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GEOPHYSICAL, GEOLOGICAL AND HYDROGEOLOGICAL INVESTIGATIONS OF BOKU THERMAL FIELD, NAZARETH, ETHIOPIA

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ABSTRACT

This paper presents the results of a multidisciplinary research program involving geological, hydrogeological and geophysical surveys carried out over the Boku fumaroles, Nazareth (Rift floor of the Main Ethiopian Rift).

The results show that the Boku thermal field is a vapor-dominated, dry type geothermal system tapping the deep-seated heat reservoirs of the shallow acidic volcanic center of Quaternary volcanics of the Rift floor.

The cap rock is formed by the self-sealing process through hydrothermal alterations of the major rock units in the area as witnessed by the surface manifestations of calcite, silica and extensive kaolinization that are suggestive of such an environment.

The aquifer system consists of the Quaternary fractured Rift floor ignimbrites. The necessary supply for the replenishment of the reservoirs is derived from the closed basin system of the Nazareth watershed and/or from the large open irrigated grounds of the Wonji state farm. The investigations have clearly mapped the Quaternary Fault Systems that are the major tectonic structures for the propagation of the deep-seated superheated vapor to the surface, and the recharging of the geothermal reservoir.

INTRODUCTION

The earth is an enormous source of heat, but most of the heat is either buried too deeply or it is too diffuse to be exploitable economically. However, geological and hydrogeological processes, at certain places, concentrate the heat to allow it to be extracted in economically useful quantities. Such heat energy, appropriately stored in the earth's crust to be amenable to economic extraction, is called geothermal energy. This energy is a potentially important and promising alternative energy source

that has seen a continual growth throughout the last half-century both in the field of exploration and exploitation and is now being considered as the potential future supplier of global energy requirements. Geothermal energy exists in abundance under the earth's crust (those of higher depth for known practical reasons are not included in the discussions related to this subject) and it has the potential to offset the energy economies of many countries throughout the world. This is particularly true with the increasing trend in scarcity and cost of fossil fuels and other natural forms of energy. Moreover, this energy, specially in volcanic regions, may be the only economic form for developing countries as electricity distribution systems are too small to justify nuclear power stations, but a comparatively small size of geothermal power stations fit the scale of the electricity supply system in these countries (*Gouel, 1976; Coolie, 1978;Gupta*, 1980; *Armstaed, 1982; Armstaed, 1983; Economides and Ungemach, 1987)*

Depending on the heat grade available from the reservoir, a geothermal reservoir may be suitable for power generation and other applications. These include space heating, process heating, agricultural and industrial uses, and non-electrical uses like hydrotherapy, extraction of minerals and chemicals and for fresh water supply (*Reistad, 1975; Nguyen, 1983).*

Although the classifications of geothermal systems are varied, the recipes for their existence as widely accepted are: a large source of heat, a reservoir to accumulate heat, and a barrier to hold the accumulated heat. Adequate supply of water is also considered to be an additional requirement of most geothermal systems. In this regard, the main controlling factors for the geothermal energy to be available for exploitation are a heat source, permeable reservoir, and cap rocks (Gupta, 1980; *Armstaed, 1983; Economides and Ungemach, 1987).*

Surface manifestations of deep geothermal activities are in the form of fumaroles, geysers, hot springs, hot grounds, steam, etc., and areas that show high temperature anomalies on the surface are potential areas of anomalously high temperatures at depth.

THE BOKU AREA

The Boku area is one such an area where the characteristic surface manifestations and all the requisite geological and hydrogelogical indications, potential for geothermal energy, are apparent. In fact it is one of the many areas within the Ethiopian Rift known to posses numerous surface manifestations of underground geothermal potential.

The Boku fumaroles are located about 5 km south of Nazareth town within the Main Ethiopian Rift in a region of active axial faulting where the Boku volcano has been extruded from north-north-east trending faults and subsequently displaced by north-north-west Wonji Fault Belt. Two areas of warm ground and fumarole activity are apparent in the area in close association with these north-north-west faults. Steam temperatures of 72- 85 °C have been measured and the area has been widely used for its thermal healing and related activities and is connected by an all weather gravel road constructed to Nazareth town. The highway to Asella crosses the caldera in to two parts. The caldera is bounded from north by Nazareth City and from south by the Wonji sugar plantation. Based on the conceptual model proposed by Tamiru and Vernier (1997) it was the aim of a multidisciplinary geological, hydrogeological and geophysical investigation programme to be carried out to elucidate its potential, its aerial extent, controlling parameters and relation to the major structural features in the area. The surveys are also to determine whether the Boku can be reasonable prospect for a small-scale geothermal development.

GEOLOGICAL AND TECTONIC SETTINGS

The major tectonic lines, which are aligned in NE-SW direction in the Rift floor, form numerous local graben and horst structures (Rift-in-Rift structures). The central volcanoes are rooted along these tectonic lines and are characterised by collapsed calderas, among which the Boku caldera occupies the southern part of Nazareth City in the MER. The volcanic eruption and emplacement of the product took place 0.8 my ago (*Alula et al., 1992*). The volcanic products from the Boku volcano can be grouped as alkaline and peralkaline rhyolite lava domes, flows and pyroclastic falls, which cover the floor complex ignimbrite flows. The major products are rhyolite lava flows, obsidian flows, pumice falls, and spatter cones with associated basaltic lava flows (*Alula et al., 1992, Tamiru and Vernier 1997*). After the emission of these products the caldera has been collapsed and given rise to post-caldera (intra-caldera) products such as scoria cones with associated basaltic lava flows. The Boku ridge forms the maximum peak in the area rising from 1600 m above sea level to 1875 m above sea level. This young volcano has been repeatedly disected by the recent deep and extensive late Quaternary faults, which are recognized as WFB (Mohr, 1971). In this regared the time coverage for the faulting of the WFB reaches as much as the age of the volcano (0.8 my *Alula et al., 1992*) or even younger. So it is possible to say that the WFB ranges from 1.6 my (*Meyer et al., 1975*) to less than 800,000 years. The main lithological units identified in the area, from older to younger, are the following (Fig.1): Rift floor ignimbrites; slightly welded tuffs; unwelded tuffs; rhyolitic lava flows; pumice fall deposits; obsidian flows, and basaltic lava flows and scorias.

Rift floor ignimbrites

The rift floor ignimbrites are the oldest unit in the area. The main outcrops are found at the enterance of Nazareth having elongated shape and bounded by fault lines. The ignimbrites are welded and massive. The total thickness is about 100 m with the age of 1.7 my (*Alula et al., 1992*).

Slightly welded tuffs

This unit is coarse grained and is rich in pumice clasts and lithic fragments. The tuff has brown color and outcrops along the eastern rim of the Boku caldera. The unit has a thickness of about 80 m.

Rhyolitic lava flows

The rhyolitic lava flows occur as a basal and upper cover on the western rim of the caldera. These flows are grayish in color and porphyritic in texture. The outcrop is not extensive and is limited around the vent. This unit confines the pumice fall and the obsidian flows and forms steep slopes around the rim.

Pumice fall deposits

Stratigraphically cover the lower rhyolitic lava flow and are areally very extensive. The unit has a characteristic vesicular texture, and in hydrothermally active areas, it is completely altered. This unit forms gentler slope even far away from the caldera.

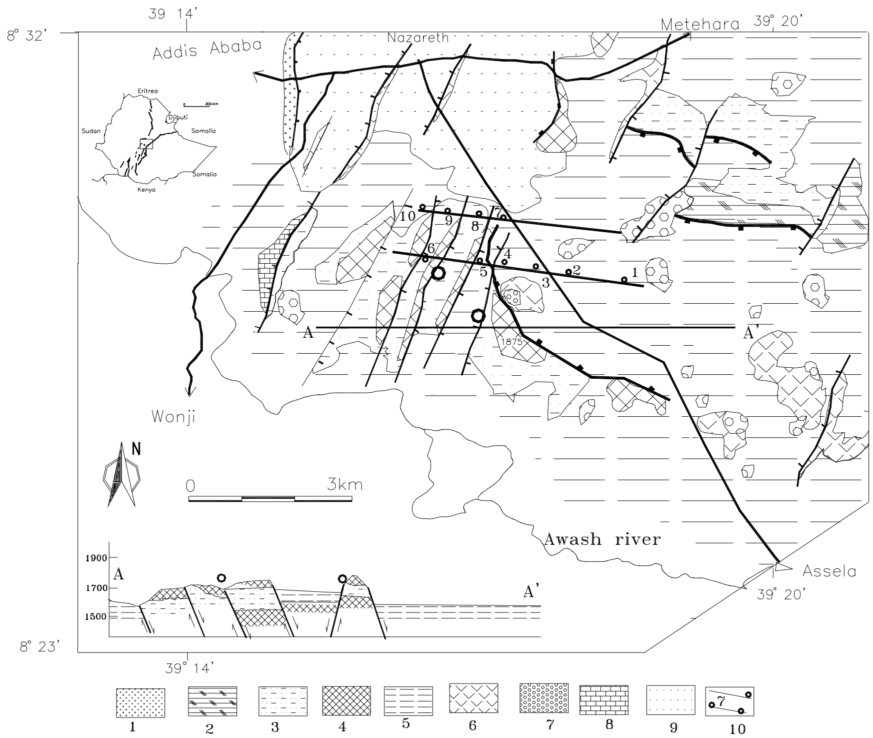

Figure 1. Geological map of Boku area.1= Rift floor ignimbrites; 2= Slightly welded tuffs; 3= Pumice fall deposits; 4= Rhyolitic lava flows; 5= Unwelded tuffs; 6= Basaltic lava flows; 7= Scoria; 8= Lacustrine deposits; 9= Alluvial deposits; 10= Resistivity profile line and VES points

Obsidian flows

These flows are limited around the caldera rim and have characteristic black color. The flows are intensively fractured and at some places weathered to the state of perlite. The unit is found to be unmapable in the considered scale.

Unwelded tuffs

The unwelded tuffs cover the entire plain areas of the region. The unit has small amount of pumice fragments, some dark colored rock fragments as much as 4 cm in diameter, and is generally dominated by ash. Since the unit is very loose, the surface runoff has formed deep gullies all over the farmland.

Basaltic lava flows and scorias

These units are the result of post caldera eruption and are localized within the caldera. The basaltic lava flows are vesicular in texture and some of them are filled with secondary minerals. In some outcrops basaltic lava flows are older than the scorias.

HYDROGEOLOGICAL OUTLINE

The Ethiopian Rift is a unique place where large amount of geothermal energy is found.

The repeated deep crustal faulting and associated volcanism restrict the hydrothermal activity within the Rift. It is characterized by high thermal anomaly where high geothermal gradients influence the shallow volcanic aquifers such as pyroclastics and basic lava flows. Local thermal anomalies are mostly associated with heat flow from the shallow magma chamber. The floor of the Main Ethiopian Rift is known to contain large number of thermal springs and fumaroles. The well-known spots are Boku, Sodere, Aluto, Wendo Genet, Corbetti, around Lake Shalla, Lake Langano etc… In these areas the main thermal manifestations are thermal water, pressurized fumaroles and hot grounds. The main thermal water conducting fracture are the Wonji Fault Belt which frequently intersect the high geothermal gradient areas near the acidic magma chamber which are present at shallow levels. In the MER the main geothermal reservoirs are Pliocene basalts and ignimbrites (*Tamiru, 1993; Berhanu, 1996; Tamiru and Vernier, 1997).*

Almost all thermal centers are found in close association with acidic volcanic centers. The deep circulation of groundwater provides a mechanism whereby heat from a large region of positive thermal anomaly can be extracted for concentration in the discharge zones. According to Tamiru and Vernier (1997), the high temperature of groundwater at shallow depth around Nazareth is likely due to the presence of high geothermal gradient at shallow depth (about 6m/°C). On the Boku ridge the rhyolite lava flows show characteristic flow structure called flow banding where the structures are intensively fractured and favor both shallow infiltration and uprising of the steam.

The inflow of new water balances, partially or fully, the heat lost through vents and fissures (or through withdrawal of borehole fluids through boreholes). Recent isotopic studies have shown that 90% of geothermal water are derived from meteoric waters although there were suggestions that waters of the magmatic or juvenile origin could be the sources (although in geopressurized geothermal systems waters of juvenile origin are accepted sources and in magmatic geothermal systems magmatic waters could be the source).

The permeable aquifers forming the reservoir must therefore have a hydraulic continuity with the large recharge areas for the rainwater to be available in continuous supply. Possible sources that can be attributed to the Boku fumaroles are waters of the Nazareth closed basin, and waters from the irrigation plains of the Wonji sugar plantation.

The recharging water will continually be flowing into the aquifer to make good any natural loss occurring at points of the surface as a fumarole. Until these days no artificial exploration of the steam has been carried out in the area. The meteoric waters may also penetrate downwards through faults at the site of a field where there are no uprising hot fluids.

The importance of the Boku caldera here as both a route for recharge of water and discharge of hot fluids should not be underestimated. It is wise to note that a caldera, like the Boku, has been subjected to such intense mechanical and thermal stress that complex faulting will have caused the formation of extensive permeability which, in time, may become covered with a cap rock as in the case of a graben. The fact that acidic magma has extruded from a Boku caldera in a relatively recent geologic times will almost certainly mean that there is still a large store of residual heat beneath the fractured zone.

Some important facts are:

- vapor-dominated geothermal fields are located on or close to volcanoes- this verifies that shallow magma chamber is their source,
- young, high temperature (500 - 1000°C) magma intrusions to within depths of a few tens of KM from the earth's surface allow the necessary heat to accumulate in economical quantities,
- faulting provides the channel for the heat to reach the surface.
- regions of Quaternary uplift and regions of late Tertiary and Quaternary subsidence (the Boku caldera) are indicative of shallow magmatic intrusions,
- to form a heat reservoir, the anomalous magmatic intrusions should encounter porous and permeable, water-filled rock strata,
- The rock types forming the lithology of the reservoir are varied (for example, if one takes the known geothermal fields of the world, fractured limestone and dolomite (Larderello, Italy), fissured greywacke (The Geysers, USA), pumacious breccia and tuff (Wairakei, New Zealand), deltaic sands (Cerro Prieto, Mexico), etc. (*Rybach and Muffler, 1981*).
- In the case of the Main Ethiopian Rift in general and Boku area in particular, the well-known reservoirs are pyroclastic rocks, specially fractured ignimbrites and fractured basaltic lava flows.
- convection currents of hot water and/or steam within the reservoir provide good heat exchange.
- there should be enough supply of water for the continuous recharge and replenishment of the reservoirs.

The location of thermal centers is controlled by young tectonic discontinuities. The entire ridge has been affected by strong hydrothermal activity. The main indications are the deposits of calcium carbonates, varities of quartz, laterite and kaolin. The surficial cover of the Boku ridge is dominated by hydrothermally altered materials.

The past intensive hydrothermal activity in the area might have reduced the overall permeability of the material; hence at present the discharge of steam is localized along deep fault lines.

The present day warm ground is restricted along the two NE-SW aligned normal fault lines: one is found where the steam bath center is located, and the other is found in front of the bathing center.

An impermeable cap rock or a cap rock with low permeability, overlying the reservoir, is necessary to prevent the escape of hot reservoir fluids through convection in vapor-dominated geothermal fields like the Boku (heat loss through conduction is not prevented by the cap rock, but heat loss by convection is much efficient in geothermal conditions than by conduction).

There are two possibilities for the formation of this cap rock. This could be an impervious clay cover, for example, over the reservoirs or the cap rock may have formed through the process of hydrothermal alteration. Hydrothermal alterations of rocks and mineral deposition are associated with geothermal fields and these are helpful in sealing off the fissures. The fields may not be having a cap rock/sealing originally and the system may have been self-sealing through this process of hydrothermal alteration (self-sealed cover of a fractured geothermal reservoir). Quartz and calcite seal the fracture and the rock is altered- kaoloinization. The surface manifestation of these alteration zones is indicative of this process *(Economides and Ungemach, 1987).*

At the Boku fields hydrothermal alterations apparent on the ground extend to about 200 m along the fault down-thrown northeast at the site of the major fumarole activity (Figure 1). East of this center, and about 1 km, another zone of hydrothermal alterations of up to 100 m-wide and extending for about 300 m along the south west down-thrown fault in association with the second thermal center is apparent. These regions of hydrothermal alterations are suggestive of the fact that the thermal field is a self-sealing type.

GEOPHYSICAL INVESTIGATIONS

A large scale geothermal exploration operation essentially aims at locating the geothermal field or low grade aquifer; decision as to whether a field, if found, is semithermal or hyperthemal; determine whether the hyperthermal field, if located, is steam or water dominated, and define as closely as possible the location, the area, depth and probable range of temperatures of any located field or low grade aquifer (*Mediav, 1970; Banwell, 1970; Banwell, 1970; Giancaro, 1973).*

Geophysics plays an essential role in exploration for geothermal sources particularly those of temperature dependent parameters. Ordinarily, geophysics would search either for structures, eligible for trapping the hot fluid, or anomalies reflecting the properties of the hydrothermal fluid and its paths for the upward and downward conducting of this fluid and its actions on the host rock. As a result, almost all the geophysical methods can be used in geothermal exploration.

The choice of the geophysical method to be used for surveying a particular potential geothermal site depends upon the local geological conditions and the objectives assigned to geophysics. One method is less likely to solve all problems encountered in geothermal exploration solely (as is the case in all other problems requiring inputs from geophysical work), and it is in general recommended that at least two methods be used, based on different criteria and parameters (*Rybach and Muffler, 1981;Economides and Ungemach, 1987).*

Depending on the selected method, the measuring densities ought to be reviewed according to the exploration content, the topographic conditions, logistics and the budget allocated for geophysical exploration.

The electrical resistivity and the magnetic surveys have been preliminarily chosen to be used in the Boku area and the results of these two surveys are presented in this paper. The small aerial extent of the surface indications, accessibility, availability of equipment, financial considerations and the initial objectives assigned to geophysical work- that of delineating the major structural controls and defining the type of geothermal system in operation at Boku- have warranted the use of these two methods.

As to the density of the measuring points, the standard sampling values of 2-4 stations/km for the electrical sounding surveys, and 100 stations/km for the magnetic surveys, envisaged in geothermal prospecting, have been used.

Electrical Resistivity Surveys

The resistivity of a geologic horizon depends on a number of parameters, the most important of which are porosity, salinity of interstitial fluid, and temperature. The effect of temperature change is the greatest specially at low temperatures (<100°C) and becomes small for temperatures > 200°C. In deeper parts of a hydrothermal system, the resistivity is more affected by porosity and salinity than by variations in temperature, where the effect is more pronounced in horizontal profiling where lateral variations in resistivity are mapped.

Therefore, at Boku the Schlumberger vertical electrical sounding (VES) and axial dipole-dipole profiling techniques have been applied for mapping both the vertical and horizontal variations in resistivity.

Superimposed on Figure 1 are shown the two traverses along which these surveys have been carried out. A total of ten VES surveys were done six on the first and longest profile and four on the second. The spacing between the VES points was chosen to be 500 m whenever the topographic conditions permitted to maintain this station separation. The two traverses are separated by one km, with maximum AB/2 of 750 m on each sounding point. Profiling surveys were also carried out on both traverses. The traverse and the survey points were so chosen to start well within the Boku caldera and extend over the currently active Boku thermal center.

The Briggs and Stratton AC generator, the heavy duty Scintrex TSQ-3 Low Frequency Square wave transmitter and the IPR-10 receiver system with the associated accessories were used for both the sounding and profiling surveys.

The data from these surveys were analyzed using the standard GEOSOFT software and sample results of the VES analysis, for traverse 2, are presented in Figures 2 for discussion in this paper. The figure gives the interpreted geoelectric section along VES points 7, 8 and 9.

Magnetic Surveys

Magnetic surveys are commonly used exploration tools for their ability in petrographic differentiation of the basement and their ability to highlight structural features like faults, grabens and horsts. In geothermal field surveys this technique is found to be even more attractive and of high potential as it is suited for mapping evidences of hydrothermal alteration zones related to the presence of a geothermal reservoir. These are often characterized by the alteration of magnetite to pyrite, and therefore give magnetic responses less than that of unaltered zones. The rapidity with which the measurements can be made and the low cost of operation were additional justification for using this method at Boku in the present study.

Accordingly, magnetic surveys were carried out using the IGS-2 Integrated Geophysical System and total field values at 10-meter intervals were measured along three profiles. Two of these profiles are the same as the profiles over which electrical surveys were done, and the additional third traverse was selected mid-way between these two (500 m from traverse 1). The total field plots along traverse two are given in Figure 2b.

DISCUSSION

Only representative geophysical interpretations are presented in this discussion. The geoelectric section given in Figure 2a is for the traverse passing through VES points 7, 8 and 9. Based on the resistivity ranges available and the stratigraphic succession of the area obtained from geologic studies, the section has been interpreted to be mainly consisting of four to five layer earth structure. A top layer of alluvial cover with approximate constant thickness of 0.9 m along the traverse and a thicker second layer of about 10 m thickness, with resistivity values ranging from 40 Ωm to 82 Ωm constitutes the thick ash deposit and pumice fall deposit layers. A third layer of considerably large but varying thickness at various points along the traverse appears as the dominant lithologic unit in the area. This is interpreted as the unwelded tuff deposits deposits. This layer is missing at depth around VES points 7 and 9 but is uninterrupted to large depth on both sides of VES 8.

Below this third layer is highly resistive (980-984 Ωm) rhyolitic lava around VES points 7 and 9 constituting the basement layer. It is probable that this section forms part of the lava flow that are visible from surface geological mapping as shown to outcrop at different locations on the geologic map. Along this traverse and within the thick layers are small lenses of weathered and unweathered basaltic lava flows that have got resistivities ranging from low to moderate values and the presence of these lenses may affect the general resistivity trend of the geoelectric section.

From the magnetic profile plot given in Figure 2b it is seen that a relatively smooth and low value of total magnetic field are recorded alone the same traverse except at the two locations around VES points 7 and 9. The magnetic field variations are in good conformity with the electrical measurements in that they accurately depict the location of the major subsurface structural units, specifically the structural contacts at depth.

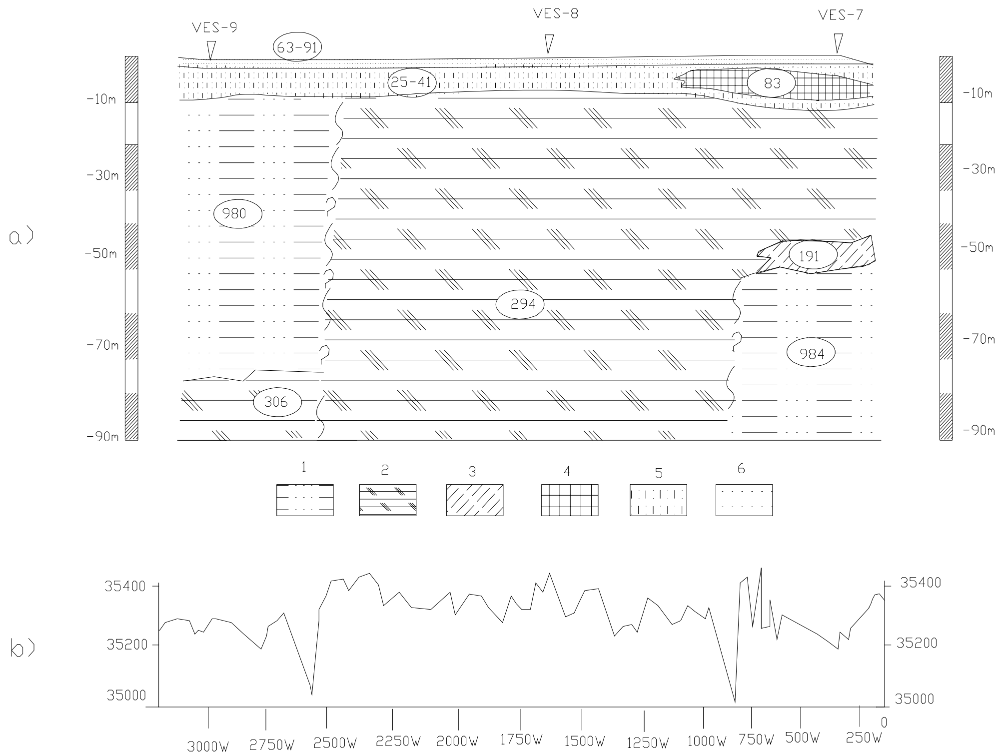

Figure. 2. Geoelectric section for VES 7, 8 and 9 (a) and magnetic profile plot along VES points 7,8 and 9 (b)

1= Rhyolitic lava flows; 2= Unwelded tuffs; 3= Weathered basaltic lava flows; 4= Basaltic lava flows;

5= Pumice fall deposits; 6= Alluvial deposits

The low almost smooth magnetic anomalies shown otherwise indicate the presence of highly hydrothermally altered rock units that are devoid of elements with magnetic properties.

CONCLUSIONS

The hydrogeological and geophysical investigations lead to the fact that the Boku fumaroles are vapor-dominated dry type geothermal resource with characteristics (in which) steam is produced in super heated state with steam temperatures generally >300°F. The cap rock was produced by a self-sealing process through the alterations of acidic volcanic rocks. The presence of different varieties of silica, calcite and kaolin are indication of the presence of strong hydrothermal activity.

The main conduits for the propagation of heat from the deep-seated thermal sources are the Wonji Fault systems mapped thorough the geophysical methods. The results of representative geoelectric and magnetic profile sections have clearly shown these structural discontinuities. In Summary:

- The recent faults of the Wonji fault Belt system act as conduits for steam to reach the surface.
- The geophysical methods have confirmed that the Boku area represents a collapsed caldera structure from which steam rises to the surface
- The possible bore hole sites for tapping the steam or thermal water are along the fault zones or zones of crossing of the fault systems shown on the geological map.

A clear indication of decrease in resistivity at depth suggest that geophysical methods with larger depth of penetration, extending to the depth of the heat and surface water interacting zone, are proposed to be carried out to map the aquifer system. Further, geochemical and isotopic studies are also proposed to identify the source of the recharge to be either of meteoric or juvenile origin.

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