Proc. 10th New Zealand Geothermal Workshop 1988

SCIENTIFIC AND BOREHOLE RESULTS OF OLKARIA NE FIELD,KENYA

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ABSTRACT

In 1986, a decision was made to more clearly delineate Olkaria NE for a 60 MWe power plant by drilling 3 wells and carrying out a workover on OW-702. Well OW-701 which had already been drilled in this area was producing about 4 MWe at 5 ba.

By May of 1988, 4 wells had been drilled in the Olkaria NE and the workover of OW-702 completed.

OW-705 and OW-706 produce an average of 2.5 MWe. OW-703 cycles severely between 7 and 3 bars and has an output of about 1-2 MWe. OW-704 has not produced yet and encountered very low temperatures below 900m.

Scientific data indicate that there is a production boundary to the field north of OW-703 and that OW-704 is outside the field. However, an area of about 12 km* exists south of OW-703 and 704, which includes Olkaria East Field and extends as far west as the Ololbutot fault. By exploring and proving the area to the west of Olkaria East Field, in which make up wells for the present power plant could be drilled, an area of about 8 km* with capacity of over 60 MWe for 25 years for NE has been proved and fully committed for power production.

INTRODUCTION

By 1986, the scientific evidence available from Olkaria indicated that although a very large area of about 80 km^2, as outlined by resistivity data (Hochstein et al, 1981), could be relatively hot, only two areas, one in the W and the other in the NE, were upflow zones. Further detailed resistivity surveys indicated that the upflow zone in the W, where 0W-301 is located (Fig.l) is a large area of about 15 km*(Mwangi and Bromley,1986).

The upflow zone in the NE was presumed to be somewhere between OW-501,702, and Olkaria East Field. OW-701 which was producing about 4 MWe at 5 ba was located within or close to this upflow zone. Resistivity data available indicated that an area of about 6 km^2 was favourable which had a reservoir resistivity of about 30-35 ohm.m. However, the northern boundary was not clearly defined and needed to be delineated by drilling. OW-501 was relatively cold (less than 200°C) in the zone above 1500m which indicated that it was on the edge of the production field.

The natural state model of the entire Olkaria field indicated that both the west and NE upflows were being recharged by a considerable volume of water and that they were controlled by the Olkaria fault(Bodvarsson and Pruess,1987). A part of the fluids upflowing in Olkaria NE were recharging the Olkaria East Field,. Some fluids were flowing from the Olkaria fault to OW-101. The Ololbutot fault, with a N-S pressure low, was acting as a drainage channel for hot fluids from N to S and also acted as a possible cold water recharge conduit from the south at deeper levels.

The chemical data suggested that the entire Olkaria field was underlain by a single neutral NaCl parent water at deeper levels(>500m), (Barnett et al, 1987). This water is overlain by a neutral to alkaline $NaHCO_3$ water at shallow levels, as is present around OW-301 and 101. These waters are formed by steam condensation. The condensate flows to OW-401 and OW-201 at shallow levels and is often associated with shallow low resistivity (Mwangi and Bromley,1987). The chloride water upflowing in the NE was inferred to flow horizontally to OW-201 and the Olkaria East Field. At Olkaria East Field this chloride water boils adiabatically and cools convectively as it ascends. Some of this fluid concentrates by evaporation at shallow levels producing highly saline (2000mg/kg chloride) springs in Hell's Gate gorge(01 Njorowa gorge).

The major concern in considering developing the Olkaria field, in 1980, was the lack of gross permeability found within Olkaria East Field which resulted in most of the wells being small producers (average 2.5 MWe). Most of the exploration wells that followed in areas outside the Olkaria East Field were sited close or at known major fractures in order to intersect high fracture permeability. OW-301 and OW-201 subsequently proved that the high production in these wells was related to fractures. The high production of OW-701 is also related to fracture(Ryder,1986). Away from these fractures, permeability is predominantly horizontal and is related to contacts between lava beds and pyroclastic horizons. Minor vertical joints in the massive lava flows constitute some random vertical permeability.

According to the Kenya National Power Development Plan simulation studies carried out in 1986(Acres, 1987), it was found economical and advantageous from the viewpoint of resources to develop 2x30 geothermal plants by 1994 and 4x55 plants by 2006.

Enough scientific evidence was available to suggest that the initial 60 MWe could be obtained from Olkaria NE. The following llOMWe could be obtained in Olkaria W or from Eburru depending on which proved more productive. This was to be assessed by drilling a number of exploration wells in each area.

To prove and commit Olkaria NE completely for production, it was necessary to drill at least three more wells(KPC, 1987). Four more wells

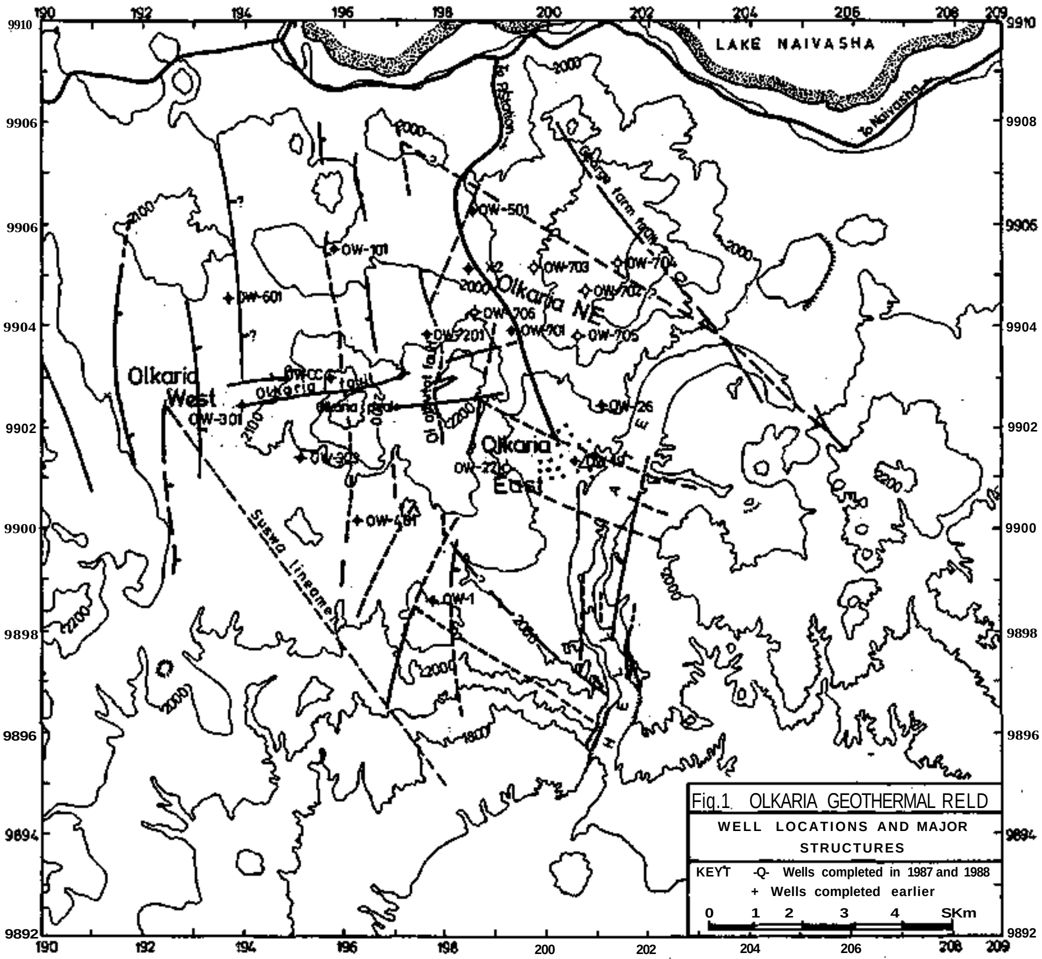


Fig.1 OLKARIA GEOTHERMAL RELD

WELL LOCATIONS AND MAJOR STRUCTURES

KEY -Q- Wells completed in 1987 and 1988

\+ Wells completed earlier

0 1 2 3 4 5Km

have been drilled since then; OW-703, 704, 705, 706 and OW-702D was completed after deviating it below the production casing of the old 702. The output characteristics of these wells, together with further geophysical work, has confirmed that Olkaria NE can indeed produce 60 MWe. This paper discusses these results.

GEOLOGY

Olkaria NE(Fig.l) is located in an area of high topography consisting mainly of rhyolites and pyroclastics originating from within and outside Olkaria.

Most of the wells were drilled with poor sample recovery which has made stratigraphic correlation very difficult. However, the available cuttings and cores indicate that the area is similar to the rest of Olkaria lithologically and is comprised of pyroclastics, tuffs, rhyolites, trachytes, basalts,and probably minor intrusives. The pyroclastics are quite extensive on the surface. Subsurface pyroclastics and tuffs are intensely altered and occur as distinct units and also as intercalations in the lavas. Rhyolites are fairly thick and those near the surface, are unaltered and outcrop as columnar jointed cliffs as in 01 Njorowa gorge. Trachytes are the most predominant lavas at depth and show moderate to intensive alteration. Basalts are found in every well in the NE except in OW-701, where a trachybasalt was found instead.

Due to the huge deposits of pyroclastics and rhyolites, only one NE-SW trending fault passing near OW-701, is seen on the surface and this fault is possibly intersected by OW-701 and 703. The extension of the Olkaria fault zone has only been inferred in this area as there is no surface evidence of its existence. However, the fault is presumed to be a major source of permeability and controls the upflow in the NE area.

The alteration mineral assemblage indicates that temperatures in excess of 300° C have existed in the NE field. This is evidenced by the occurrence of biotite in OW-501 and 703 and garnet and talc in OW-704. Illite and interlayered chlorite-illite in OW-501 and 703 are indicative of the existence of a condensate layer which has mixed with deep circulating chloride water. Smectite and interlayered smectite-illite also occur in these two wells at deeper levels indicating that there has been some inflow of cold water in the area from the north. These minerals are absent in OW-701 and 702.

Correlation of some alteration minerals demonstrates that the chlorite occurrence is at a very shallow depth in OW-701 and 702. This indicates that the chloride reservoir in this area is nearer the surface than in OW-501, 703 and 704 and that the upflow area is near the two wells.

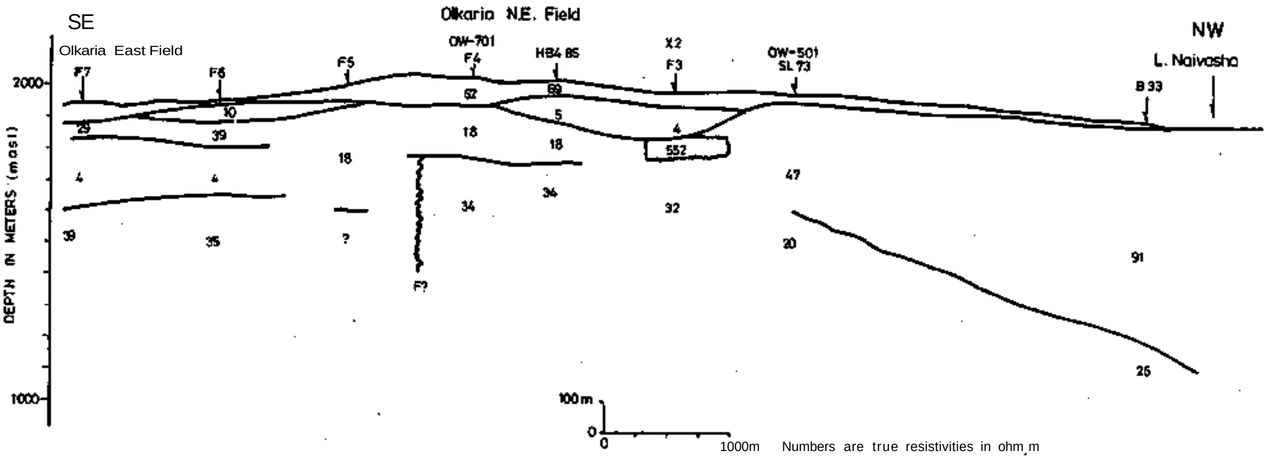


Fig. 2. A NW-SE Resistivity section

The epidote occurrence does not correlate well with the present temperature as epidote is often found in close association with basalts even outside its temperature stability limits.

GEOPHYSICAL STRUCTURE

The best evidence for the geothermal production boundary in the NE is obtained from the resistivity sounding data.

Soundings made at OW-702,705 and 706 give an interpreted geothermal reservoir resistivity of about 30-35 ohm.m which is present within 100 to 300m of the surface. At OW-501 and 703, resistivities of about 20 ohm.m were found from the same depth to about 1000m. These lower resistivities were found to be caused by low temperature clay minerals, mainly smectite, which were found to a great depth in these wells. Such resistivities were not found at OW-702 and 704 area where these clay minerals were absent (Leach and Muchemi,1987). A resistivity of about 40 ohm.m was found at OW-702 and 704 at similar depths, instead.

Measurements made farther north of these peripheral wells indicated that surface high resistivities of greater than 40 ohm.m increase in thickness towards Lake Naivasha(Fig.2). However, at depth, resistivities are lower than 30 ohm.m. The increase in thickness of the resistive surface layer implies that the cold rocks thickens away from the upflow area as would be expected at the edge of the geothermal system.

Referring to the resistivity section of Fig.2, it can be seen that very low resistivity(4-5 ohm.m) zones are found at shallow levels in the Olkaria East Field and also a short distance to the northwest of OW-701 in the X2 area. The area in between has an intermediate resistivity of about 18 ohm.m at similar depths. The two shallow 4-5 ohm.m resistivity areas are caused by the presence of concentrated chloride waters produced by boiling and evaporation, a part of which leaks as hot springs into 01 Njorowa gorge. It is suggested that the main NE upflow zone is to be found north of the edge of the low resistivity zone and south of OW-701 and is probably associated with the eastern extension of Olkaria fault zone. This location of the upflow zone is supported by chemical evidence.

A careful analysis of **all** the resistivity data and supplementary evidence from aeromagnetic data suggest that OW-703 and OW-704 are indeed on the edge of NE production field. A suitable area for exploitation, in which reservoir resistivities are 30-35 ohm.m, include Olkaria East Field and extend to Ololbutot fault.

CHBMISTRY OF THE NE WELLS

OW-501 has a mixed sodium chloride and sodium-bicarbonate type water but with salinity and excess enthalpy much lower than the Olkaria East wells. The well is fed from hot and cooler horizons. OW-701 discharges uniform sodium chloride water which is slightly more carbonated and gassy but has a lower excess enthalpy than the Olkaria East wells. The well feeds from hot and cooler zones with the composite quartz temperature of about 260°C. OW-702D has higher CO_2 than the rest of the NE and Olkaria East wells. Interpretation of down hole samples indicates that the well penetrates zones of diluted and undiluted waters. At 900 and 1100m, the water is diluted by steam condensate. OW-703 has a similar salinity as the Olkaria East Field but has higher concentrations of carbonate species in the water and lower COj in the non-condensable gas. The interpretation of the chloride versus quartz temperature diagram for this well shows that the well has distinct zones of diluted and undiluted sodium chloride waters. In some near surface levels, dilution by cold water rather than steam condensate is occurring. OW-704 has also sodium bicarbonate waters with clear chemical zoning. A water sample collected from 1100-1200m had a quartz temperature of about 100°C and higher concentrations of bicarbonate. It was obvious that the water did not originate from the deep system. A deep circulating fluid was found at 900, 1050 and 1300m. OW-705 has a lower salinity than the rest of the Olkaria NE wells.

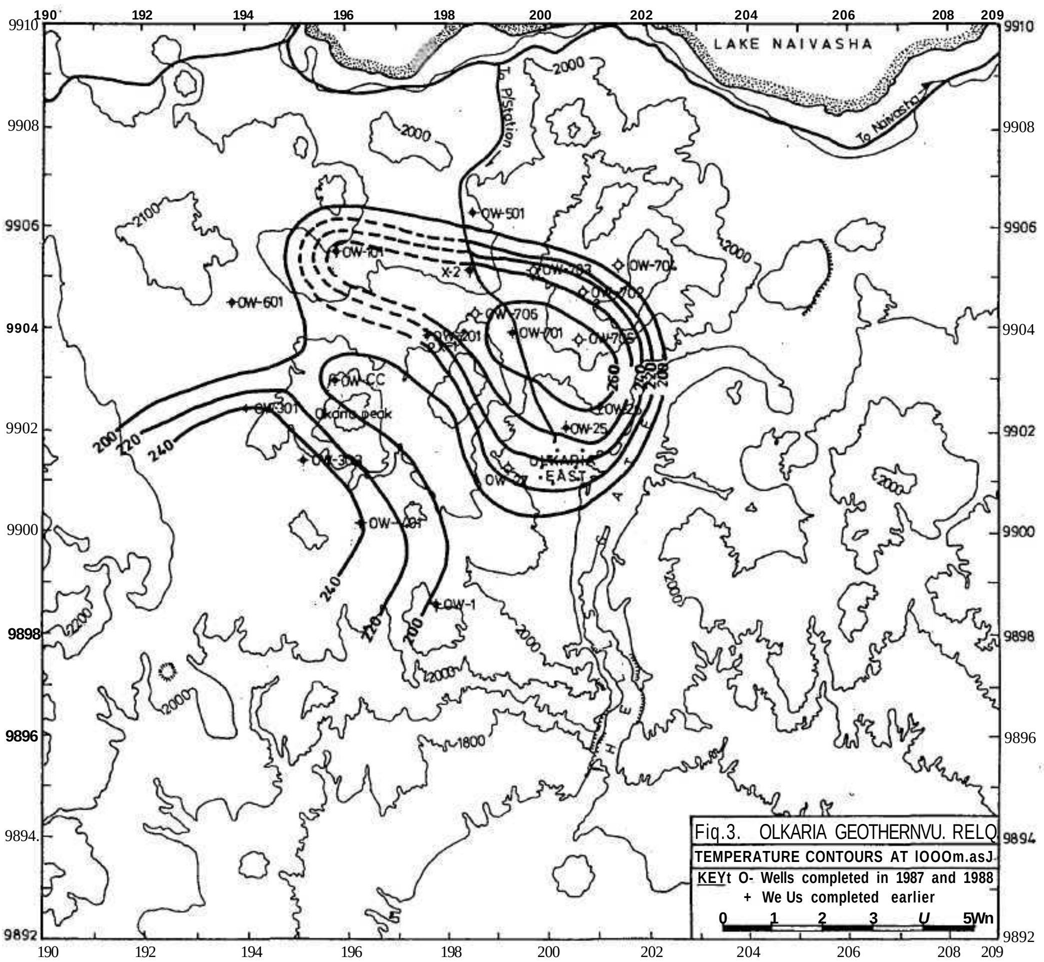
The chemical structure of Olkaria NE is therefore seen as interlayered zones of diluted chloride water, undiluted chloride water and steam heated water particularly in the wells on the periphery of the field. A careful consideration of all the waters in Olkaria field inidicate that the undiluted parent sodium chloride water is about 300-450 ppm chloride. Diluted and steam heated waters are to be found mainly within the top 1000m with pH of about 8-10. OW-501, 702D, 703, 704 and 705 are therefore periphery wells. OW-701 which is less degased than Olkaria East Field and has a uniform sodium chloride waters is closer to the upflow zone. The sodium-bicarbonate water once believed to exist only in the W is very common in the NE wells and envelopes the main reservoir. It is also clear that all the wells drilled so far are not tapping from the main upflow zone. This suggests that the major upflow area is between OW-701 and Olkaria East Field supporting the geophysical interpretation.

PHYSICAL PROPERTIES OF THE WELLS

Except for OW-701 and 704, all the wells in the North East have transmissivities in the range 0.9 to $2.5x10^{-8}$ m^3/Pas, and outputs of about 1.0 to 2.5 MWe. OW-701 intersects very high permeability and has a transmissivity of $6.0x10^{-8} m^3$/Pas and a correspondingly higher output of 4.2 MWe. OW-704 encounters shallow lateral flowing hot fluids at 800-900m and although the well has temperatures less than 200°C below 900m, it penetrates excellent permeability at 1000m. All the wells encounter permeability in the depth range 1550-1250 masl and recovery of the well following drilling indicates two-phase conditions at these depths. However, all the wells have major permeability in the liquid zone at 100-800m masl and very little permeability below 400 masl.

Except for OW-701, which has a WHP of up to 37 bars, the rest of the wells do not self discharge because of the presence of a relatively cold water zone overlying the reservoir. These wells require compression to stimulate discharge and have maximum shut in WHP's of 0-20 bars. On discharge, all the wells produce excess enthalpy fluids in the range 1200-1650 kJ/kg which is lower than the 2000 kJ/kg for the Olkaria East wells. OW-702D is choked by the 7" casing used to repair the 9 5/8" production casing, after developing leakages. OW-703 cycles severely on discharge with an output in the range of 1-2 MWe and a WHP less than 5.0 ba 60% of the time. OW-704 cannot discharge by compression due to its low temperatures. OW-705 and 706 both produce a steady output of 2.5 MWe.

OW-101 is self discharging and produces 1.3 MWe. It encounters temperatures in excess of 270°C below 500 masl. OW-X2 has temperatures above 240°C below 900m and it produced a small cyclic flow from the 4" diameter casing during tests conducted in the early 70's. OW-501 has high temperatures below 1000m but small permeability and discharges saturated 260°C fluid at a low WHP after it has been airlifted.



Fiq.3. OLKARIA GEOTHERNVU. RELQ
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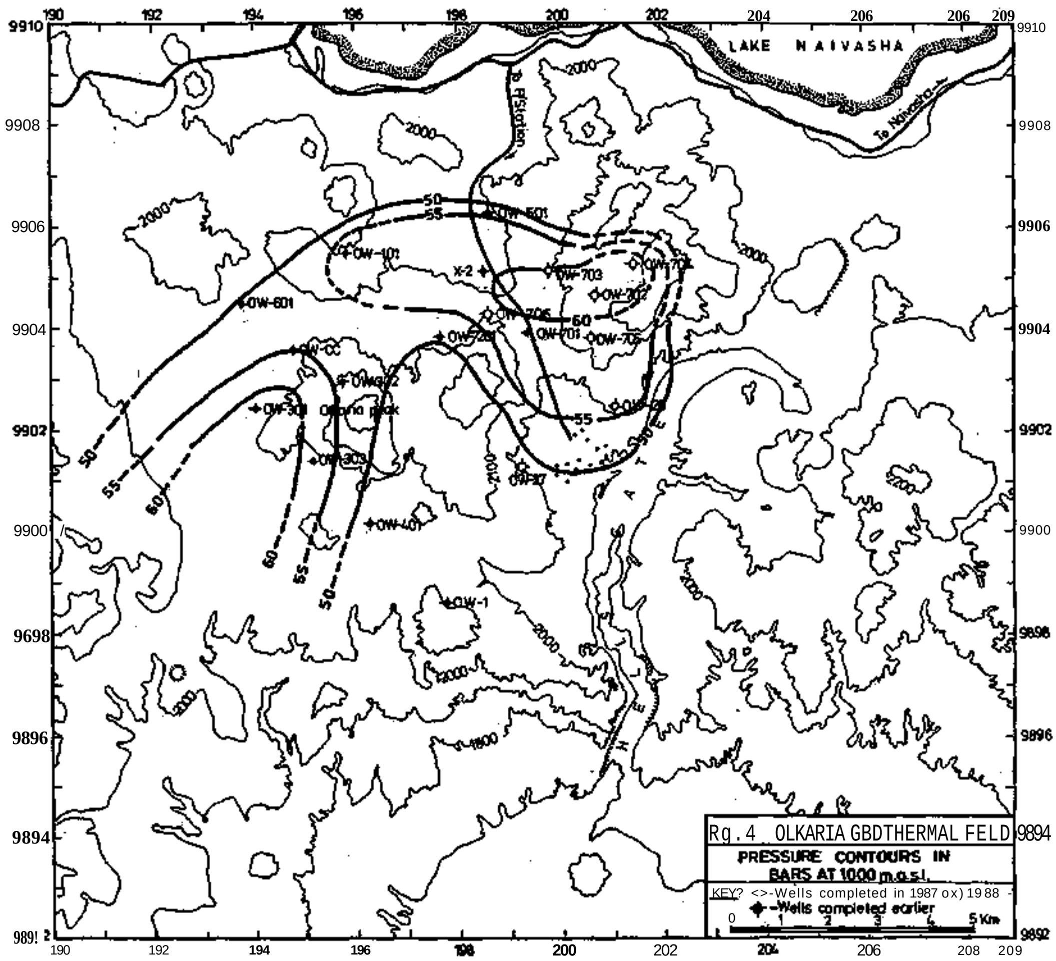


TEMPERATURE AND PRESSURE DISTRIBUTION

The additional temperature and pressure information obtained from OW-703, 704, 705, 706 and OW-702D greatly modified the temperature and pressure distribution present in 1986.

A significant change in the proposed temperature distribution (Fig.3) in the North East resulted when the very low temperatures in OW-704 were discovered. The temperature distribution at 1000m masl suggests that the upflow zones of the system are on an NW-SE trending axis through OW-701 and 26 with a possible centre to the SE of OW-701. This is also suggested by resistivity and chemical data. There is an extension towards OW-101.

The 220°C isotherm defines most of the proven area for development in the NE. At deeper levels, the temperatures in the wells show that the general area to the north of Olkaria East, as far as OW-101 and OW-501, is underlain by a hot reservoir with a temperature greater than 280°C. The highest temperature is around OW-701.

The pressure distribution in the NE (Fig.4) is distorted by the high hydrostatic gradients in OW-702D and OW-704 due to the low temperatures at the time that the measurements were made. Pressures at 1000 masl(where most of permeability occurs) are similar in wells OW-701, 703, and X2, but measured pressures in OW-705 are up to 7 bars lower and similar to those of OW-26 in the Olkaria East. Therefore, the true high pressures measured in Olkaria NE are at OW-701, which is closest to the inferred upflow.

NUMERICAL SIMULATION

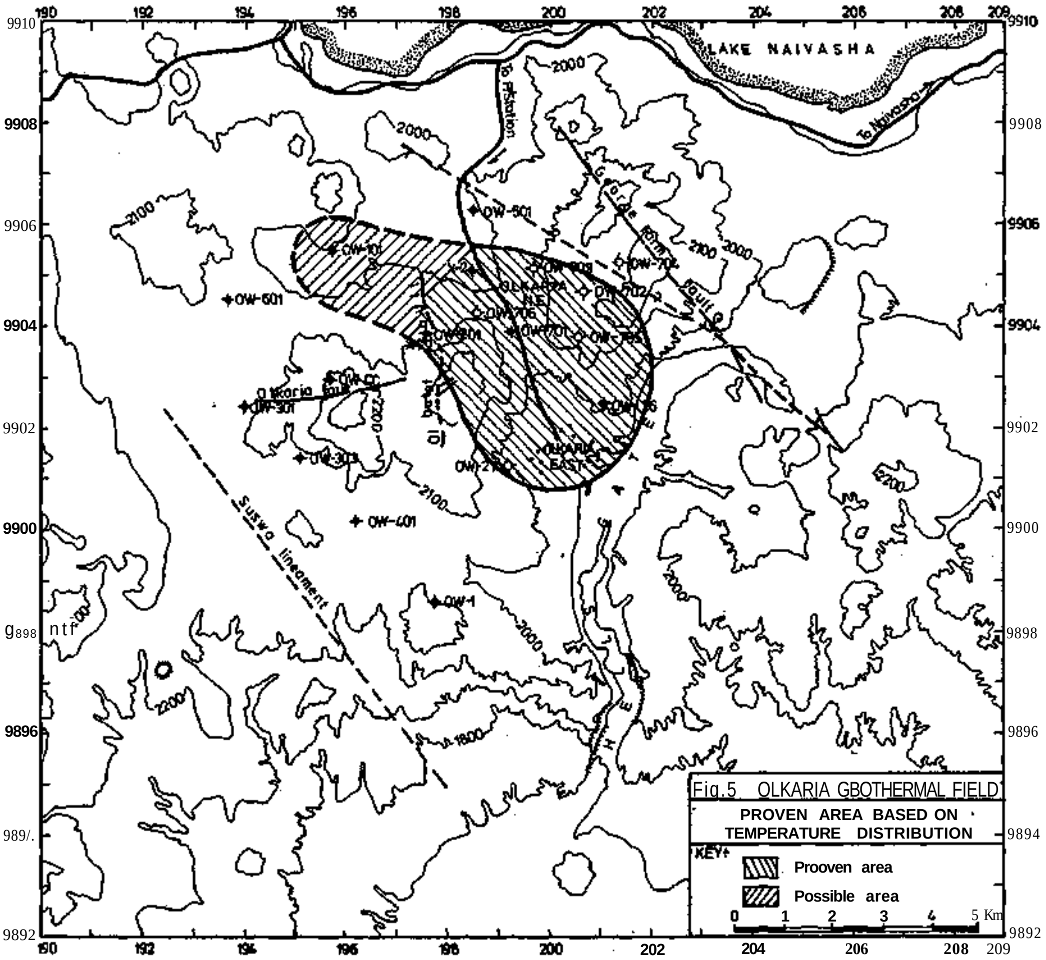
A numerical simulation of the natural state of the entire Olkaria field, based on geological, geophysical, geochemical and reservoir engineering data, is being developed (Bodvarsson and Pruess, 1987). The model incorporates major hydrogeological features; upflow zones around the OW-301 and 701-702 areas, large scale fluid movement dominated by the known major faults and substantial steam losses, especially along the Ololbutot fault south of OW-201.

The final results are yet to be published but the preliminary data using a 3D model, covering an area of 110 km^1, matched reasonably well the observed thermodynamic conditions in Olkaria East and in the exploration wells which had been drilled. The total heat loss mainly through surface fumaroles and conduction was considered to amount to 400 MWt.

The total recharge to the Olkaria system was estimated to be about 600 kg/s and upflowing at Olkaria NE and W. Most of the area required about 4% effective porosity to attain this but the fracture permeability within known faults has to be about 100-250 millidarcies to obtain a good model fit. It was estimated that about 50 kg/s of hot water from the NE upflow recharges the Olkaria East field. The model provides a good background for exploitation studies and will be updated and refined particularly in view of the system boundary found at OW-704.

POWER POTENTIAL

From the observed temperature and pressure



distribution, the potential production area in the NE is mainly centered around OW-701. Conditions in OW-704 show the well feeds from a lateral flow at shallow depth on the north east edge of the field. Extension to the north is mainly limited by the low permeability in OW-703 and OW-501 and low temperatures at shallow depth in OW-501. There is evidence for cold water encroachment into the field from the north and northeast.

Results from OW-706 and OW-201 show that the Ololbutot fault forms the western boundary while results from OW-X2 and OW-101 show there is a possible narrow extension to the west, towards OW-101.

Fig. 5 is based on these observations and the 220°C isotherm which at 1000m masl, encloses most of the proven and potential areas. An area of 12 km* , including Olkaria East, has been proved by the exploration in the NE and a recent well, OW-27, west of Olkaria East Field. With the Olkaria East production supported by 4 km^2 and an average productivity of 10 MWe/km^2/25 years, an area of about 8 km^2 is available for NE development capable of supporting 80 MWe. It is expected that higher productivity could be achieved by wells drilled in the upflow zone or located to intersect structural targets. For development purposes, the Olkaria NE is therefore proven for development of 2x30 MWe power plants.

Acknowledgments

We acknowledge the approval to publish this paper by our management, The Kenya Power Company Ltd.

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