OCCURRENCE AND DISTRIBUTION OF HIGH TEMPERATURE GEOTHERMAL SYSTEMS IN KENYA

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SUMMARY - The high temperature geothermal Occurrences in Kenya are all located in the tectonically active Rift Valley associated with regions of Quaternary volcanism and more so calderas. The sizes of the geothermal fields, productivity of wells and reservoir characteristics vary greatly but are mainly controlled by secondary permeability caused by tectonics and geologic setting. The geophysical structure is controlled by NW, NNE and oblique E-W trending faults which also control hydrology and fluid flow patterns although this has not been established conclusively.

1. INTRODUCTION

High temperature geothermal systems that are considered in this paper are those having temperatures of more than 200°C at the top of the reservoir. In Kenya, their Occurrence and distribution has a correlation with the geologic and tectonic evolution of the Rift Valley where all the systems are located. Preliminary geothermal investigation shows that at least eleven geothermal systems exist within the Rift Valley. *All* the eleven prospects are associated with Quaternary volcanoes, nine of which have calderas. The caldera volcanoes are: Suswa, Longonot, Eburru, Menengai, Korosi, Paka, Silali, Emuruangogolak and possibly Olkaria (Fig. 1). Namarunu and Barrier are the non caldera volcanoes with geothermal potential. The other possible hi& temperature geothermal prospects are the Lakes Baringo and Bogoria areas which have high temperature fumaroles. Out of the above prospects, Olkaria and Eburru have been explored by deep drilling With Olkaria producing 45 MW_e since 1981 but the Greater Olkaria is capable of producing more than 200 MW_e. The Eburru system is capable of producing 15-20 MW_e for 25 years (KPC, 1991).

2. GEOLOGY

The development of the Rift Valley started during early Miocene with initial volcanism on the flanks of the rift but the activity later migrated to the rift floor with continued volcanism of flood basaltic and trachytic rocks (Baker, 1987). The central sector experienced the most intense volcanic activity with the development of the thickest pile in the region of more than **3** km in the Olkaria-Eburru sector. The products, however, are likely to be thinner to the north and south of the central sector where Precambrian metamorphic rocks outcrop on the

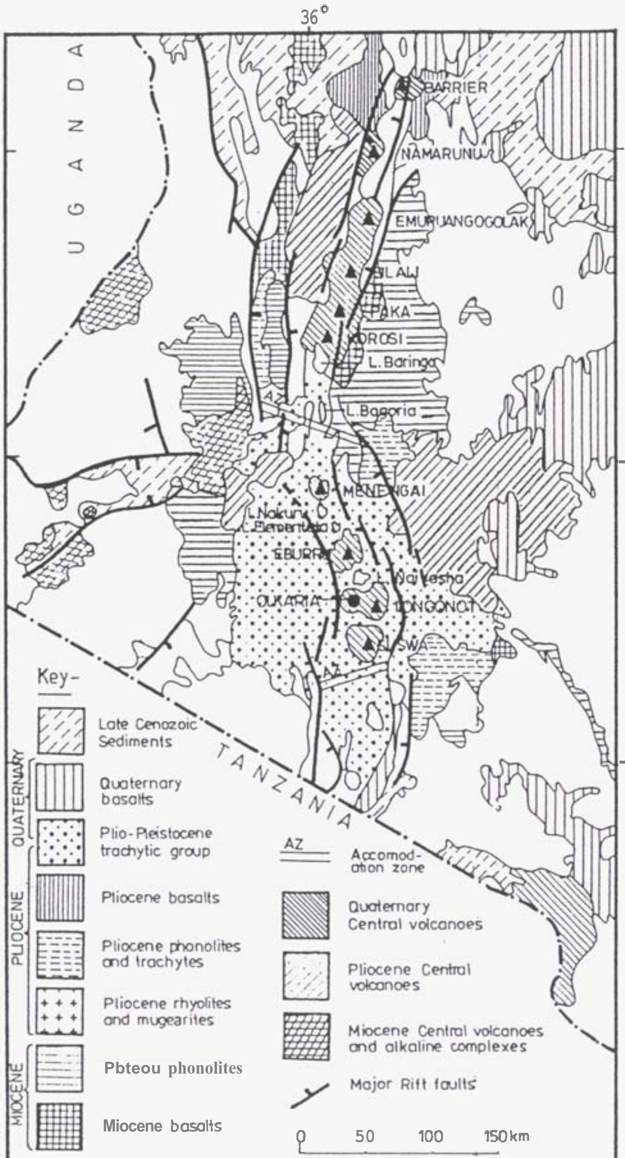

Figure 1- Kenya Rift Valley and Quaternary volcanoes

flanks.

The present structure of the rift is dominated by steeply dipping (>60^o) normal faults which have a trend varying from NNW to NNE but some oblique faults also occur of which the major ones ate related to shear (accommodation) structures that occur along the rift. The strike of the most important rift forming faults broadly follow the trends in the east dipping Precambrian metamorphic rock foliations and defines NNE striking northern and southern rift segments and a NNW to NW striking central segment (Fig. 1). The central segment, however, also has younger rift floor faults trending between N and NNE directions. Although the structural pattern and faulting of the Kenyan rift system was, to some extent, influenced by the grain in the Precambrian rocks, the main driving force could have been convection currents separating the crustal plates and hence is a zone of asthenospheric upwelling. This explains the high heat flaw that occurs within the Rift Valley.

Large Quaternary caldera volcanoes occur within the rift floor at intervals of less than 50 km and are all considered as promising geothermal prospects which include: Suswa, Longonot, Olkaria, Eburru, Menengai, Paka, Korosi Silali and Emuruangogolak. Namarunu and Barrier, in the far north, are the other smaller volcanoes with geothermal potential. The common rock types in these prospects include trachytes, basalts, rhyolites, trachy-andesites, phonolites, trachy-phonolites and basaltic-andesites. Trachytes are the most abundant rock type, more so, the Plio-Pleistocene plateau group which are extensively faulted and forming the base for the Quaternary volcanoes.

In the Eburru-Olkaria sector where deep drilling has been carried out, trachytes and pantelleritic rhyolites and their pyroclastic equivalents dominate both on the surface and sub-surface. Minor welded tuffs occur in the sub-surface. The Occurrence of these rhyolites is a unique feature of the Olkaria and Eburru geothermal areas and the Namarunu volcanic centre. A syenitic intrusive rock was encountered in Eburru geothermal Field during drilling and the shallowest dyke was penetrated at about 800 m.a.s.l. Such intrusives have not been encountered in Olkaria Field but they could occur under the other major volcanoes within the rift since syenitic clasts have been observed within their pyroclastics.

Suswa volcano which is the most southern geothermal prospect has a geology that consists of undersaturated trachytes, trachy-andesites and minor basaltic-andesites. These lavas form a cover of more than 200 m within the caldera and this has been observed to significantly prevent the geothermal fluids from reaching the surface and hence the reason for reduced surface geothermal activity in the area. Mt. Longonot volcano is similarly dominated by undersaturated trachytes but pumice fall is quite abundant in the caldera and on the flanks of the mountain and thus preventing geothermal fluids from reaching the surface except around the summit crater. Menengai and the other northern volcanoes have a lithology dominated by trachytic and basaltic flows and pyroclastics that occur both within the caldera and on the flanks. The young lavas within these calderas also cap geothermal fluids and manifestations only occur where the rocks are fractured.

3. GEOTHERMAL ACTIVITY

The most common geothermal manifestations that occur in all the prospects are: fumaroles, hot grounds, steaming grounds and steam jets. The manifestations strongly follow the structural pattern of faults and fractures in areas of recent volcanism, more so, Quaternary volcanic centers. In most of the prospects, the manifestations Occur mainly along N to NNE faults and ring structures but in some areas, the manifestations are also associated with oblique structures. These manifestations have hence been used as indicators of the existence of geothermal systems associated with shallow magma chambers. The only exception where manifestations are very strong but not associated with any volcanic centre is the L. Bogoria system which has spouting springs (Geysers) and steam jets discharging at temperatures close to the local boiling point (96^{o}C).

Fumaroles and hot grounds are associated with both *strong* and weak surface alteration in which the dominant secondary minerals are kaolinite, montmorillonitic clays , silica residue, alunite, alunogen, alumina and occasional native sulphur. This alteration assemblage occurs mainly over the presumed upflow regions of the high temperature geothermal prospects which are, in nearly all cases, located on the top part of the volcanoes. On the slopes of the mountains, alteration of the rocks still occur but are often weaker or absent in some cases implying that the steam is devoid of magmatic gases (CO_2 and H_2S). The assemblage usually consists of kaolinite, silica and montmorillonites but sulphur, alunite, alumina and alunogen are typically absent. These regions define outflow from the systems as in the case of Eburru Field.

Most of the prospects, however, are characterised by concealed outflows of condensates and deep thermal fluids. The only exceptions are possibly the Kapedo and Lorusio springs which appear to tap condensate mixed with ground water from the nearby Silali volcano. Other springs occur to the NW of Emuruangogolak and they are likely to obtain part of the water from condensate from the volcano. The springs deposit travertine on the surface (Dunkley and Smith, 1990). Chemical geothermometry of the spring waters, however, indicate temperatures of less than 200^{o}C (Tole, 1988). Apart from fumarolic emissions, ground temperature is also a useful indicator of the existence of a geothermal system. The ground temperatures (1 m depth) measured within these geothermal fields and prospects are close to boiling point (96^{o}C) within the calderas and on the high grounds of the volcanoes but are usually much lower outwards.

4. GEOPHYSICAL STRUCTURE

The geophysical structure of the known geothermal fields is strongly related to the tectonic and geological episodes. The method that has frequently been used is the DC Schlumberger electrical resistivity sounding method augmented by gravity, magnetics and magnetotellurics. Most of the resistivity sounding surveys have been carried out in the region between Menengai and Suswa craters. The Olkaria and Eburru Fields are the most explored.

The aeromagnetic surveys carried **out** within the Rift Valley show that the anomalies have a dipole nature which make interpretations difficult. However, the anomalies have **E-W** trends probably related to old pre-rift structures which may be zones of weakness that influenced the formation of the volcanic complexes. Geological evidence also indicates that rocks with different magnetic signatures were **formed** during different episodes. This further makes interpretation of the magnetic properties in terms of geothermal potential difficult. Some of the positive anomalies as observed in **Olkaria** have been mistakenly associated with demagnetization but the rocks encountered during drilling are essentially non-magnetic. In some areas, low magnetic field strength anomalies may be attributed to basaltic lavas emplaced within the present magnetic epoch, so that they have high magnetic susceptibility.

The available regional teleseismic data indicates that the western part of the central rift region is associated with a large travel time residual anomaly which seems to indicate the presence of low density materials towards the Mau escarpment. The accommodation zones (Fig. 1) are associated with low residual travel time indicating high density bodies which are possibly related to shallow magmatic intrusions. From the seismic data, it has been postulated that the major detachment faults extend to the Lithosphere-Asthenosphere boundary (Green et al, submitted). Decompression melting has also been suggested within the crust and where deep faults extend to the zone, they may form important channels of convective flow of hot fluids which may form other geothermal systems that are not associated with volcanic centres.

Gravity data has also been used together with resistivity data in modelling the structures and possible sources of heat for the geothermal systems. The regional data, though lacking in details, indicate that the central part of the Rift Valley is associated with an axial high gravity anomaly trending in a general **N-S** direction but is often truncated by oblique structures.

The central volcanoes, fault zones and calderas are often associated with different gravity signatures. For instance, the Suswa caldera has a high gravity anomaly while the Longonot caldera has a low gravity anomaly. The differences are expressions of the geological episodes and modes of formation of the calderas rather than indicators of the source of heat. The low gravity anomaly calderas are associated with thick deposits of volcanic ejecta while the high gravity anomaly calderas are caused by accumulation of dense mafic lavas within the calderas. High gravity localized anomalies as in Eburru may also be due to dense cold syenitic intrusives (Simiyu, 1990) and therefore not all high density bodies can be associated with heat sources.

Resistivity data has been the most useful in the exploration of geothermal systems. Analysis of the data shows that low resistivity (< **30** Ωm) may be caused by either high temperatures, good permeability or hydrothermal alteration **of** the reservoir rocks or surface alteration of pyroclastics by steam condensate.

Correlation of the resistivity anomalies in Olkaria shows that the resistivity structure at 800 m.a.s.l. (Fig. 2) is a good indicator of reservoir properties in the geothermal' systems. In most cases, low resistivity (< **30 Ωm)** correlates with reservoir temperatures of more than 240^{o}C below this elevation.

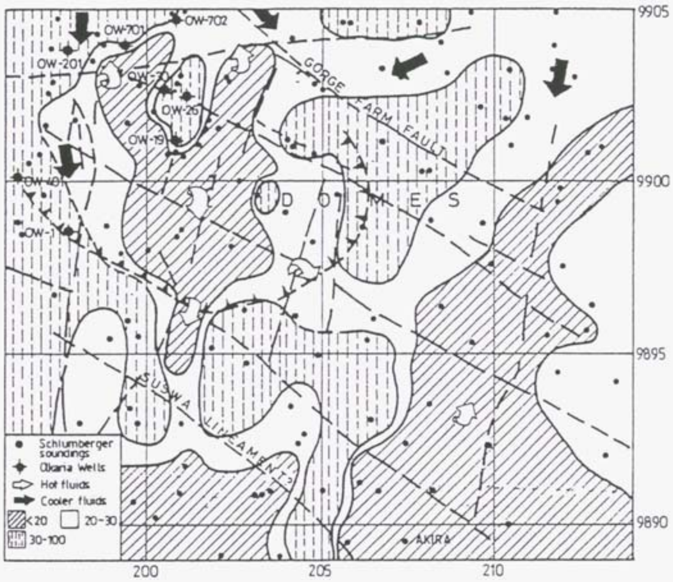

Figure 2- Resistivity map at 800 m.a.s.l for the Greater Olkaria area

The regions of highest temperatures and permeability are found in areas defied by resistivity of less than 20 Ωm. Olkaria West Field has the lowest resistivity (< 5 **Ωm)** anomaly which has been correlated with higher degree of hydrothermal alteration due to a thicker deposit of tuffs as compared to either Olkaria East, NE (Fig. **3)** and Eburru Fields. Areas of low resistivity in the zone above 1400 m.a.s.l. are related to outflows and presence of acid steam condensate. The regions of intermediate resistivity (30-100 Ωm) at depth represent areas of low temperatures of between (100-200^{o}C) depending on the permeability distribution. Most **of** the wells located within these areas often show temperature inversions at depth. The boundaries of the low and intermediate resistivity anomalies at a depth below 1000 m.a.s.l. are sharp indicating that the geothermal reservoirs are mainly controlled by vertical permeability and therefore essentially difficult to explore.

Resistivity data from Olkaria East Field indicates a near surface low resistivity associated with hydrothermal alteration of pyroclastics and tuffs, a resistive caprock associated with steam zone and a deeper liquid dominated reservoir associated with low resistivity. This sequence might be an important indicator of the reservoir characteristics in other unexplored areas. The main conductive zones are usually found within narrow **N-S** graben structures and sometimes bound by **ring** structures of the volcanoes as for the case of Eburru

(Fig. 4). Upflow areas seem to be at intersections of any of the following structures: N-S, NE, NW and oblique E-W structures probably related to the older basement structures.

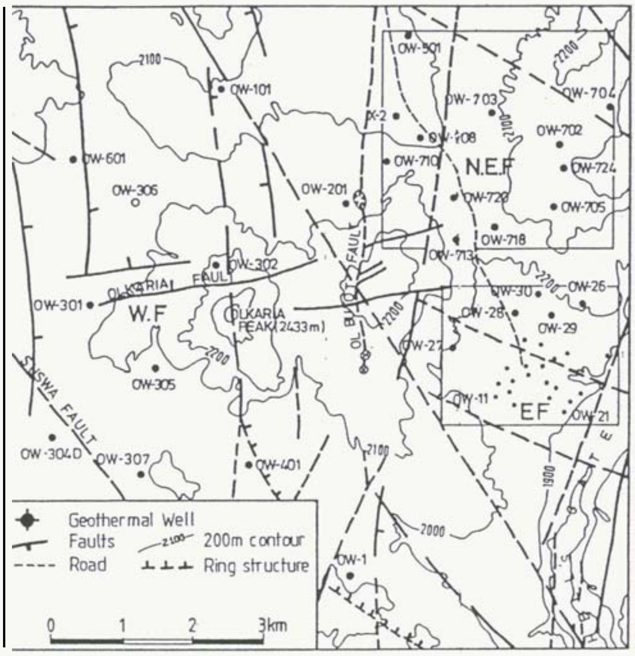

Figure 3- Structural map of Olkaria Geothermal Field showing well sites

The intersections of the structures may form zones of weakness where both magmatic material and geothermal fluids are injected closer to the surface than other areas within the Rift Valley. Further evidence from MT data also indicate that these anomalous areas are also associated with second deep (5-6 km depth) conductive anomaly. However, due to the limited data, this has not been determined conclusively. It should also be noted that there are some areas of low resistivity anomaly which are not associated with any volcanic centres and because of that, they have been given low preferences and no deep drilling has been carried out to explore them.

5. HYDROLOGY

The hydrological structure may be deduced from measured and interpreted water levels in shallow and deep wells in the Rift valley. The deep wells are restricted to Olkaria and Eburru Geothermal Fields while the shallow ones are mainly boreholes in the areas around lakes, Naivasha, Nakuru, Bogoria and Longonot volcano. These studies indicate that there exists several hydrological zones with different fluid transmission properties which are controlled by rift tectonic structures. These zones can be divided into shallow and deep regimes that seem to have no obvious hydrological connections between them.

5.1 Shallow Hydrology.

The shallow hydrology is deduced from bore hole data, especially around Lake Naivasha and the area between Lakes Nakuru and Bogoria. Although piezometric levels show major fluctuations in response to infiltration, the mean water level in wells shows a gentle gradient from the flanks to the rift floor and a north-south gradient also exists around Lake Naivasha (McCann, 1972, 1974). The amount of water runoff that drains into the Lakes during rainy seasons is also large and seem to be a major recharge for the surrounding boreholes.

In Olkaria Field, shallow perched aquifers corresponding to lake level have been intercepted at depth interval of 80-200 m. The chemical characteristics of the fluids, however, show that the waters are condensate and are therefore most likely to be derived from the deeper geothermal system. A major discontinuity seem to exist to the south where several wells drilled have not intercepted water at equivalent elevations.

In the area around Lakes Nakuru and Bogoria, piezometric contours from bore hole data indicates a gradient towards the central part that includes Menengai caldera (Geotermica Italiana, 1987). Hydrological data is, however, scarce for the area north of L. Bogoria. In Silali-Emuruangogolak area, hot springs flow rather abundantly from open fractures on the ground and

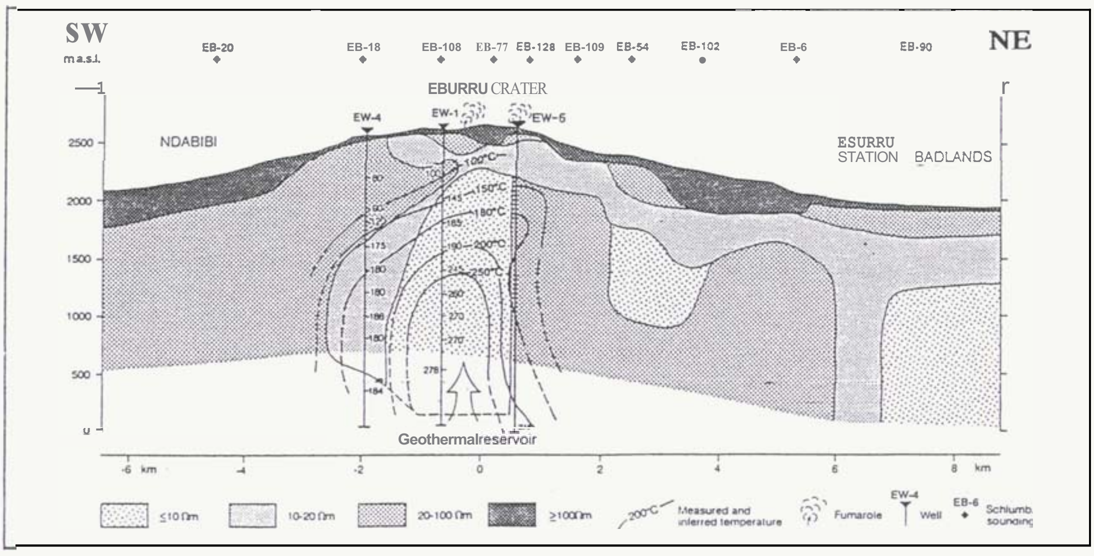

Figure 4- 2-D Resistivity section across Eburru Geothermal Field.

combine into a large stream (Suguta) that flows northwards towards Lake Turkana. The source of the water is doubtlessly the shallow water system which is heated by a near surface heat source but modified by geothermal fluids from the nearby prospects.

5.2 Deep Hydrology

The deeper hydrology has been deduced from well data in the Olkaria and Eburru geothermal Fields. The data shows that there is significant variation in the deep system and that more regimes exist at depth where the known water level is not continuous. In Olkaria area, the water level only exists in the North East Field where the upflow of the eastern sector of the system is believed to exist. The water rest level constructed from pressure pivot points corresponds to a level of 1600-1650 m.a.s.l which is about 200 m below the mean annual level of Lake Naivasha (Ambusso and Ouma, 1991). This therefore, suggests that no hydrological connections exist between the Olkaria system and the shallow basin around the Lake.

In the East Olkaria Field, which is to the south of the North East Field, no free water level exists as the upper part of the reservoir has a steam cap which extends to the south of the field. However, the system pressure at depth are lower than those of the North East Field and a gradient of 9 bars per kilometre has been deduced (Bodvarsson and Pruess, 1981). In the Olkaria West Field, a steam zone exists over much of the area and disguises the water level. However, the water level occurs in OW-601 (Non-productive) to the far North west of the field and is within the 1600-1650 m.a.s.l range which shows continuity of deeper hydrology.

In the Eburru geothermal Field which is located 40 km north of Olkaria, no shallow water levels were intercepted during drilling. However, the interpreted deep water level is somewhat difficult to establish since all Eburru wells, apart from EW-02, have a common pivot point at around 750 m.a.s.l. The water rest level in EW-01 and EW-06 are at 1863 and 1814 m.a.s.l respectively which are within the range of the lake level. The water level in the other wells are lower by upto 100 m. These lower levels are consistent with a northerly flow as deduced from measurements in shallow wells around the lake.

6. DISCUSSION

The analysis of the available geologic, geophysical and reservoir data from the geothermal prospects, it is evident that the physical characteristics and production capacity of the geothermal prospects depend mostly on tectonic and geological evolution of the various segments of the Rift Valley. The prospects differ significantly in terms of size, reservoir characteristics and structural setting. Although localized heat sources are a main feature of consideration during exploration, vertical permeability is a critical factor. This means that the prospects are essentially difficult to explore. Although the near surface cold water reservoirs show significant lateral variations, the deep reservoirs are probably in communication with the recharge areas through the rift faults and the older oblique structures.

The systems have temperatures in excess of 250°C in most parts of the reservoirs with the highest measured temperature in the Greater Olkaria Field being 340°C while in Eburru a value of 280°C has been recorded. In the Eburru Field, the main reservoir lies from about 1000 m below the surface while the Olkaria system occurs below about 400-600 m. Their vertical extents, however, have not been established but are thought to be in the range of few hundred metres (1000-2500 m) and shows substantial underpressure. A caprock composed of basalts and trachytes has been identified to cover most of the East and NE Fields but none has been identified for the Olkaria West and Eburru Fields.

The areal extent of the fields are remarkably different with the Greater Olkaria covering an area of about 50-80 km^2 while Eburru is 2-5 Km^2 (Fig. 5).

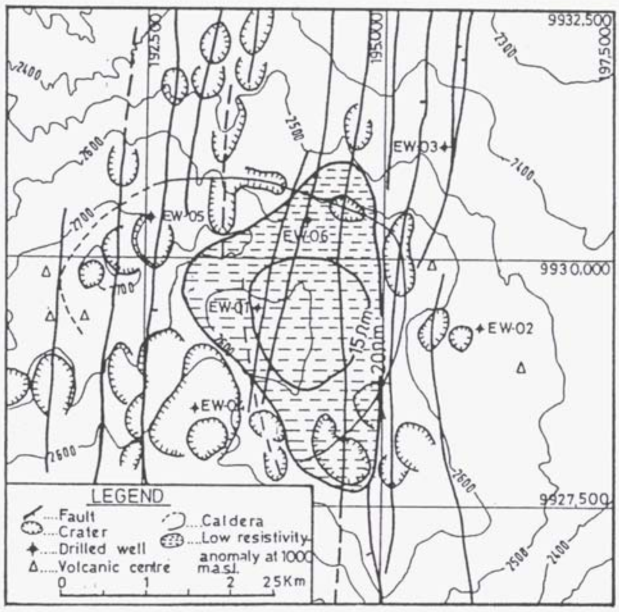

Figure 5- Structural and Resistivity map of Eburru Geothermal Field.

The coverage appears to be controlled by the *size* of the heat source and confining structures. The Eburru system is restricted to the eastern part of an infilled caldera of about 3 km diameter while the Olkaria system occurs in the northern and western parts of a ring structure thought to be a large caldera having a long diameter of about 11km.

The fields show strong evidence of fault controlled permeability with the Olkaria system being closely associated with Olkaria fault which strides both Olkaria NE and West Fields in a SW-NE direction and is the presumed upflow of hot water in the NE Field which then flows mainly to the south and recharges most of the East Field. The high permeability associated with Olkaria fault is thought to result from the intersection of the fault and the abundant **N-S** faults which are covered by the Quaternary volcanic products.

The average permeability thickness in Olkaria, as in Eburru, is about 2 Darcy-metres. This is also indicated by the low mass output from the Olkaria wells whose average mass flow is about 50 t/hr, however, **Eburru** well EW-01 has a mass flow of about 76 t/hr. More locally, however, significant variations occur and values higher than 10 Darcy-metres have been determined for some wells along the Olkaria fault in the North East Field where the reservoir rocks are most fractured.

The production zones in these fields, as identified from well tests, are distributed at various parts of the wells especially at lithological contacts with the main producing zones occurring within the Plio-Pleistocene trachytes which underlie the Quaternary volcanics. This **zoned** production is responsible for cyclic behaviour in a number of wells. Most wells in Olkaria discharge fluids with enthalpies greater 2000 J/g which are always in excess of corresponding liquid enthalpies at measured temperatures. This effect is attributed to the low permeability of the reservoir rocks and relative mobility of the phases. In the Eburru system, the **main** production zones occur above the syenite intrusive body at about 2200 m and 1000 m drilled depth. In contrast to the Olkaria system, the discharge enthalpy is low and compares to the enthalpy at measured temperature. This shows that less phase separation has occurred in the reservoir than at Olkaria.

Long term production in Olkaria has shown that reservoir response to production is quite varied and depends on both local and regional features. The overall change in production has been gradual with field average decline rate of **4%** per year. **As** compared to other fields over a similar period of production this value is low and reflects the effect of high storage but low withdrawal rates from the reservoir. Changes in physical parameters in the fields have shown strong dependance on the region of the reservoir in question since cooler fluids surround the reservoirs. In the central part of the reservoir, minimal changes in temperatures have occurred and measured temperatures are upto $5^{o}C$ below the pre-production values. This reflects near isothermal depletion of the reservoir. However, in the peripheral and less central wells, interference due to entry of cooler water has been detected through development of inverted temperatures; increase in well instability and decline in discharge enthalpy. However, on the overall, there has been little detriment on field production.

7. CONCLUSIONS

Kenya has an abundance of high temperature geothermal systems which are all located within the Rift Valley associated with Quaternary volcanic centres. The systems are difficult to explore since most of them occur on high grounds (mountains) but the most useful geophysical method is the DC Schlumberger resistivity sounding. The systems vary in size between 2 km^2 to more than 50 km^2 and the reservoirs occur in narrow zones controlled by faults, fractures and caldera structures. Permeability is generally low in the fields but higher productivities occur within fault/fracture zones.

8. ACKNOWLEDGEMENT

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