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Heat Transfer by Hydrothermal Systems in the East African Rifts

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ABSTRACT

Moderately intense volcanic and geothermal activity occurs along the two continental rifts in East Africa, each c. 2 000 km long. An inventory of known major geothermal and volcanic systems in the rifts is presented.

Volcanism and rifting started in the Eastern Rift (Eritrea/Djibouti to Northern Tanzania) at least 15 Mill. yr ago. Over 30 major hydrothermal systems occur along this branch (almost half have steaming ground) together with at least 10 volcanic-geothermal and 10 volcanic systems which have been active during the last 2 000 yr. The hydrothermal systems discharge heat at a rate of at least 4 000 MW. Volcanism and rifting began c. 10 Mill. yr ago in the Western Rift (Northern Uganda to Southern Malawi). However, there are only 3 major high temperature systems in this rift together with 4 active volcanic systems. A few concealed advective geothermal systems occur at the margin and probably at the bottom of deep rift lakes. The total anomalous heat discharged by the Western Rift is an order-of-magnitude less than that discharged by the Eastern Rift. There appears to be an overall inverse relation between the energy released by crustal earthquakes and that transferred by geothermal systems.

1. INTRODUCTION

Crustal deformation of the African Plate and some hot spot (Upper Mantle) activity have produced anomalously hot, upper crustal rocks, volcanism, and local intrusions beneath the two c. 2 000 km long continental rifts forming the East African Rift System (EARS). The Eastern Rift extends from Eritrea and Djibouti to Northern Tanzania and traverses 5 countries. The Western Rift extends from Northern Uganda southward to Malawi through 7 countries. Tanzania is the only country which hosts both rifts.

Comprehensive catalogues of volcanoes in Africa contain valuable information about the magnitude of volcanic activity but do not distinguish between volcanic and volcanic-geothermal systems (Simkin and Siebert, 1994). Nor do most published papers, country reports and reports of aid-sponsored studies classify important geothermal systems since minor and major prospects are usually listed together. For such separation a magnitude approach is required using, for example, the magnitude of discharged heat as a discriminating parameter. This concept was used to classify separately all known geothermal systems in the Eastern Rift (Hochstein, 1999) and those in the Western Rift (Hochstein, 2000). An attempt is made here to present a summary of all major geothermal systems in both rifts and to compare their occurrence with respect to geological settings and seismicity patterns.

2. TERMINOLOGY, METHODS, AND CLASSIFICATION

The term ‘geothermal system’ includes both volcanic and non-volcanic systems. In a ‘volcanic system’ heat and mass are transferred intermittently from a magma reservoir to the surface. A ‘hydrothermal non-volcanic system’ transfers heat continuously from a crustal heat source to the surface by free or forced convection involving meteoric water. A ‘volcanic-hydrothermal system’ is a combination of a hydrothermal and a volcanic system. All three systems occur in both rifts.

Published reconnaissance studies and country surveys allow an assessment of simple thermal spring systems which can be distinguished from other hydrothermal systems because of their low heat discharge (< 1 MW). Over 40 single thermal springs occur along the floor of the Eastern Rift; even more (c. 50) are associated with the Western Rift and its margins. These springs are not described here. The remaining geothermal prospects are discussed below.

Hydrothermal systems which discharge heat at a rate > 10 MW are called ‘major hydrothermal systems’. References containing information about major hydrothermal systems in the Eastern Rift have already been cited (Hochstein 1999), so most are not repeated. Several references to systems in the Western Rift are quoted in section 4. The heat discharge rate of a few large major systems with rates > 100 MW is known from detailed ground-surveys (Hochstein and Kagiri, 1997). The areal extent of intense hot ground of many large prospects can be inferred from infra-red (IR) surveys and show some correlation with heat loss data. My observations, based on visits to most major hydrothermal prospects in Ethiopia, Kenya, and Tanzania between 1982 and 1995, are also used to rank heat loss data.

Another important parameter used to rank hydrothermal systems is the deep fluid temperature T, as indicated by cation and gas geo-thermometers of discharged fluids. The major hydrothermal systems in the rifts have been grouped into high-T resources (T > 225 deg C), intermediate-T resources with equilibrium temperatures 125 > T > 225 deg C, and low-T resources where T < 125 deg C.

Several types of major hydrothermal systems occur in the two rifts, namely: advective systems, steaming ground systems associated with liquid dominated or natural 2-phase reservoirs, as well as hypersaline brine systems. Advective systems derive from groundwater infiltrating the shoulders or flanks of the rift. There are several types of advective systems in the two rifts. Steaming ground systems are hydrothermal systems confined to rift settings where almost all heat is discharged by steam at the surface with only minor liquid discharges (steam condensates).

Identification of volcanic-hydrothermal systems is only tentative; in this study it is based on fumarole temperatures (not exceeding local boiling T) of vents over volcanic massifs, gas composition (traces of magmatic constituents), and absence of (historic) volcanic activity. Their heat discharge rate is poorly known.

Because of their poorly known episodic activity, heat transferred by volcanic systems can not be assessed. However, taken over long geological periods, their average heat transfer can reach values similar to those of major hydrothermal systems. Long- term discharge rates between 100 and 400 MW, for example, have been reported for the Erta Ale Volcano in Northern Ethiopia (Oppenheimer and Francis, 1998).

The geological setting of the rifts, the extent of Quaternary volcanic rocks, and the location of major faults was taken from the UNESCO Atlas (UNESCO 1976) showing compatible litho-stratigraphic data for each rift. Crustal earthquakes occur beneath both; these events and their magnitudes m_b and m_S are listed in the USGS- and Berkeley Earthquake Catalogues. To convert the magnitude(s) into released seismic energy, the (energy power spectrum) magnitude M_E and the seismic moment M_0 of larger events was taken from the Harvard CMT catalogue. This information was used to construct a regional magnitude M vs. energy E relationship following the approach of Choy and Boatwright (1995).

3. THE EASTERN RIFT

The location of active volcanic- and major non-volcanic systems in the Eastern Rift is shown in Fig.1. Present-day rift rate is c. 5 mm/yr in the Ethiopian segment but it probably only a few mm/yr at the S end of the Kenya segment (R.Bilham, pers. comm.). Volcanic activity and rifting occurred already along the whole length of the rift at least 15 Mill. yr ago. There are 12 volcanic systems in the rift, active during the last 2 000 yr, probably 11 volcanic-hydrothermal systems, and at least 31 major hydrothermal systems. The extent of Quaternary volcanic rocks and tephras at the surface, which cover c. 45% of the rift floor, and the trace of major faults are also shown in Fig.1. Most of the hydrothermal systems lie close to the axis of the rift. Their wider distribution in northern Ethiopia is due to a ‘triple junction’ of the rift near Tendaho (2.4 in Fig.1) where the rift changes direction to the NW and another eastern branch extends towards Djibouti. The E branch hosts large earthquake swarms.

A 300 km long segment without hydrothermal- and volcanic activity occurs between Lake Turkana and Lake Abaya; here the elevation of the rift valley is less than 500 m (a.s.l). The rift is updomed in the central part of the Ethiopian and the Kenya segment where the valley floor rises to a level of 1 500 m and where the rift shoulders stand more than 1 000 m above the valley floor. The arid to semi-arid climate along the rift restricts infiltration. Precipitation rates are less than 0.2 m/ yr in the northern segments (Afar and Djibouti), in the Lake Turkana region, and at the southern end of the Kenya segment. Significant recharge of hydrothermal systems along the rift derives therefore from rainfall over the higher standing flanks and shoulders of the rift.

3.1 Advective systems.

Almost half of the major hydrothermal systems (16 out of 31) are advective. There are three types: (1) intermediate-T systems (discharge boiling alkaline water), (2) intermediate to low-T systems with discharge T < 65 deg C, and (3) advective brine systems.

A type locality for the first type is the Lake Bogoria system (4.9 in Fig.1) where cation geothermometers point to reservoir temperatures of < 150 deg C; at least 100 MW of heat discharges here. Similar systems discharge much less heat (order of c. 10 MW), such as that at Lake Shalla (3.10), Lake Abaya (3.11), and at Danab (2.10). Five large advective systems (type 2) in Ethiopia discharge hot water between 45 and 65 deg C, namely prospects 2.3, 3.2, 3.4, and 3.7a, 3.7b in Fig.1. Their rate of heat discharge lies between 40 MW (3.7a) and 100 MW (3.7b). The Hippo Pool (3.7b) is the largest thermal spring in the entire rift.

Six advective brine systems (type 3) occur in the rift at localities marked as 1.3, 1.8, 2.5, 4.4, 4.14, and 5.1 in Fig.1. In each case highly mineralized thermal waters with total dissolved solids (TDS) between 15 and 40 g/kg discharge at margins of saline lakes (T between 40 and 60 deg C). Heat is discharged at rates between 50 to 100 MW at Lake Natron (5.1), c. 100 MW at Lake Afrera (1.8), and at least 100 MW at Lake Magadi (4.14). Thermal brines in Kenya and Northern Tanzania are all sodium carbonate type waters but those in Ethiopia are of the sodium chloride type.

Stagnant hypersaline brine systems occur at Dallol (1.2) and near Lake Assal (2.5). At Dallol, the brine (TDS up to 300 g/kg) occurs in several pools with temperatures up to 110 deg C; at Lake Assal, hypersaline brine (TDS c. 160 g/kg) has been encountered in several deep wells with T up to 350 deg C at 2 km depth. The heat source appears to be a high standing intrusion in each case.

3.2 Steaming ground- and other high temperature systems

Heat is discharged by steaming ground and steam vents over many high standing volcanic complexes in the rift. These have been called ‘steaming ground systems’ (Hochstein and Browne, 2000) where vapour from the top of a boiling liquid-dominated or natural 2-phase reservoir ascends to the surface. Condensates can accumulate in perched aquifers discharging bicarbonate-type of thermal waters in the foothills. Type localities are the Olkaria and the Eburru prospects (4.10 and 4.11 in Fig. 1) which have been explored by deep drilling, leading to the construction of two electrical plants (45 and 30 MWe) at Olkaria. Field studies showed that c. 400 MW and c. 175 MW are discharged at Olkaria and Eburru respectively (Hochstein and Kagiri, 1997).

Using the characteristics of manifestations at Olkaria and Eburru as criterion, together with information of a very detailed reconnaissance study of the N segment of the rift (Dunkley et al. 1993), the heat loss of other steaming ground systems in Kenya can be estimated. IR-data indicate that the extent of steaming ground at Paka (4.7) and Korosi (4.8) is similar to that at Eburru; the extent of similar manifestations at Silali (4.6) and Emuruan-Gogolak (4.5) is half an order of magnitude less. Hence, discharge rates between 100 and 200 MW and between 30 to 60 MW respectively are indicated for these systems.

It is likely that steaming ground systems would revert to liquid dominated if the groundwater level rose as a result of higher precipitation. This is indicated by the occurrence of widespread sinter deposits on the lower flanks of steaming ground systems in northern Kenya, deposited at times of high standing ancient lake levels (Sturchio et al., 1993).

Steaming ground also occurs over volcanic complexes in Ethiopia and Eritrea (1.1, 1.11, 2.2, 2.7, 2.9, 3.3, 3.5, 3.9, and 3.11). In some cases the hot liquid level stands above the rift valley floor leading to flank discharges of NaCl-type thermal water or concealed outflows. Flank discharges occur, for example, at Aluto (3.9) and Allalobeda (2.7) and concealed outflows emerge from the Corbetti Caldera (3.11). The Aluto reservoir has been explored by deep drilling and a small electrical plant (7 MWe) has been installed here. The natural heat loss at Aluto has been estimated to be c. 90 MW. The manifestations at Dofan Volcano (3.3) have affinity with those of a volcanic-hydrothermal system.

Occurrences of aligned patches of steaming ground are not a sufficient criterion to infer the existence of steaming ground systems. In the Hanle area (Djibouti), halfway between localities 2.10 and 2.5 in Fig.1, a 2km deep hole was drilled near such features. No thermal reservoir was encountered showing that vapour can move laterally away from feeding fractures. A concealed outflow of hot water (up to 250 deg C) was discovered in deep drillholes at Tendaho (2.4) but its reservoir (liquid dominated) is not well known; the nearest surface manifestations are weakly steaming ground. There are several other high T prospects in the rift, listed, for example, in the UNDP (1971) report and by Endeshaw (1988), where heat discharge appears to be between 3 and 10 MW; these prospects are not shown in Fig.1.

3.3 Seismicity

Seismicity associated with the rift is moderate. Between 1965 and 2002 there were a total of c. 75 earthquakes with magnitudes $m_b > 5.0$, releasing c. 2 PJ energy. Almost half of the quakes (n = 35) occurred along a c. 100 km wide and c. 2200 km long strip centred on the dominantly N-S trending rift axis. There is significantly less seismicity in the Kenya segment, between 4 deg N and 2 deg S, where no quake with $m_b > 4.8$ has been recorded (only 0.3 PJ was released by all events with $m_b < 5.0$). In the c. 450 km long, E-W trending rift segment towards Djibouti, c. 40 events with $m_b > 5.0$ were recorded, including an M 6.6 event in 1961, the largest earthquake in the Eastern Rift. Two thirds of these quakes were associated with 8 major swarms, together releasing 0.7 PJ. The swarm activity points to magma injected at shallow crustal levels.

4. THE WESTERN RIFT

Some rifting in the western branch has probably occurred during the entire last 10 Mill.yr. Inferred present-day rift rates are only 1 to 2 mm/yr (R.Bilham, pers. comm.). It is likely that plastic deformation of a more ductile lithosphere at its contact with the cold Tanzanian craton (Archean age) has caused heating of the rift. The location of major geothermal systems is shown in Fig. 2. Volcanic rocks of Quaternary age cover only c. 7 % of the axial strip of the rift whereas large and elongate, deep lakes cover almost 75 %. This setting partly explains why only a small number of geothermal prospects have been reported. Important published geothermal inventories containing some information about heat losses are those by Le Bail and Buchstein (1969) for Zaire, Kirkpatrick (1969) for Malawi, Dixon and Morton (1970) for Uganda, Sakungo (1988) for Zambia, and Martinelli et al.(1995) for Mozambique. An inventory of hydrothermal systems in Tanzania has been presented by Hochstein et al. (2000).

4.1 Geothermal systems

Sparse volcanism occurs at the junction of Uganda, Rwanda, and Congo (Zaire) in the Virunga volcanic field with its active 3 centres (6.5, 6.6, and 6.7 in Fig.2). Another small volcanic field lies at the northern part of the Malawi segment of the rift, the Rungwe volcanic field in S Tanzania, with its historically active Kiejo Volcano (5.12).

There are probably only 3 prospects which can be classified as major intermediate-T to high-T geothermal systems and which discharge heat at a rate of at least 10 MW. The group includes the Songwe prospect (5.11) and that at Kibiro (6.1); the discharge rate of the Pemba prospect (6.8) at the northern tip of Lake Tanganyika is poorly known but it is connected with a high-T system. None of these prospects occur within the two volcanic fields. However, the Songwe prospect (with spectacular travertine terraces) is the terminus of a large concealed outflow of a high-T system, probably hosted by the Rungwe volcanic field. The Kayumba (May-Ya-Moto) prospect (6.4) may be associated with a concealed outflow from the Virunga volcanic field; it is the only prospect in the rift exhibiting both hot springs and steam vents.

Intermediate-T advective systems occur at Buranga (6.2), Cape Banza (6.10), and probably at Kilambo (5.13). The heat discharge rate at Buranga is of the order of 30 MW, the largest rate of any of the systems described sofar. The Kilambo prospect (3 to 10 MW) might also be associated with an outflow. Brine systems with some advective flow constitute a sub-group of advective intermediate-T systems; a major brine system occurs at Lake Katwe (6.3). Because of conductive losses, the heat transferred by systems with concealed outflows will be always greater than that given by the surface discharge rate of their manifestations.

Other advective systems probably discharge thermal water at the bottom of Lakes Tanganyika, Malawi, and Kivu (max. depths are c. 1.4, 0.7, and 0.4 km respectively). It has been suggested that most of the dissolved total solids in Lake Kivu and the other lakes are from thermal springs (Degens et al. 1973). The hydrological setting of the rift lakes favours the development of heat sweeps. Sparse heat flow measurements in these lakes, however, do not allow the inference that advective systems at the bottom of the rift lakes are common.

Over 30 thermal springs discharging > 1 MW occur between 100 and 300 km to the west of the rift, mainly in the old Katanga Province of Zaire, where segments of heated crust exist. The locality of seven intermediate-T, hot spring systems, each discharging heat at a rate between 3 and 10 MW (spring T > 75 deg C), is shown in Fig. 2. Of historical interest is the hot spring system at Kiabukwa (6.11), about 300 km west of the rift, where the first small, now defunct geothermal power plant (0.2 MWe) in Africa was constructed in the 1950's. In the 1980's it was planned to exploit the shallow hot spring reservoir at Kapisya (6.12) near Lake Tanganyika; that plant was not completed.

4.2 Seismicity

As pointed out by Fairhead and Stuart (1982), pronounced seismicity is associated with the western rift and this also occurs west of the rift to the west across the whole Katanga Province. Seismic data for 1980-2002 confirm this pattern. Events with magnitudes $m_b > 5.0$ (n = 115) released c. 15 PJ of seismic energy since 1965 beneath a 100 to 150 km km wide and almost 2000 km long strip centred on the rift axis. Almost half of this energy came from 5 events with $m_b > 6.2$, the largest an M 7.4 event observed in 1990. Large seismic swarms have not been recorded; there are no obvious gaps in the seismicity pattern based on events with $m_b > 5.0$.

Table 1: Energy transfer along the East African Rifts

	Western Rift	Eastern Rift
n Active Volcanoes (active last 2000 yr)	4	12
n Volcanic Hydrothermal Systems	0	11
n Major Hydrothermal Systems (Q > 10 MW)	7	31
n Thermal Spring Systems (Q< 1 MW)	c. 50?	40
Heat discharge rate of all exposed		
Hydrothermal Systems and Thermal Springs (MW)	c.300	4000
n Earthquakes with m_b > 5.0 (1965-2002)	c.115	35 (NS rift)
		c.40 (Afar rift)
Total Seismic Energy released (PJ)	c.15	2

5. CONCLUSIONS

At least 54 geothermal systems occur in the Eastern Rift. The heat discharge rate of 14 (out of 31) major hydrothermal systems is approximately known from field studies (subtotal c. 1 550 MW); the largest discharge (at least 400 MW) occurs at Olkaria (Kenya). An order of magnitude estimate of the heat losses of the other 17 systems was obtained by ranking the extent and type of their manifestations (including IR data where available) and comparison with systems of known discharge. These prospects fell into a group of three with rates of 10 to 30 MW, eight in a group of 30-100 MW, and six in a group of 100-300 MW. This indicates a subtotal of c. 1800 MW for the 17 systems. Few data are available for volcanic-hydrothermal systems; discharge rates of 2 such systems (out of 11) are of the order of 30-100 MW. Ranking the extent of manifestations of similar prospects indicates that the heat discharge of the 11 volcanic-hydrothermal systems is probably between 600 and 1000 MW. All systems together therefore discharge at least 4 000 MW.

Only 7 major hydrothermal systems are known for the Western Rift (including 3 high temperature systems). Their heat discharge rate lies in the range of 10 to 30 MW; systems with concealed outflows may have greater heat losses. If the heat discharge of all known hot spring systems is included, the total discharge of anomalous heat by hydrothermal systems along the whole rift is probably c. 300 MW. However, up to 75 % of the rift floor is covered by deep lakes and it is likely that some advective systems occur at their bottom as indicated by a chemical balance study of Lake Kivu (Degens et al. 1973). Two advective systems have already been found along the shores of Lake Tanganyika (Pflumio et al. 1994). Assuming proportionality in overall anomalous heat transfer between the land- and lake-covered segments of the rift, one could speculate that anomalous heat may discharge at three times a greater rate through the lakes. The resulting total for the whole Western Rift, however, would still be at least half an order of magnitude less than that for the Eastern Rift. A summary of key data is shown in Table 1.

An inverse proportionality of energy transfer within the two rifts, compared to the discharged anomalous thermal energy, is indicated for the radiated seismic energy released during the last 37 years by crustal earthquakes. This amounts to c. 2 PJ for the Eastern Rift and c. 15 PJ for the Western Rift. A similar inverse proportionality is also indicated on a regional scale for Kenya where the released seismic energy was significantly less over a c. 500 km long rift segment with clustered hydrothermal systems.

If most of the anomalous heat associated with the two rifts were caused by plastic deformation of a ductile lithosphere, the observed inverse proportionality would be a paradox unless the capacity of rocks in the crust (and lithosphere) to store deformation would be vastly different between but also within the two rifts. This can be caused by differences in fluid saturation (hydrated minerals, for example) of rocks beneath the rifts where ‘dry’ rocks exhibit a high strain storage capacity resulting in strain release by earthquakes with somewhat higher magnitude. The weakening effect of hydrated minerals on the rheology of ‘wet’ lithosphere rocks has been demonstrated by model calculations (Regenauer-Lieb et al., 2001). ‘Dry’ crustal (lithosphere) rocks could therefore occur beneath the Western Rift and ‘wet’ rocks beneath the Eastern Rift.

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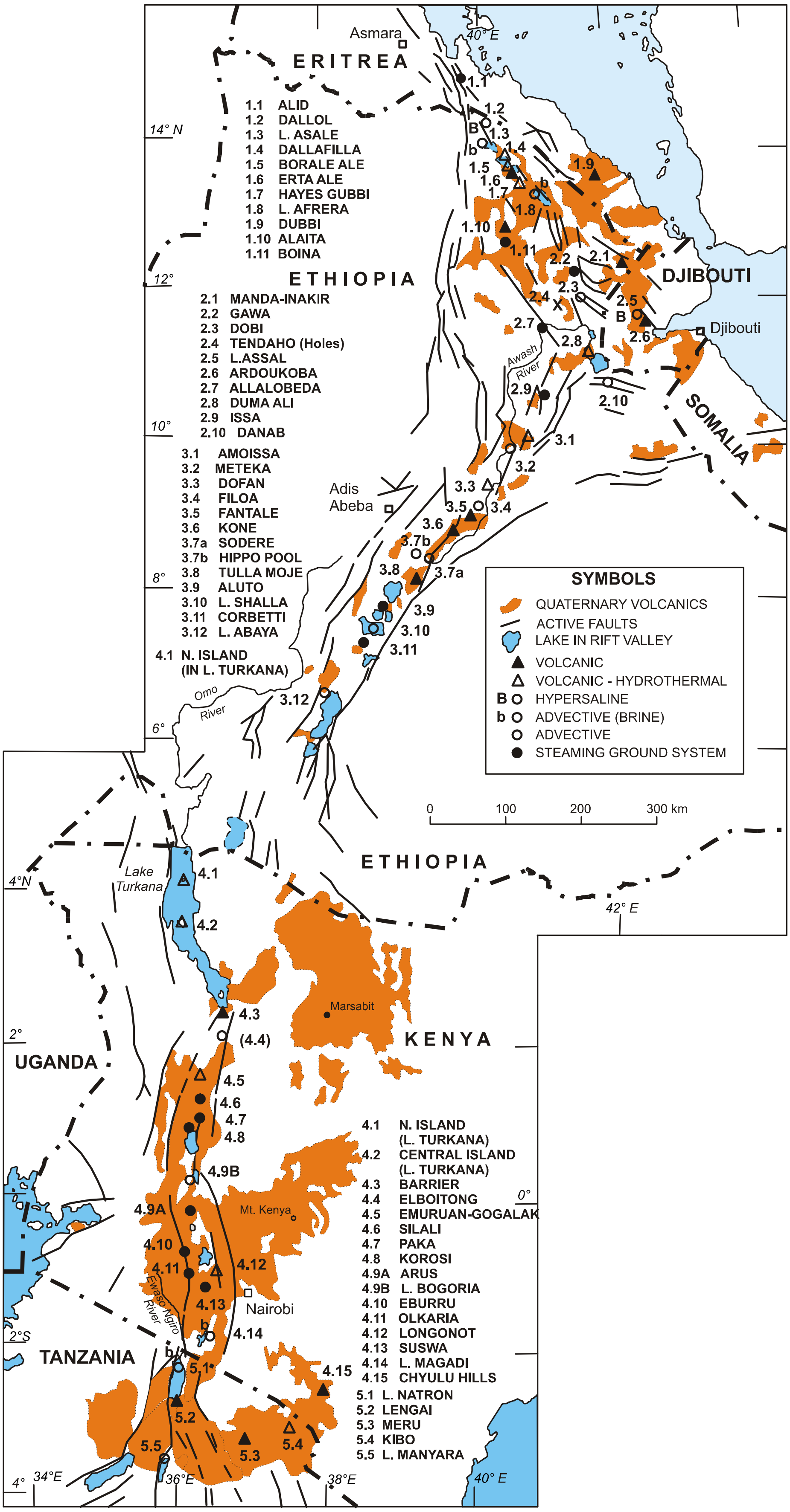

Figure 1: Location of major geothermal systems along the Eastern Branch of the East African Rift System (Eritrea to Tanzania).

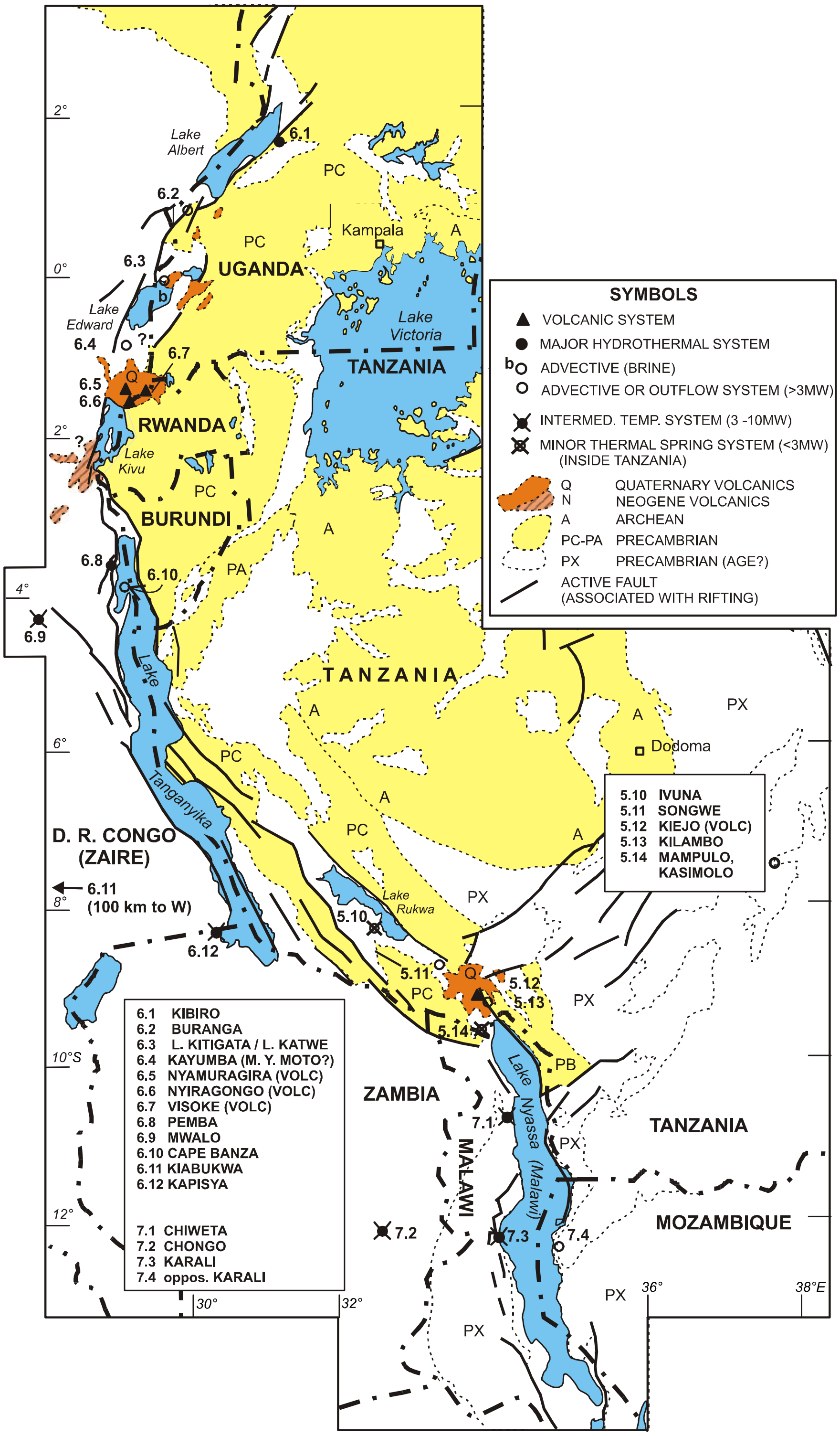

Figure 2: Location of major geothermal systems along the Western Branch of the East African Rift System