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Short communication

CONCEPTUAL MODEL FOR BOKU HYDROTHERMAL AREA (NAZARETH), MAIN ETHIOPIAN RIFT VALLEY

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ABSTRACT: In tectonically active areas, fractures of various extent play a very important role in groundwater circulation and storage, increasing also the permeability of rocks. Since hot springs are generally non-gravity types, tectonic discontinuities act as a vertical pipe line for zenithal flow of thermal water and steam. On the Boku rhyolite ridges, active deep faults tap steam from high thermal anomaly area to the surface. Tension and laminar fractures within the rhyolite flow foliation structure increase the vertical permeability of the rock and the discharging surface area. The applied conceptual model has shown that the major deep aquifers are within the floor complex ignimbrites overlain by rhyolite lava domes. By using a simple mathematical equation, the minimum theoretical depth of the provenance of thermal water has been determined (about 400 m) which could be taken as the minimum depth of open fractures that act as conduits for hydrothermal fluids.

Key words/phrases: Boku fumaroles, foliation fractures, hydrothermal area, minimum theoretical depth, Wonji Fault System

INTRODUCTION

The modelling of thermal aquifers is quite essential to understand the provenance, the mode of discharge and controlling structures of thermal waters. This paper deals with a conceptual model for a hydrothermal area. The term "conceptual" indicates something which is useful for the solution of some problems, that can not be quantitatively measured or verified by the means of the present studies. Hence, the proposed model hypothesizes a possible hydrogeological section of the studied area with important hydrostructures which increase water circulation and storage capacity of the rocks.

Usually the location of hydrothermal centres is directly determined by means of geothermometers. However, the minimum theoretical depth of the provenance of thermal water is treated in this paper in order to determine the extent of fracture pattern by using the temperatures of both infiltrating water and thermal water at the surface.

The active Boku fumaroles, which are located in the tectonically active central part of the Main Ethiopian Rift Valley, are associated with the acidic central volcano which has been erupted in the late Quaternary. Since the hydrothermal activities are localized on the western shoulder of this volcano, more specifically outside the caldera, an appropriate conceptual model is prepared to show the major hydrothermal fluid carrying structures and the associated rhyolitic fractures (foliation fractures) which diffuse the steam at the surface.

The Boku area was surveyed in the months of March and April, 1996 during which temperature measurements and reconstruction of the local geology with the relative stratigraphy were carried out.

VOLCANIC SETTINGS

The Main Ethiopian Rift, which occupies the central part of the country, is made of Pliocene and Quaternary volcanic products represented by fissural basaltic lava flows and acidic lavas with pyroclastics erupted by central volcanoes (Mohr, 1971).

The major tectonic lines are aligned NNE-SSW and NE-SW forming local graben and horst structures. The axial part of the rift is dominated by acidic volcanoes that mainly erupted along these tectonic lines. They are characterized by either collapsed or circular caldera, among which the Boku collapsed caldera occupies the southern sector of the Nazareth town.

The representative volcanic stratigraphy of the central part of the Main Ethiopian Rift, as stated in Mohr (1983) is given in Table 1, where local stratigraphic section is also represented.

Table 1. The Nazareth area volcanic stratigraphy. (Mohr, 1983 and the references therein; Alula Damte *et al.*, 1992). Quaternary = 0–1.7 my; Pliocene = 1.7–5 my.

Age (in millions)	Main lithology	Thickness (in meters)
0.25	Boseti and Gadamsa basalts	≅ 3-4
-	Unwelded ignimbrites	≅ 5
0.45-0.4	Bofa basalts (Olivine basalts)	-
0.5	Gadamsa ignimbrites	≅ 20-50
0.6	Adama-Boku basalts	≅ 5
0.8	Boku rhyolites	≅ 200
1.6	Wonji basalts	-
1.7-1.6	Boseti ignimbrites; floor complex ignimbrites	> 100
3.3-3.1	Tede rhyolites	

Boku volcanic ridge is made of alkaline and peralkaline rhyolite lava domes and flows (0.8 my, Alula Damte *et al.*, 1992) which cover the floor complex ignimbrites in the central part of the Rift (Fig. 1). From stratigraphic point of view, the Boku rhyolites fall between Adama-Boku basalts and Wonji basalts. The acidic rocks consist of rhyolite lava domes, obsidian flows, tuffs and ashes.

The occurrence of repeated step faulting makes it clear that the Boku hydrothermal area is located on still active and deep tectonic zone. The rhyolites and obsidian flows are strongly foliated and the top part is hydrothermally altered. The severe refolding of the rock bodies gives rise to peculiar foliation structures which are characterized by tension and laminar fractures.

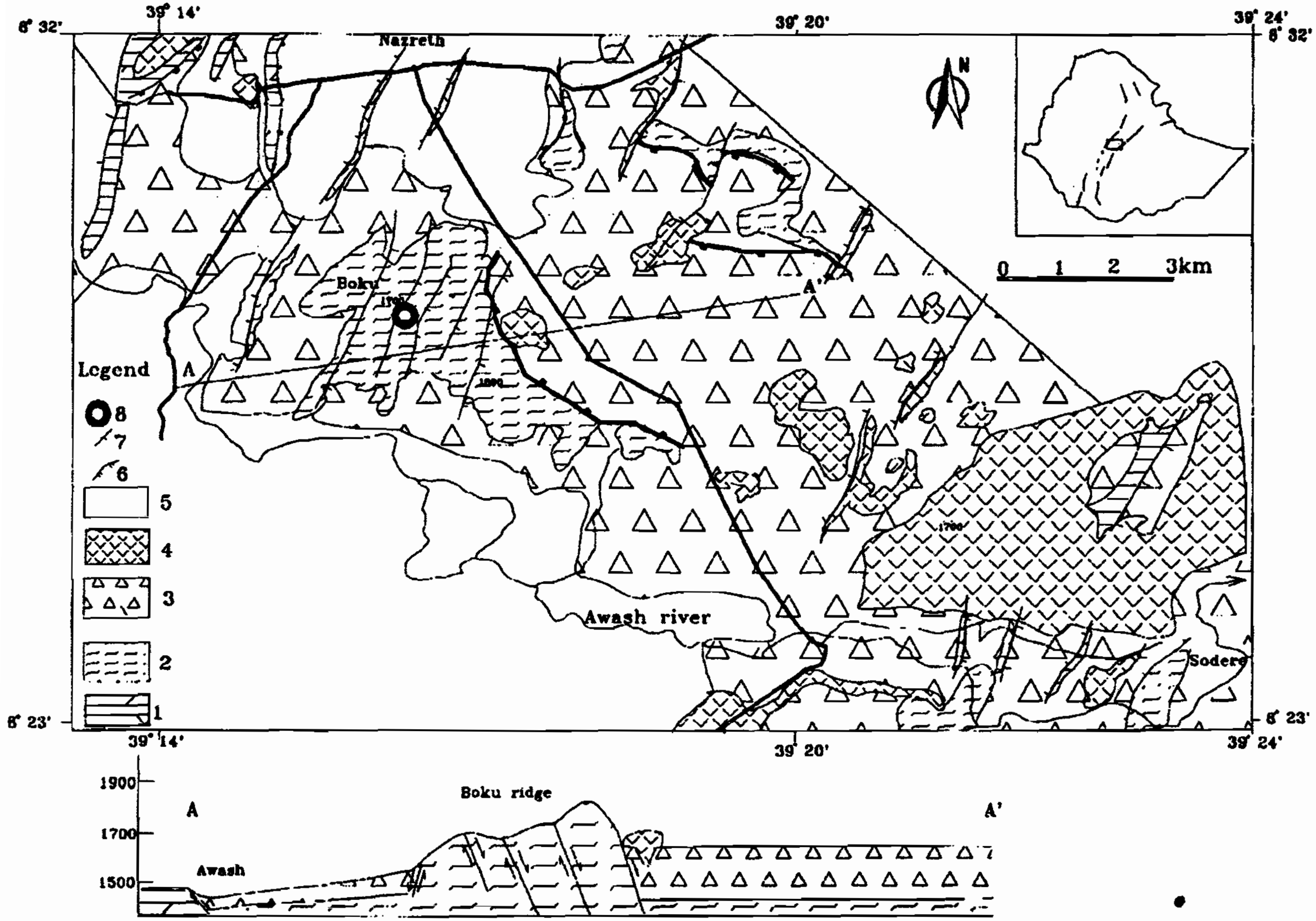

Fig. 1. Geological map of Boku area. (Modified from Alula Damte *et al.*, 1992). 1, Floor complex ignimbrites; 2, Rhyolite lava domes; 3, Unwelded ignimbrites; 4, Olivine basaltic lava flows and related spatter cones; 5, Alluvials; 6, Caldera collapse; 7, Faults; 8, Fumarole site.

HYDROGEOLOGY

The Ethiopian Rift Valley is characterized by high geothermal energy and hydrothermal activity attributed to its high thermal anomaly. A large number of thermal springs and fumaroles are associated with central acidic volcanoes where younger fractures, which post date the volcanic activity, discharge hydrothermal fluids. These fractures, in the central part of the Ethiopian Rift Valley, are represented by Wonji Fault Belt (Mohr, 1971; Di Paola, 1972), which tap thermal water and steam from the underlying geothermal reservoirs that are probably located near shallow magma chambers.

The studied steam area is located near the Boku caldera which directly shows the presence of collapsed magma chamber underneath. The Pliocene ignimbrites and basalts are the important aquifers in the Ethiopian Rift valley both from hydrogeological (Tamiru Alemayehu, 1993) and geothermal point of view (Tesfaye Chernet, 1982; Berhanu Gizaw, 1996). The groundwater temperature in these aquifers, in the Nazareth area with a bore hole depth of 100 m, reaches 26° C. In nearby Debre Zeit area, the temperature of the groundwater within basaltic and ignimbritic aquifers at a depth of 140 m, is about 18° C, which is a characteristic value for normal groundwater (Tamiru Alemayehu and Vernier, 1995).

The high temperature anomaly of groundwater in the Nazareth area could be attributed to the shallow location of high geothermal gradients that are due to repeated tectonic and volcanic activities. In the investigated area, the floor complex ignimbrites are extremely welded and intensively fractured, so that taking into consideration also their stratigraphic position, they are promising aquifers, where fracture permeability prevails on pore permeability.

The rhyolite lava domes are refolded and intensively fractured with major fractures like tension cracks (or longitudinal fractures) and laminar fractures (open foliation planes) which increase the permeability of the rock. The laminar fractures mostly assume vertical direction which favour both vertical infiltration of meteoric water and discharge of steam and thermal waters.

The temperature of condensed water from Boku fumaroles as measured by Habteab Zerai and Melese Balachew (1987) was 72° C, while recently measured temperatures show the average value of 78° C. The Boku steam site is characterized by dispersed patches of hot grounds with temperatures of 60-65° C. The major hydrothermal products, red soils and secondary minerals, are mainly dominated by quartz and kaolin. The dominant types of hydrothermal manifestations are steam, localized thermal water drops and hot grounds. In favourable aquifer geometry and based on the presence of hydrostructures shallow aquifers recharge the deep geothermal reservoirs. However, in the case of Boku fumaroles, the area acts as a discharging zone.

CONCEPTUAL MODEL

The hydrogeological model of Boku fumarole site could correspond to the presence of deep floor complex ignimbrite aquifers with overlying refolded and fractured rhyolite lava domes. The rhyolitic fracture pattern seems to increase discharging area by tapping steam from the deep running faults (Fig. 2). These faults, indeed, may feed vertical laminar fractures and tension fractures and act as a vertical pipe line. The foliation fractures (tension cracks and laminar fractures) increase largely the vertical permeability of rhyolites. The deep running recent faults are substantially inclined and curved to reach high thermal anomaly areas. The infiltrating water from south and south-western part, mainly from the great alluvial terrains fed by Awash river, may recharge the high geothermal gradient areas. The minimum theoretical depth of the provenance of thermal water can be evaluated using the formula given by Celico (1986).

$$P = P_e + (T - T_a)\, G$$

where: P = minimum theoretical depth;
P_e = the thickness (m) of the rock which could be affected by external temperature;
T = temperature of thermal water (° C);
T_a = temperature of infiltrating water, ° C (equal to mean yearly air temperature minus 2 or 3° C);
G = geothermal gradient (m/° C).

The geothermal gradient in the Ethiopian Rift Valley, as calculated from the temperature data of Berhanu Gizaw (1993, 1996), is about 6 m/° C. P_e is extremely variable, ranging from 15 to 17 m in the porous rocks, from 24 to 27 m in limestones, and from 35 to 39 m in granites (Celico, 1986). Since rhyolites are the dominant lithology in the studied area, it is possible to say that volcanic rocks are more compacted than limestones, but less than granites, so that, for their massive nature they could transmit the effect of external temperature at a greater depth, which could be assumed to be closer to granites. Hence, for Boku rhyolites, the value of 35 m is considered for P_e. Being $T_a = 15°$ C, and T = 78° C, then the calculated value of P will be 413 m. This value could also be considered as minimum depth of tapping fractures.

Since the steam temperature at the surface is undoubtedly higher than the condensed water, the expected value of P will also be high. In fact, other factors being constant, a value of 100° C for T would give a value of 545 m for P. The steam and the thermal water (actually in small drops) may have the same aquifer. However, the steam may be partially transformed into hot water by the contact with shallow cold water.

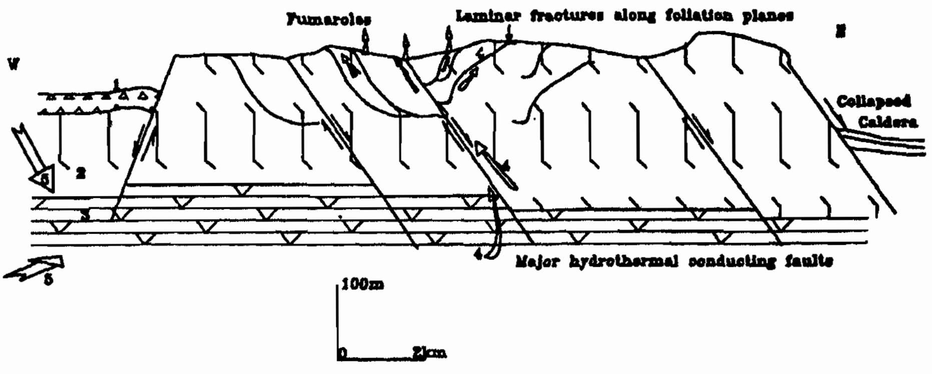

Fig. 2. **Conceptual model for Boku hydrothermal site.** 1, Unwelded ignimbrites; 2, Foliated and fractured rhyolite lava domes; 3, Floor complex ignimbrites; 4, Direction of steam and hot water movement; 5, Major recharge from south and southwestern part.

CONCLUSION

The geothermal fluids, in the Boku area, come to the surface along deep fractures. The most important fractures are recent faults accompanied by tension and laminar fractures which increase the vertical permeability of rhyolites and discharging surface area. The minimum theoretical depth of the fractures is about 400 m, but this value could be rather higher to discharge fumaroles with higher temperatures like Boku. The geothermal gradients around Nazareth is very high as indicated by higher shallow groundwater temperature ($\approx 26°$ C) which could be due to repeated tectonic and volcanic activities.

It is hoped that the model will be an important tool to show the effect of volcanic structures on circulation of groundwater.

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