50	Tanda Mukola						
51	Kashiba						
52	Basumba						
52.a	*Un-named: Several sprs*	*c 60*	*Manjakito fault*				*Much free CO_2*
53	Nyangezi (Nya Ghezi)	40	#2. Walungu	S Kivu	28.871	-2.650	
54	Mahyuza	66	#3-5, 12 Kabare		28.841	-2.244	
55	Kankule 1 & 2	72			28.836	-2.249	
56	Maziba	40			28.8	-2.1	
57	Muganzo						
58	Mayi ya Moto	95	#6. Rutshuru	N. Kivu	29.350	-0.900	pH: 8.0-8.9, Na (HCO_3-Cl-SO_4) type water; T_{depth}=163-177°C
59	Kambo	40	#7. Kasindi		29.670	0.063	
60	Masambo	43	#8, 9. Beni		29.696	0.181	
61	Mutsora	57			29.742	0.306	
62	Mbau		#10, 11, Beni?		29.140	0.390	
63	Kikingi				29.570	0.540	
64	Kisuma	39	#15. Masisi		28.880	-1.600	
65	Nyabugezi		?				
66	Kalieri		Katale ?	?			
67	Pemba	103	NW. L. Tanganyika		29.092	-3.95	$NaHCO_3$ type water; massive sulfide deposit; T_{depth}=219°C
68	Cap Banza (Manza)	96			29.27	-3.97	NaCl type water; aragonite deposition; T_{depth}=179 °C
69	Mwalo	> 75	Upper Luama River basin		28.185	-4.248	
70	Kiabukwa	> 75	South of L. Moero		28. 266	-9.917	Site of a 200kW geothermal power plant during the 1950s

*Note: Some coordinates are approximate, except for those quoted from Mambo Vikandy et al (2008). Others may be those of nearby places with the same names as those of the thermal springs. There may also be more than one place in D.R.C. with the same name, e.g. Kasongo

Sources: # 1-52a: Waring (1965); 11, 33, 53-66: Mambo Vikandy S. et al (2008); 58, 67-70: Hochstein (2000); 69: RIGFC (1982); 67 & 68: Tiercelin et al (1993).