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# RECENT EXPLORATION AND DEVELOPMENT OF THE OLKARIA GEOTHERMAL FIELD

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## INTRODUCTION

Exploration of the Olkaria geothermal field in Kenya (Fig.1) was commenced in 1956 with the drilling of two hot but unproductive shallow investigation wells (X-1 and X-2, Fig.2). Between 1971 and 1972 a surface exploration program was undertaken, jointly funded by the Kenya Government and United Nations. This resulted in the drilling of a number of further exploration wells during the period 1972 to 1976. The first of these (OW-1) was unsuccessful, however, the second (OW-2) encountered in an area now known as the Olkaria East Wellfield, OEW, (Virkir, 1987), a vapour zone at about 240 C. underlain by a dilute NaCl reservoir in which deeper temperatures closely followed boiling point for depth conditions.

Four exploration wells were subsequently drilled as stepouts from OW-2 with very similar conditions encountered. Following a feasibility study carried out in 1976, production drilling was commenced which progressed through to the staged commissioning between 1981 and 1985 of a 3 X 15 MW(e) turbine power station in the Olkaria East area. A detailed account of this initial phase of exploration and development is given in Svanbjornsson et al. (1983).

In the early 1980's with the OEW area fully committed to commercial development the Kenya Power Company (KPC) focussed attention on exploration of the greater Olkaria geothermal system. The reasons for this were threefold:

1. A reinterpretation of geophysical data indicated the greater Olkaria geothermal system to have an areal extent of at least 80 sq. km. (Hochstein et. al., 1981).

2. Hydrological considerations indicated that the chloride reservoir encountered in the OEW was an outflow derived from a primary upflow located somewhere to the northwest, in a region of the field which had yet to be drilled (Grant and Whittome, 1981).

3. Although fluid qualities in OEW wells were high, productivities were invariably low (averaging 2.0 MW(e)/well) due to poor reservoir permeability. Nonetheless, the geophysical and hydrological evidence for a large geothermal system provided good evidence for there necessarily being better permeability elsewhere in the field.

A program of continued surface exploration studies and deep well investigation drilling was thus initiated in 1981. To the end of 1986 this has included additional geophysical studies; the drilling of 10 exploration well8 widely sited over approximately 50% of the area of the greater Olkaria field area as defined by geophysics; surface and subsurface geological and petrological studies; well measurements and discharge testing; and geochemical evaluation of well fluids.

This paper reviews reservoir data obtained during evaluation of these recent exploration wells. The results of recent surface geophysical surveys and modeling are reported elsewhere in this volume (Anderson and Mwangi, 1987). A conceptual geohydrological model for the Olkaria field is then presented, and ramifications of the model with respect to future exploration and development options are examined.

## GEOLOGICAL SETTING

The Olkaria geothermal field is associated with one of several young silicic volcanic centers related to a N-S trending belt of volcanism developed along the western valley floor of the Kenya segment of the East Africa Rift system. This belt includes Mount Suswa to the south and the Eburru volcanic complex to the north (Fig. 1).

Although geological structure is dominated both regionally and within the Olkaria area by N and NNW trending normal step faults there are several major NW striking faults which also affect the rift floor in the Olkaria area (Ogoso-Odongo, 1986). These latter structures include the Suswa lineament and the Gorge Farm Fault (Fig.2) which are interpreted to be downthrown to the southwest and northeast respectively. The Olkaria geothermal field thus occupies a relatively elevated horst block between these two structures.

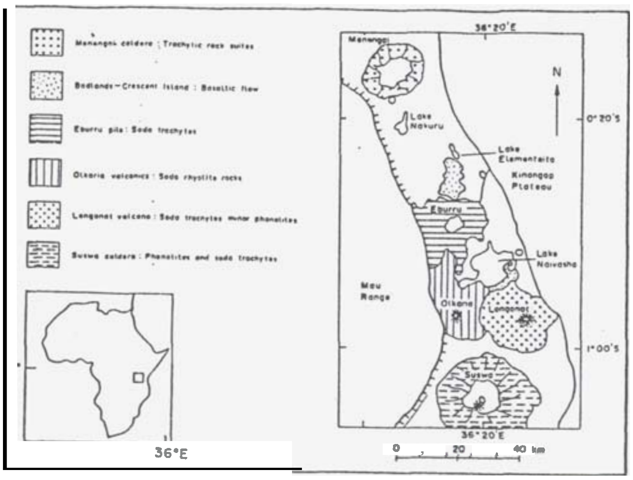


Figure 1. Location of Olkaria Geothermal Field and Regional Geological Setting (Reproduced from Ogoso-Odongo, 1986).

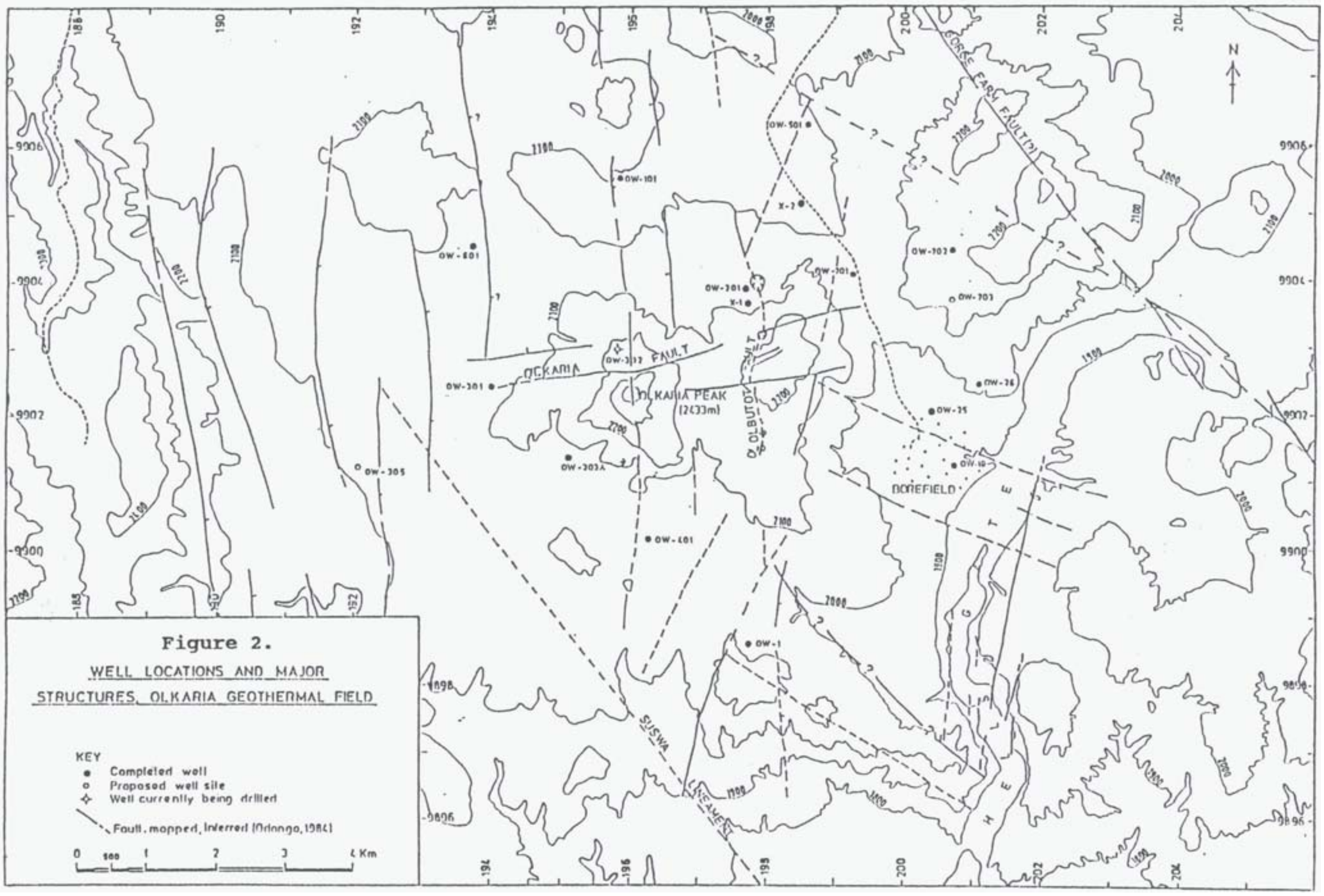


**Figure 2.**
WELL LOCATIONS AND MAJOR STRUCTURES, OLKARIA GEOTHERMAL FIELD

There are a number of parallel ENE striking normal faults with clearly observed surface expression in the central Olkaria area collectively known as the Olkaria Fault Zone (Fig. 2). This zone is considered to be deeply penetrating and it appears to exert a fundamental control on the deep movement of geothermal fluids up to exploitable depths.

Areas of altered and warm ground are extensive throughout the Olkaria area (Glover, 1972) and together with present surface manifestations show a close association with a dominant N-S structure (the Ololbutot fault in the central Olkaria area), and the ENE trending Olkaria fault zone.

Surface mapping by Naylor (1972) identified the Olkaria area as the remnant of an old caldera complex, although this has been questioned by more recent workers (e.g. KRTA 1984), and accepted by others in modified form only (e.g. Virkir, 1985). N-S trending rift floor faulting subsequently provided loci for later eruptions of rhyolite and pumice domes, and massive flows of comendite (sodic rhyolite) now exposed along the walls of the 01 N'jorowa gorge. Late volcanic activity associated with Olkaria volcano and the Ololbutot fault zone produced rhyolite and pumiceous obsidian flows. Much of the area has been subsequently mantled with a surface cover of young (Quaternary) ejecta believed to have originated primarily from Longonot volcano, and Mount Suswa.

## GEOLOGICAL INDICATIONS FOR PERMEABILITY

In many geothermal fields the economic viability of successful resource exploitation is highly dependent upon the nature and extent of permeability within the reservoir rocks. A primary objective of the ongoing exploration drilling program at Olkaria has been to attempt to locate better reservoir permeabilities and correspondingly improved well outputs relative to those of the present borefield.

A study by Browne (1984) of the subsurface geology and alteration mineralogy in a number of wells in the EPF showed that steam production is obtained mainly from within a locally developed fracture dominated reservoir of rhyolite and basalt lavas, where fracturing is due primarily to vertical jointing produced by cooling of thick lava flows, rather than faulting or tectonic disturbance.

This work has been recently extended by Leach and Muchemi (1987, this volume) through examination of cores and cuttings from the recent exploration wells. Significant conclusions resulting from their study with respect to permeability include:

1. pyroclastic units (except at shallow levels) at one time had excellent primary porosity but are now essentially sealed with hydrothermal alteration minerals.

2. jointed basaltic lavas are also largely sealed, though remain the source of some secondary permeability.

3. the dominant source of permeability appears to be related to fracturing and brecciation localised in discrete fault zones. It is interpreted that these zones are widely spaced, with little movement and subsequent fracturing taking place between faulted blocks.

It is thus evident that deep permeability throughout the Olkaria field is predominantly structurally controlled. Primary lithological permeability appears to be important in relatively unaltered pyroclastics at shallower depths but because of the considerable variation in thickness and distribution of these units such permeability is very likely to be quite variable throughout the field. Plutonic rocks have not yet been conclusively encountered at depth in any of the Olkaria wells but the occurrence of occasional shallow intrusive dykes indicates that there may be some secondary permeability developed locally about these during emplacement.

## GEOCHEMICAL RESULTS

Olkaria well discharge chemistries show a range in reservoir water compositions as can be seen in Fig. 3. On the basis of relative proportions of Cl and HCO3 they can be usefully classified into 3 water types:

1. an alkaline Na-Cl water with HCO3 < 10 % encountered in the eastern sector wells (all of the OEW wells and OW-201, 701 and 702).

2. a neutral to alkaline Na-HCO3 water with relatively high B levels and Cl < 10 % encountered in the two tested western sector wells OW-101 and 301.

3. a mixed alkaline Na-Cl-HCO3 water in which Cl> HCO3 > 10 % encountered in the southern area of the field in well OW-401.

Downhole samples collected from western wells show that in this sector there are deeper secondary zones producing Na-Cl water which underlie a relatively shallow (+1200 to +1400 m msl) layer of sodium bicarbonate water (see Fig.3). On discharge these wells produce a mixture of fluids from both zones which due to higher permeabilities in the shallow zone are dominated by the Na-HCO3 water.

The Olkaria reservoir is thus interpreted as a relatively simple two layer chemical system with a neutral chloride water extending continuously at depth through the whole field and overlain in parts by shallow, relatively cool bicarbonate water derived from condensation of steam and gas evolved through boiling in the deep chloride reservoir. The distribution of these fluids in the reservoir can be clearly mapped by petrological determination of the characteristic hydrothermal alteration suites associated with each fluid type (see Leach and Muchemi, 1987, this volume).

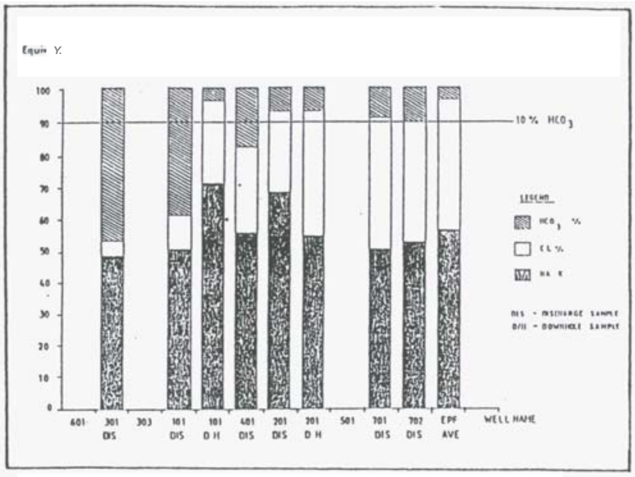


Figure 3. West to East Section of Well Chemistries.

Although extensively developed in the west the shallow HCO3 layer does not apparently extend eastward beyond the Olobutot fault as this water type is not evident in either discharge fluids or alteration suites in any of the eastern sector wells. It is thus indicated that:

1. the boiling chloride water source from which the condensate derives is located in the western sector, associated with a high pressure and temperature region developed in the vicinity of OW-301 (see Figs. 7 & 8).

2. the Ololbutot fault which is conspicuously associated with an anomalous depression in central field temperatures (see Fig.8) may be acting as sink for condensate thus preventing any further eastward flow.

The evidence for the existence of a hydrologically continuous chloride water reservoir at depth in the Olkaria system is contained in Fig. 4. This shows that the chemistry of the Na-Cl water in both western and eastern sector wells is consistent with derivation from a primary chloride water containing 300-450 mg/kg Cl, at 300 C. or higher.

Figure 4. Plot of Reservoir Cl (mg/kg) vs. TSiO2 (deg. C.).

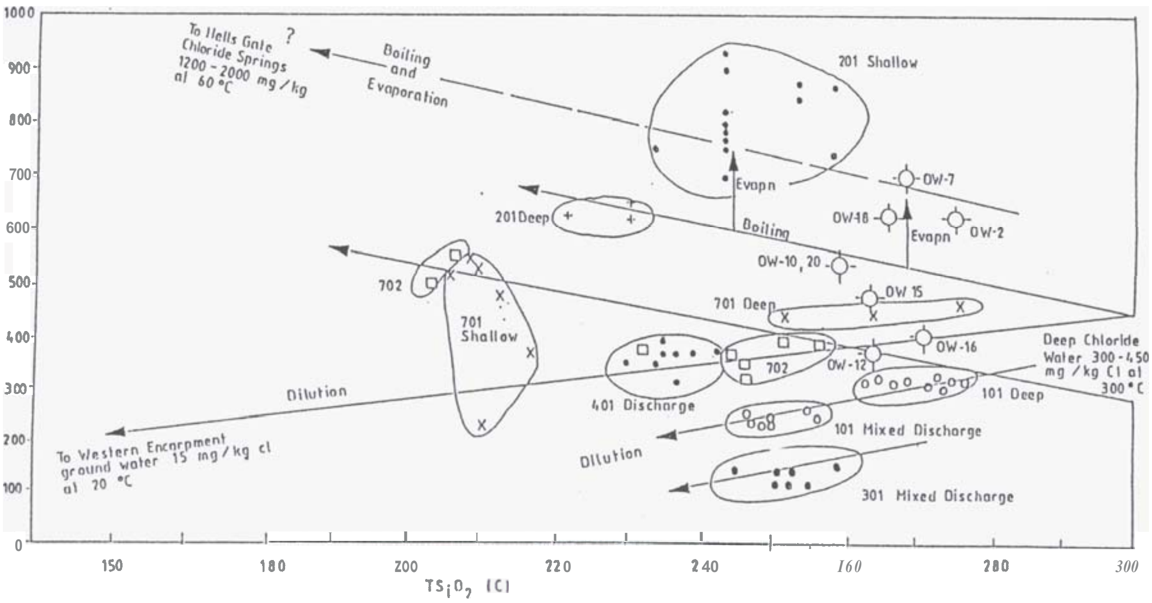

Fig. 4 also shows that vertical chemical gradients in the reservoir are pronounced. In the western sector wells chloride water grades abruptly upwards into HC03 water. In the eastern wells deep chloride water can be seen to undergo adiabatic boiling, cooling and increasing mineralisation during upward convective movement to more shallow levels (see for example deep and shallow water compositions for wells OW-701 and 702 in Fig.4). At relatively shallow levels in the eastern sector evaporative processes appear to be become important. Such processes are considered to provide the dominant control on the genesis of high Cl surface springs (2000 mg/kg-Cl) discharging at an elevation +1800 m msl in the 01 N'jorowa gorge, and a shallow low resistivity layer indicated from geophysical data to be overlying the OEW area.

These geochemical relationships together with hydrologic information gained from gas chemical data have been used to construct the conceptual geochemical process diagram shown in Fig. 5. This summarises chemical and physical processes thought to be occurring in the Olkaria reservoir.

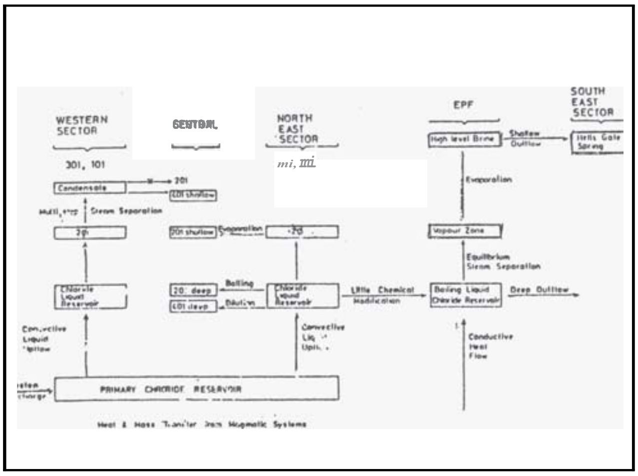


Figure 5. Geochemical Process Diagram.

## RESERVOIR HYDROLOGY

The location of feed zones in selected production and all exploration wells is shown in Fig. 6 projected onto a W-E section line. It is evident from this that most Olkaria wells intersect two distinct reservoirs; a discrete upper aquifer, and a less well defined deeper reservoir.

The upper aquifer defines a thin almost horizontal reservoir at an average elevation of +1300 MSL and is about 100m thick. It covers most of the field drilled to date but appears to be absent in wells OW-501 and 601. It is this aquifer which produces HC03 water in the western wells, and adiabatically cooled derivatives of deep chloride water in the eastern wells. Waters throughout the upper aquifer are boiling and in some locations form steam dominated zones, such as that seen in the OEW area, due to pressure gradients associated with lateral flow of waters.

Beneath the shallow aquifer there is a thick liquid dominated reservoir extending from +1200 MSL down to at least 0 MSL. This reservoir is characterised by randomly distributed permeablity throughout its thickness. Geological evidence given previously indicates that this results from random well bore intersections with discrete fault zones

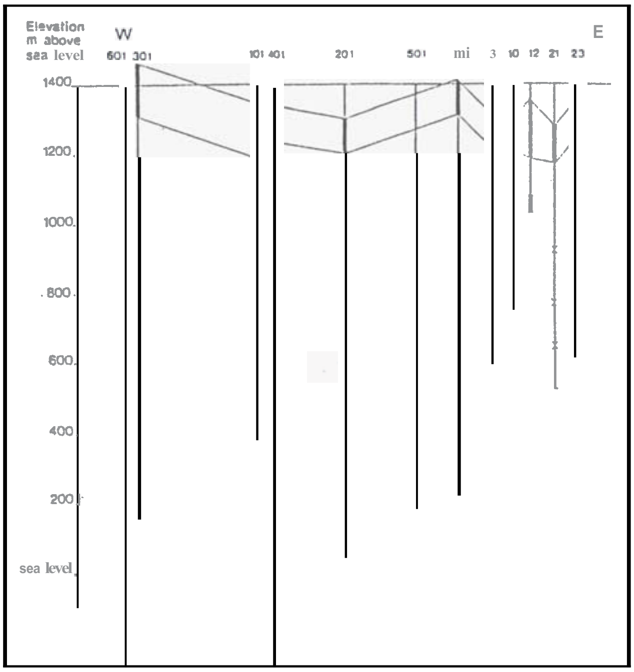


Figure 6. Location of Olkaria Well Production Zones

which frequently have no surface expression due to the extensive tephra cover over the area.

In most locations the shallow aquifer is overpressured with respect to the deep reservoir. This results in internal downflows occurring in many wells. Such discontinuities in the vertical pressure gradient occur due to differences in permeability and pressure gradients in the two reservoirs.

Pressure and temperature distributions at +900 m msl in the deep reservoir are shown in Figs. 7 & 8. Two regions of high pressure and temperature are identified, one in the east near 702 and the other in the west near 302. These are both open to the northeast and west respectively due to the limited resource area yet tested by drilling.

These two features are interpreted to indicate convective upwellings of hot chloride water. Although manifest within drilled depths as two localised features it is considered on the basis of the chemical evidence above that the two pressure and temperature highs derive from a deep reservoir chloride water associated with an intrusive heat source. This deep water convects upward through structural permeability offered by the Olkaria fault. At comparatively shallow levels it then appears that the upflow is perturbed by cooler fluids associated with the Ololbutot fault.

The upper aquifer across the field is interpreted to be fed in the region of each pressure high with fluid from each apparent chloride upflow. In the east this consists of boiling chloride water but in the west it consists predominantly of the bicarbonate rich condensate. This may indicate that the western portion of the upflow is boiling at greater depth due possibly to higher gas partial pressures in the deep chloride water in this region and with multi-step steam separation processes occurring, whereas the eastern portion of the upflow may be less gas rich and dominated by equilibrium steam separation boiling.

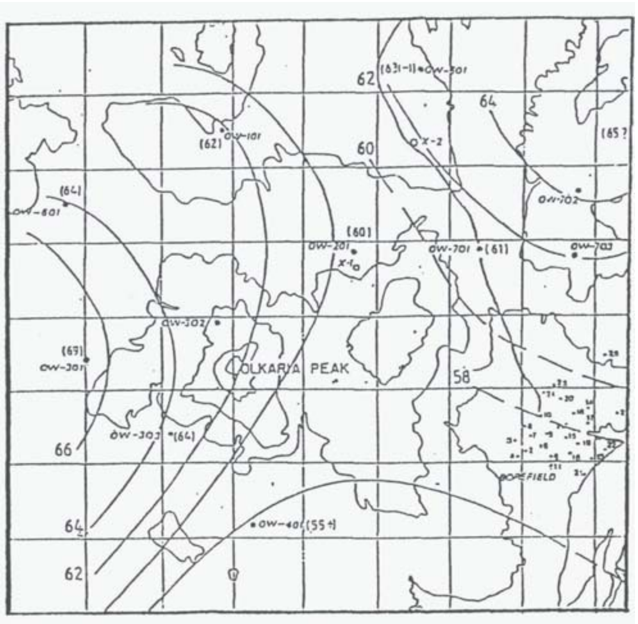


Figure 7. Isobars (bar) at +900 m msl.

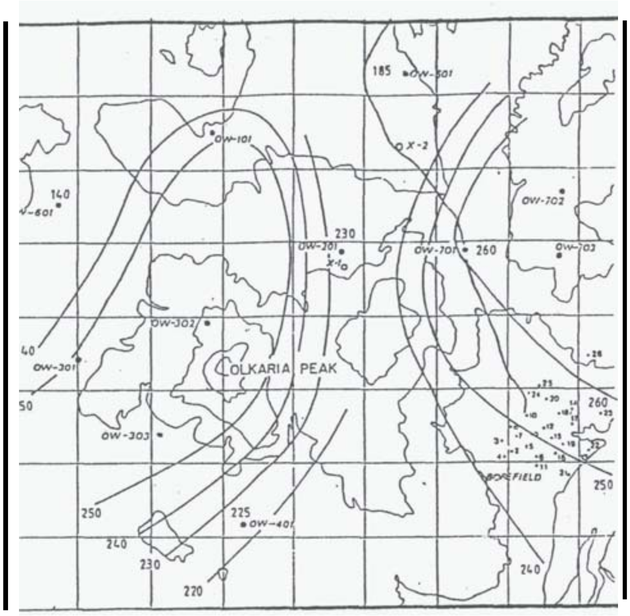


Figure 8. Isotherms (deg C.) .at +900 m msl.

The perturbation generating the two apparent upflows is a pressure and temperature sink which is clearly associated with the N-S trending Olobutot fault situated between the western and eastern sectors of the field. Cooling fluids outflowing from both the deep reservoir and upper aquifer from the two pressure highs appear to descend into the Olobutot structure and then to flow southward away from the field along this fault. Temperature inversions at deeper levels in wells OW-201 and 401 also indicate that the Ololbutot fault is acting as a conduit for cool water intruding laterally into the reservoir at depth.

These interpretations are summarised in the hydrogeological model given in Fig 9. Of particular relevance to ongoing exploration of the Olkaria resource is the indication contained in the model for potentially prime resource in undrilled country to the west of OW-302. This view is reinforced by the fact that this western region shows a large area of very low resisitivities which extend to depth from 500-900m below surface. An exploration well to test this area has been programmed for drilling in 1988.

## FUTURE DEVELOPMENT

The exploration well drilling program carried at Olkaria over the past six years was designed with two principal objectives; to prove sufficient productive reservoir for future development, and to identify regions within the reservoir with greater permeability than has been obtained in the existing borefield. Results obtained todate have substantially expanded the size of the inferred resource potential beyond that earlier confirmed and developed in the OEW, and has shown that although permeabilities in some exploration wells are higher than for OEW wells they are nonetheless quite variable and generally unpredictable.

As permeability in the chloride reservoir appears to be invariably related to discrete fault zones it is thus of considerable future importance to obtain a more detailed understanding of the structural controls on fluid movement in the Olkaria system. It is only when this understanding has been obtained that consistently higher well outputs, and thus reduced development costs, will be able to be attainable.

**Results presented here indicate that the two recently identified upflow regions, the north east and the and western sectors are two obvious locations at which future development may proceed.**

North East Sector:
Data obtained from wells OW-701 and 702 confirm a substantial northward extension of the resource on which the OEW development is based. The existing production wells confirm a resource area of 2 sq.km. within an inferred reserve of 5 sq.km. Wells OW-701 and 702 infer an additional reserve of 2 sq.km. which together with the area between the 700 series wells and the OEW infer a total reserve of 11 sq.km. for this sector.

Calculations of stored heat contained in the eastern sector using a heat recovery of factor of 0.3 for rock and 0.8 for fluid, and an electrical conversion efficiency of 15 %, infer an energy recovery capacity equivalent to 16 MW(e)/ sq.km. over a 25 year plant life, i.e. 175 MW(e) in total for the sector.

As 45 MW(e) of this reserve must remain dedicated to steam supply to the existing plant it is thus indicated that an additional generating capacity of up to about 100MW(e) could be installed in this sector.

At present it is uncertain whether wells drilled in the eastern sector will be of greater productivity than existing production wells. OW-701 has a fluctuating discharge characteristic but appears to produce an average output of about 4MW(e), and OW-702 was completed with a drillstring in the well and is thus unsuitable for production.

Western Sector:
The region surrounding OW-301 is also promising as a potential future production area, particularly in that:

1. with an output of 5 MW(e) OW-301 is significantly more productive than existing production wells (approximately twice that of the average OEW well).

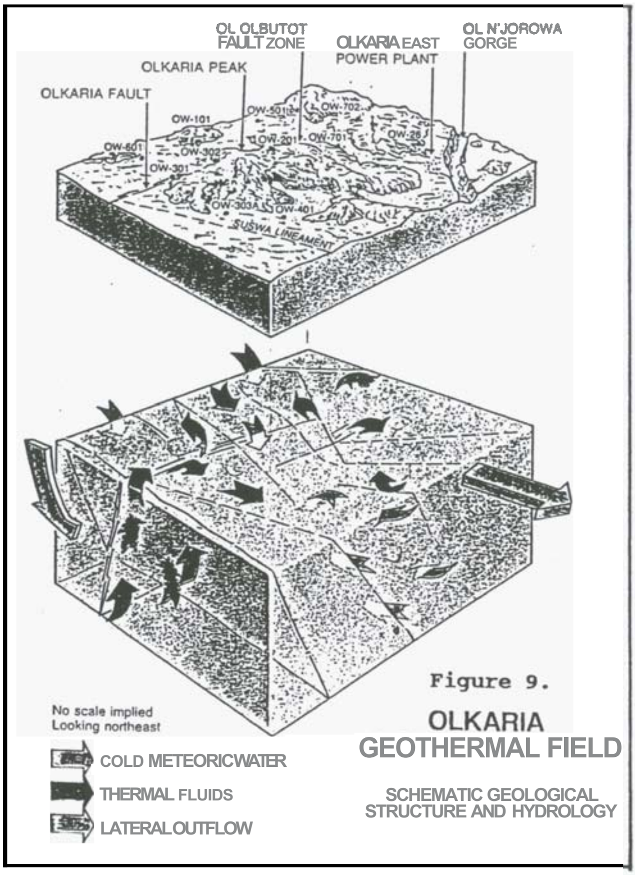


Figure 9.

2. resource data indicates that the western sector shows good potential for the existence of a substantial upflow of primary reservoir fluid.

Well OW-303A was completed prematurely with a drillstring in the hole and it does not therefore adequately test the reservoir volume into which it was drilled. Nonetheless, temperature measurements made down to 1000 m depth in the available open hole show that it intersects reservoir temperatures comparable with those measured at similar depths in OW-301.

These two wells are then considered to collectively test a reservoir area of 3 sq.km., which on the basis of stored heat calculations made using the same assumptions as for the eastern sector yield an inferred energy recovery capacity of 14 MW(e)/sq.km. over 25 years, i.e. equivalent to 42 MW(e) for the sector. It is felt that this figure will be significantly expanded when evaluation of existing well OW-302 has been completed. The drilling in 1988 of a proposed well further to the west of OW-301 is also seen as being of considerable importance in confirming both the resource potential of the western sector, and the possibility that enhanced average well productivities might be obtainable in this region.

Considerable impetus has been recently given to geothermal development in Kenya as a result of the formulation of a national energy plan for the next 20 years (Acres International, 1987) in which geothermal power is identified as being the most economically favorable option for base load power generation. The plan calls for the commissioning of an additional 2x30 MW(e) units between 1993 and 1994, and the later staged commissioning of 2x55 MW(e) units, the first in 1996 and the second in 1999.

On the basis of resource criteria the north east Olkaria sector has become the most attractive development option for the 2x30 MW(e) station, and the subsequent 2x55 MW(e) station has been tentatively assigned to either the western Olkaria sector and/or the Eburru exploration prospect located approximately *30* km to the north of Olkaria, depending on the outcome of future drilling results.

The current geothermal program being undertaken by the Kenya Power Company is thus directed toward the drilling and testing of 3 additional delineation wells in the north east Olkaria sector prior to undertaking an engineering preinvestment study in early 1988. This study will provide the basis upon which future commitment may be made to development of a 60 MW(e) power station in this sector. Delineation drilling in the west Olkaria sector will continue during 1988, and the drilling of a 4-8 well exploration program will also commence at Eburru to provide the necessary resource information to enable commitment of one or other of these two areas to the subsequently required 110 MW(e) development.

## ACKNOWLEDGMENTS

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