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Geothermal systems along the East-African Rift

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ABSTRACT

Crustal deformation of the African Plate and inferred hot spot activity (Upper Mantle) have produced anomalously hot, upper crustal rocks and local intrusions beneath the c. 2000 km rift. Geothermal and volcanic activity is moderately intense; 30 major hydrothermal systems with significant natural heat discharge have been found (5 of these have been explored by drilling), 14 volcanic centres have heen active during the past 2000 yr, and 10 centres are probably volcanic-hydrothermal systems. There are c. 50% more geothermal systems per unit length in the Ethiopian than in the Kenyan Rift.

The arid to semi-arid climate of the rift favours the development of two types of hydrothermal systems, namely steaming ground and advective. Steaming ground systems are associated with older volcanic dome complexes where heat transfers at shallow levels dominantly by steam. In advective systems, beat is swept from hot rocks within the rift by deeply penetrating groundwater and the heat transfers to the surface by hot water only. Leaching of saline sediments may lead to the development of thermal brine lakes.

KEYWORDS

Geothermal systems, convective heat transfer, heat discharge, continental rift, East Africa

Introduction

The eastern branch of the African Rift extends for almost 2000 km from Tanzania in the south to Eritrea in the north and cuts through five countries; three of these (Djibouti, Ethiopia, and Kenya) are developing their geothermal resources. Comprehensive catalogues of volcanoes in Africa which have heen active in historical time (or during the last 2000 yr) exist, for example, Simkin and Siebert (1994), whereas listings of active, non-volcanic geothermal systems in country reports (e.g. Endeshaw, 1988, for Ethiopia; Kamondo, 1988, Riaroh and Okotb, 1994, for Kenya) are dated or incomplete. These and similar reports cannot be used to identify the important systems since minor and major prospects have usually been listed together. An attempt is made in this study to identify all major geothermal systems, including volcanic systems, in the whole eastern branch of the Rift using published and unpublished material as well as my own observations.

Major geothermal systems were identified by looking at those which discharge heat at ground surface at rates of >> 3 MW. There are data available from reconnaissance studies which allow assessments of the minimum discharge rates either from reported liquid discharges, or from the extent of hot ground evident on infra-red surveys. For Ethiopia the results of an UNDP project (1971) and for Kenya studies by the British Geological Survey (Clarke et al., 1990; Dunkley et al., 1993) were used to infer minimum heat discharge rates. A number of studies have been published about the Djibouti prospects (for example, Zan et al., 1990) whereas only one prospect has been reported for Eritrea (Lowenstern et al., 1997). Where applicable, my observations from visits of prospects in Tanzania, Kenya and Ethiopia made between 1982 and 1995 are used. Even so, it is possible that a few major systems have not yet been been recognised.

After eliminating all fields with low heat losses (i.e. < 3 MW), those remaining can be classified. For this the volcanic systems were included since some of their manifestations discharge steam from a mantling or capping hydrothermal reservoir. A classification of the high temperature systems in Kenya has already been attempted (Hochstein and Kagiri, 1997).

Preliminary classification and spatial distribution of systems

Since both volcanic- and non-volcanic geothermal systems are discussed, a simple classification of them was attempted. The terminology used is explained below.

The term 'geothermal system' describes any natural system where heat is transported from a heat source to a heat sink, the term includes, therefore, both volcanic and non-volcanic systems. In a 'volcanic system' heat and mass are transferred from a magma to the surface via magmatic fluids and episodic discharge of magma at the surface; meteoric fluids, i.e those derived from infiltrating surface water, are not involved. A 'hydrothermal system' transfers heat from a heat source (often a cooling pluton) to the surface by free convection of a mixture of meteoric fluids and sometimes traces of magmatic fluids. Liquids discharged at or near the surface are replenished by meteoric water derived from outside which moves by advection towards the hot reservoir. A combination of a hydrothermal- and a volcanic system produces a 'volcanic-hydrothermal system' where ascending magmatic (primary) fluids mix with meteoric (secondary) fluids.

Volcanic-hydrothermal systems were only recognized about a decade ago (Giggenhach, 1997). The magmatic component in the discharged steam has to he identified isotopically. Such data are not available for most of the active volcanic centres in the rift. A less stringent criterion, namely prevailance of fumaroles on top of volcanoes with no historic records of eruption, was used instead since the meteoric water component appears to be dominant if the temperatures of all fumaroles above a (dormant) volcanic centre are at or below boiling. Distinction between volcanic and volcanic-hydrothermal systems, however, is still difficult if there is a historic record of significant lava and tephra eruptions.

After the first round 14 volcanic systems, at least 10 volcanic-hydrothermal systems, and **30** major hydrothermal systems were identified for the whole eastern branch of the African Rift. All major hydrothermal systems discharge > 10 *MW* heat each. These are shown in figures 1 and 2. At the lower end, there are at least 40 warm and hot spring systems in Ethiopia, Kenya and northern Tanzania which each discharge between **0.3** to **3** *MW*.

Most of the major geothermal systems shown in figures 1 and 2 lie close to the axis of the rift. **The** extent of Quaternary volcanics and of major, mainly tensional faults is also shown (from UNESCO, 1976). The systems show a clear alignment apart from those at each end of the rift. Their wider distribution in northern Ethiopia is due to the triple junction in the vicinity of Lake Abbe (near feature 2.6 in figure 1) where a northwest trending active rift branches off towards the Erta Ale volcano (1.6 in figure 1).

A 300 km long gap without geothermal and volcanic activity occurs between Lake Turkana and Lake Abaya (figure 1). This gap (level of rift valley < 500 m) separates the Ethiopian- and Kenyan sectors where the rift valley floor reaches elevations of up to 1500 m in both central parts and where the updomed rift shoulders stand more than 1000 m above the floor of the rift.

Doming in the Kenya sector, probably associated with the development of an asthenosphere plume, may have begun c. 15 Million yr ago when volcanic activity started (Smith, 1994). The Quaternary volcanics shown in figure 2 cover most of the areas with earliest activity. Updoming in the Ethiopian sector started earlier, probably 20 to 30 Million yr ago, and led to the deposition of thick flood basalts, probably derived from a deep mantle plume (Hill et al., 1992). Tertiary volcanic rocks are not shown in figure 1.

The line density of active geothermal systems can be used for comparison. There are c. 29 major systems in the Ethiopian sector, from Lake Abaya in the south to Alid in the north (distance c. 950 km), pointing to a spatial density of **3** systems per 100 km; for the Kenyan sector this density is c. 2 systems per 100 km.

Setting and classification of hydrothermal systems

The arid to semi-arid climate of the rift restricts and even inhibits infiltration. Precipitation rates, for example, are less than 0.2 m/yr in the low lying parts of **northern** Ethiopia, Eritrea, and Djibouti. Low precipitation rates (< 0.2 m/yr) also prevail at the southern end of the rift and in the Lake Turkana region in the middle. As the level of the rift valley floor increases in the updomed Kenyan and Ethiopian sectors, the precipitation increases. However, potential evapotranspiration rates are of the order of *2* to **3** m/yr for most of the rift valley. Significant water infiltration occurs therefore only over the flanks and shoulders of the rift at altitudes > 1700 m where precipitation exceeds evapo-transpiration. Subsurface run-off supplies numerous shallow lakes in the rift valley, most of which are alkaline, and a few streams. A river with perennial flow, the Awash River, drains the Lakes District in

Ethiopia. There are no long **rivers** with perennial flows in the Kenyan Rift valley, only short ones, such as the Ewaso Ngiro, originating from the western rift flank.

Fields with hydrothermal manifestations in ***the*** rift discharging heat at a high rate (i.e. >> 3MW) are mainly of two types, namely those which discharge only steam and others which discharge only thermal, often highly mineralised water, but almost no steam. About 80% of all hydrothermal systems are characterised by either **of** these two groups **of** manifestations.

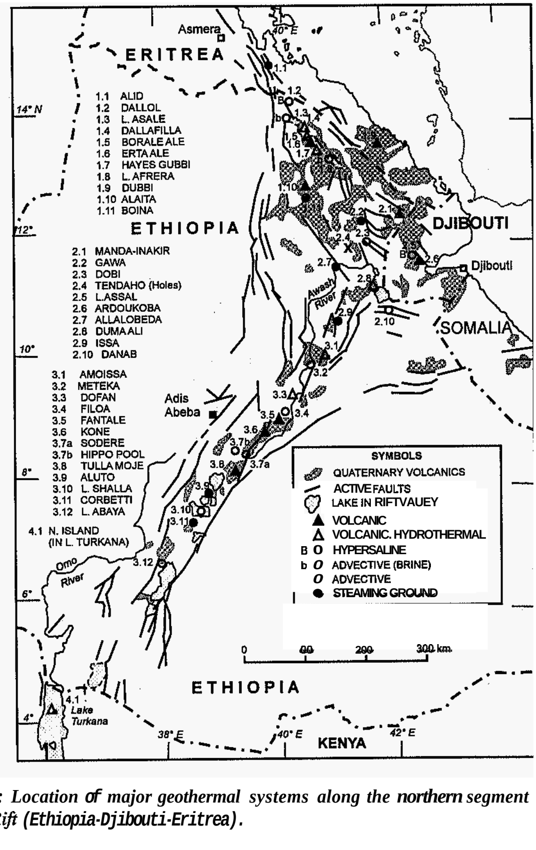

Figure 1: Location of major geothermal systems along the northern segment of the East African Rift (Ethiopia-Djibouti-Eritrea).

Steaming ground systems

Heat is discharged by steaming ground and minor steam vents over many high standing volcanic complexes lying in the rift valley. Systems, with this type of manifestations have been classified as 'steaming ground systems' (Hochstein and Kagiri, 1997). Type localities are the Olkaria and the Eburru prospects (4.10 and 4.11 in figure 2) which have been explored by deep drilling leading to the construction of a 40 MWe electrical plant at Olkaria; c. 400 *MW* and up to c. 175 *MW* of heat are discharged at Olkaria and Eburru respectively. Their reservoirs contain a mixture of hot water and vapor; however, no deeper liquids discharge at the surface, only minor condensates (transferring, for example, c. 1 *MW* of heat at Olkaria).

In a steamimg ground system vapor from the top of the reservoir, hosted by an older volcanic centre, ascends to the surface via fractures. Previous steam discharge has altered the surface rocks, kaolinite and alunite being dominant alteration minerals. After some time the surface layer becomes impermeable even to vapor which then condenses with the condensates descending. Condensation maintains a steep near-surface temperature gradient and a significant portion of heat is transferred by conduction through the thin, moist surface layer. Condensates also collect in perched aquifers which may feed thermal springs in the foothills.

Using the characteristics of the manifestations at Olkaria and Eburru as criteria, other steaming ground systems in Kenya were identified, namely those labelled 4.6, 4.7, 4.8 and 4.13 in figure 2, using the data in Dunkley et al. and my own observations.

An unlabelled prospect in figure 2, lying between prospects 4.9 and 4.10, is probably a variant of a steaming ground system. 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).

There are also a number of steaming ground systems in Ethiopia (1.1, 1.11, 2.2, 2.7, 2.9, and 3.1 1 in figure 1) of which the Allalobeda prospect (2.7) appears to be the largest one. The Aluto prospect (3.9) has a similarity to a steaming ground system although conductive heat transfer at the top is limited by a pumice layer which is almost impermeable to steam. The Aluto reservoir has been explored by deep drilling. It is also a 2-phase reservoir, and a c. 7 MWe (net) electrical plant has been installed there recently. The saturated reservoir stands above the level of the rift valley floor which explains why minor amounts of neutral pH NaCl type of hot water discharge on the valley floor. The natural heat loss bas been estimated to lie between 60 and 120 MW (Hochstein, 1983).

In the Hanle Area (Djibouti), halfway between features 2.10 and 2.5 (figure 1), a 2 km deep hole was drilled. This showed that vapor can move laterally in the rift, away from feeding fractures; no reservoir was found below steaming ground near the drillhole (Zan et al., 1990). The finding was used in this study to adopt a conservative attitude in assessing similar manifestations (i.e weak steaming ground) in Ethiopia.

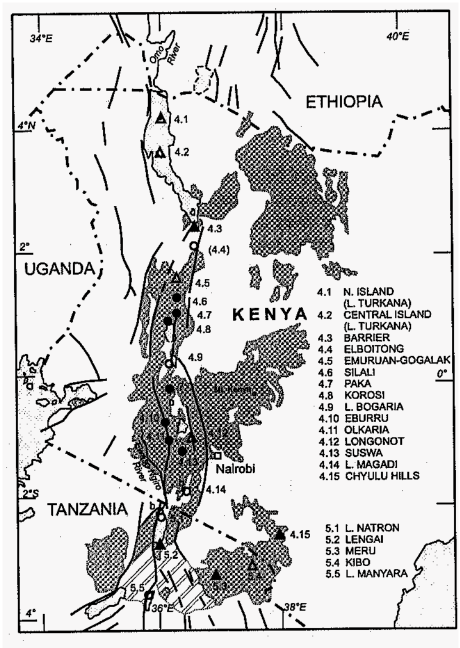

Figure 2: Location of major geothermal systems along the southern segment of the East African Rift (northern Tanzania-Kenya); symbols are the same as those in figure 1.

Advective systems

Mineral equilibria of most prospects which discharge only thermal water indicate temperatures of < 225°C, in many cases even < 150°C. These systems have been called 'advective-' or 'heat sweep' systems (Hochstein and Kagiri, 1997) since they derive from groundwater infiltrating the shoulders and/or the flanks of the rift. Under the influence of its hydrostatic head some of this water can penetrate to great depths where heat is 'swept' from hot **rocks** ('forced convection' or 'advection'); the heated water emerges through fractures on the rift floor (crustal intrusives or cooling plutons at higher crustal level are not required as heat sources). In the setting of the rift valley three types of advective systems were recognised:

(1) Intermediate temperature systems, where boiling alkaline water is discharged by at least one hot spring; (2) Intermediate to low temperature systems whose discharge temperatures are usually **less** than 65°C; and (3) Advective brine systems.

A type locality for (1) is the Lake Bogoria system (4.9 in figure 2) where boiling water discharges to heights of a few meters in a few hot pools. Mineral equilibrium temperatures (T (KMg) and T (NaK)) are < 150°C, some constituents probably derive from shallow leaching rather than deep fluid/ rock interactions. The heat discharged is significant (probably 100 to 200 MW). Boiling fluids with similar compositions to those at Lake Bogoria also discharge at Lake Shalla (3.10 in figure 1) where mineral equilibria point to *c* 150°C for the deeper fluid; visible hot springs, however, discharge only c. 11 *MW*. Manifestations similar to those at Lake Bogoria occur at Lake Abaya (3.12 in figure 1). but only c. 10 *MW* **of** heat is discharged at the surface by hot water. At Danah (2.10 in figure 1) a few minor springs also discharge alkaline water at boiling point. Both prospects have been tentatively classified as advective systems because of their hydrological settings.

There are at least five large, low temperature, advective systems in Ethiopia which discharge hot water at 45 to 65 "C, namely prospects 2.3, 3.2, 3.4, and 3.7a,b (figure 1). Their rate of heat discharge lies between 40 *MW* (3.7a) and 105 *MW* (3.7b). Indeed, the Hippo Pool (3.7b) is the largest, single thermal spring in the whole rift. Deeper aquifer temperatures of < 150°C are indicated by the silica and (K/Mg) geothermometers. The only thermal springs in the Kenyan Rift, similar to those in Ethiopia, are the Kapedo Springs which discharge a bicarbonate type of water at **the** western foothill of the Silali volcanic-hydrothermal system (transferring c. 40 *MW)*. The Kapedo Springs are not listed here as a separate system since they are probably part of the Silali system.

Six advective brine systems occur in the rift, namely 1.3, 1.8, 2.5 (in figure 1) and 4.4, 4.14, and 5.1 (in figure 2). In each case highly mineralized thermal waters with total dissolved constituents between 15 to 40 g/kg are discharged by thermal springs along the shore of shallow lakes, all in an arid climatic setting. Evaporation leads to a concentration of the dissolved constituents in the lakes, attaining concentrations between 150 to 300 g/kg (hypersaline brines). The temperature of the shore springs is usually between 40 and 60°C, their mineral content is most likely derived from leaching of sediments containing evaporites and is not controlled by deeper fluid/rock equilibria. Silica geothermometers point to distant aquifer temperatures of up to 110°C. In the case of one of the better studied hypersaline lakes (Lake Magadi, 4.14 in figure 2), isotope data (Clarke et al., 1990) point to a rather local origin for some of the advected waters, the 20 km distant Ewaso Ngiro River.

The heat discharged by these systems can be significant. In case of the Lake Afrera prospect (1.8). c. 60 small brine springs along the shore discharge heat at a total rate of c. 100 *MW*. The heat output of thermal brine springs at Lake Magadi was estimated to be c. 300 MW

(Crane, 1981); in 1995 this output appeared to be **less.** The Elboitong prospect (4.4 in figure 2) in northern Kenya is an interesting variation of an advective brine system; at Elboitong boiling brine (c. 20 g/kg dissolved constituents) is discharged by some springs along the rift wall. The brine evaporates forming crystalline carbonates of sodium (trona) on the valley floor, a mineral which is also dominant at Lake Magadi and Lake Natron. Thermal brines in Kenya and Northern Tanzania are all sodium carbonate type waters, those in Ethiopia are of the sodium chloride type.

Other systems

There are a few other high temperature systems in Ethiopia which differ from those discussed so far. Stagnant hypersaline brine systems have been found at Dallol and near Lake Assal (1.2 and 2.5 in **figure** 1). The hypersaline system near Lake Assal is marked by minor fumaroles and steaming ground. Six deep wells have been drilled here (Zan et al., 1990) encountering hot hypersaline brine with temperatures up to 350°C at 2 km depth, the dissolved constituents amount to c. 160 g/kg. At Dallol hypersaline brines (up to 300 g/kg) occur in several hot pools (surface temperature up to 110°C) which are located on top of a salt dome. The source of heat appears to be a high standing intrusion which heats the brine by conduction. No heat **loss** data are available for either prospect.

A concealed outflow of hot water (up to 250°C) was discovered by drillholes near Tendaho (2.4 in figure 1) but its reservoir has not been found yet. The nearest surface manifestations are weakly steaming ground (not included in **figure** 1 because of its apparently low heat discharge).

Discussion

There are at least 54 major geothermal systems along the c. 2000 km long eastern branch of the African Rift system. Heat discharged by c. one thiid of the 30 major hydrothermal systems is between 10 and 400 *MW*, with the largest transfer (c. 400 MW) occuring at Olkaria (Kenya). Only a few heat **loss data** are available for the volcanic- and volcanic-hydrothermal systems. Long term discharge rates between 100 and 400 MW have been cited for the Erta Ale Volcano (Oppenheim and Francis, 1998) and c. 30 to 100 *MW* are indicated for the volcanic-hydrothermal system of Emuaran Gogolak (Hochstein and Kagiri, 1997).

The rather unusual types of hydrothermal systems **in** the rift can be appreciated by comparing them with others showing also a clear alignment but associated with a different type of active margin and a different climate. For example, the c. 45 major geothermal systems along the 1800 km long segment of the Sumatra Arc (Hochstein and Sudarman, 1993). These can be grouped into 18 volcanic- and volcanic-hydrothermal- and **27** major hydrothermal systems. The spatial density of systems along the two different plate margins (i.e. continental rift versus subduction) is almost the same and their overall total heat discharge appears to be similar.

However, in Sumatra almost all major hydrothermal systems appear to have liquid dominated reservoirs since natural recharge by infiltration is plentiful (precipitation rates > 3m/yr). Advective brine systems and steaming ground systems have not been found. This comparison supports the argument that the type of hydrothermal systems in the African Rift are controlled by the present-day climate.

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